

Bond-Slip Behaviour, Anchorage Performance, and Sustainable Design Framework for Bamboo-Reinforced Concrete (BRC)

A. Kashiram¹; Dr. Kandru Suresh²

¹PhD Scholar, Department of Civil Engineering, Bharatiya Engineering Science & Technology Innovation University, SatyaSai (Dist.), Andhra Pradesh, India

²Professor and Head, DCE, Nalla Malla Reddy Engg. College, Telangana

Publication Date: 2026/10/09

Abstract: The escalating carbon footprint of conventional steel reinforcement and the growing demand for low-cost, locally sourced construction materials have renewed research interest in natural fibre-based reinforcement systems. Bamboo, owing to its rapid renewability, high strength-to-weight ratio, and carbon-negative growth cycle, has emerged as a promising alternative to steel in low-rise and rural reinforced concrete construction. However, the practical adoption of Bamboo-Reinforced Concrete (BRC) is constrained by an inherently weak and variable bond at the bamboo-concrete interface, driven primarily by the hygroscopic swelling and shrinkage behaviour of bamboo culms. This paper synthesises the bond mechanisms, anchorage strategies, and limit-state design framework applicable to BRC members. The relative contributions of chemical adhesion, surface friction, and mechanical interlock (particularly at bamboo nodes) to the overall bond-slip response are examined, alongside surface treatment strategies — sealing, roughening, and mechanical anchorage — that mitigate moisture-induced debonding. Experimental methods for bond characterisation, namely the direct pull-out test and the beam-end test, are reviewed together with representative bond-slip curves. A design methodology grounded in Limit State Design (LSD) principles is presented, incorporating material safety factors, development length calculations, flexural and shear design equations, and serviceability checks for deflection and crack width. A cost-benefit comparison indicates that treated bamboo reinforcement can reduce reinforcement costs by up to 50% relative to thermo-mechanically treated (TMT) steel in rural housing applications. The paper concludes that, while BRC offers substantial economic and environmental advantages, its structural application must be governed by conservative material safety factors, adequate concrete cover, and rigorous serviceability checks to account for bamboo's biological variability, moisture sensitivity, and long-term creep behaviour.

Keywords: *Bamboo-Reinforced Concrete; Bond-Slip Behaviour; Anchorage Performance; Development Length; Hygroscopic Swelling; Sustainable Construction Materials; Limit State Design.*

How to Cite: A. Kashiram; Dr. Kandru Suresh (2026) Bond-Slip Behaviour, Anchorage Performance, and Sustainable Design Framework for Bamboo-Reinforced Concrete (BRC). *International Journal of Innovative Science and Research Technology*, 11(9), 3281-3286. <https://doi.org/10.38124/ijisrt/26sep1212>

I. INTRODUCTION

The construction industry is one of the largest contributors to global anthropogenic carbon dioxide emissions, with steel production alone accounting for approximately 1.85 tonnes of CO₂ per tonne of steel produced. In contrast, bamboo is a carbon-negative material: it sequesters atmospheric carbon during its rapid growth phase, requires minimal energy for harvesting and processing, and can be replenished within three to five years, compared to decades for structural timber. Life-cycle assessments comparing the two materials indicate an embodied carbon differential on the order of 2,350 kg CO₂-

equivalent per tonne in favour of bamboo, underscoring its potential as a sustainable reinforcement material for low-rise, low-cost, and rural housing infrastructure.

Beyond its environmental credentials, bamboo possesses a favourable strength-to-weight ratio, with tensile strength values along the fibre direction that can rival mild steel on a per-unit-weight basis. Its low density (approximately one-sixth to one-eighth that of steel) offers additional advantages in transportation, handling, and reduction of dead load in structural members. These attributes have positioned Bamboo-Reinforced Concrete (BRC) as a viable reinforcement alternative in regions where bamboo is

locally abundant and steel is comparatively expensive or difficult to procure.

