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Performance Evaluation of Hybrid Bamboo Reinforced Concrete Beams through Validated Numerical Modelling.

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ABSTRACT

The building industry's demand for steel reinforcement bars has increased with the rapid growth and developments in the world. However, steel production contributes to harmful waste and emissions that cause environmental pollution and climate change-related problems. As an alternative, bamboo, a readily available natural green building material is being proposed as a substitute for steel rebars because of its cost-effectiveness, sustainability, and reasonable tensile strength. In this research, hybrid beams were analyzed through validated Finite Element Modelling (FEM) by replacing the steel rebars with bamboo as reinforcement materials. The standard-size beams were subjected to three-point loading in FEM to study the parameters such as load-displacement response, energy absorption, maximum capacity, and failure patterns. The Gene Expression Programming (GEP) is next used to help develop a simplified equation for prediction of the flexural strength of bamboo reinforced concrete (BRC) beams. This study concluded that the partial replacement of flexural steel with bamboo in reinforced concrete beams would not compromise the overall capacity and energy absorbing capabilities of the structure. Moreover, it could offer an economical and viable alternative.

KEYWORDS: Green Building Material, Reinforcement. FEM, Replacement, Bamboo, GEP

1. INTRODUCTION

Environmental pollution has increased because of production of building materials such as concrete and steel, etc. (Barbuta et al. 2015). The construction industry is among the most polluting industry in the world (Dräger and Letmathe 2022) The ecology is significantly damaged during the production of steel and concrete (Chaturvedi and Ochsendorf 2004). To reduce the carbon footprint of construction materials, it is imperative to invest in sustainable alternatives to fulfil the rising demand of the building industry.

A forest product with high social, economic, and ecological importance is bamboo(Muhtar 2020a). Bamboo is one of the potential substitute materials that is gaining popularity as a natural, sustainable resource that can take the place of steel as reinforcement in reinforced concrete (Al-Fasih et al. 2021). Bamboo can grow at mean sea level in a variety of situations up to elevations of 3000–4000m, and it has an astounding range of altitude for its growth. Due to tension brought on by the bending of plants by air currents, the extent of fiber distribution in its dimensions sections has a significant concentration near the outside portion (Qaiser et al. 2020a). Wood and bamboo must be used as building material as they are environmentally friendly (Xu et al. 2022). Since bamboo is a quick-renewing plant with a faster growth rate than trees, it is more suitable to be used as a sustainable source of wood for industry, particularly in construction projects, it needs to be protected from several conditions such as temperature, moisture, and pests. Therefore, treatment is needed to preserve the bamboo. Because bamboo has so many promising features, it is appropriate to be used as a substitute for structural wood in building (Chaowana 2013), which indirectly aids in the preservation of the environment worldwide. Bamboo is often thought to be more flexible than wood whereas typical bamboos are stiff and inflexible and are comparable to hardwoods (Obataya, Kitin, and Yamauchi 2007). It has excellent fire resistance due to its high silicate acid concentration. It can withstand a temperature of 400° C when filled with water (Sethia and Baradiya, n.d.). In comparison to compression, bamboo has higher tensile strength (Awalluddin et al. 2017). At the age of three to five years, the bamboo material can attain its maximum strength (Liese 1987). Researchers have examined the viability of using bamboo as a building material in western nations and found out that it is advantageous for usage in light prefabricated constructions since it is a lightweight material (Li et al. 2012).

Comparing bamboo reinforced concrete's (BRC) mechanical qualities to those of plain concrete's (PC) and steel-reinforced concrete's (SRC). According to reports, 35% of the SRC's strength was made up of BRC members, whose numbers had doubled above that of PC (Liu et al. 2021). Beams, columns, and slabs were some of the BRC members that underwent testing, (Archila et al. 2018)provided a critical evaluation of the applicability of BRC based on a case study, and Ghavami (Ghavami 2005) conducted a review on BRC application in structures. In comparison to SRC, both writers underlined the material's benefits and drawbacks in terms of durability, mechanical qualities, and environmental friendliness. Therefore, it is essential to study the behavior of the BRC beams, such as the flexural strength of the BRC beams.

Concrete has been used widely as a building material because of its several benefits, including affordability, accessibility, and fire resistance. Due to its extremely low tensile strength, it cannot be used independently everywhere. Steel rebar is commonly used to reinforce concrete. Although steel has a much higher tensile strength than concrete does, it should only be used in limited circumstances because it is expensive and a significant energy consumer (Ramaswamy and Mathew 2019). People have recently become more interested in finding alternate ways to employ locally available things to meet the rising demands for concrete constructions due to the high cost and global shortage of steel rebar production (Agarwal and Maity 2011).

The same is true for countries with developing economies where the majority of the population lives in rural regions. For this reason, the research has focused on several alternatives to steel reinforcement that can be used (Sevalia et al. 2013). Bamboo may prove to be one of the best materials to strengthen with concrete in order to achieve desired effects, especially in substandard construction. It is a naturally occurring, inexpensive substance that is widely accessible and offers some resistance when put under compressive and tensile pressures. Because of its high tensile strength bamboo is a good choice for constructions that must withstand tensile loads (Amada and Untao 2001). Although it grows natively in many countries all over the world, certain kinds are grown artificially. Around latitudes of about 40° south, or in regions with average annual temperatures between 20° C and 30° C, bamboo forests can be found throughout the tropics and subtropics and at elevations between 20 and 3,000 meters, bamboo that is suitable can be found and these plants can be fully grown in a span of three to four years (Terai and Minami 2012). Caori.P experimentally determined the values of Elastic modulus and Poisson ratio in compression perpendicular and parallel to fibers. For compression parallel to the fiber tests, the Poisson's ratio ranged from 0.621 to 1.506 while for compression perpendicular to the tests, it ranged from 0.013 to 0.278(Takeuchi, Estrada, and Linero 2016)

The requirements to make bamboo reinforcement impermeable can be met by a wide variety of waterproofing materials. To guarantee there is no swelling, thorough testing must be performed before to use. Internodes and nodes have quite different structures and structural relationships because the former is brittle while the latter are ductile (Sakaray, Togati, and Reddy 2012). The area of the knot has been observed as the weakest spot in a full bamboo twig exposed to tensile loadings (Sabbir, Mamun, and Fancy 2012). Using the whole bamboo as reinforcement will cause a lack of bond between concrete and reinforcement. A study states that corrugated bamboo is beneficial to avoid bond slip and offer sufficient flexural capacity (Qaiser et al. 2020c).

The more starch a bamboo plant contains, the more susceptible it will be to insect attack. Therefore, the more resilient the bamboo will be with a decreasing starch content when moisture is lost, the better the seasoning (Wakchaure and Kute 2012). Being an environmentally beneficial material, bamboo aids in lowering atmospheric CO_2 levels. Therefore, integrating bamboo in concrete to create green structures may be a smart option (Sakaray, Togati, and Reddy 2012).

On bamboo-reinforced concrete beams, Markos Alito conducted several tests. In order to fully utilize the mechanical characteristics of bamboo, he found that the design of bamboo and steel-reinforced beams was comparable ('BAMBOO REINFORCEMENT AS STRUCTURAL MATERIAL FOR ...' 2017.). Additionally, it was demonstrated in a study that bamboo-reinforced members showed high load capacities in horizontal planes compared to unreinforced counterparts (Mark and Russell 2011).

When exposed to flexural loads, bamboo reinforced concrete constructed from materials performed better than steel reinforced concrete (Karthik, Rao, and Awoyera 2017). According to current study, notably in areas where the availability of steel is limited, the bamboo material can be used as a substitute for steel reinforcement (Wibowo, Wijatmiko, and Nainggolan 2017).

Dewi and Nuralinah (Dewi and Nuralinah, n.d.) investigated the impact of including bamboo reinforcements, such as pegs, in concrete beams that were tested with a four-point loading configuration. They discovered that by including these pegs in addition to the bamboo reinforcement, the concrete beams' capacity and strain energy increased. Agarwal (Agarwal, Nanda, and Maity 2014) discovered that a two-point load test arrangement boosted the load-carrying capability of a concrete beam reinforced with a treated bamboo of just 1.49% area by up to 29.41%. According to Tan (Tan et al. 2017), a concrete beam entirely reinforced with bamboo was able to attain around 46% of the load-carrying capability of a concrete beam reinforced with steel. Khan (Khan 2014) discovered that the geometry of the bamboo reinforcement bar had a substantial impact on performance, with square bamboo-reinforced concrete beams having a higher flexural strength than triangular and rectangular bamboo-reinforced concrete beams.

