

Bamboo Reinforcement in Concrete: An Experimental Study on Flexural Strength and Its Sustainability

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Abstract—The rapid growth of population and infrastructure demand has significantly increased the consumption of conventional construction materials such as steel and cement, both of which have embodied energy and contribute considerably to global greenhouse gas emission.

In search of sustainable, economical and renewable alternatives, bamboo has emerged as a promising reinforcement material due to its high tensile strength, low carbon footprint, rapid growth rate, and natural availability.

This study integrates findings from existing experimental investigation and systematic literature reviews to evaluate bamboo's mechanical properties, feasibility and performance as reinforcement in concrete.

The reviewed literature reveals that bamboo exhibits tensile strength ranging from approximately 100- 300 mpa, a modulus of elasticity comparable to low-grade steel and exceptional energy absorption due to its hollow tubular structure. Different species such *Bambusa balcoa*, *Dendrocalamus asper* and *Bambusa vulgaris* show strong potential for construction application.

Experimental studies confirm that bamboo reinforced concrete demonstrates adequate compressive, tensile, and flexural strength while also offering, 30-40% cost savings significantly and lower carbon emission compared to steel-reinforced concrete. However, challenges remain in durability, water absorption joint connection, and standardization.

Overall, this combined research highlights that bamboo can serve as an eco-friendly, renewable and economical alternative to steel reinforcement for low-to medium load concrete structures. The study supports the growing global shift toward sustainable construction practices and promotes bamboo reinforcement as available step toward reducing environmental impact in the construction industry.

Index Terms—Bamboo reinforcement, Low carbon footprint, Greenhouse gas emission, Tensile strength, Modulus of elasticity, Flexural strength, Compressive strength, Alternative to steel reinforcement.

I. INTRODUCTION

The construction industry is one of the largest contributors to global greenhouse gas emission, responsible for nearly one-third (1/3) of total CO₂ output. Rapid population growth and the rising demand for new housing and infrastructure have intensified the consumption of energy - intensive material, particularly steel and cement, in countries like, India the use of steel in the construction sector has increased significantly. Creating economic pressure and environmental challenge due to high production energy, resource extraction and emissions.

In this context, researchers are actively exploring sustainable alternative that can reduce environmental impact without compromising structural performance. Bamboo has gained increasing attention as a renewable, fast-growing, and abundantly available natural material with strong potential for reinforcement in concrete structure.

Growing up to **30-40 meters within 3-5 years**, bamboo is one of the world's fastest -renewing woody plants. Its hollow circular structure provides high tensile strength, resilience, and resistance against dynamic loading -properties similar to those required for reinforcing steel.

Historically used for scaffolding, housing, frameworks, flooring and traditional construction, bamboo is now being investigated scientifically as a structural reinforcement material studies suggest that

properly treated bamboo exhibits tensile strength that rivals mild steel, with significantly lower embodied energy environmental footprint.

Bamboo's lightweight nature, biodegradability and cost-effectiveness make it ideal for sustainable construction, especially in rural and affordable housing sectors.

Recent literature also highlights the need for eco-friendly materials aligned with global climate agreements such as the Paris agreement and sustainable development goals. (SDGS).

Bamboo directly supports these goals by reducing carbon emission and dependence on non-renewable resources. However despite its advantage, challenge such as high-water absorption, susceptibility to decay, non-uniform mechanical properties, and lack of standardized design guidelines continue to limit its widespread adoption.

This study synthesizes insights from experimental research and systematic reviews to provide a comprehensive understanding of bamboo as reinforcement material in concrete.

It examines bamboo's mechanical properties' treatment methods, structural performance in concrete members, and its feasibility as sustainable alternative to steel. The goal to contribute to the development of innovative, eco-friendly reinforcement solution suitable for modern construction needs.

