

LOW COST HOUSING: AN EFFECTIVE APPROACH WITH BAMBOO REINFORCED BEAM

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Abstract

Bamboo has been used as a construction material for centuries due to its renewable nature and versatility. Known for its sufficient strength and low weight (weight-to-strength ratio), bamboo is easy to work with using simple tools, making it an attractive alternative for sustainable building. With urban housing shortages worsening due to rising costs, exploring innovative construction technologies has become essential. Bamboo can be employed in both technical and non-technical applications, offering a potential solution. The construction industry is one of the largest consumers of energy and materials, highlighting the urgent need for sustainable development that meets present demands without compromising future generations. However, the widespread adoption of bamboo as a reinforcement material faces challenges, particularly the lack of comprehensive data on its interaction with concrete, as well as its long-term strength and durability. The present study area focused on the region of North East India, where the bamboos are sufficiently available. The study evaluates the feasibility of using bamboo as reinforcement in cement concrete structures. Through various tests and property analyses, bamboo-reinforced beams were compared with traditional steel-reinforced beams. Bamboo strips were treated with protective measures to enhance their strength, demonstrating their potential for use in low-cost, low-rise and also environment friendly housing construction.

Keywords: Bamboo reinforcement, Cement concrete beam, Low cost housing, Steel reinforcement

Introduction

Bamboo is an economically significant plant with various uses and environmental benefits. Enhancing the availability of information on bamboo is crucial for promoting its sustainable use and conservation, not only in its natural habitats but also in cultivated areas worldwide. Bamboos are evergreen perennial flowering plants belonging to the grass family, similar to other grasses; bamboo stems typically

have hollow internodes. These are among the fastest-growing plants on earth, due to their unique rhizome-dependent growth system. Depending on the species, bamboo can grow 5 to 10 times faster than hardwood. Bamboo has been used for low-cost construction, such as building houses and bridges from long years ago. In modern times, it has found new applications in designer homes and decorative

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products. It is an environmentally sustainable building material, and many tropical and subtropical regions have native bamboo species. Moreover, the energy required to produce steel is nearly 50 times greater than that needed for bamboo. Therefore in this way it is eco-friendly. Bamboo is also sufficiently resistant to earthquakes (Karakus-Zambak and Celik, 2025) due to its high residual strength, which allows it to absorb shocks. Despite its advantages, bamboo has not gained widespread popularity as a reinforcement material, primarily due to the lack of structural design data, its exclusion from building codes, and its low durability. The traditional knowledge of bamboo construction, passed down through generations, should be preserved as valuable standard practices for the same types of conditions, informed by social customs and practical wisdom. The validation of such structures should rely on documented evidence of their resilience to earthquakes, hurricanes, and other extreme conditions. The research progress focused on using of as a construction material, specially for low-rise houses (Muhtar, 2024; Muhtar and Manggala, 2024). Apart from the mechanical properties of bamboo, the investigations also carried out to find out its strength incorporating different parameters (Tazowar *et al.*, 2023; Yan *et al.*, 2025).

Literature review

Several standards provide guidance on key parameters for using bamboo as a construction material. In India, IS 8242:1976 outlines test methods for split bamboo (Bureau of Indian Standards, 1976). Test methods for bamboo, including the evaluation of mechanical and physical properties, are also provided in IS 6874:2008 and ISO 22157:2019 (Bureau of Indian Standards, 2008; International Organization for Standardization, 2019). In addition, IS 15912:2018 provides guidance on structural design using bamboo as a construction material (Bureau of Indian Standards, 2018). IS 9096:2006 further provides guidelines on preservation and treatment methods for bamboo intended for structural applications (Bureau of Indian Standards, 2006). The study (Govindan *et al.*, 2022) performed to examine the influence of mechanical performance of bamboo incorporated as reinforced in concrete beams at various loading scenarios, specifically flexural load tests like two point load test, which include that the beams reinforced with bamboo splints and steel rebars exhibit enhanced resistance to flexural forces. Notably, this hybrid reinforcement not only preserves but, in some cases, improves the beam's maximum deflection capacity. Another study