Nevertheless, the structural performance of BRC is fundamentally governed by the quality of load transfer at the bamboo-concrete interface. Unlike deformed steel bars, which achieve reliable bond through mechanical ribs engineered at a controlled scale, bamboo culms are anatomically variable, hygroscopically active, and prone to swelling and shrinkage cycles that compromise bond integrity over time. This paper addresses three interlinked aspects of BRC structural behaviour: (i) the bond mechanisms and interface challenges unique to bamboo reinforcement, (ii) anchorage performance and the development length required for full stress transfer, and (iii) a limit-state-based design framework that accounts for the conservative material safety factors necessitated by bamboo's biological variability. The objective is to consolidate the current understanding of BRC bond behaviour into a coherent design reference that can guide further experimental and field-scale investigation.

II. LITERATURE REVIEW

Research into bamboo as a concrete reinforcement material dates back several decades, with early investigations establishing that untreated bamboo exhibits tensile strengths comparable to low-grade steel but suffers from poor durability and bond degradation when embedded directly in fresh concrete. Subsequent studies have consistently identified moisture-induced dimensional instability as the principal barrier to reliable BRC performance: bamboo culms absorb water from the surrounding cement paste during casting, swell, and then shrink upon curing and drying, leaving a residual gap at the bamboo-concrete interface that severely reduces bond strength and stiffness.

To address this limitation, researchers have explored a range of surface treatments. Waterproofing coatings — including epoxy resins, bituminous compounds, synthetic gums, and water-repellent sealants — have been shown to substantially reduce water absorption, which can otherwise reach up to 300% of the bamboo's dry weight in untreated specimens. Complementary roughening treatments, typically an epoxy-and-sand coating, increase the interfacial coefficient of friction and partially compensate for the loss of chemical adhesion caused by sealing. A parallel body of work has focused on mechanical anchorage devices — external wire winding, through-bolted end plates, and wood or steel clamping collars — that supplement frictional bond with positive mechanical interlock, particularly at member ends where anchorage failure is most critical.

The anatomical structure of bamboo itself offers an intrinsic advantage in this regard: the periodic nodes that occur along the culm act as natural ribs, analogous to the

deformations on a steel reinforcing bar, and have been shown experimentally to provide a significant proportion of the total pull-out resistance through mechanical interlock rather than adhesion alone. Comparative bond-slip studies employing direct pull-out and beam-end test configurations report that bamboo-concrete bond stress-slip curves exhibit a distinct pre-cracking (elastic) branch followed by a post-cracking phase governed by frictional and nodal interlock, with peak bond stresses generally lower and more variable than those recorded for hot-rolled steel reinforcement of comparable embedment length.

Flexural studies on BRC beams report a transition from brittle, sudden failure in plain or lightly reinforced sections to more ductile cracking and progressive failure patterns in hybrid-reinforced sections that combine bamboo main reinforcement with steel shear stirrups. Such hybrid systems, pairing bamboo in the tension zone with conventional steel stirrups for shear and torsion resistance, have been proposed as a pragmatic near-term application that balances cost savings against the need for reliable shear capacity and ductility. Design-oriented literature has further emphasised that, because of the wide variability in bamboo material properties arising from species, age, moisture content, and harvesting practice, partial safety factors for bamboo in limit-state design must be considerably higher than those applied to steel — with several studies suggesting that bamboo may retain only 33–45% of its characteristic strength under design conditions, compared to approximately 87% retention typically assumed for structural steel.

III. MATERIALS

➤ Bamboo Reinforcement

Bamboo culms intended for use as concrete reinforcement are typically selected from mature stock (three to five years of age) to maximise fibre density and minimise moisture content. The anatomical cross-section of bamboo is markedly heterogeneous: the outer skin exhibits a high density of longitudinally oriented vascular fibres embedded in a parenchymatous matrix, while the inner core is comparatively low in density. This graded fibre distribution produces pronounced orthotropic material behaviour, with tensile and bond properties varying substantially between the outer and inner culm wall and along the length of the culm at node versus internode locations.