II. METHODOLOGY

- Bamboo reinforced concrete construction follows same design, mix proportions and construction techniques as used for steel reinforced.
- Bamboo used as a substitute for steel in concrete and mechanical properties of bamboo reinforced concrete are compared with conventional concrete.
- The mechanical properties such as:
 - a) Compressive strength
 - b) Tensile strength
 - c) Flexural strength is tested and
 - d) Compared with conventional concrete.

The results help in evaluating the effectiveness of bamboo reinforced concrete.

- Bamboo has been traditionally used in construction for load bearing purpose like scaffolding. Its use as reinforcement is a new concept in civil engineering being natural,

biodegradable, and renewable, bamboo, is an eco-friendly material suitable for sustainable construction.

- Steel has been a preferred reinforcing material in construction for centuries due to its strength and durability. However, in many developing countries the growing demand for steel often exceeds its availability. This situation highlights the need for an effective alternative material.
- Bamboo is abundantly available and exhibits desirable mechanical properties such as high tensile strength and resilience. Its structural characteristic, particularly its hallowed tubular form, contribute to its strength and resistance to external forces like wind. These properties make bamboo a promising substitute for steel reinforcement.
- To evaluate the feasibility and reliability of bamboo as a reinforcing material in concrete, suitable bamboo specimens are selected and prepared.

Various tests are conducted, including:

1. Fineness of cement
2. Sieve test
3. Consistency of cement
4. Specific gravity (aggregate).
5. Sieve analysis (aggregate.)
6. Compressive strength test.

PROPERTIES	BAMBOO
Specific Gravity	0.570 to 0.650
Average Weight	0.620kg/m
Modulus of Elasticity	1.6 to 2.1×10 ⁶ kg/cm ²
Compressive Stress	790 t 860 kg/cm ²
Safe working stress in tension	150 to 340 kg/cm ²
Safe working stress in shear	120 to 170 kg/cm ²
Bond stress	5.5 kg/cm ²

Table 1. Properties of Bamboo

To check the flexural strength of the beam reinforced with bamboo. Cement concrete flexural elements of the dimension 500x100x100 mm were prepared.

Methodology: Bamboo Reinforced Concrete (BRC)

Selection of Material:

- Cement: OPC (e.g. M25 grade concrete)

- Fine aggregate: River sand
- Coarse aggregate: 10mm size
- Water: Potable water
- Bamboo: Mature (3–4-year-old), straight and defect-free.

Cement: The cement used in this research was Ordinary Portland Cement (OPC), 43 & 53 grades, meeting the specifications of IS 12269:1987. The cement was recently manufactured, showed uniform coloration, and contained no lumps or foreign particles. Its physical characteristics were evaluated following IS 4031 (Part 1-1988), while the chemical properties were assessed according to IS 4031 (Part 2-1985) to ensure that the material met the requirements for high-quality concrete production.

- Fresh, uniform grey colour, lump-free.
- Stored on pallets in a dry room, away from walls/floor to prevent moisture ingress.
- Use within 3 months of manufacture for consistency.



Fig.1.1 Cement

Fine Aggregate: The fine aggregate consisted of clean river sand. It passed through a 4.75 mm IS sieve and was retained on the 600 mm sieve, Complying with Zone II grading of 15383:1970. The sand used was free from impurities such as clay, silt, organic matter, or debris. Its clean and well-graded nature made it suitable for producing consistent and workable concrete mixes.



Fig.1.2 Fine Aggregate

Coarse Aggregate: Crushed granite obtained from nearby quarry served as the coarse aggregate for this study. Aggregates with nominal sizes of 10 mm and 20 mm were used.

The aggregates were tested for essential physical properties such as specific gravity, impact strength, and water absorption following the guidelines of IS 2386 (Part 1, 3, and 4):1963

These tests confirmed that the aggregates met the required standards for use in structural concrete.

- Hard, durable, clean, and roughly cubical.
- Free from dust, clay lumps, soft/porous particles.
- Use single size or a blend to achieve a smooth grading curve.



Fig.1.3 Coarse Aggregate

Water: Water is one of the construction materials, but people still have ignored the quality aspect of the element. The water is required for making mortar, curing works, and during the experimental investigation of concrete mix, etc. Potable water (if it's fit to drink, it's typically fit for concrete).