(De Sousa Leite *et al.*, 2024) investigated that bamboo splints influenced the mechanical performance of reinforced concrete beams under varying loading, three-point and four-point flexural tests. It concluded that beams reinforced with bamboo splints alongside steel rebars exhibit enhanced resistance to flexural forces, particularly demonstrating superior performance under three-point bending conditions. The study (Yan *et al.*, 2025) bamboo-reinforced concrete beams were proposed as a solution to the low flexural stiffness observed in pure bamboo beams. It demonstrated that incorporating bamboo reinforcement enhanced the overall flexural performance and led to improved damage patterns. The research (Widayanto *et al.*, 2025), carried out with Wrapping bamboo rebars with fiberglass tape enhances their durability and potentially reduces brittleness. The study (Tazowar *et al.*, 2023), examined the bond behavior of three surface-treated bamboo with various corrugation patterns alongside non-corrugated and epoxy-treated samples using pull-out tests. It concluded significant increases in bond strength for all corrugated patterns compared to plain bamboo. Another study (Javadian *et al.*, 2016), also performed to increase the bonding properties of bamboo reinforced composite in concrete with the help of pull-out test. It also found an epoxy-based coating with use of sand particles provides better results without effect on bond strength. The research work (Zhao *et al.*, 2025) concluded control over fibers orientation and dispersion, bamboo fibers enhanced the mechanical uniformity and shrinkage resistance of ultra-high-performance concrete. The other research (Muhtar and Manggala, 2024) focused on common rural houses that are often vulnerable to earthquake events, because of making without reinforced concrete members. The study tried to explore the use of bamboo reinforcement in making concrete columns. It evaluated the seismic behavior, such as lateral load carrying capacity, patterns of cracks, drift ratio, stiffness and ductility parameters of concrete columns incorporated with bamboo reinforcement. Another researcher (Muhtar, 2024), performed the efficiency of bamboo reinforced concrete used in the foundation of low rise houses. The research work (Karakus-Zambak and Celik, 2025), also focused on ductility of bamboo reinforcement for low rise construction. It concluded that properly treated bamboo is a viable alternative to steel reinforcement in reinforced concrete beams, within a limited range of ductility. The study (Dubey *et al.*, 2025) performed the application of a machine learning process to find out deflections in bamboo-reinforced concrete beams. A review article (Azuwa, 2024) outlines the steps to understand the effects of reinforced bamboo on

bond strength of concrete beams, which added the use of chemical with sand and aggregate for achieving high-quality reinforcement bonds. Another review article (Himasree *et al.*, 2023) tried to summarise the state of the art of bamboo-reinforced concrete use as structural members. The report (Brink and Rush, 1966) involved designing and constructing bamboo-reinforced concrete structures. It provided information for selecting and preparing bamboo for reinforcement, discussed construction principles, design procedure and charts tailored to bamboo-reinforced concrete. The research (Tera, 2024) performed to enhance the bond stress between concrete material and bamboo reinforcement. Bamboo bars were coated with rubber and resin based chemical to maintain high bond strength.

It has been observed that previous studies tried to find out the mechanical performance and surface treatment methods of bamboo, focusing on aspects such as the flexural strength and deflection capacity of bamboo-reinforced beams, as well as the limitations in ductility to some extent. On the other hand, very few studies have been conducted on the construction of low-cost or non-engineered houses using locally available bamboo.

The present study focused on bamboo species that are locally available and commonly used within the same region. Bamboo was collected from nearby areas and tested for various mechanical properties. After undergoing appropriate treatment, the locally sourced bamboo was used as reinforcement in beam construction. These beams were then tested in the laboratory. So, there is no need to transport bamboo

over long distances or incur high costs through bulk purchasing like steel reinforcement. The study focuses on a cost analysis comparing bamboo and steel as reinforcement materials, along with exploring low-cost housing approaches suitable for hilly regions.

Study Area

In India bamboo is a vital forest (Figure 1) species, widely distributed across the country. It plays a significant role in supporting rural economical development. Indian bamboo forests cover approximately 14 million hectares, making the country the second richest in bamboo. It may use as timber to the common people. It is the fastest-growing plant which belongs to the Poaceae (Gramineae) family of grasses (<https://www.sentinelassam.com/north-east-indianews/>, <https://www.britannica.com/plant/Poaceae>, accessed on 26/11/2024). The North-Eastern states (Figure 1) of India exhibits a rich diversity of bamboo, which are integral to the food and nutritional security of tribal communities in the region. Approximately 50% of the country's bamboo species are cultivated in these states, including Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, and Tripura (<https://www.sentinelassam.com/north-east-india-news/>, accessed on 26/11/2024). Basically the present study focused on the area of Arunachal Pradesh, India.

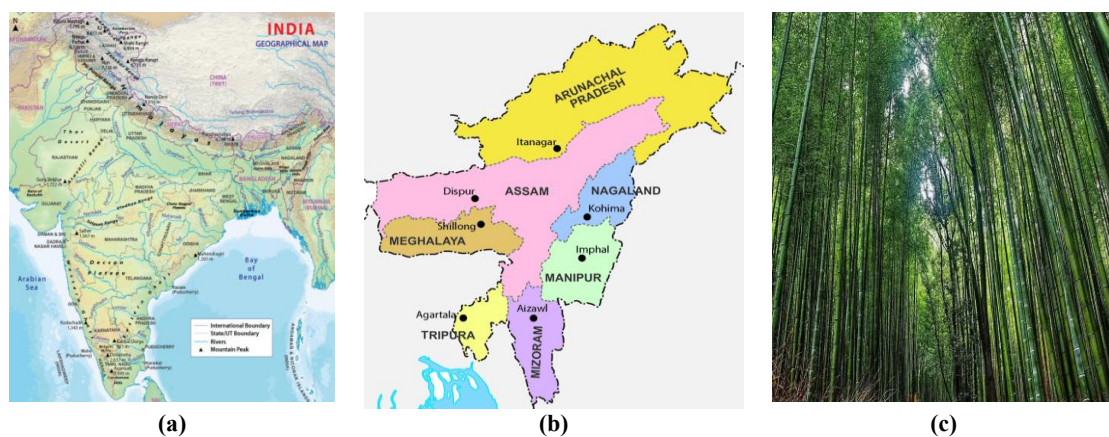


Figure 1. (a) Map of India (b) North-East India (c) Forest of bamboos at North-East India.

