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Review paper

Study of behavior of locally available bamboo as a sustainable reinforcement for concrete structures

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Abstract: In the developing countries, to build earthquake resistance construction along with seismic retrofit technology, the focus towards global warming problems along with sustainable society, production utilizing natural material, Bamboo lower-cost faster-growing and broad distribution of growth is promoted crucially. To get knowledge about the Bamboo Reinforced Concrete's (BRC) mechanical behavior along with to verify the variations of structural properties betwixt Steel Reinforced Concrete (SRC) and BRC, researches have been made by several authors. BRC beams are simple, effective, along with cost-effective for rural construction and for which the trials are made in these studies. There is a huge concern over the lifespan of bamboo as it is employed as a substitute for steel; thus, it is enhanced by undergoing certain mechanical along with chemical treatments. The parametric study displays that regarding the robustness along with stability, bamboo is utilized in Reinforced Concrete (RC). Here, the Bamboo Reinforcement's (BR) performance together with its durability is illustrated by assessing the laboratory determinations as of the available literature.

Keywords: bamboo, bamboo reinforcement, bamboo-reinforced concrete (BRC), concrete durability life cycle assessment (LCA), chemical treatments of bamboo, bamboo materials

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1. Introduction

India, the most famous country in the world is home to various sections of people living below average poverty line. Recently, the deficiency in housing amenities amongst these people owing to unaffordability has turned into a great concern [1]. Normally, using RC, the majority of the civil engineering structures are created. The Mechanical Properties (MP) of steel and concrete are significantly diverse, which is regarded as a vital feature of RC. Particularly, steel transforms itself like plastic, whereas concrete is defined by crack propagation [2]. Since concrete alone is not strong enough to give sufficient tensile resistance, reinforcements are utilized in the concrete structure. Concrete is best at bearing compression than tension, so it causes the requisite for the steel reinforcement to endure tensile stresses [3]. However, the steel's cost, self-weight, embodied energy (energy absorbed by whole the processes related to a product's lifecycle) is very high. Steel is imported from foreign countries in Sri Lanka that amplify its cost and carbon footprint [4]. Natural fibers were utilized to create a huge diversity of products varying as of the roofing of houses to clothes, during earlier times. But, natural fibers have evolved as a substitute for traditional glass along with carbon fibers in the creation of thermoplastic composites, in the past few years [5].

The largest portion of the materials utilized in concrete manufacture is un-maintainable as they are produced as of non-renewable sources. Moreover, besides other negative consequences at the time of concrete mixing along with the on-site application, concrete may produce 4-8% of the world's CO2; in addition, they absorb a major quantity of natural resources [6]. For structural applications, to lessen the effects of the above-said complications, a sequence of engineered wood or bamboo products has been created, which have the reward of improved dimensional stability, extra homogeneous MP, along with good durability because, in their manufacturing process, certain issues like knots are eliminated or arbitrarily distributed [7]. The latest engineered bamboo product is Bamboo scrimber and its bamboo materials have an extremely high utilization rate. With the aid of motor-driven rollers, strips split from bamboo culms are crushed with projection to become bamboo bundles [8]. At present, Bamboo is the most hopeful plant. Higher-strength, wear resistance, shock absorption, energy-saving, sound absorption environmental protection, lightweight, durability, heat insulation, et cetera are the Bamboo fiber composite material's features. Certainly, this material has wide growth prospects [9, 10]. Here, for the concrete framework, bamboo is given as reinforcement. Bamboo has greater tensile and flexible capability and exhibits greater bonding with concrete. Cost-effective, recyclability (in a few months attains full development), and production costs are lesser for bamboo. The fundamental arrangement of bamboo is exhibited in Figure 1.

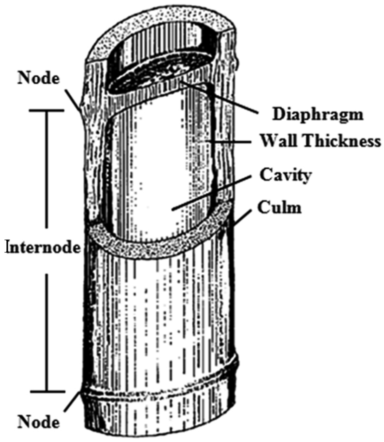

Fig. 1. Basic Structure of Bamboo

2. Literature survey

The paper is ordered as: BRC is illustrated in Section 2.1. The BRC's durability is evaluated in Section 2.2. The practical utilization of bamboo as a reinforcing component is explicated in Section 2.3. BRC together with SRC's life cycle analysis is assessed in Section 2.4. Bamboo's chemical treatments are illustrated in Section 2.5.