Moreover, one of the recent research projects tested the mechanical characteristics of bamboo, including tension strength, bond strength, and water absorption. The presence of knots affected the tensile strength results, and failure occurred at nodes in all samples. This study concludes that in bamboo-reinforced concrete beams, the ultimate capacity increased significantly with corrugated reinforcement compared to wired reinforcement, and all beams failed due to pure flexure (Qaiser et al. 2020b). These studies conclude that Bamboo is a suitable sustainable alternative to steel reinforcement in the flexural members and due to its properties, it can potentially replace 50% of the reinforcement resulting in a hybrid beam. For the easy calculation of the flexural strength of hybrid beams without numerical and experimental analysis, AI tools can be used to predict the model.

A rapid spike in the use of soft computing techniques to build an empirical model has been observed recently (Javed, Amin, et al. 2020; Javed, Farooq, et al. 2020). Gene expression programming (GEP) is one of the popular soft computing methods utilized by various researchers in several engineering perspectives. GEP was used to create an equation to calculate flexural strength of BRC beams using variable parameters of bamboo. Several studies (Imam et al. 2021; Azim et al. 2020a) have demonstrated the effectiveness of GEP as a tool for creating prediction models for various applications in civil engineering. Several GEP models were put up by Murad (Yasmin Zuhair Murad, Hunifat, and AL-Bodour 2020a; 2020b; Y. Murad 2020) to forecast the shear strength of exterior and interior RC beam-to-column joints subjected to monotonic, uniaxial, and where the developed GEP models were effective under biaxial cyclic loading in comparison to code formulations, better. Many academics (H. Naderpour and Mirrashid 2018; Tarawneh et al. 2021; Hosein Naderpour, Haji, and Mirrashid 2020; Ebid and Deifalla 2021; M. F. Iqbal et al. 2021; Y. Murad et al. 2020; Shahmansouri, Akbarzadeh Bengar, and Ghanbari 2020; Mansouri, Güneyisi, and Mosalam 2021; Wei and Xue 2021; Y. Murad, Ashteyat, and Hunaifat 2019; Azim et al. 2021; Beheshti Aval, Ketabdari, and Asil Gharebaghi 2017; M. F. Iqbal et al. 2020; Yasmin Z. Murad, Tarawneh, and Ashteyat 2020; Azim et al. 2020b) have demonstrated that GEP is a useful technique for creating forecasting models for various uses in civil engineering. In the recent research works there is no significant work on predicting or developing Gene Expression Model on finding out the flexural strength of BRC beams. Machine learning techniques have become a leading contender for being able to predict uncertainty in material properties and configurations with accuracy. Multiple evolutionary techniques have been used to create squat wall shear equations (Gao et al. 2019). For instance, Ghaboussi et al. (J. Ghaboussi, J.H. Garrett Jr. 1991) have successfully used artificial neural networks (ANNs). The shear strength of RC squat walls under cyclic or monotonic loads has been predicted by many authors using artificial intelligence (AI) software. Regarding chromosome representation, GEP differs from other known artificial intelligence (AI)-based methods (Tariq, Khan, Ullah, Zamin, et al. 2022a). In summary, a reappraisal of the flexural strength model of the BRC beams is essential to collecting the available experimental data. This thought has motivated the current study to create a simplified regression-based model employing the gene expression programming machine learning method (GEP). This model will help us save both money and time.

Based on literature review, most of the investigations are focused on treatment of bamboo, stiffness reduction, mechanical properties of bamboo and fire resistance of Bamboo fiber reinforced (S. Kavitha and T. Felix Kala 2021; Muhtar 2020b; Awalluddin et al. 2017). There is lack of research on the comparative study of flexural strength of hybrid BRC beams with the steel reinforcement and its empirical model.

The recent studies are mainly focused on experimental investigation, there still exists a significant gap for numerical investigations related to the performance of BRC. The concept of hybrid BRC beams has yet to be fully explored which could offer strength comparable to SRC beam without significantly compromising the strength and performance. Therefore, this study aims to investigate the feasibility of using bamboo as a steel replacement material in reinforced concrete. Moreover, this research attempts to numerically simulate the behavior of BRC beams of full size compared to previous studies where only small-scale experiments have been conducted.

The aims of this study are as follows:

1. Comparative analysis of Hybrid, BRC and SRC beams to determine usefulness of bamboo.
2. Propose a strength assessment model for Hybrid BRC beam using AI based tools (GEP).
3. Validation of proposed strength assessment model through numerical schemes.

To accomplish the goals of the study, the validated FEM models of BRC and SRC beams were preprared considering nonlinear properties of concrete, steel and bamboo. The specimens were tested under three-point loading conditions, to determine the flexural strength of BRC beam using numerical method. Afterthat, GEP is used to proposed a strength assessment model for Hybrid BRC beams for the calculation of flexural strength of Hybrid beam saving resources and time. The methodology of numerical modeling and GEP is provided in section 2 and the results of the analysis are discussed in section 3.

2. MATERIALS AND METHODS

2.1 Constitutive modeling of material:

The Concrete Damaged Plasticity (CDP) model is a widely used tool for modeling the inelastic behavior of concrete and other quasi-brittle materials in finite element analysis. The CDP model is a continuum-based damage model for concrete that is based on plasticity. The model infers two primary failure mechanisms of concrete materials, namely compressive crushing and tensile cracking. To govern the yield surface's development, two hardening factors, , ε_{c}^{pl} and ε_{t}^{pl}, are utilized. These factors correspond to the compressive and tensile equivalent plastic strains, respectively, and correspond to the failure mechanisms under compression and tension loading. The damage variables can have values ranging from 0 to 1, with 0 being intact material and 1 denoting complete loss of strength. The following equations, $\sigma_{t} = (1 - d_t)E_o(\varepsilon_{t} - \varepsilon_{t}^{pl})$ and $\sigma_{c} = (1 - d_c)E_o(\varepsilon_{c} - \varepsilon_{c}^{pl})$ give the stress-strain relations under uniaxial compression and tension loading. Where, E_o is the initial (undamaged) elastic stiffness of the material and d_t and d_c are the tension damage variable and compression damage variable, respectively. The plastic flow parameters of concrete materail are utilized from the previous research (Senthil, Rupali, and Satyanarayanan 2017; Senthil, Rupali, and Kaur 2018; M. A. Iqbal et al. 2012).

The behavior of steel and bamboo bars was simulated with elasto-palstic behavior modeling approach (Zhao et al. 2021). This study used the concrete and steel properties from the past research study by Muhtar (Muhtar 2020a). The bamboo’s tensile strength, strain and density was taken from (Muhtar, 2020; Qaiser et al., 2020). Table 1 displays the properties and characteristics of bamboo and steel reinforcement, which were employed in the study, whereas Table 2 exhibits the parameters applied for modeling concrete behavior through the Concrete Damaged Plasticity (CDP) approach (Xiao et al. 2017).

Table 1. Mechanical and Material Properties

Material	Density	Elastic	Poisson	Ultimate	Ultimate

	(Kg/m^3)	**Modulus (MPa)**	**Ratio (μ)**	**Compressive Strength (MPa)**	**Tensile Strength (MPa)**
Bamboo	700	17200	0.20	150	214
Concrete	2300	33600	0.15	31.31	3.13
Steel	7850	200000	0.30	172.3	400

Table 2. CDP Parameters

Parameters	**Value**
Dilation Angle	40
Eccentricity	0.1
Compressive strength of concrete, f_c'	18 MPa
Poisson ratio of concrete (μ)	0.15
fb_o/fc_o	1.16
K	0.67
Viscosity Parameter	0

2.2 Model Description

The behavior of BRC and SRC beams was modelled using the ABAQUS/CAE software (Abaqus 2020, 2009). The concrete beam having a cross section of 500 x 500 mm and length of 4300 mm was used with a 50 mm clear cover on each side of the beam. The shear stirrups of 10 mm size were spaced 200 mm apart.

Due to limited research on the comparative studies of flexural strength of BRC and SRC beams, the following five beams shown in

Table 3, were modelled with different set of reinforcement. Model B1 was used as the reference beam which consists of steel reinforcement and steel stirrups as shown Figure 1(a). Model B2 was a doubly reinforced beam with bamboo bars as longitudinal reinforcement without stirrups as shown in Figure 1(b). In model B3, bamboo stirrups were used to hold the doubly reinforced bamboo bars as shown in Figure 1(c). Furthermore, model B4 replaced the bamboo stirrups with steel stirrups, and reinforcement was kept the same as in model B3. Model B4 is shown in Figure 1(d). Lastly, in model B5, beam was reinforced with 50% steel and 50% bamboo and steel stirrups, and it was referenced as the hybrid beam. Model 5 is represented in Figure 1(e).