(Sources: <https://www.mapsofindia.com>, <https://www.sentinelassam.com>, accessed on 24/11/2024)

Need of bamboo in place of steel

Demand for steel-reinforced concrete is increasing, specially in high population countries, yet they often lack the resources to produce the necessary steel. This naturally available, environment friendly, sustainable and highly resilient material has the potential to become an ideal replacement in regions where use of steel is challenging. Bamboo has shown remarkable tensile strength in trials, even surpassing that of reinforcement steel, thanks to its hollow, tubular structure that has evolved over millennia to withstand wind forces in its natural environment. Its lightweight nature also makes bamboo easy to harvest and transport. Apart from this, bamboo's rapid growth and its environment friendly nature make it an extremely cost-effective option. Its cultivation as a building material could also help mitigate climate change, as the plant absorbs large amounts of CO₂ during its growth. Despite these advantages, challenges remain in developing bamboo as a viable reinforcement material.

Low cost house with bamboo reinforced beams

The large numbers of population of developing and underdeveloped countries were using their habitats as a form of non-engineered structures.

These types of structures are basically made of naturally available materials, like local wood, bamboo, grass, mud etc. Therefore, bamboo is an easily available and low cost material, which is used as an important structural material. The present study tries to implement the bamboo as beam reinforcement for low cost low rise houses. Figures 2(a) and 2(b) show the existing low cost houses in hilly areas from North-East India. Figure 2(c) illustrates a general idea to provide the same type of low cost low rise house using bamboo reinforced concrete beams. This bamboo reinforced concrete beams can be a better, economic and pollution free replacement of steel reinforced concrete beams.

Bamboo Species in Arunachal Pradesh and Their Uses

Globally, there are approximately 1,250 bamboo species, with 130 found in India, 89 in North East India, and around 57 in Arunachal Pradesh. In these regions, bamboo grows naturally in forests and is also cultivated in homesteads and fields.

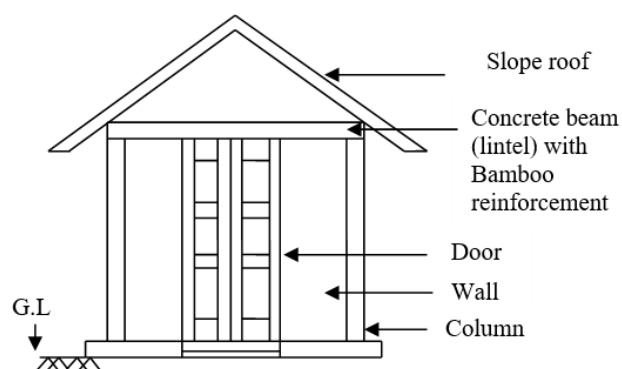
Bamboo Species in Arunachal Pradesh and Nearby Regions: Arunachal Pradesh is home to about 57 bamboo species, though only a few are widely cultivated for their commercial viability. Some notable species include: These species are integral to various applications, from construction and crafts to culinary uses, highlighting the diverse



(a)



(b)



(c)

Figure 2. (a), (b) Real type house in North-East India. and (c) Sketch of typical low-cost low rise house with bamboo reinforcement concrete beam.

(Sources: [https:// www.google.com/image](https://www.google.com/image), Accessed on 28-10-2024).



Figure 3. (a) Stem or Culm (longitudinal view) and (b) Cross section of stem

utility of bamboo in the region. Strength-wise Most Commonly Used Bamboos: (i) *Bambusa Balcooa* (Bhaluka): Higher strength: Dimensions: Culms 25 to 30 meters high; (ii) *Bambusa Tulda* (Jati): Medium strength; (iii) *Bambusa Pallida* (Bijli): Lower strength. Among these, *Bambusa Balcooa* (Figure 3) is preferred for use as reinforcing material in beam construction due to its higher strength. These types of bamboo are sufficiently available in the North-eastern region of India. They offer greater strength compared to bamboo found in other regions.

Properties of Bamboo

Bamboo's Physical Structure: Though bamboo is often likened to wood because of its similar chemical composition, its physical structure is distinct. Unlike wood, which has anisotropic properties with uniformly oriented grains, bamboo consists of parallel fibers aligned along the culm's axial direction. Moreover, while wood produces branches with uniform grain patterns, bamboo creates nodes at points where branches grow, giving rise to grass-like leaf structures.