2.1. Bamboo-reinforced concrete

The bamboo's MP together with its occurrence in emerging regions has brought about its experiential usage as reinforcement in concrete structures. Bamboo is often mentioned as a higher strength along with a highly renewable replacement for timber; in addition, as a "strong-as-steel" RC. The BRC and its advantages are exhibited in Table 1.

Table 1. Bamboo RC and Their Advantages

Author	Variety of bamboo	Compressive strength (MPa)	Advantages
Archila Hector F. et al. [11]	Guadua angustifolia	65	A substitute to cement is offered by the lesser energy-intensive production procedure.
Alireza Javadian et al. [12]	Raw bamboo with numerous types of coating	20	A sufficient bonding was formed with the concrete matrix by the bamboo-composite reinforcement devoid of coating.

Continued on next page

Table 1 [cont.]

Author	Variety of bamboo	Compressive strength (MPa)	Advantages
Masakazu Terai and Koichi Minami [13]	3 varieties of Bamboo	40	Any bond betwixt the bamboo and the concrete would be broken completely by the drying process.
Masakazu Terai and Koichi Minami [14]	Bambusa Nutans	76	The BRC columns' ductility is depicted to be reliant on concrete strength.
Sajjad Qaiser et al. [15]	Bambusa Nana	35	The strength enhancement in bamboo reinforced beams, bond stress comparisons along with their aptness or incompatibility as a rebar element in concrete beams has been divided.
Lakshmi E. Jayachandran et al. [16]	Bambusa Nana	83	The localized peak pressures along with stress distribution patterns in the grain layers that are over the analytical methodologies' scope are detected by the numerical methodology.
Purushottam Kumar et al. [17]	Bambusa Tulda	44	To address the complications in the utilization of bamboo as concrete reinforcement material, these designed composite bars are utilized.
Akmaluddina et al. [18]	Gigantochloa atter	48	Augmented the ductility rate.
Muhtar et al. [19]	Dendrocalamus Brandisii	31	This confirmed that the steel reinforcement's bond strength is superior t the BR's bond strength.
Diwakar Bhagat et al. [20]	Dendrocalamus Strictus	50	A green structural engineering material is provided by FRBC as a alternate for steel along with RC.
Nathan Schneider et al. [21]	Phyllostachys edulis	48	The evaluation outcomes displayed that bamboo is a reliable substitute for steel as the TS for concrete structures.
Carlos A. Benedetty et al. [22]	Bambusa Polymorpha	40–50	There was no proof that the augmentation in embedment length elevated the pullout load.
Pankaj R. Mali and Debarati Datta [23]	PCC (Plain Cement Concrete)	65.10	The FS is increased.

2.2. The durability of bamboo reinforcement in concrete

Bamboo's robustness is highly associated with its natural composition. In addition to other lingo-cellulosic components, bamboo includes lignin, cellulose, along with hemicelluloses. In bamboo, the aforementioned components' chemistry alters with age (for instance, when the plant attains its maturity), which causes cell death along with tissue decay. The BRC's durability is elaborated below.

X.B. Li et al. [24] explicated the influence of height, age, along with the radial position on the bamboo stems' chemical composition. At all '3' ages, a significant elevation in holocellulose together with α-cellulose content was established as of the culm's base to the top. Bamboo age was interrelated crucially with certain gravity. In the 3 along with 5-year-old bamboos, Alcohol-toluene extractive content was augmented as of the stem's base to the top; it also displayed a continuous elevation with the increase in age. In the epidermis, the extractive along with content was higher; in addition, the holocellulose along with -cellulose content was lower. Nevertheless, this material's actual nature was continued to be verified.

Sina Youssefian and Nima Rahbar [25] investigated the strength together with stiffness's molecular origin in bamboo fibrils. The fibers' natural composite structure comprised cellulose micro-fibrils in a matrix of entangled hemicellulose along with lignin termed Lignin Carbohydrate Complex (LCC). From these materials, the bamboo's unique properties were extracted. To study the adhesive connections' MP betwixt the material in Bamboo Fibers (BFs), atomistic simulations were utilized. To understand the elastic moduli, the adhesion interactions betwixt the materials and cellulose micro-fibril faces, the lignin's molecular models, hemicelluloses, along with LCC structures were presented. Nevertheless, the non-bonded energies' effects weren't equivalent.