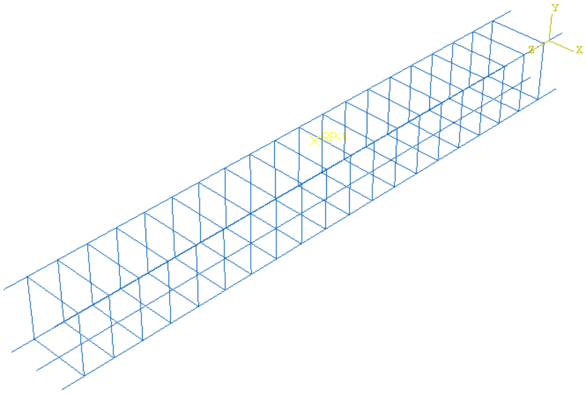
Table 3. Description of Beam Models used in this study.

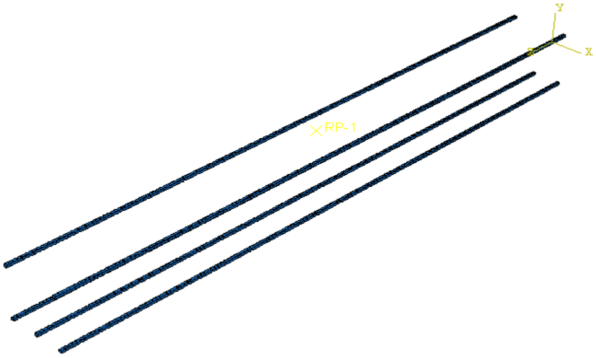
Designation	Specimen type	Description
B1-4SB-SS (Control)	Steel	Doubly reinforced beam with steel bars and steel stirrups
B2-4BB	Bamboo	Doubly reinforced beam with bamboo bars only
B3-4BB-BS	Bamboo	Doubly reinforced beam with bamboo bars and bamboo stirrup
B4-4BB-SS	Bamboo and Steel	Doubly reinforced beam with bamboo bars and steel stirrups
B5-2BB-2SB-SS	Bamboo and Steel	Doubly reinforced beam with 50% steel and 50% bamboo and steel stirrups

Five beam models were prepared with different reinforcement distribution. The reinforcement for each beam is decided from the reference beam which was a typical beam with steel rebrs only. The minimum area of steel is calculated for the beam and the number of the bars were decided. The formula used to calculate the minimum area of steel is as follow (ACI Collection of Concrete Codes, Specifications, and Practices, 2019):

$$A_s)_{min} = \frac{1.4}{f_y} b_w \tag{1}$$

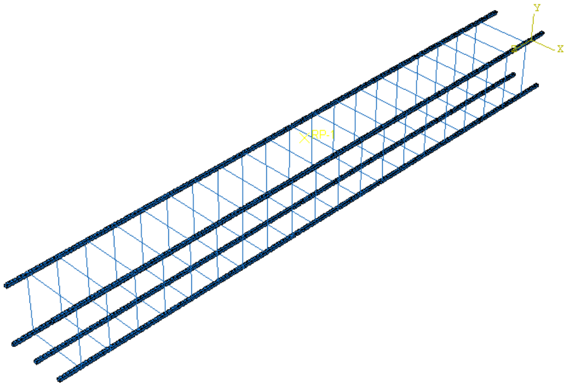
Where, b_w = width and d = effective depth of beam. The steel bar of 22 mm diameter was used to provide required steel reinforcment and same number of bars were provided in all specimens. The corrugated bamboo of 20 x 20 mm size was used for the analysis of BRC beams as shown in Figure 2.

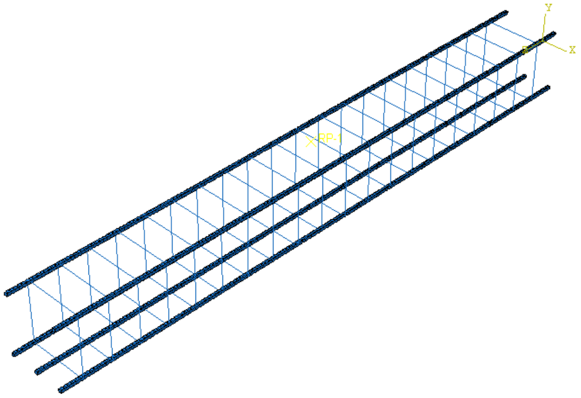


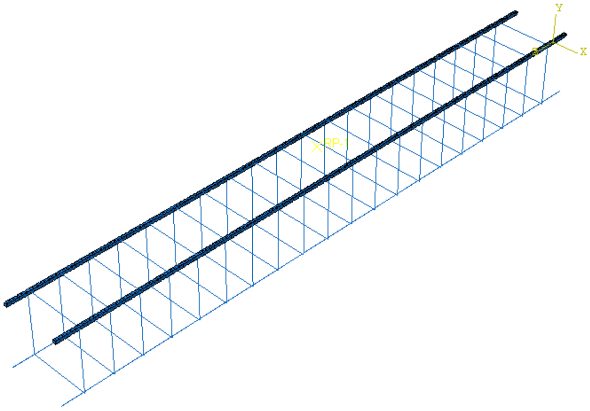


a) Beam reinforced with steel bars and steel stirrups (B1-4SB-SS)-Control

b) Beam reinforced with bamboo bars only (B2-4BB)







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Representation of Beam Models used in this study.

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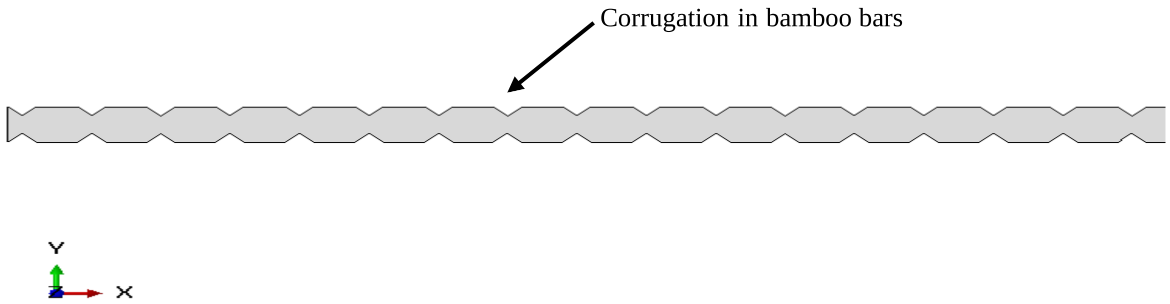


Figure 2. Shape of Corrugated bamboo used in FEM.

2.3 Boundary Conditions, Interactions, and Loading:

To model the bond between concrete and bamboo, the embedded region method was used in numerical program. The method perfectly links the host element (concrete) and the slave element (reinforcement bars) as shown in Figure 3. This method also enables the displacement of the bars to be compatible with the displacement of the nearby concrete components.

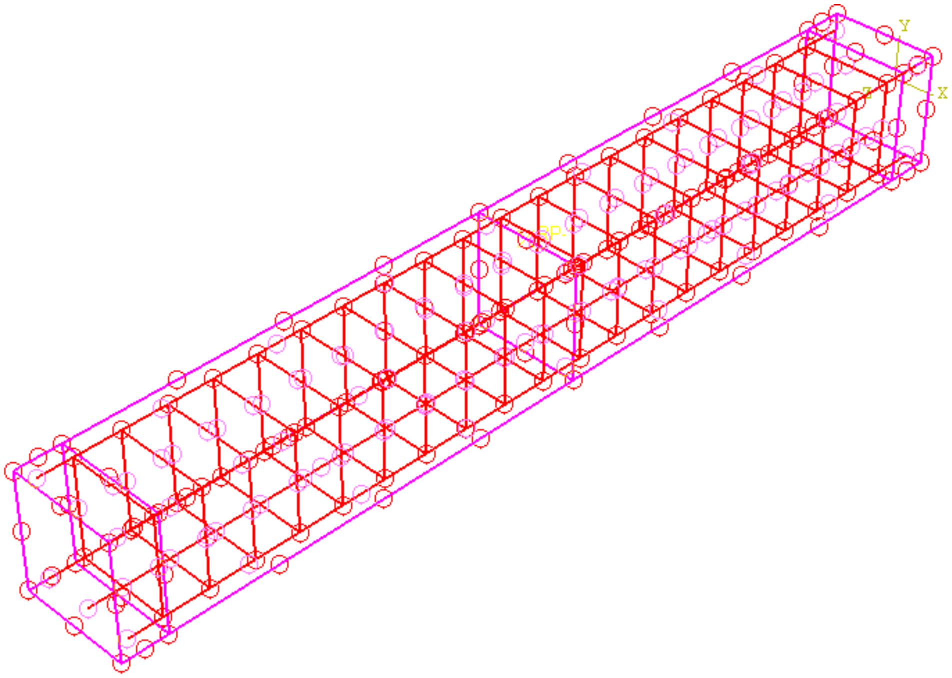


Figure 3. Embedded Reinforcement and Host Beam

The capacity curve was obtained in the following stage by applying the displacement-controlled 10 mm loading at the reference position. The kinematic coupling constraint was used to apply laod through reference node, coupling nodes. The reference point (RP-1) and top surface interacted through a kinematic link. This procedure then resulted in the load versus displacement curve at the reference position. The simply supported boundry conditions were used for application of laoding. The details of boundary conditions and kinematic coupling are shown in Figure 4.