Shrinkage and Swelling: As similar to wood, bamboo experiences dimensional changes as it absorbs or releases moisture. As a hygroscopic material, bamboo's moisture content adjusts according to the surrounding humidity and temperature.

Mechanical Properties: Mechanical and physical properties of Indian bamboo, along with their permissible values, are considered wherever required, according to IS-15912:2018. and IS 6874:2008

Grading of Structural Bamboo: Bamboo meets the necessary strength and stiffness requirements for structural use, it must be graded based on specific characteristics. The grading process involves sorting bamboo according to the following criteria as specified in IS 15912:2018 (Bureau of Indian Standards, 2018): diameter,

length, taper and straightness of stem of bamboo tree; node distribution and distance between two consecutive nodes; thickness, density, durability and Strength of culm; also depending on and seasoning of bamboo.

Gradation by Mean Outer Diameter: Structurally use purpose bamboo divided as group A and group B, in accordance with IS 15912:2018 (Bureau of Indian Standards, 2018). The culms are categorized into the following grades based on their mean outer diameter: special grade: diameter of culm between 70-100 mm; grade 1: diameter within 50-70 mm; grade 2: this values between 30-50 mm; grade 3: diameter of culm less than 30 mm. Structural group C: 20 mm increase with mean outer diameter of other grades.

Length of Bamboo: The Minimum length of culms should preferably be 6 meters to facilitate close fittings at joints and other structural construction connections.

Taper: The taper should not exceed 5.8 mm per meter length for all grades.

Curvature: The limit of curvature is 75 mm over a 6-meter length for all grades

Thickness of culm: The thickness of wall 8 mm is preferred for better load carrying capacity. The load calculations should align with IS 875 (Part 5):1987 (Bureau of Indian Standards, 1987).

Permissible Stresses: The permissible stresses values of bamboo use as a structural material are provided in IS 15912:2018 (Bureau of Indian Standards, 2018) and (Karakus-Zambak and Celik, 2025).

Laboratory experiment on specimen of bamboo

Experiments are performed in Laboratory to find out the several design parameters of bamboo which used as reinforcement instead if steel during construction of bamboo cement concrete beams.

Static bending test

Preparation test specimen: The specimen should be a split bamboo. Width should be two times of thickness of bamboo. Depth should be same as the thickness. Length should be 14 times of the depth and 5 cm extra. For small variations in thickness, the span can remain constant. Ensure the specimen is free from defects such as cracks or crookedness. It should be tested with centre-internodes and having a rectangular cross-section. This test performed with universal testing machine (UTM) (Figure 4a).

- a) Modulus of rupture (kgf/cm^2) = $(3PL/2bh^2)$
 b) Modulus of elasticity (kgf/cm^2) = $(3PL/4b^3d)$

where,

P= load at proportional limit (kg); b = width of specimen (cm); h= depth of specimen.

L= span length of specimen; d = deflection at proportional limit (cm).

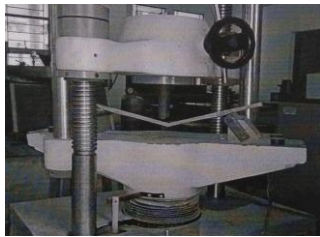
Compressive strength test

Preparation test specimen: It should be considered within internodes. length is same as its outer diameter. Ensure that end planes of the specimen are perfectly perpendicular to its length and flat. This test is performed with a compressive testing machine (CTM) (Figures 4(b)-(d)).

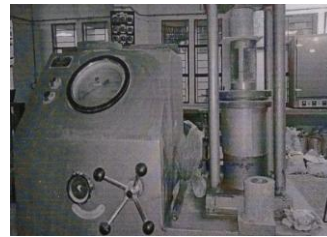
Maximum compressive strength (MPa) = (F/A) , where, F= maximum load (N); A= area of cross-section of specimen (mm^2)

Tensile strength test

Preparation test specimen: Direction of the bamboo fibers should be parallel to its longitudinal axis. Specimens should contain one node at its middle location. Length should be 40 cm and width should be 10- 20 mm. Thickness should be equal to or less than its thickness. The split ends of bamboo should be laminated with aluminum wire for better grip. Figure 4(e), and 4(f) are shown about the tensile test.



(a)



(b)



(c)



(d)



(e)



(f)

Figure 4. Various experiments performed on Bamboo specimen (a) Static bending test performed with UTM, (b) Compressive test performed with CTM, (c) Bamboo specimen before compressive test, (d) Bamboo specimen after compressive test, (e) Tensile test performed with UTM and (f) Bamboo specimen after tensile test

Maximum tensile strength (MPa) = (F/A) , where, F = maximum load (N); A = area of cross-section of specimen (mm^2).

Moisture content test

Preparation test specimen: The same type of bamboo specimens was used for the moisture content test. Samples were collected immediately after the mechanical tests, specifically from areas near the point of failure. Each specimen measured 25 mm in length and 25 mm in width, including the full wall thickness of the bamboo.

Numerically, Moisture content = $(m_i - m_o)/m_o$ where, m_i = specimen weight; m_o = oven dried weight of specimen.