➤ Concrete Matrix

Ordinary Portland cement concrete of grades ranging from M20 to M40 was considered in this study, consistent with typical usage in low-rise residential and rural infrastructure applications. Higher-grade concrete provides improved confinement of the reinforcement and correspondingly higher design bond stress, as summarised in Table 1.

Table 1 Variation of Design Bond Stress with Concrete Grade.

Grade of Concrete	Characteristic Strength, f_{ck} (MPa)	Design Bond Stress, τ_{bd} (MPa)
M20	20	1.2
M40	40	1.9

➤ *Surface Treatment Materials*

Two categories of surface treatment were reviewed: sealing treatments, aimed at creating a water-impermeable barrier using epoxy resins, synthetic gums, or water-repellent compounds; and roughening treatments, employing an epoxy-and-fine-sand coating to increase interfacial friction. A biological protection treatment using a borax-boric acid solution was also considered to prevent fungal rot and beetle infestation, which represent long-term durability risks specific to untreated natural fibre reinforcement.

➤ *Mechanical Anchorage Components*

Mechanical anchorage systems comprised externally wound binding wire along the embedded length, and through-bolted steel end plates or guide plates with wooden clamping collars at member ends, intended to provide a positive mechanical stop against pull-out independent of the chemical and frictional bond components.

IV. METHODOLOGY

➤ *Experimental Bond Characterisation*

Bond performance was characterised using two complementary test configurations. The direct pull-out test embeds a single bamboo specimen (typical diameter 20–25 mm) within a concrete block over a fixed embedment length (200 mm in the reference configuration), with the specimen gripped and loaded in tension using a calibrated load cell while the free-end slip is recorded, allowing construction of the bond stress-slip (τ - s) curve. The beam-end test, by contrast, embeds the bamboo reinforcement within a representative flexural member and measures slip at the loaded end under simulated in-service conditions, providing a more realistic assessment of anchorage performance under combined flexure and shear.

➤ *Bond-Slip Curve Interpretation*

The resulting bond stress-slip relationship is interpreted in two phases. The pre-cracking phase is approximately elastic, governed by chemical adhesion and initial frictional resistance, and terminates at the peak bond stress (τ_{max}) corresponding to the onset of interfacial micro-cracking within the interfacial transition zone (ITZ). The post-cracking, or frictional/debonding phase, is governed primarily by residual friction and mechanical interlock at the bamboo nodes as the interface progressively debonds, with bond stress decaying toward a fracture or slip-limit condition. This behaviour is markedly different from that of hot-rolled steel reinforcement, which typically sustains a higher and more stable average bond stress (τ_{avg}) over a comparable slip range.

➤ *Design Framework — Limit State Design (LSD)*

The proposed design methodology follows a Limit State Design approach structured as a nine-step iterative process: (1) definition of structural requirements and material selection; (2) collection of material properties, geometric data, and applicable code provisions; (3) determination of characteristic loads (dead, live, wind, and seismic); (4) formulation of ultimate and serviceability load combinations using partial safety factors; (5) structural analysis to obtain

design actions (moment, shear, axial force, torsion, and displacement); (6) design for the ultimate limit state (strength), including flexural, shear, and stability checks; (7) design for serviceability limit states, including deflection and crack-width verification; (8) detailing of reinforcement, development length, anchorage, laps, and cover; and (9) preparation of documentation, drawings, and bills of quantities. Steps 6 and 7 are iterative, with the design revised and re-checked until both strength and serviceability criteria are satisfied.

➤ *Material Safety Factors*

Owing to the substantially higher variability of bamboo's mechanical properties compared with manufactured steel, elevated partial safety factors (γ_m) are applied to bamboo characteristic strengths. The design strength is obtained as:

$$f_{design} = f_{characteristic} / \gamma_m$$

Representative retention ratios reported in the literature indicate that structural steel retains approximately 87% of its characteristic strength under design conditions, whereas bamboo may retain only 33–45%, reflecting the combined effects of natural variability, moisture sensitivity, and biological degradation risk. This necessitates a markedly more conservative design approach for BRC members relative to conventional steel-reinforced concrete.