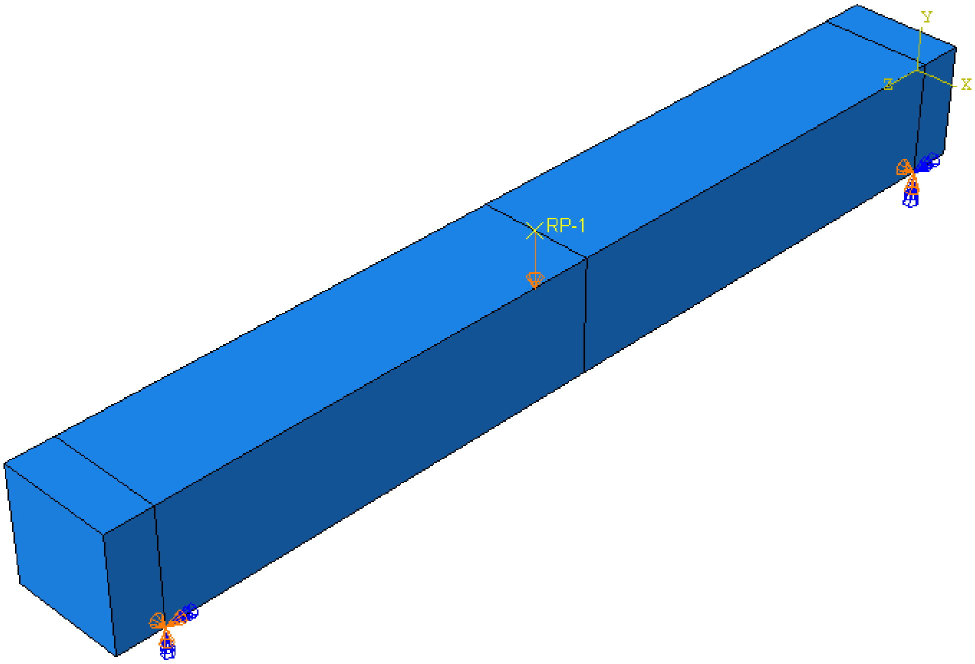


Figure 4. Boundary Condition at supports.

2.4 Mesh Analysis:

Reduced integration with 3-Dimensional, Continuum, 8 Node Elements (C3D8R) was used to mesh the solid elements. The bar elements were meshed with 2 nodes three-dimensional truss element (T3D2). The analysis for different mesh size of 200 mm, 150 mm, 100 mm, 50 mm, and 30mm was performed to see mesh sensitivity of the models. The smaller mesh size took more computational time and shows no significant changes in the numerical results. A mesh size of 100 mm was considered to produce the desirable results as discussed in model validation section.

2.5 GEP Algorithm

Gene expression programming (GEP) is a genetic algorithm (GA) used for generating mathematical models in a domain-independent manner from input data. Unlike traditional GAs and genetic programming (GP), GEP employs a distinct chromosome representation. GAs use linear strings of fixed length, while GPs use nonlinear entities of varying sizes and shapes (Tariq, Khan, Ullah, Shayanfar, et al. 2022; Tariq, Khan, Ullah, Zamin, et al. 2022b; Tariq et al. 2021). In contrast, GEP combines both a fixed-length linear string and a ramified structure of various sizes and shapes. Multiple iterations were conducted in the evolutionary process of GEP, involving adjustments to the number of chromosomes, genes, head size, and linking functions. Through this process, GEP selects the most promising candidates from the initial population based on their fitness, optimizing the solutions. It is important to note that increasing the number of genes and chromosomes can lead to complex functions that accurately fit the results. However, there exists a trade-off between simplifying the mathematical model by controlling the number of genes and chromosomes and achieving the desired level of accuracy (Tariq, Khan, Ullah, Shayanfar, et al. 2022; Tariq, Khan, Ullah, Zamin, et al. 2022b; Tariq et al. 2021; Teodorescu and Sherwood 2008; Ilie et al. 2017).

Achieving convergence to the global optimal solution is a crucial aspect of the GEP algorithm. However, there are instances where the algorithm may struggle to select the best solution among multiple competing candidates. This can lead to an indefinite sequence of steps, potentially resulting in a non-terminating program or an illogical expression. To address this issue, adjustments can be made to the linking function or the number of genes and chromosomes to improve the algorithm's performance (Kose and Kayadelen 2010).

In the past ten years, the benefits of GEP have made it increasingly popular in the field of structural engineering. Numerous researchers (Pham and Hao 2016) have utilized GEP to create sophisticated models for accurately estimating the capacity of different structural elements. In this study, GEP was effectively employed to predict the flexural strength of Hybrid BRC beams.

Figure 5 illustrates the different stages involved in the optimization process of GEP. The optimization procedure begins with the selection of control parameters, including the function set, terminal set, fitness function, control parameters, and stop condition. Prior to executing the evolutionary algorithm, the fitness function is defined, and an initial population of random strings, referred to as "chromosomes" in genetic programming terminology, is created. These strings are translated into expression trees, and the fitness scores of each chromosome are evaluated based on their results. If the fitness criterion is not met, a roulette-wheel sampling method is employed to select certain chromosomes for mutation, generating new generations. Conversely, when the variables are appropriately tuned to the fitness function, the chromosomes are optimized.

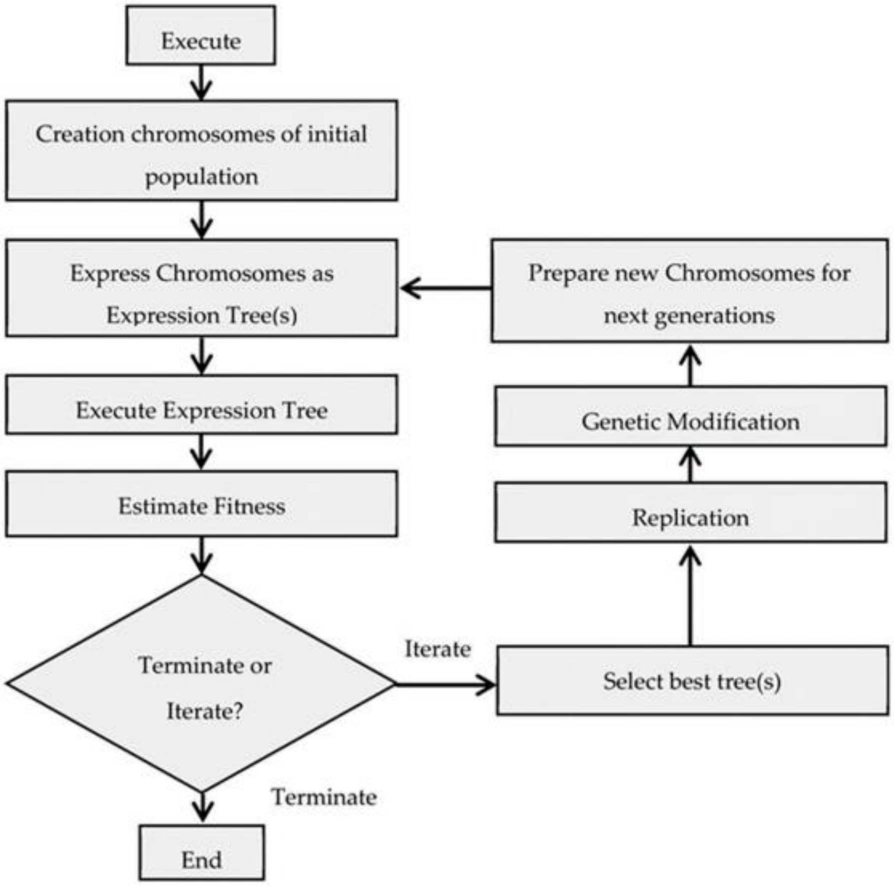


Figure 5. Flow chart representing steps of GEP (Tariq, Khan, and Ullah 2022)

3. RESULTS AND DISCUSSION:

Load displacement curves of all the models are obtained from the analysis and are represented in the Figure 6 and percentage reduction in strength of all beams as compared with control beam B1 is shown in Figure 7. Curve of B1 is considered as the reference curve. Curve of B2 shows that the ultimate strength of this model is 47% less than the model B1. Curve of B3 and B4 represent that the ultimate strength of these models is 46% and 49% less than the model B1. It further exhibits that there are no significant changes in the strength of beam by just replacing the bamboo stirrups with steel stirrups. This is because stirrups are only used to hold the primary reinforcement bars properly and helps resist diagonal shear cracks. Furthermore, curve of B5 displays that the ultimate strength of this model is about 7% less than the model B1. This hybrid beam exhibited increase in the strength of about 40%, 39% and 42% as compared to B2, B3 and B4 models, respectively.