Efe Ikponmwosa et al. [26] recommended a bamboo-reinforced foamed concrete slabs' structural behavior comprising Polyvinyl Wastes (PW) as a fine aggregate's partial replacement. Density, CS, failure pattern, crack development pattern along with propagation, the ultimate moment, and load-deflection characteristics were the structural properties being studied here. The outcomes displayed that (a) the foamed aerated concrete specimens' CS was enhanced with the partial substitution of sand with PW, (b) a shear bending failure was exhibited by the slab specimens with PW as a partial replacement, (c) with an augmentation in the sand replacement's level with PWs, a lower value of deflection was recorded by the entire slab specimens with PW as a partial replacement for the same loading, and (d) an enhancement in the slab specimens' bending performance was caused with an augmentation in the quantity of sand substituted with PWs.

J.G. Moroz et al. [27] recommended bamboo meant for RC masonry shear walls. The traditional steel reinforcement was utilized to reinforce one wall vertically along with horizontally in bond beams. Different quantities of Tonkin cane BR were utilized to reinforce the other wall vertically along with horizontally in bond beams. According to this study, it was established that bamboo was a highly reliable alternate for steel, which could be utilized for lower-cost housing applications in areas where bamboo was highly economical than steel. Nevertheless, it was established that the augmentation in ultimate load with a decline in ductility was the key variation in utilizing a higher-strength block.

S. Karthik et al. [28] illustrated the BRC along with SRC's strength property comprising manufactured sand together with mineral admixtures. Concrete samples like cylinders, cubes, along with beams were generated along with examined at predetermined periods regarding standard needs. By utilizing the SEM along with FTIR, a micro-scale evaluation was conducted on the bamboo; in addition, its TS was also estimated. The micro-scale together with TS evaluation's outcomes displayed that bamboo was robust as well as ductile material. Nevertheless, a poor bonding was formed by this methodology betwixt bamboo and the concrete matrix.

Hongxia Fang et al. [29] produced the thermal treatment's influence on the robustness of short BFs together with their reinforced composites. It examined the heat treatment's consequence on the chemical transformation; in addition, it amalgamated enhanced strength of short BFs along with their reinforced composites. The outcomes displayed that cleavage of the hemicelluloses' acetyl groups generated with augmenting temperature along with holding-time and it accomplished above 190°C for over 3 h, which brought about an elevation in the cellulose content in conjunction with a decline in the accessible hydroxyl groups' concentration.

Kefei Liu et al. [30] evaluated a BF that possessed engineering properties along with performance appropriate as reinforcement aimed at asphalt mixture. The lignin fiber asphalt mixture's MPs were superior to that of BF; similarly, the BF asphalt mixture's road performance like lower-temperature crack resistance, higher-temperature stability, and moisture stability was superior to that of lignin fiber. A close association was formed by BF with the mixture which in turn would augment the structural asphalt's proportion in the mixture via adsorption. The existence along with the production of larger cracks in the mixture could be delayed and controlled by the distributed fibers by forming a 3D-network structure in the asphalt mixture.

2.3. Practical uses of bamboo as reinforcing material

Despite the opposition to the BRC's usage in primary structural members by the authors, there are certain associated applications that may be practical. Here, problems like dimensional stability, the relation betwixt bamboo and concrete, dimensional stability are handled as mentioned here. Bamboo's practical usage as reinforcing materials is illustrated.

Banjo A. Akinyemi and Emidayo E. Omoniyi [31] designed ferrocement jackets for the restoration along with fortification of bamboo-supported acrylic polymer altered square concrete columns. The recognition was provided to the crack pattern together with columns' failure modes. In association with the control column, the greatest mean ultimate load was acquired as of the column with ferrocement along with polymer inclusion of 60% enhancement. From the columns revamped with ferrocement substance, the minimal axial deflection was 93% and the lateral deflection was 72%. With a steady increase of load, the cracks in the interface along with its broadcast created, and fresh cracks began to create at sectors nearer to the upper face in proximity with the machine. However, the cracks overpowered it.