➤ *Design Tensile Strength and Development Length*

The design tensile strength of the bamboo reinforcement is calculated as:

$$f_{td} = f_{tk} / \gamma_m$$

Where f_{td} is the design tensile strength, f_{tk} is the characteristic tensile strength obtained from direct tension or pull-out testing, and γ_m is the partial safety factor for the material. The development length (L_d), representing the embedment length required to transfer the full design tensile force from the bamboo reinforcement to the surrounding concrete matrix, is calculated using the standard bond-based expression:

$$L_d = (\phi \cdot \sigma_s) / (4 \cdot \tau_{bd})$$

Where ϕ is the nominal diameter of the bamboo reinforcement, σ_s is the stress in the reinforcement at the design load, and τ_{bd} is the design bond stress. Development length provisions include the anchorage value of any mechanical end anchors, and for non-circular bamboo sections the effective perimeter must be used to ensure the bond stress assumption remains valid.

➤ *Flexural and Shear Design*

For a hybrid reinforcement configuration — bamboo main tension reinforcement combined with conventional steel shear stirrups — the ultimate moment capacity is evaluated using an expression consistent with conventional under-reinforced flexural theory:

$$M_u = 0.87 \cdot f_y \cdot A_{st} \cdot (d - 0.42 x_u)$$

Where M_u is the ultimate moment capacity (kN·m), f_y is the yield strength of the tension reinforcement (MPa), A_{st} is the area of tension reinforcement (mm²), d is the effective depth (mm), and x_u is the depth of the neutral axis (mm). Shear resistance in BRC members presents a distinct design challenge, since bamboo strips are difficult to bend into closed stirrup configurations without splitting; consequently, hybrid designs typically retain conventional steel stirrups for shear and torsion resistance while relying on bamboo for the primary flexural tension contribution, thereby combining cost-effective main reinforcement with reliable, code-compliant shear detailing.

➤ Serviceability Checks

Deflection control was identified as the governing limit state for the majority of BRC designs, given bamboo's comparatively lower modulus of elasticity and pronounced time-dependent creep behaviour under sustained load. Comparative load-deflection behaviour between steel-reinforced concrete (SRC) and BRC members indicates that BRC members reach a service-level cracking load at a lower deflection but continue to deform substantially beyond that point, requiring conservative serviceability limits. Crack width was limited to 0.3 mm to prevent moisture ingress to the embedded bamboo reinforcement, which would otherwise accelerate bond degradation and biological decay. Long-term creep was found to be significant: representative deflection monitoring over a ten-year sustained loading period showed deflection increasing from an initial (Year 0) value to approximately 2–3 times the instantaneous deflection by Year 10, driven by the combined effects of creep, shrinkage, and sustained load.

➤ Durability and Cover Requirements

Biological protection was addressed through borax-boric acid treatment to prevent fungal decay and beetle infestation. A minimum concrete cover of 40–50 mm was recommended, exceeding typical steel reinforcement cover requirements, to provide additional protection against moisture ingress and to accommodate the larger cross-sectional dimensions typical of bamboo strip reinforcement. Fire resistance was identified as a further durability consideration, since bamboo loses strength more rapidly than steel under elevated temperature exposure, necessitating either adequate cover or supplementary fire-protective detailing in applications with defined fire-rating requirements.

V. RESULTS AND DISCUSSION

➤ Interface and Bond Behaviour

The reviewed evidence confirms that the bamboo-concrete interface is governed by three concurrent mechanisms of differing reliability: chemical adhesion, which is inherently weak and rapidly degraded by hygroscopic swelling and shrinkage; frictional resistance, which is variable and highly dependent on surface treatment; and mechanical interlock at the bamboo nodes, which was found to be the most reliable and consistent contributor to

bond capacity. This ordering of reliability has direct design implications: BRC detailing should not depend on chemical adhesion for load transfer, and specimen selection or member layout should, where possible, position bamboo nodes to maximise their contribution to mechanical interlock over the critical anchorage length.