Limits:

Chlorides and sulphates within code limits to avoid steel corrosion (still relevant for durability even when steel is not the main reinforcement).

No oils, sugars, or organic contaminants.

Water–cement ratio (w/c) Usually 0.40–0.50 for M20–M30 mixes used in beam testing; choose one value via trial mixes for target slump and strength.

Sl. No.	Description	Water Sample	Maximum Permissible Limit
1.	PH value	8.9	6.9
2.	Hardness (ppm)	403	1000
3.	Sulphate (ppm)	100	400
4.	Chlorides (ppm)	137	500

Bamboo: Bamboo serves as the tensile reinforcement. Because it is a natural, anisotropic, hygroscopic material, careful selection and treatment are essential.

Selection criteria:

Mature culms (3–4 years old) for stable properties.

Straight internodes, minimal surface checks, no fungal attack.

Outer diameter and wall thickness sufficient to cut uniform strips (10–12 mm wide for small beams).

Physical & Mechanical Properties (Anatomy):

Hollow culm with nodes; fibres denser near the outer skin (hardest layer), giving maximum tensile capacity along the length. Typical properties (ranges; measure actual values in lab):

- Density: 600–800 kg/m³ (varies with species and moisture).
- Moisture Content (as-received): 8–15% after seasoning; can be >25% if green.
- Tensile Strength (parallel to grain): 150–300 MPa.
- Compressive Strength (parallel): 40–80 MPa.
- Modulus of Elasticity: 10–20 GPa.
- Shear Strength (parallel): 8–12 MPa (influences splitting at nodes).

Implications for design/testing: high longitudinal tensile strength but low transverse strength; bond with concrete must be improved.

Water Absorption & Swelling Behaviour:

- Bamboo is hygroscopic; absorbs water through vessels and parenchyma.
- Consequences: swelling → loss of bond, micro-cracking at interface; drying shrinkage → debonding.
- Mitigation: seasoning (air/oven), resin/bitumen/epoxy coating, sand-epoxy roughening, end-sealing near cut faces, and use of ties to limit splitting.

Bamboo Treatment Methods:

(a) Natural and Physical

- Seasoning: Air-dry in shade with ventilation (3–6 weeks) or kiln drying to ~10–12% moisture.
- Heat treatment: Mild thermal treatment (80–120 °C) to reduce sugars and improve dimensional stability.
- Mechanical preparation:

Stripping: Cut into uniform strips (10–12 mm width, 4–8 mm thick).

Surface roughening: Light scoring; or wrap with GI binding wire; or sand-epoxy coat to improve bond.

End sealing: With bitumen and epoxy to limit moisture ingress.

(b) Chemical

- Boric acid–borax (e.g., 1:1 ratio, ~6–8% solution) soak for 24–48 h → insect/fungus resistance.
- Copper-chrome-boron (CCB) or CCA alternatives (where permitted) for long-term durability.
- Water-repellent coats: Bitumen and coal-tar, epoxy, polyurethane, or varnish; apply thin, uniform coats leaving local roughened zones (or sprinkle sand over wet epoxy) to keep bond.
- Limewash for economical insect and moisture control in non-critical applications.

Practical bond detail: After coating, create a sand-epoxy layer on the tension face (sprinkle clean sand on wet epoxy). Provide GI wire ties at 150–200 mm c/c to control splitting at nodes.

Bamboo intended for reinforcement application. These steps include undergo a series of preparatory steps to make it suitable for structural application. These steps include:

- Weathering
- Chemical preservation
- Surface modification

These processes enhance durability, reduce moisture-related issues, and improve bonding with concrete.



Fig.1.4 Bamboo

1. Weathering (Seasoning of Bamboo)

Purpose: To reduce moisture content and stabilize the bamboo.

Fresh bamboo contains a lot of water and sugars. If used directly:

It shrinks after drying → causes cracks in concrete

It attracts insects and fungi

It loses strength over time.