The numerical model was further evaluated by comparing the energy absorption and failure patteren of all the beams. Area under the load deflection curve was considered to estimate the energy absorption of all models as shown in 8. The comparison of reduction in energy absorption of all models with B1 is provided in Figure 9. Energy absorption for beam B1 is 2134.3 KN-mm and for beam B2 is 988.13 KN-mm which is 54% less than B1 whereas energy absorption for beam B3 and B4 are 1023.7 KN-mm and 1000.7 KN-mm respectively. The beam B5 has value of 1859.27 KN-mm which is about 13% less than the beam B1. Tensile damage of beam B1 is distributed over the larger area of beam as shown in Figure 10a. whereas tensile damage of beam B2, B3 and B4 is distributed over the much smaller area as compared to the beam B1 as shown in Figure 10b, Figure 10c and Figure 10d respectively. The tensile damage for beam B5 is very similar to beam B1 as shown in Figure 10e. This further implies that beam B5 could be a suitbale replacement of B1 and could offer economical and environmental friendly alternative.

The successful application of Gene Expression Programming (GEP) in predicting flexural strength without the need for numerical or experimental work is a significant finding. The coefficient of determination, which quantifies the accuracy of the regression analysis, revealed that our results were highly precise. Moreover, the equation derived from the expression tree demonstrated its efficacy in accurately calculating the flexural strength. The similarity between the predicted magnitudes of flexural strength obtained through GEP and those extracted from Finite Element Method (FEM) analysis further validates the reliability of our approach. This breakthrough in accurately estimating flexural strength not only saves time and resources but also offers a promising alternative to traditional experimental methods. These findings open up new avenues for leveraging GEP as a powerful tool for predicting and analyzing complex material properties in various engineering applications.

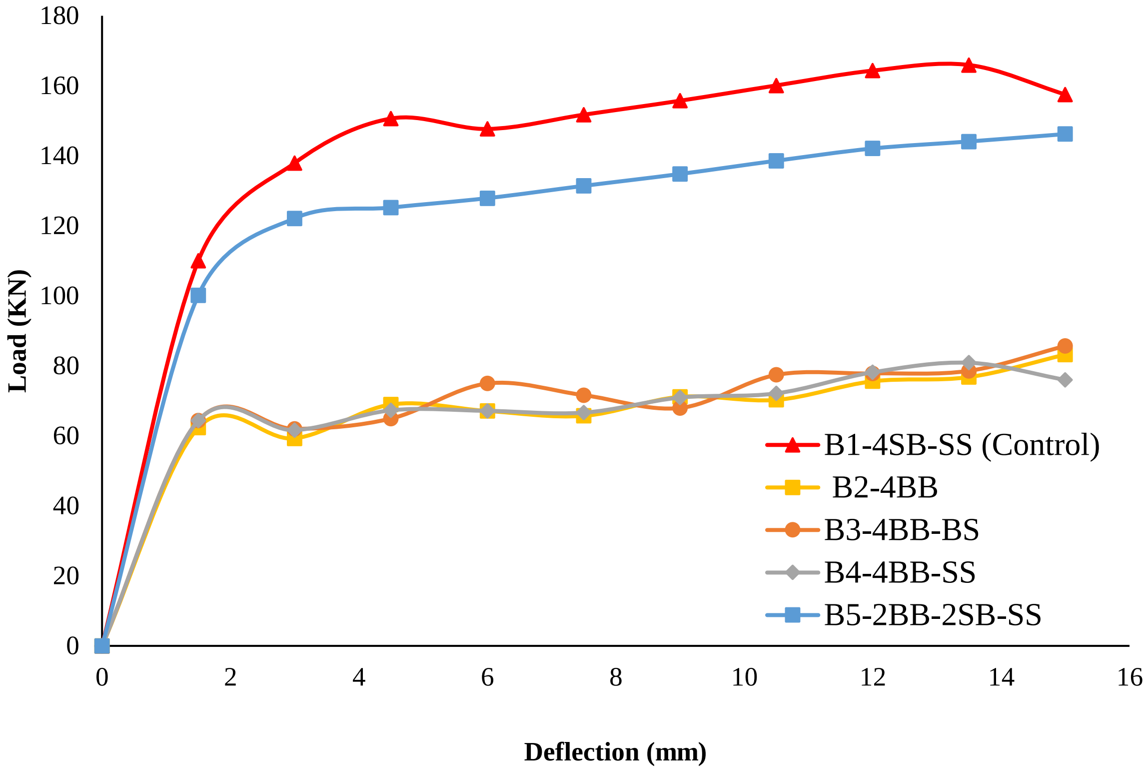


Figure 6. Load vs. deflection response of beams described in Table 3

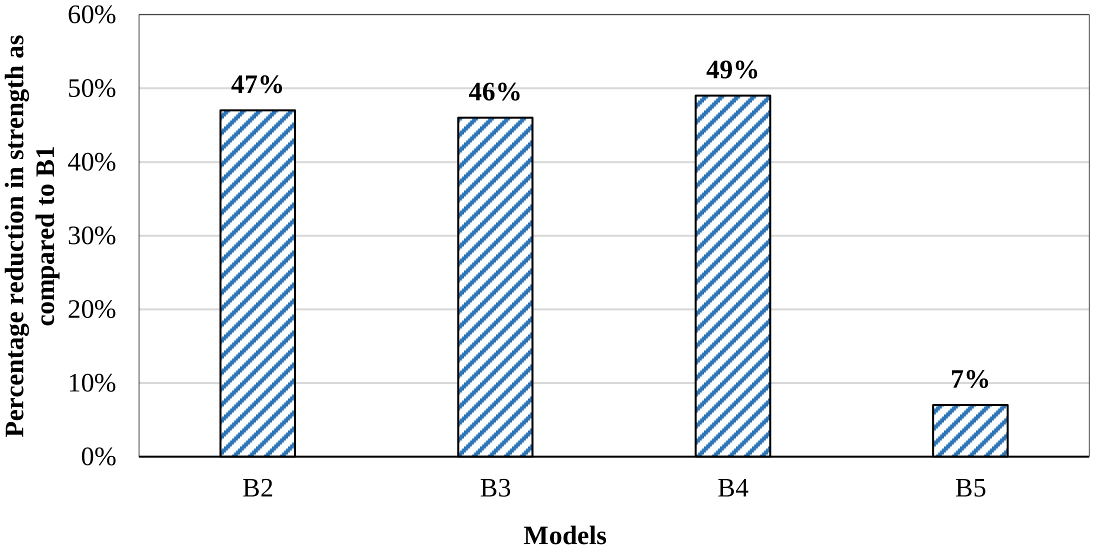


Figure 7. Percentage reduction in strength of all beams as compared to control beam (B1)

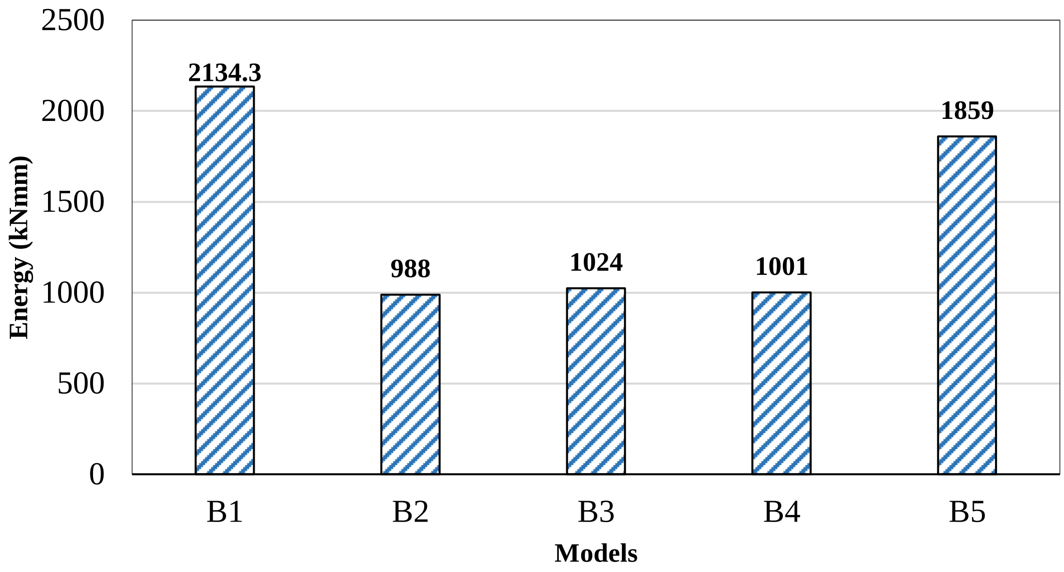


Figure 8. Energy absorption of all beams (B1 to B5)