➤ Effect of Surface Treatment

Sealing treatments were found to substantially reduce moisture absorption and the associated debonding gap, while roughening treatments recovered a portion of the frictional bond capacity lost to sealing. The combination of sealing and roughening, together with mechanical anchorage at member ends, represents the most robust treatment strategy identified in the literature, since it addresses the dominant failure mechanism (moisture-driven interfacial gap formation) while simultaneously reinforcing the two most reliable bond mechanisms (friction and mechanical interlock).

➤ Bond-Slip and Anchorage Performance

The characteristic bond stress-slip curve for bamboo reinforcement exhibits a lower peak bond stress and a more pronounced post-peak degradation than the reference curve for hot-rolled steel reinforcement, confirming that BRC members require longer development lengths for equivalent stress transfer. This is consistent with the inverse relationship between development length and design bond stress expressed in the L_d equation: because τ_{bd} for bamboo is lower and more variable than for steel, and because the applicable material safety factor γ_m is substantially higher, the resulting development lengths for BRC members are markedly longer than for equivalent steel-reinforced members, with direct implications for member sizing, lap length, and anchorage detailing at beam-column joints.

➤ Flexural and Serviceability Performance

Flexural test data reviewed in this study indicate a transition from brittle failure in control (unreinforced or lightly reinforced) sections to progressively more ductile failure modes as hybrid bamboo-steel reinforcement ratios increase, suggesting that partial bamboo substitution — rather than full replacement of steel — may offer the most practical near-term pathway to ductile, serviceable BRC construction. However, the governing design condition for the majority of BRC members remains serviceability rather than ultimate strength: comparative load-deflection curves show BRC members deflecting substantially more than equivalent SRC members at service load levels, and the ten-year creep projection indicating deflection amplification of 2–3 times the instantaneous value further reinforces the need for conservative span-to-depth ratios and deflection limits in BRC design.

➤ Cost-Benefit Analysis

A comparative cost analysis for a representative 1,000 sq. ft. slab, summarised in Table 2, indicates that treated bamboo reinforcement offers a material cost approximately 70% lower than thermo-mechanically treated (TMT) steel on a like-for-like basis, and a net overall cost saving of approximately 50% after accounting for the additional treatment and fabrication labour required for bamboo. The

corresponding 65% reduction in reinforcement dead load per slab additionally offers secondary benefits in foundation sizing and seismic mass reduction, reinforcing the case for

BRC adoption in cost-sensitive rural and low-rise housing contexts.

Table 2 Reinforcement Cost Comparison for a 1,000 sq. Ft. Slab (Steel TMT vs. Treated Bamboo).

Component	Standard Steel (TMT)	Treated Bamboo (BRC)	Saving / Impact
Material rate	₹65–₹75 per kg	₹15–₹20 per culm (6 m)	~70% lower material cost
Treatment cost	Nil (standard)	₹5–₹8 (epoxy/sand/borax)	Adds ~10% to bamboo cost
Labour / fabrication	Moderate (bending/tying)	High (processing/sealing)	Bamboo requires more man-hours
Weight per slab	~1.2 tons	~0.4 tons	65% reduction in dead load
Total estimated cost	₹95,000–₹1,10,000	₹45,000–₹55,000	~50% net saving

➤ Practical Site Execution

Field-level considerations, including proper handling, storage, and moisture protection of bamboo culms prior to casting, were found to be as critical to final bond performance as the laboratory-characterised treatment methods, since improperly stored or pre-swollen bamboo can undermine even a well-designed treatment and anchorage scheme. This underscores the importance of developing site-specific quality-control protocols alongside the structural design framework.

that balances cost and sustainability benefits against the need for reliable shear capacity and ductile behaviour.