Methods:

- Air drying (natural weathering):

- Bamboo is stored in a dry, shaded place for 4–8 weeks
- Protected from direct sunlight and rain
- Water soaking + drying:
- Bamboo is immersed in water for a few days to remove sugars, then dried

Result:

- Reduced moisture content (ideal: ~12–15%)
- Improved dimensional stability
- Less cracking and shrinkage

2. Chemical Preservation

Purpose: To protect bamboo from insects, fungi, and decay.

Bamboo is organic and biodegradable. Without treatment:

Termites and beetles can destroy it
Fungal decay weakens structure.

Common Chemicals Used:

- Borax + Boric acid solution
- Copper sulphate
- Creosote (less common for indoor use due to toxicity)

Methods:

- Soaking method: Bamboo submerged in chemical solution
- Pressure treatment: Chemicals forced into fibers (more effective)
- Brushing/spraying: For small-scale use

Result:

- Increased lifespan (can last years instead of months)
- Resistance to biological attack

3. Surface Modification

Purpose: To improve bonding between bamboo and concrete and reduce water absorption.

Problem without treatment:

- Bamboo surface is smooth and non-porous
- Poor adhesion → slippage inside concrete
- Swelling due to water absorption → cracks concrete

Techniques:

1. Roughening the surface
 - Scratching or sanding bamboo
 - Creates better mechanical grip
2. Applying coatings

- Bitumen (asphalt coating)
- Epoxy or waterproof sealants

This helps:

Reduce water absorption

Prevent swelling

3. Wrapping

- Coir rope or wire wrapped around bamboo
- Acts like ribs in steel reinforcement
- Combined Benefits of These Processes

After proper preparation, bamboo gains:

- Improved durability
- Resistant to decay and insects
- Reduced moisture problems
- Less swelling and shrinking
- Prevents cracking in concrete
- Better bond strength
- Stronger interaction with concrete
- Less slippage under load
- Increased structural reliability

Can safely be used in:

Beams

Slabs

Columns (light structures)

- Important Limitations (Even After Treatment)
- Lower strength compared to steel
- Not suitable for heavy-load or high-rise structures
- Requires careful design and supervision

Before using bamboo as reinforcement:

Weathering → reduces moisture and stabilizes

Chemical preservation → prevents biological damage

Surface modification → improves bonding and durability

Preparation of Bamboo Reinforcement:

- Cut bamboo into required strips
- Remove outer smooth layer to improve bonding.
- Seasoning for 2-3 weeks. (drying)
- Apply chemical treatment:
 - a) Bitumen, Epoxy, Araldite coating
 - b) Prevents water adsorption and swelling.
- Apply sand coating over wet bitumen.
 - a) Improve bond with concrete.

Design of Concrete Mix:

Used standard mix design ratio of M20 grade e.g. (1:1.5:3)
 Maintain proper water cement ratio. (0.45-0.5)

Preparation of Reinforcement Cage:

Arrange bamboo strips as main reinforcement (tension zone): Provide

- a) 2-3 bamboo bars at bottom.
- b) Steel stirrups (optional) or bamboo ties.

Maintain: Proper spacing

- a) Clear cover (20-25mm)

Casting of Beam Specimen:

- Clean and oil the mould (100x100x500mm)
- Place reinforcement cage inside mould
- Pour concrete in layout
- Compact using: Tamping rod and vibrator
- Finish surface smoothly.

- Demoulding and Curing:
- Demould after 24-48 hours
- Cure specimens in water for 28 days
- Testing of Specimens (Flexural test):
- Conduct flexural strength test using.
- Universal testing machine (UTM).

- a) Using Two-point or three-point loading on beam sized 100x100x500

❖ Formula (for flexural strength)

$$Fr = PL / bd^2$$

Where,

Fr = Flexural strength (N/mm²)

P = Maximum applied load at failure

L = Span length distance between fracture location and nearest support

b = Average width of specimen

d = Average depth of specimen.