Pull-out test

Length of anchored bamboo bar = 750 mm. Height of cylindrical mould = 300 mm Diameter of cylindrical mould = 150 mm. Grade of cement concrete used as M20 (1:1.5:3). Slipping should not occur between bamboo and concrete while the bamboo bar is broken from the length which is not embedded in the concrete cylinder. If load at bond failure is P , then bond strength (T) is given by:

$T = P/(\pi dL)$, where, P = pull-out load (Tensile force); d = diameter specimen; L = length/height of the specimen.

Results are collected from laboratory tests on bamboo samples which are used as reinforcement in construction of cement concrete beams are represented in Table 1.

Preparation of bamboo as use for reinforcement

The bamboos are prepared through several processes (Figure 5(a), 5(b)) for use as reinforcement in cement concrete beams.

Size of bamboo: Considered length of bamboo strips = 700 mm; thickness of bamboo = 12 to 15 mm; node to node distance (internodes) = average 28 to 33 cm.

Cutting of bamboo: Bamboo is cut into splits of 700 to 800 mm in length using a motor-driven woodcutter. The splits are then finished with a plane jack. Projections at the nodes of bamboo strips are left as is to enhance bond strength.

Improvement of bond strength: Aluminum wire is tightly wrapped (Figure 6(a)) around the full length of the bamboo strips to enhance bond strength. This technique improves the grip between the concrete and the bamboo strips, which are used as reinforcement. The aluminum wire creates a corrugated surface similar to that of HYSD (High Yield Strength Deformed) bars, improving the bond with the concrete.

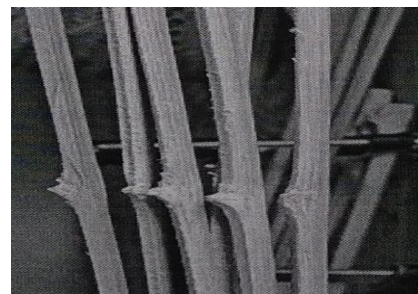
Prevention of Moisture Penetration: During casting of structural elements such as beams or columns, it is essential to consider the impact of moisture from the concrete mix on bamboo performance. Although water is necessary for the hydration process in concrete, it can cause seasoned bamboo to rot if not properly protected. To prevent decay and ensure durability, a protective coating

Table 1. Results of laboratory experiments performed on specimen of bamboo

Values of various design parameters	
Parameter	Range
Static bending strength (MPa)	101-180
Compressive strength (MPa)	55-100
Tensile strength (MPa)	111-220
Density (kg/m^3)	500-900
Bond strength (MPa)	70-110



(a)



(b)

Figure 5. Bamboo specimen shaped as reinforcement for beam construction (a) Cutting of Bamboo specimen with saw and (b) Bamboo specimen in shape of reinforcement

must be applied to the bamboo before use. Algi Coat RC-104 (Figure 6(b)) is commonly used as a protective layer, though other water-repellent products such as Pidilite water repellent can also be effective. After applying the coating, a layer of sand is sprinkled over the bamboo strips (Figure 6(c)) to enhance the bond between the bamboo and the cement paste.

The curing of constructed beams was done by normal standard procedure, typically applied to conventional cement concrete beams. The bamboo was used at normal temperature for beam construction.

Construction of cement concrete beam with of bamboo reinforcement

The frameworks are made according to size of the constructed beam (Figure 7(a)). Prepared bamboo strips (4 numbers) are bound with binders to make the skeleton or cage of cement concrete beam (Figure 7(b)). The bamboo made skeletons are placed into the frameworks and poured with green cement concrete (Figure 7(c)). On the other hand reinforced cement concrete (RCC) beams with steel reinforcement are constructed with the same

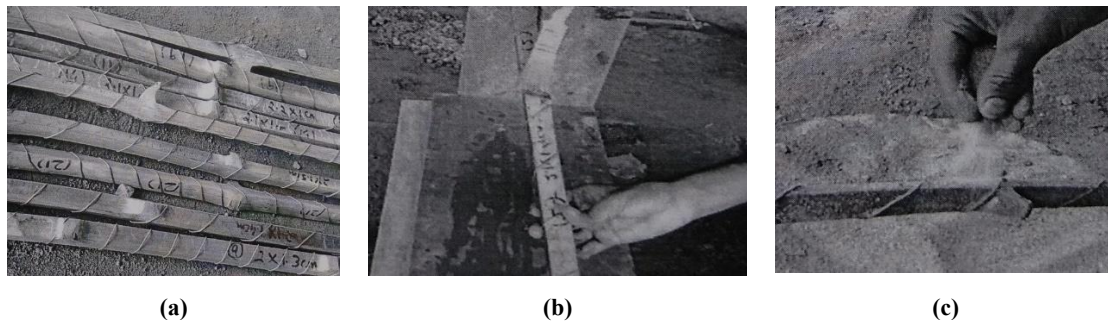


Figure 6. Preparation shaped bamboo specimen for use as reinforcement in beam construction (a) Wrapped with Aluminum wire, (b) Coated with ALGI Coat RC-104 and (c) Sprinkled sand over coating