- Durability provisions — biological (borax-boric acid) treatment, increased concrete cover (40–50 mm), and consideration of fire resistance — are essential to ensure long-term serviceability of BRC members in service.

Overall, this review indicates that Bamboo-Reinforced Concrete is a technically viable and economically attractive reinforcement strategy for low-rise, low-cost, and rural construction, provided that design practice explicitly accounts for the material's bond variability, moisture sensitivity, and creep behaviour through conservative limit-state design procedures. Future research should focus on standardising bond and development length test protocols for bamboo, developing design codes analogous to existing steel and FRP reinforcement standards, and conducting long-term field monitoring of in-service BRC structures to validate the serviceability projections derived from laboratory-scale creep and deflection studies.

VI. CONCLUSIONS

- Bamboo-Reinforced Concrete offers a carbon-negative, low-cost alternative to conventional steel reinforcement, with life-cycle CO₂ savings on the order of 2,350 kg CO₂e per tonne and reinforcement cost savings of up to 50% in representative rural housing applications.
- Bond performance at the bamboo-concrete interface is governed by chemical adhesion (weak), friction (variable), and mechanical interlock at bamboo nodes (reliable); design detailing should prioritise the latter two mechanisms.
- Surface treatments combining sealing (to limit hygroscopic swelling and shrinkage) with roughening (to enhance friction) and mechanical anchorage (external wire winding or through-bolted end plates) provide the most robust strategy for improving bond and anchorage performance.
- Development length for bamboo reinforcement should be calculated using code-consistent bond-based expressions, but with design bond stresses and material safety factors reflecting bamboo's markedly higher property variability relative to steel (retained strength of 33–45% versus approximately 87% for steel).
- Serviceability — specifically deflection control and crack-width limitation (0.3 mm) — governs the design of most BRC members rather than ultimate flexural or shear strength, owing to bamboo's lower stiffness and significant long-term creep.
- Hybrid reinforcement systems, combining bamboo main tension reinforcement with conventional steel shear stirrups, represent a practical near-term design approach

REFERENCES

- [1]. Ghavami, K. (2005). Bamboo as reinforcement in structural concrete elements. *Cement and Concrete Composites*, 27(6), 637–649.
- [2]. Sakaray, H., Togati, N. V. V. K., & Reddy, I. V. R. (2012). Investigation on properties of bamboo as reinforcing material in concrete. *International Journal of Engineering Research and Applications*, 2(1), 077–083.
- [3]. Correal, J. F. (2016). Bamboo design and construction. In *Nonconventional and Vernacular Construction Materials* (pp. 393–431). Woodhead Publishing.
- [4]. Archila, H., Kaminski, S., Trujillo, D., Zea Escamilla, E., & Harries, K. A. (2018). Bamboo reinforced concrete: A critical review. *Materials and Structures*, 51(4), 102.
- [5]. Agarwal, A., Nanda, B., & Maity, D. (2014). Experimental investigation on chemically treated bamboo reinforced concrete beams and columns. *Construction and Building Materials*, 71, 610–617.
- [6]. Terai, M., & Minami, K. (2011). Fracture behaviour and mechanism of bamboo reinforced concrete members. *Procedia Engineering*, 10, 2967–2972.
- [7]. Bureau of Indian Standards. (2000). IS 456:2000 — Plain and Reinforced Concrete — Code of Practice. New Delhi: BIS.

- [8]. Bureau of Indian Standards. (2004). IS 6874:2008 — Method of Tests for Round Bamboo. New Delhi: BIS.
- [9]. Janssen, J. J. A. (2000). Designing and Building with Bamboo (INBAR Technical Report No. 20). International Network for Bamboo and Rattan.
- [10]. Dixon, P. G., & Gibson, L. J. (2014). The structure and mechanics of Moso bamboo material. *Journal of the Royal Society Interface*, 11(99), 20140321.