Comparison of Results:

Test 3 types:

1. Plain concrete beam
2. Steel reinforced beam
3. Bamboo reinforced beam

Research shows bamboo beam can achieve 70% strength of steel RC beam and are much better than plain concrete.

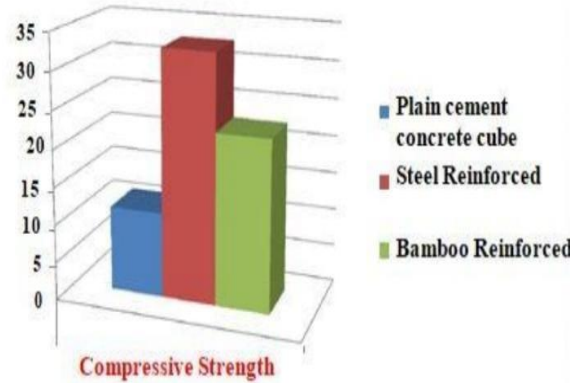


Fig.6. Comparison of Bamboo reinforced Concrete Column with Steel Reinforced and Plain cement Concrete Column

Conclusion from Results:

- Bamboo reinforcement increases flexural strength by 40–50% compared to plain concrete.
- Though its strength is lower than steel RC, the ductility and low cost make it ideal for non-critical applications such as low-rise housing, temporary shelters, and eco-friendly buildings.
- The study validates bamboo’s mechanical reliability and sustainability potential for the next generation of green materials in construction

Discussion

Comparison between cost of steel and bamboo reinforcement concludes with the result that structures reinforced with bamboo as reinforcement is found cheaper than that of with steel reinforcement.

- **Structural Feasibility:** Bamboo, when properly treated and embedded in concrete, behaves as a ductile tensile reinforcement, improving flexural capacity and toughness compared to plain concrete.
- **Bond Behaviour:** Chemical treatment and bitumen coating enhanced bond strength between bamboo and concrete, minimizing slippage.
- **Failure Behaviour:** Bamboo RC beams showed gradual, predictable failure, unlike the brittle collapse of plain concrete.
- **Sustainability:** Bamboo is renewable, biodegradable, lightweight, and locally available making it an excellent candidate for sustainable construction and rural infrastructure.

III. LITERATURE REVIEW

Bamboo has been used traditionally in housing and temporary structures due to its high strength-to-weight ratio and availability. Studies confirm that mature bamboo has tensile strength of 200–300 MPa, making it a sustainable alternative for low-cost housing.

Mechanical Properties

- Tensile Strength: 150–300 MPa
- Compressive Strength: 40–80 MPa
- Elastic Modulus: 10–20 GPa
- Density: 600–800 kg/m³ Its fibre structure aligned longitudinally provides excellent tensile capacity but poor bonding with concrete laterally.

3.1 Durability and Treatment

Bamboo is vulnerable to biological decay. Common treatments:

- Boric acid–borax solution for pest resistance.
- Bitumen coating to reduce water absorption.
- Water seasoning for stability.

3.2 Previous Studies

- Ghavami (2005) proved bamboo RC beams improved flexural capacity by 25–30% over plain concrete.
- Agarwal et al. (2014) found that treated bamboo increased strength and ductility.
- Sharma et al. (2017) reported gradual failure, similar to steel RC.

3.3 Research Gap

Lack of:

- Codal provisions for bamboo RC.
- Long-term durability data.
- Full-scale beam testing.
- This research addresses these gaps through laboratory experimentation.

IV. PROPOSED RESEARCH CONCLUSION

This comprehensive analysis confirms that bamboo-reinforced concrete (BRC) represents a high-potential, sustainable alternative to conventional steel reinforcement, particularly for low-rise and modular construction. The synergy between chemical preservation, moisture-wicking barrier coatings, and mechanical shear connectors effectively mitigates bamboo's natural anisotropy and bond-slip issues,

enabling it to match the flexural performance of traditional materials at a fraction of the weight and cost. To advance this field, future research should shift toward Bio-mimetic Grading where the orientation and density of bamboo strips are strategically varied within the concrete matrix to match stress-flow paths- and the development of Self-Healing Interphases, utilizing bio-admixtures that dynamically.