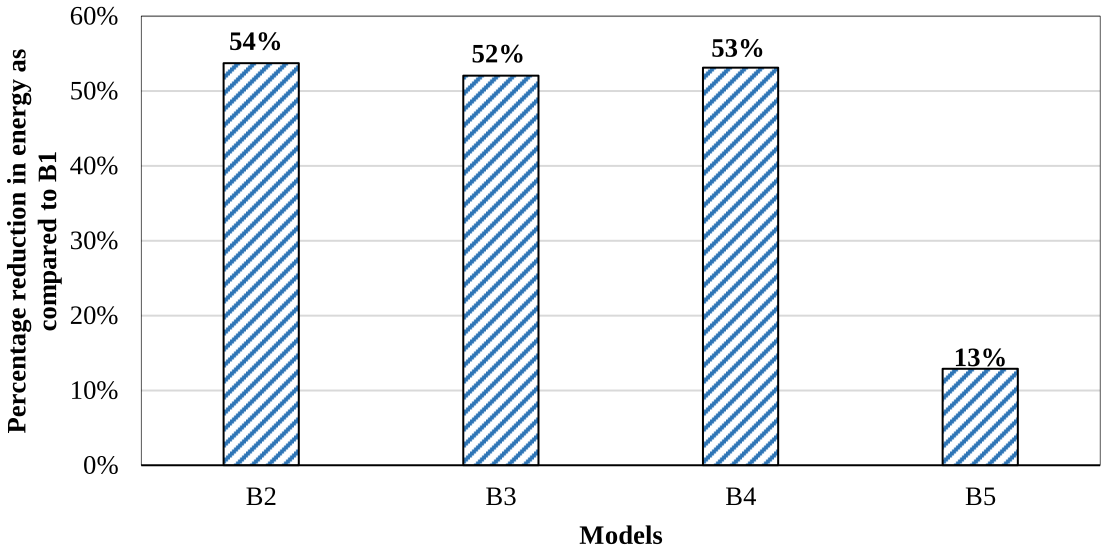
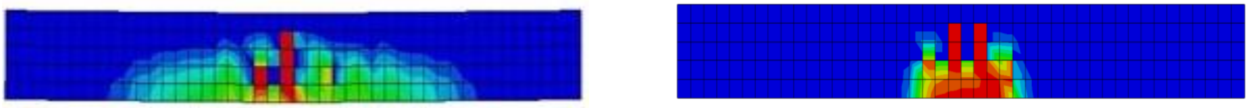
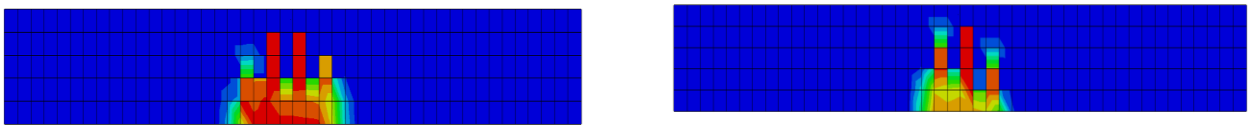


Figure 9. Comparison of energy reduction of all models with B1.



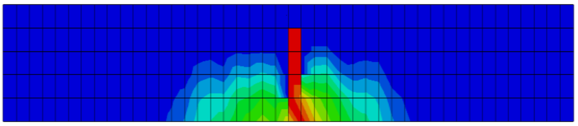
(b) B2-4BB



(c) B3-4BB-SS

(d) B4-4BB-BS

l)



(e) B5-2BB-2SB-BS

Figure 10. Tensile damage in beams

3.1 Model Validati

In a previous study (Qaiser et al. 2020c), both BRC and SRC beams were experiemntaly tested. The beams had a cross-section of 230 x 230 mm and a length of 1.88 m, with a clear cover of 38 mm from each side and bottom. The reinforcement consisted of two layers of tension reinforcement and hanger bars to hold the stirrups with a spacing of 115 mm. The experimental setup involved three-point loading, with supports placed at 75 mm from both ends. Using the experimental data and properties listed in Table 1, two numerical models were developed to demonstrate the effectiveness of FEM technique. The goal of this analysis was to confirm the applicability of FEM in predicting the behavior of BRC and SRC beams by comparing the FEA (Finite Element Analysis) results with those obtained by the experimental work for the two considered beams. Figure 11 illustrates the meshed geometry of numerical model for validation.

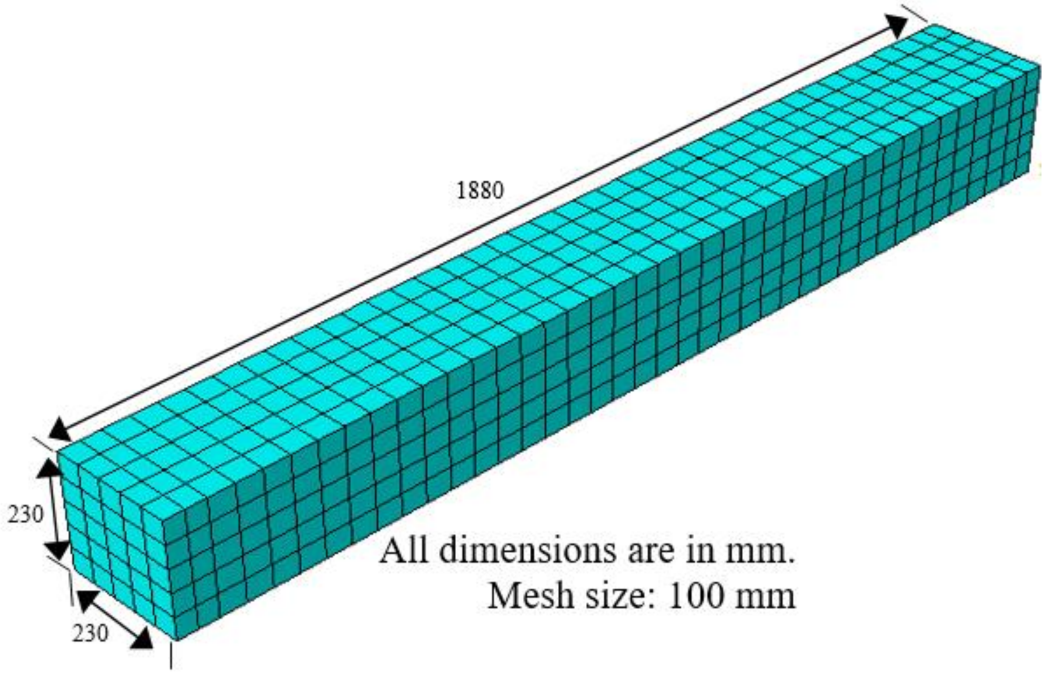


Figure 11. Meshed geometry of numerical model for validation

To perform numerical modeling of the test specimen, the methods described in previous sections were employed to replicate the constitutive behavior of the materials and implement the necessary modeling parameters. For the comparison, the experimental and the numerical load vs. displacement response of speciemens is compared in Figure 6. The results of the finite element analysis (FEA) closely matched the experimental results. Notably, it is worth emphasizing that there was minimal difference between the load-deflection curves of SRC beam obtained from the experiment and the FEA. Furthermore, the FE failure load was higher by 4% at a deflection of 12 mm and experimental failure load was higher by 6.5% at a deflection of 15 mm and both FEA and experimental results of SRC beams exhibited the same deformation value with 10 mm, as illustrated in Figure 12. Moreover, the performance of both curves was identical until failure beyond 10 mm deformation.

For BRC beams, the FE curve is steeper than the experimental curve from the starting point to the point of deflection at 4.3 mm. Furthermore, the experimental failure load had 2.85% higher value than the FE results.

The load vs. deflection curve of experimental and numerical analysis of SRC and BRC beams are fairly similar and show good agrreement between experiemental and numerical modeling results, as illustrated in Table 4.

A successful simulation of the behavior of SRC and BRC beams in flexure was made by showing the load–defection relationships.