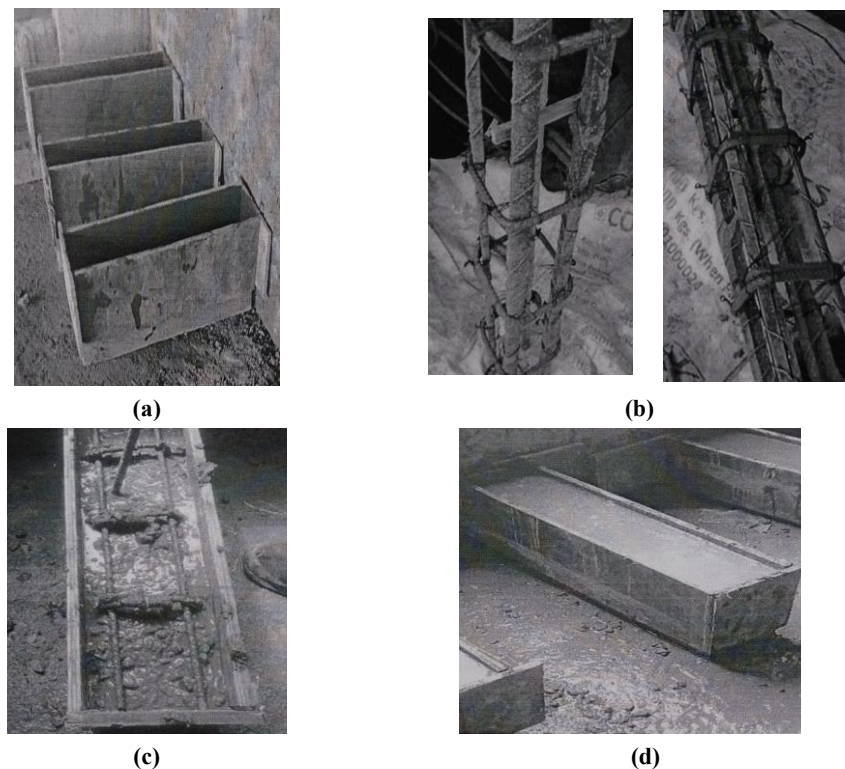


Figure 7. Casting of bamboo reinforced concrete beam (a) Frame work of beam casting, (b) Bamboo skeleton or cage, (c) Pouring of concrete beam and (d) Concrete beam after casting

dimensions as the bamboo reinforced cement concrete (BRCC) beams are made. The freshly constructed all beams of both types (RCC and BRCC) are placed 28 days for hardening (Figure 7(d)) to gain its proper strength. The mix design as per Indian code IS 456:2000 (Bureau of Indian Standards, 2000) which is used for steel-reinforced concrete is equally suitable for bamboo-reinforced concrete. However, the concrete slump should be kept as low as possible to maintain workability, as excessive water can lead to bamboo swelling.

To mitigate cracking caused by swelling, especially when waterproofing seasoned bamboo is not feasible, high early-strength cement is recommended.

Bamboo strips are placed not less than 1-1/2 inches apart from the surface of the concrete beam. During the use of complete bamboo stems, alter top and bottom ends directions of the culms at every row; ensuring that nodes or collars are staggered. Placing the bamboo in this manner provides an equal distribution as reinforcement. Various parameters considered for design and construction of beams (RCC and BRCC) are represented in Table 2. Harden beams are tested in the laboratory after 28 days (after curing). Two point bending tests (Figure 8) are performed to find out the peak loads for each beam. Peak loads of each beam during the two point bending tests are collected from graphs shown in Figure 9 for BRCC beams

Table 2. Design parameters of constructed beams

Parameter	Value
Beam length	700 mm
Beam cross-section	150 × 150 mm
Concrete grade	M20
Steel grade	Fe415
Nominal mix proportion (cement:sand:coarse aggregate)	1:1.5:3
Water-cement ratio	0.47-0.50
Beam type	Reinforcement ratio (% of total cross-sectional area)
RCC (steel)	Specimen 1: 0.45; Specimen 2: 0.67; Specimen 3: 0.89
BRCC (bamboo)	Specimen 1: 0.30; Specimen 2: 0.40; Specimen 3: 0.50

Table 3. Calculation and comparison of flexural strength of RCC and BRCC beams

Beam No.	Width (b) (mm)	Depth (d) (mm)	Supported length (L) (mm)	Peak load (P) (N)	Flexural Strength (σ_f) = $(PxL)/(bxd^2)$ (MPa)
Specimen no.1, RCC	150	150	700-2×50 = 600	46×10 ³	8.18
Specimen no.2, RCC	150	150	700-2×50 = 600	50×10 ³	8.89
Specimen no.3, RCC	150	150	700-2×50 = 600	64×10 ³	11.38
Specimen no.1, BRCC	150	150	700-2×50 = 600	45×10 ³	8.00
Specimen no.2, BRCC	150	150	700-2×50 = 600	49.5×10 ³	8.80
Specimen no.3, BRCC	150	150	700-2×50 = 600	62×10 ³	11.02