Zhiyuan Wang et al. [32] advocated bamboo-concrete composite beams' flexural behavior with Perforated Steel Plate (PSP) linkage. Utilizing PSP as connectors, a fresh kind of bamboo-concrete composite framework was contributed. Initially, the bamboo-concrete shear connector's slip behavior was examined via push-out examinations to research the compound effect. Then, 10 bamboo-concrete composite beams' 4-point bending assessments were executed. The outcomes showcased that the bamboo-concrete shear connectors' failure happened betwixt the PSP and the concrete, along with it was devoid of clear destruction betwixt the bamboo and the PSP.

Nabihah Rahman et al. [33] designed an improved bamboo composite with a defensive covering for a structural concrete application. Initially, by treating the samples to diverse corrosive surroundings usually experienced in the building material's life span, the bamboo composite material's durability and protective epoxy coating's efficiency were estimated. For 28 days, the samples are submerged in simulated acidic rain together with concrete pore water solutions, and water, in accelerated situations. For analyzing the diverse corrosive surrounding's effect on the bamboo composite material's behavior, tensile assessment and micro structural investigation were executed. Especially in an acidic surrounding, the outcomes showcased that the epoxy coating's application effectively safeguarded bamboo composite material's reliability without considerably impacting its mechanical capability.

Pankaj R. Mali and D. Datta [34] studied bamboo RC slab panels' investigational appraisal. Via concrete slab panels' investigational testing, the bamboo profile's feasibility along with efficacy was deployed as reinforcement. As stated by Eurocode EN-1448-5 (2006), a sum of 15 concrete slab panels was formulated. When the stated bamboo strip was employed as reinforcement in concrete slab panels, the outcomes revealed that there was an enhancement in the load-carrying along with deformation capability as analogized with PCC together with RCC (Reinforced Cement Concrete) slabs. Fascinatingly, the slabs' structural behavior utilizing freshly designed BR had revealed considerable development in the flexural performance. However, it was slightly superior to the RC slabs with M.S. Bars as a major reinforcement.

K.S. Akhil et al. [35] recommended model footing behavior on bamboo mat-reinforced sand beds. The outcomes of studies executed on sand beds reinforced with conventional woven bamboo mats were illustrated here. When the reinforcement was positioned at the optimum length, an enhancement of 2.5 times was observed in the bearing capacity. The reinforcement's spacing betwixt '2' layers of bamboo mats was established to be equivalent to the optimal depth value of 0.3B. When '4' layers of reinforcement were positioned at 0.3B, an enhancement of around 7 times was noticed in the bearing capacity. The outcomes displayed the bamboo mat's promising ability for soil reinforcement.

2.4. Life cycle assessment of bamboo and steel-reinforced concrete

Several investigations mentioned here premise BRC as a "green" or "sustainable" substitute to SRC. This part tries to enumerate the above said claim utilizing Life Cycle Assessment (LCA) is a technique employed to review the complete life environmental consequences and/or products and services cost. The BRC along with SRC's LCA is illustrated in this portion.

S. Karthik and P. Rama Mohan Rao et al. [36] designed an ANNOVA Taguchi technique for bamboo or steel's flexural member as RC. The FS values were acquired after curing for 28, 56, and 84 days, and to discover the optimization values, ANNOVA software along with the Taguchi technique was utilized. The FSs' maximum load-carrying capability was achieved, and the 25% BRC flexural members' outcomes were acquired with good strength. As of this work, the flexural behavior of bamboo/steel-concrete members' optimization value was found. But, the device augmented the steel for the above reinforcement in the structural components. However, the bad RC ratio was increased.

Ji ng Zh ou et al. [37] designed stone dust concrete composite columns impeded with Bamboo Plywood (BP) along with thin-walled steel-tube schemes. By evaluating the whole procedure of specimen destruction, the thin-walled steel tube's failure modes, the load-displacement curves, in conjunction with various composite elements' strain development patterns, the failure model was enlightened. The analysis outcomes showcased that the BS-DCC specimens' failure modes in compression were controlled by adhesive cracking failure BP among the slanting binding bars in the column's center along with the BP on the tension side and inner steel tube's yielding. But, the investigation on the stone dust's application was inadequate.