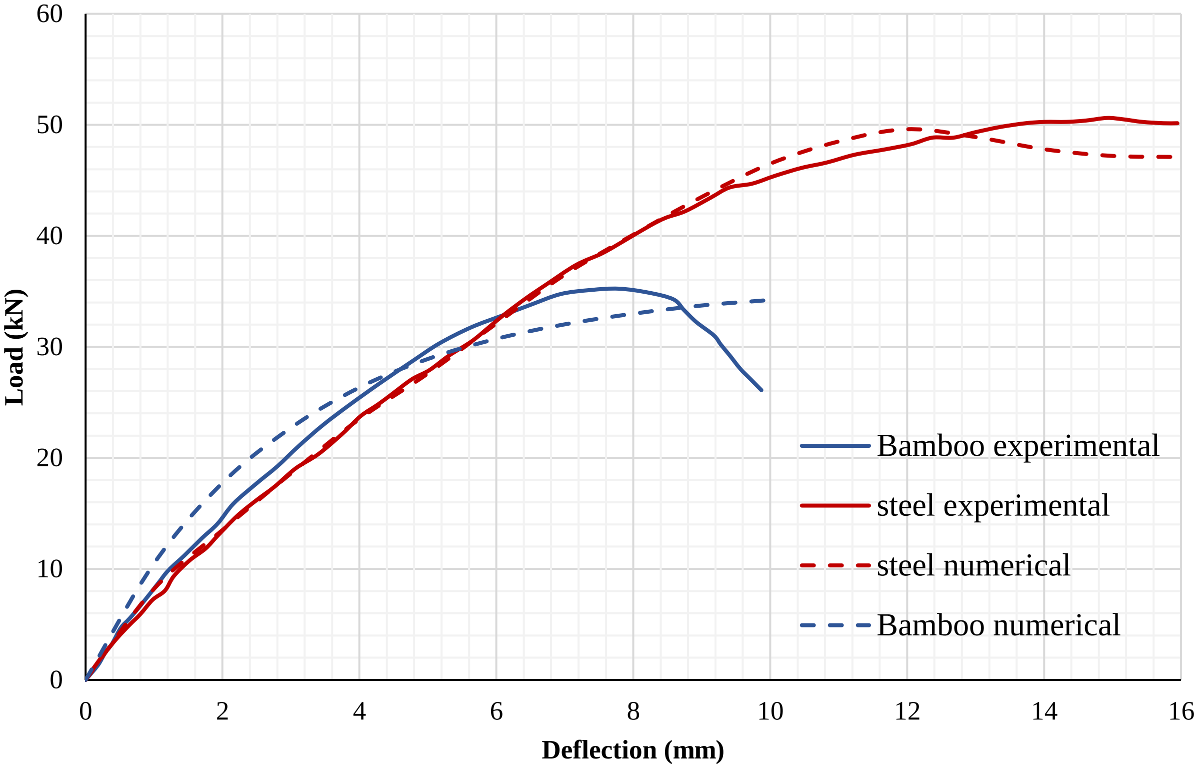


Figure 12. Comparison of experimental and numerical results

Table 4. Experimental and FEA Results

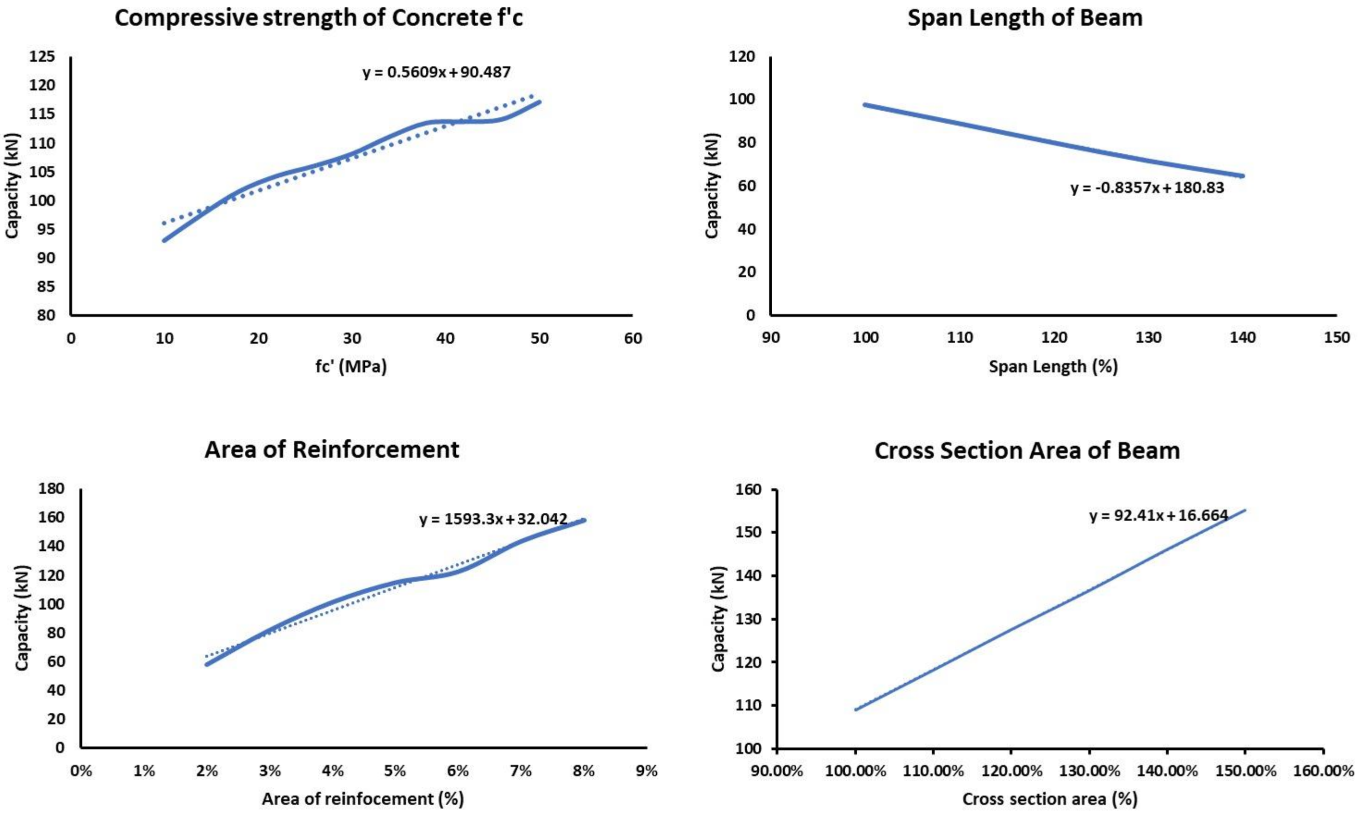
Beam	**Pu (kN)**		
	Exp	**FE**	**Exp/FE**
SRC	51	49.6	1.028
BRC	35	34.22	1.023

3.2 Database for GEP based Model:

Total 40 number of models were created in ABAQUS by changing different key parameters. The dataset used for developing a reliable predictive model includes important influencing parameters. Identifying these parameters necessitates a thorough examination of experimental investigations. Key parameters such as cross-sectional area of concrete, area of reinforcement, depth of beam, span length of beam and concrete compressive strength increase are crucial. Table 5 presents these parameters and their respective ranges within the dataset.

Table 5. Distribution of key influence parameters

Parameters	**Range**
Concrete Compressive strength (fc’)	10 MPa – 50 MPa
Span Length (L)	100% - 140%
Area of Reinforcement (Ar)	2%-8%
Area of Cross-section (Ac)	100%-150%
Depth of beam (D)	200 mm – 350 mm



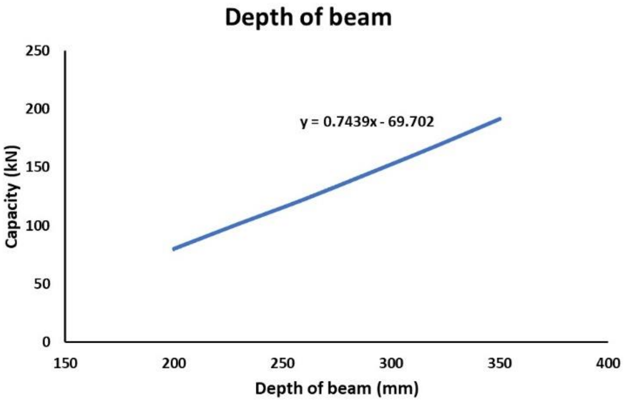


Figure 13. Influence of Important Parameters against Capacity in Parametric Analysis

3.3 Proposed GEP Model for Estimating Flexural Strength of Hybrid BRC beams.

This section presents a GEP model for estimating the peak impact force on an RC beam. The equation used to represent the GEP models generated from the dataset mentioned earlier is extracted from the Sub ET (sub-elemental tail) of the genetic algorithm:

$$Pu = G_1 + G_2 + G_3 \tag{2}$$

$$G_1 = -(1.63fc' + 0.03L + 61.13) \tag{3}$$

$$G_2 = \frac{184.14fc' + 1.34Ar + L}{DL - 4Ac} \tag{4}$$

$$G_3 = D - \frac{62.8D - 37.8Ar}{fc' - Ar + 671.9} \tag{5}$$

Where L and D are the Length and depth of the beam respectively; fc' is the concrete compressive strength; Ar and Ac are the area of reinforcement and cross-section respectively. The expression tree of the estimation model is also given in Figure 14:

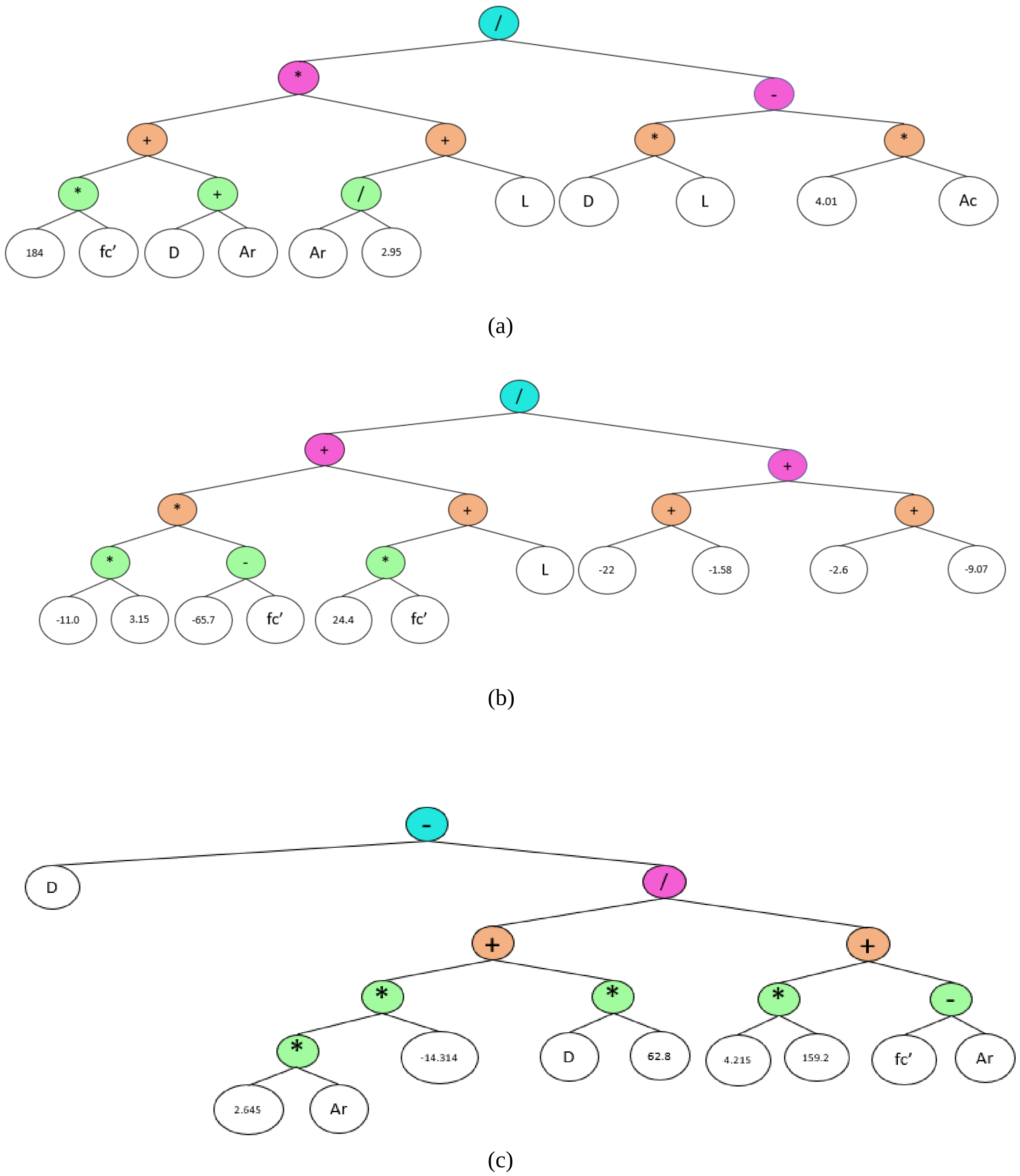


Figure 14. Gene expression tree for the flexural strength calculation. (a) Sub ET-1 (b) Sub ET-2 (c) Sub ET-3

After the model development, statistical performance check such as coefficient of determination is used to gain quantitative insight into the model. The coefficient of determination (R^2) testing the model reliability can be determined by the expression:

$$R^2 = 1 - \frac{\sum[Experimental\ value - predicted\ value]^2}{\sum[Experimental\ value - Experimental\ value_{mean}]^2}$$

where the value of R^2 close to 1 is considered an accurate prediction. Results of the regression analysis are shown in Figure 15. The coefficient of determination (R^2) of the regression analysis is 0.979 that is closer to 1.

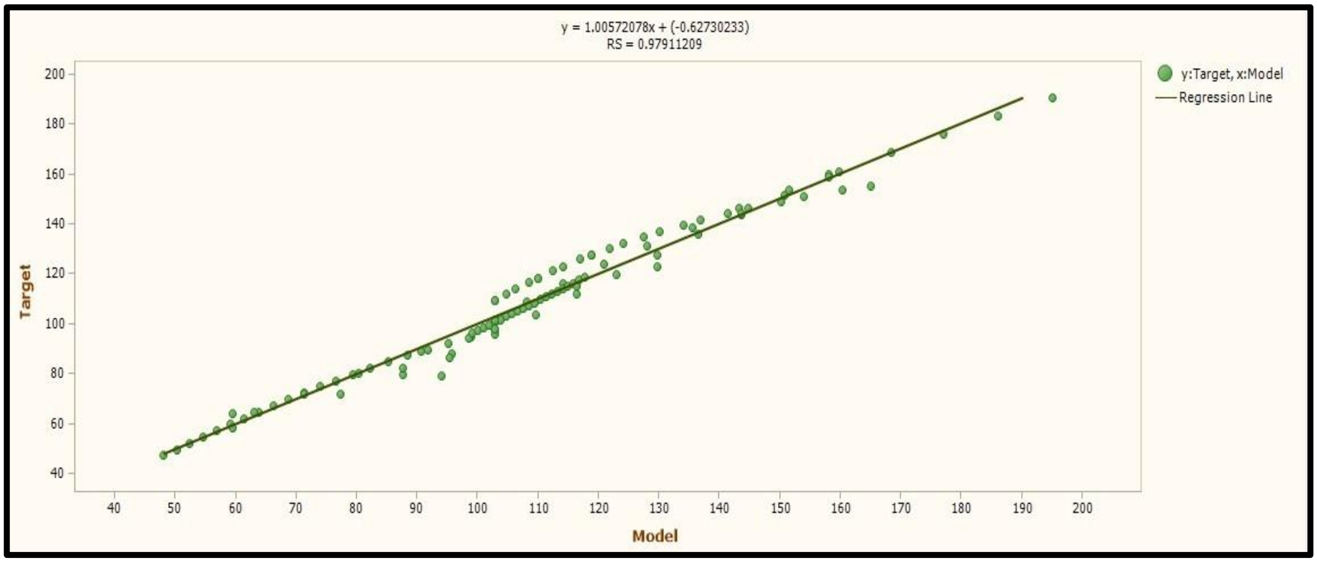


Figure 15. Results of Regression Analysis

4. CONCLUSIONS

The current study investigated the suitability of bamboo reinforcement to replace the steel rebars based on the validated FEM. Based on the analysis results, following conclusions could be drawn to answer research questions mentioned below.

- Using bamboo as the sole reinforcement may not produce the same results as a typical beam reinforced with steel due to the difference in stiffness and overall strength of bamboo. The hybrid bamboo and steel reinforced beams could offer a feasible alternative with reduced impact on the environment.
- Energy absorption of model B1 and B5 are comparable. There is only 13 % reduction of energy absorption of model B5 as compared to B1. The proposed hybrid beam could exhibit comparable serviceability performance with less amount of reinforcement.
- A beam reinforced with a combination of 50% steel and 50% bamboo in the tension region could provide reasonable ultimate strength which is about 7% less than a SRC beam. The suggested amount of bamboo as a steel replacement in construction of beams has the potential to substantially reduce the demand for steel.

- When factors such as cross-sectional area of concrete, area of reinforcement, depth of beam and concrete compressive strength increase, they have a positive influence on producing more flexural strength. Conversely, increasing the beam span has a negative effect on producing flexural strength of BRC beams.
- The proposed model's predictive capability is demonstrated by a coefficient of determination of 97.9%.

To gain a more definitive understanding of the potential of bamboo as a reinforcement material, additional work is needed to further explore the use of bamboo in combination with steel in concrete memebrs. Additionally, to improve the strength of BRC beams, the addition of bamboo fibers could be suggested as a possible direction for future research.

1. ACKNOWLEDGMENTS

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2. CONFLICT OF INTEREST

Authors declare no conflict of interest.

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