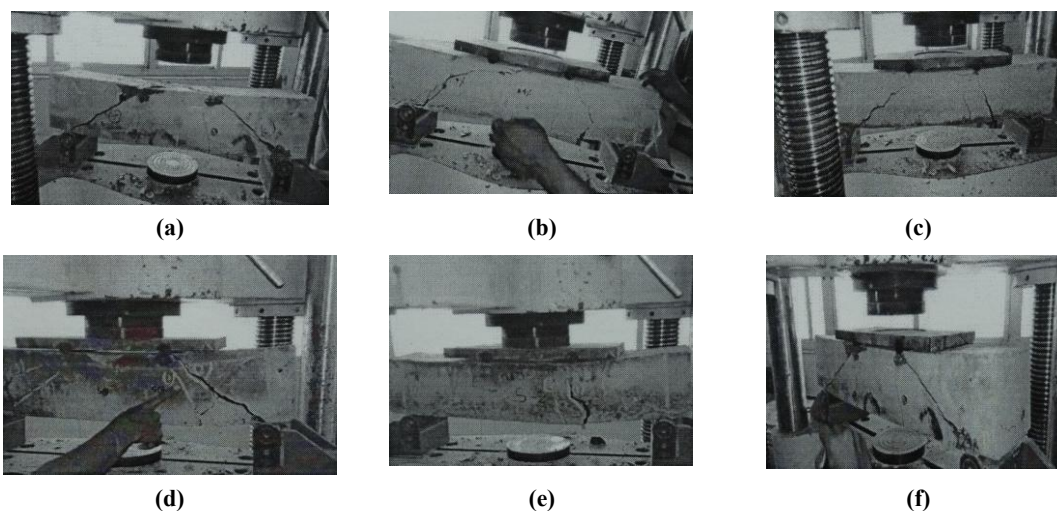


Figure 8. Two point bending test of RCC and BRCC beams and location of cracks formation (a) Specimen no.1, RCC, (b) Specimen no.2, RCC, (c) Specimen no.3, RCC, (d) Specimen no.1, BRCC, (e) Specimen no.2, BRCC and (f) Specimen no.3, BRCC

and Figure 10 for RCC beams. Flexural strength of RCC and BRCC beams are calculated with the help of the observed peak loads (Table 3). A comparison is performed between the flexural strength of both types of beams (Table 3).

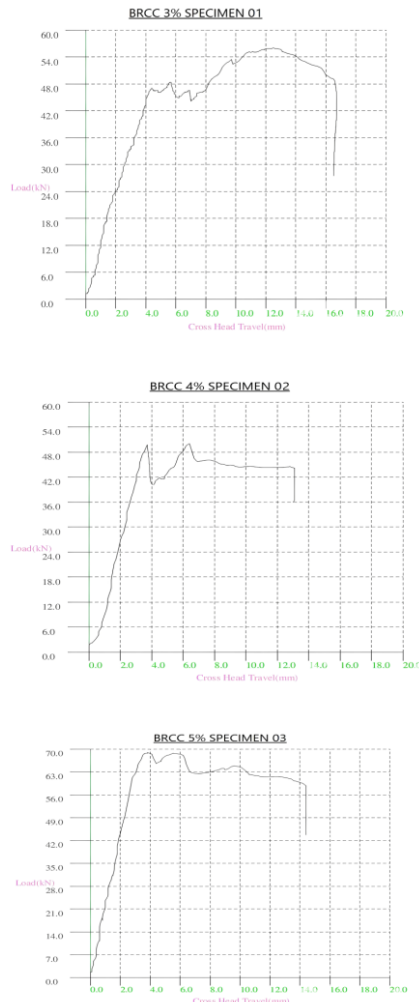


Figure 9. Peak loads of two point bending tests of BRCC beams`

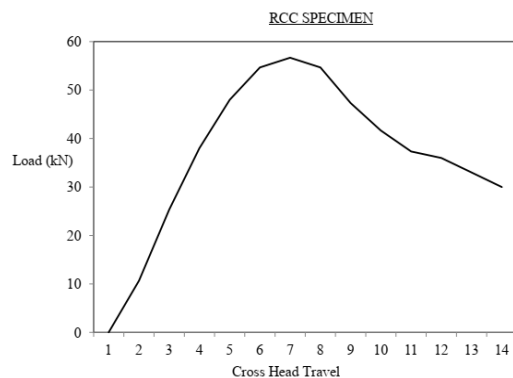


Figure 10. Combined graph for peak loads of two point bending tests of RCC beams

Observation of failures and cracks criteria

Two point bending test performed and during the test the criteria of failures and cracks are observed as follows:

Specimen no.1, RCC: Gradual failure and generation of first, second, third and fourth cracks at the distance of 200mm, 190mm, 410mm and 390mm respectively from right support (Figure 8(a)).