Xiaocun Zhang et al. [38] advocated a steel-bamboo composite frame arrangement's life cycle carbon release decrease potential for residential houses. A process-based technique was acquired to appraise the emissions which were regarding the operation, construction, production, together with end-of-life phases' inventory examination, and for evaluating the parameter uncertainty's influences on the comparison, a Monte Carlo simulation was executed. The heating, lighting, and cooling were the affecting elements for the emissions of both structural systems, and it was specified by the contribution coefficients of the desired process, while galvanized steel sheet together with bamboo scrimber's production must be highlighted to decrease discharge as of the steel-bamboo framework.

Mayank Mishra et al. [39] designed a neural network-centric method to forecast the defection of plain, BRC beams, and SRC from investigational data. For the above said 3-beam typologies constructed in the lab under 2-point loading for 28 days, the experiment was performed to record data at normal load increments. For building the ANN, 122 laboratory test data were documented totally. Forecasting the relation between the applied load, the reinforcement's percentage (quantity) (used as input); in addition, the beam's defection (acquired as output) are associated with the suggested technique.

P.O. Awoyera et al. [40] illustrated an investigational and arithmetical study of large-scale BRC beams that consists of crushed sand. Utilizing ABAQUS software, finite element/numerical modeling along with the examination of beams was conducted. By a preset 3D model, a non-linear model study with static loading was determined. At mode I, the concrete fracture pattern was smudged crack. The findings stated that a part (50%) or whole (100%) substitute of steel with bamboo in conjunction with an entire substitute of river sand with crushed sand produced a fairly alike performance in flexure as the control beams.

2.5. Chemical treatments of bamboo

Chemical treatment is the process of utilizing numerous chemicals as a preservative for wood or bamboo. The bamboo's chemical treatments are illustrated in Table 2.

Table 2. Chemical Treatments of Bamboo

Author	Variety of bamboo	Treatment	Parameter ERS discussed
Bhavna Sharma et al. [41]	Laminated Bamboo (LB), Hemi-cellulose bamboo, mo so bamboo	Bleaching along with Caramelisation	Fracture together with crack propagation is huge, increased strength
Adesna Fatrawana et al. [42]	Dendrocalamus asper	Steam treatment, Steam + washing with distilled water Steam + washing with 1%sodium hydroxide Solution	Bending potency augments, gratify lesser requisite CSA 0437 (grade 0–1).
Nayebare Kakwara Prosper et al. [43]	Phyllostachys Pubescens	Impregnation together with leaching	proclaimed anti-mold features
Min Jay Chung et al. [44]	Moso bamboo (phyllostachys PubescensMazel), Makino bamboo (phyllostachys makinohayata)	Epidermal Peeling Treatment (EPT), Steam Heating Treatment (SHT)	Higher mechanical strength, decreased density, increased durability.
Kun-Tsung Lu [45]	Ma bamboo (Dendrocalamus latiflorus Munro)	Hydrogen peroxide Treatment	Enhanced wet capacity along with adhesion covering
Fangfang Zeng et al. [46]	Bamboo shoots	UV-C treatment, Chilling	Ameliorate proline accretion together with chilling tolerance.
Iman Ferdosian et al. [47]	LB	Heat treatment with soya bean oil for 2hr	Wet ability as well as bonding strength
Chikako Asada et al. [48]	Moso Bamboo	high-pressure steam treatment amalgamated with the milling treatment	Augments mechanical strength
Hong Chen et al. [49]	BFs	Treat the bamboo with different concentrations of NaOH	Increased wet ability in conjunction with thermal properties
Guanben Du et al. [50]	(Denddrocalamus brandisi)	microwave plasma treatment	Surface performance
Ya Mei Zhang et al. [51]	Phyllostachys pubescen bamboo	Thermal treatment	Ameliorates the bamboo's quality

Rather than the traditional steel reinforcement, the concrete reinforced with bamboo demonstrates a varied behavior; consequently, it should be structured utilizing various paradigms. The outcomes displayed the performance of numerous materials utilized in BRC. Regarding certain performance matrices, the materials' performance is gauged.

Several methodologies' Flexural Strength is depicted in Figure 2. The Flexural Strength of GGBS-MK [52], BFRC plates [53], BRC [54], ANN [55], ABLCC [56], and UH-PFRC [57] are 40%, 30%, 25%, 13.6%, 28% and 64% respectively.