V. PERFORMANCE-BASED OPTIMIZATION (PBO)

Rather than using generic bamboo, research should transition toward Species-Specific Reinforcement Mapping. Just as steel grades (e.g. Fe500) are selected for load, different bamboo species (e.g. *Dendrocalamus asper* for structural columns vs. *Bambusa balcoa* for beams) should be mapped based on their specific vascular density and elastic modulus, creating a bespoke engineering standard for bio-based building.

By framing your conclusion in this way, you shift the narrative from "can we use bamboo?" to "how can we optimize bamboo to outperform traditional materials in sustainable, carbon-negative frameworks?" utilizing bio-admixtures that dynamically seal micro-cracks at the bamboo-concrete boundary. By transitioning from simple reinforcement to an integrated, engineered composite system, bamboo can evolve from a 'low-cost' alternative into a high-performance material capable of supporting resilient, low-carbon infrastructure for the next generation of global construction."

VI. FUTURE- FACING RESEARCH CONCEPTS

Future Work or Discussion sections:

1. Functionally Graded BRC: Instead of uniform spacing, propose placing bamboo reinforcement in a gradient pattern that mimics the cellular structure of bone, which handles stress more efficiently than traditional uniform steel rebar spacing.

2. Smart-Monitoring Integration: Propose embedding fiber-optic or piezo-resistive sensors directly into the bamboo-concrete interface. Because bamboo is organic and porous, it can potentially house internal moisture-monitoring sensors to alert owners to internal

decay before structural integrity is compromised-a "self-diagnosing" building component.

3. Bio-Polymer Matrix Infusion: Suggest the use of vacuum-assisted resin infusion (VARI) to force eco-friendly bio-polymers into the vascular bundles of the bamboo before placement. This creates a synthetic-natural hybrid that drastically increases the elastic modulus and prevents water absorption at the cellular level.

4. Carbon-Negative Admixtures: Discuss replacing standard concrete mixes with bio-char infused concrete.

This creates a dual-sustainability effect: the carbon-sequestering potential of the bamboo is paired with the carbon-absorbing properties of bio-char concrete, creating a true "Carbon-Negative" building unit.

Additive to Integrated Design: Current research treats bamboo as an addition to concrete. Future research must view BRC as an integrated composite. By pre-treating bamboo in a moisture-controlled vacuum, we can achieve an interphase bond that is chemically bonded rather than mechanically forced. This eliminates the anisotropy gap -the difference in elastic modulus between the concrete and the reinforcement - reducing the internal stresses that cause premature debonding.

The Hygroscopic Balance Theory: A critical, often overlooked area is the hygroscopic compatibility between bamboo and concrete. Since concrete is alkaline and bamboo is organic, their expansion rates under temperature and humidity differ. Proposing an interface buffer layer (such as a thin layer of hydrophobic, flexible polymer) would allow the bamboo to breathe inside the concrete without causing micro-cracking at the bond surface-a major advancement in durability testing.

Performance-Based Optimization (PBO): Rather than using generic bamboo, research should transition toward Species-Specific Reinforcement Mapping. Just as steel grades (e.g., Fe500) are selected for load, different bamboo species (e.g., *Dendrocalamus asper* for structural columns vs. *Bambusa balcoa* for beams) should be mapped based on their specific vascular density and elastic modulus.

Future Scope

Bamboo reinforcement has the potential to revolutionize sustainable civil engineering practices. Future research must focus on bridging the gap between laboratory-scale innovation and real-world implementation through:

- Scientifically proven treatment and hybrid methods,
- Comprehensive durability testing, and
- Development of standard design guidelines.

Once standardized, bamboo can be confidently used as a mainstream green reinforcement material, enabling the construction industry to achieve the goals of low-cost housing, carbon-neutral structures, and sustainable development for future generations.

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