Specimen no.2, RCC: Gradual failure and generation of first and second cracks at the distance of 190mm and 210mm respectively from right support (Figure 8(b)).

Specimen no.3, RCC: Gradual failure and generation of first and second cracks at the distance of 200mm and 405mm respectively from right support (Figure 8(c)).

Specimen no.1, BRCC: Gradual failure and generation of first, second, third and fourth cracks at the distance of 200mm, 400mm, 600mm and 00mm respectively from right support (Figure 8(d)).

Specimen no.2, BRCC: Gradual failure and generation of first, second, third and fourth cracks at the distance of 380mm, 210mm, 600mm and 184mm respectively from right support (Figure 8(e)).

Specimen no.3, BRCC: Gradual failure and generation of first, second, third and fourth cracks at the distance of 205mm, 380mm, 170mm and 550mm respectively from right support (Figure 8(f)).

Discussion

The mechanical properties of bamboo, determined through laboratory experiments, demonstrate its suitability as a construction material, particularly for low-rise, low-cost housing. As shown in Table 1, the tested parameters confirm bamboo's adequate strength for structural applications. Bamboo is a natural, plant-based, and biodegradable material, which makes it susceptible to moisture and pest attacks. Therefore, applying appropriate protective measures against moisture (Figure 6) enhances its resistance and significantly improves the durability of bamboo reinforcement. Incorporation of fine aggregate on bamboo reinforcement enhanced its bonding strength with cement concrete. On the other hand, bamboo has a much lower thermal expansion coefficient compared to steel. Since this study focuses on low-rise, low-cost housing where large beam sizes are not required, the effects of thermal expansion are less impactful.

Table 4. Cost Comparison between steel reinforcement and bamboo reinforcement

Steel Reinforcement	Bamboo Reinforcement
Unit weight of 8 mm diameter bars: 0.395 kg/m	Average cost of an 8 to 10 m dry Balcooa bamboo culm (from the Assam region): 100 rupees
Total length for 15 bars of 700 mm each: $15 \times 0.7 = 10.5$ m	Approximately 25% of the bamboo is used to produce 11 strips, costing: $0.25 \times 100 = 25$ rupees
Total weight of reinforcement: $0.395 \times 10.5 = 4.1475$ kg	Cost of finishing (carpentry work) for the bamboo strips: 70 to 80 rupees (approximate)
Cost of steel reinforcement @ 69.72 rupees/kg: $69.72 \times 4.1475 = 307.8$ Indian Rupees	Total cost of bamboo reinforcement: $25 + 75 = 100$ Indian Rupees

During bending tests, the BRCC beams exhibited an average peak load of approximately 60 kN (Figure 9), which is comparable to the performance of conventional RCC beams (Figure 10). The locations of cracks formation and failure patterns were also observed (Figure 8), which are acceptable as compared to RCC beams. A comparison of the flexural strength of RCC and BRCC beams, presented in Table 3, demonstrates the viability of bamboo as a reinforcement material. Previous studies have also contributed valuable insights in this regard. The findings of this investigation may support future implications for code developments and construction practices. Additionally, a cost analysis conducted during the construction of both RCC and BRCC beams revealed that bamboo reinforcement is more economical and cost-effective than steel reinforcement. Table 4 provides a detailed comparison, highlighting bamboo's potential as a sustainable and affordable alternative for low-cost housing making.

Conclusion

The present paper tried to represent a close comparative analysis between BRCC and RCC beams. The study mainly focused on the use of bamboo as construction material replacement of steel, specially for low- cost and low rise houses. The investigation pointed out the following conclusion:

- The commercialization of bamboo as a reinforcing material is highly justified, given its comparable flexural strength to conventional RCC beams, as demonstrated in this study.
- Lightweight in nature and effective strength as compared to its weight (mechanical properties), bamboo reinforcement holds significant promise for low-rise housing.
- Bamboo is a sustainable and widely available material in many regions. Unlike steel, it does not require energy-intensive manufacturing processes, which significantly lowers both

construction costs and carbon emissions. Its use also contributes to reducing greenhouse gas emissions and minimizing the overall environmental footprint.

d) The cost analysis reveals that steel is approximately three times more expensive than bamboo. This significant price difference highlights bamboo's potential to reduce construction costs, particularly for non-engineered buildings, while simultaneously improving access to sustainable housing.

e) Bamboo with relatively high strength is readily available in the hilly regions of Northeast India. This makes it a highly effective material for constructing low-rise houses with improved structural performance

f) Adopting bamboo as a beam reinforcement material offers an effective and affordable solution for constructing low-cost housing, particularly in rural and hilly regions, and is especially beneficial for low- to middle-income communities.

Declaration of interest statement

The manuscript with entitled "Low cost housing: an effective approach with bamboo reinforced beam", authored by Pranab Kumar Das and Mainak Mallik is our original research work. Therefore, I (we) have nothing more to declare.

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