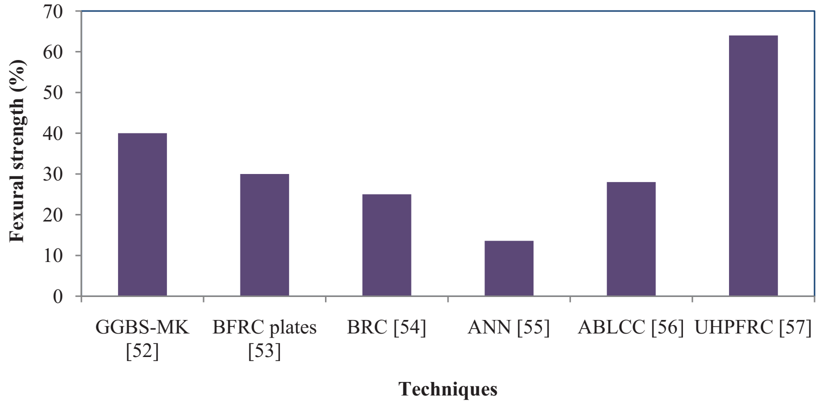

Fig. 2. Flexural Strength of Various Techniques

The bamboo materials' Compressive Strength is exhibited in Figure 3. A Compressive Strength of 35% and 92% is obtained by the GGBS-MK [52] and Bambusa balcoa [54]; similarly, it was about 18.4%, 17.67%, 52.4%, and 34.8% for ANN [55], Soaking bamboo (NaOH) [57] and SFRC [59] respectively.

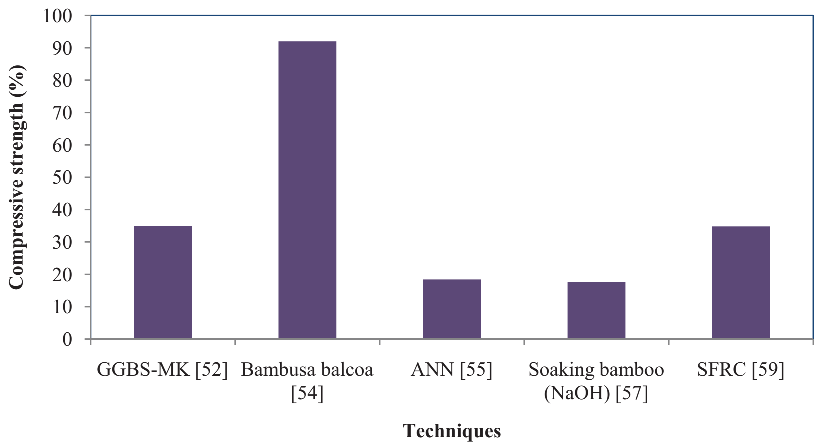

Fig. 3. Compressive Strength of Bamboo Materials

3. Integrating and interpreting results of scientific research presented in the literature review

As illustrated in the preceding portions, an apparent changeover as of flexure- to shear-dominant behavior at a bamboo reinforcing ratio = 0.048 was specified by the slabs' behavior. In accordance with the evaluation, it was established that the augmentation in the effectual steel reinforcing ratio over 0.0083 offers no more structural advantage. The aforementioned illustrations of slab behavior along with prediction are centered on the third-point flexure experiential arrangement. To reinforce externally-bonded LB plates are illustrated. Debonding is minimized with the LB's low stiffness; thus, permitting the laminate's strength to be perfectly developed. A small impact on the slabs' uncracked along with service load level behavior was created by the LB's low stiffness. Nevertheless, the ultimate capacity is augmented. At ultimate capacity, the slabs' deformation capacity is enhanced regardless of the elevation in the reinforcing ratio.

In India, some of the northern regions ponder bamboo as an effectual along with apt material as it is a rapidly grown gigantic grass. It imparts durability, robustness, along with flexibility whilst employed as a reinforcement material. In accordance with the analysis made by the researchers, a lower modulus of elasticity is possessed by bamboo. Therefore, cracking isn't prevented by it whilst exposed to heavy load. Conversely, owing to its FS, the load-carrying capacity is augmented. Overall, bamboo is the best, economical, along with environment-friendly; thus, it is recommended as a substitution for steel in a masonry structure. The ultimate limit state behavior is considerately supposed to be managed by the LB's rupture owing to its lower reinforcing ratios along with the lower stiffness. As said by the study, it was established that the steel- along with bamboo-reinforced beams' FS is augmented with an elevation in the curing systems. Whilst considering strength, steel-reinforced beams are far better.

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