Primljen / Received: 2.5.2023.
Ispravljen / Corrected: 25.1.2024.
Prihvaćen / Accepted: 20.3.2024.
Dostupno online / Available online: 10.5.2024.

Effect of groove patterns on composite bond strength in bamboo-reinforced concrete

Authors:

M. Sadique Ameen, MCE
Visvesvaraya National Institute of Technology, India
sadiqueameen007@gmail.com
Corresponding author

Assoc.Prof. **Debarati Datta**, PhD. CE
Visvesvaraya National Institute of Technology, India
debaratidatta@apm.vnit.ac.in

Original research paper

M. Sadique Ameen, Debarati Datta

Effect of groove patterns on composite bond strength in bamboo-reinforced concrete

The use of bamboo as a reinforcement material in concrete has garnered attention in recent years due to its low cost, renewability, and high strength-to-weight ratio. However, the bond strength between bamboo and concrete is a crucial factor affecting the overall performance of bamboo-reinforced concrete structures. In this study, the bond between bamboo and concrete is investigated through pull-out tests. Three different groove patterns - rectangular, semi-circular, and V-notch - are examined for their bond strength. Various chemical treatments are also being explored to reduce the water absorption capacity of bamboo splints. The highest bond strengths achieved after using Bond Tite adhesive and bituminous paint are 1.94 MPa and 1.41 MPa, respectively. The findings of this study can be valuable in optimizing the design and construction of bamboo-reinforced concrete structures.

Key words:

bamboo reinforcement, different grooving patterns, grooved bamboo strips, surface treatments, mechanical interlock

Izvorni znanstveni rad

M. Sadique Ameen, Debarati Datta

Učinak uzoraka utora na čvrstoću prionljivosti u betonu ojačanom bambusom

Upotreba bambusa kao materijala za ojačanje betona posljednjih je godina privukla pozornost zbog niske cijene, obnovljivosti i visokog omjera čvrstoće i težine. Međutim, čvrstoća prionljivosti bambusa i betona ključni je čimbenik koji utječe na ukupnu učinkovitost betonskih konstrukcija ojačanih bambusom. U ovom je istraživanju veza između bambusa i betona istražena pull-out metodom. Ispituje se čvrstoća prionljivosti triju različitih uzoraka utora - pravokutni, polukružni i V-urez. Također se ispituju različite kemijske obrade kako bi se smanjila sposobnost apsorpcije vode bambusovih traka. Najveće čvrstoće prionljivosti postignute nakon primjene Bond Tite adhezivne i bitumenske boje su 1,94 MPa odnosno 1,41 MPa. Rezultati ovog ispitivanja mogu biti korisni u optimizaciji projektiranja i izgradnje betonskih konstrukcija ojačanih bambusom.

Ključne riječi:

ojačanje bambusom, različiti uzorci utora, bambusove trake s utorima, obrada površine, mehaničko uklještenje

1. Introduction

Steel-reinforced concrete stands as one of the most significant innovations in the structural industry. Concrete, the most prevalent building material globally, boasts exceptional durability, demands minimal maintenance, and offers versatility in shaping. Furthermore, it exhibits remarkable compressive strength. To compensate for concrete's relatively low tensile strength, steel, albeit costlier, is employed. Numerous research endeavours aim to substitute steel with more affordable and readily available materials, particularly in developing nations. Nevertheless, steel possesses outstanding mechanical properties and proves to be more cost-effective than alternative materials [1].

In countries like India, where there is a high demand for housing, the use of construction materials has surged, leading to the depletion of traditional natural resources such as iron ore required for steel reinforcement. Moreover, the production of these conventional materials contributes to environmental degradation due to greenhouse gas emissions. The emissions from steel production, primarily carbon dioxide but also including SOx, NOx, and PM2, have a significant environmental impact [2]. Additionally, the manufacturing process generates solid waste, hazardous waste, and polluting wastewater, further harming the environment. As the demand continues to rise, the cost of steel has markedly increased over the years, necessitating the exploration of alternative sustainable materials. Worldwide, numerous scholars are conducting research to identify substitute materials for traditional building materials [1]. Some of these alternatives include bamboo, jute, fly ash, rice husk, recycled aggregates, palm oil shell, among others. Extensive studies are underway to explore these alternative building materials, which are both cost-effective and environmentally sustainable.

Bamboo emerges as a promising alternative to steel, boasting impressive strength and flexibility that render it suitable for construction purposes. In some instances, bamboo rivals steel in both tension and compression. Its inherent flexibility enables it to withstand earthquakes and strong winds, making it particularly well-suited for certain structural applications [1]. Recognised increasingly as a viable and sustainable building material, bamboo has been utilised in construction for centuries across the globe. With its favourable mechanical properties and positive environmental, social, and economic impacts, bamboo presents itself as a potential substitute for steel reinforcement, especially in low-cost structures within rural and urban areas. Notably, bamboo's strength-to-weight ratio surpasses that of steel by over six times [3].

Bamboo cultivation yields significant environmental benefits. During its growth, bamboo absorbs approximately 1 tonne of CO_2, whereas steel production emits around 50 times more CO_2 into the environment [4]. As the fastest-growing renewable and eco-friendly material, bamboo holds great potential as a sustainable alternative to traditional steel reinforcement. However, a fundamental concern regarding its utilisation lies in the poor bond between bamboo and concrete.

Bamboo, a type of natural grass, boasts over 1200 species worldwide [2]. The availability of different bamboo species varies depending on factors such as region, soil type, climate, and water availability. According to IS 15912–2018 [5], India is home to over 100 bamboo varieties, with some being solid and others predominantly hollow. Thus far, rigorous testing has been conducted on 20 species. It is recommended to utilise bamboo in its round form from sixteen different species for structural applications. The strength characteristics of these species vary based on the climatic and geographic conditions in which the bamboo clump has developed.

In this study, the bamboo species Dendrocalamus strictus (D. strictus), commonly referred to as Manvel and abundantly available in the local region, is utilised. The physical and mechanical properties of D. strictus, as outlined in IS 15912 – 2018, along with the experimental values obtained, are detailed in Table 1. This species is among those recommended by the code for structural purposes.

Bamboo, being a natural material, exhibits varying properties dependent on the climate and soil conditions of a particular area. Factors such as temperature, humidity, and soil composition can impact the density, strength, and durability of bamboo harvested in diverse regions. Moreover, sustainable harvesting practices, including the age at which bamboo is harvested and the methods employed, can influence its strength and longevity. The age at which bamboo is harvested plays a significant role in determining its mechanical properties. Younger bamboo tends to be more flexible, whereas older bamboo may exhibit greater density and strength. The optimal harvesting age may differ among species and regions, with local practices guiding decisions on when to harvest bamboo for specific applications. Taking into account these considerations, IS 15912 – 2018 and NBC (National Building Code of India) [7] have systematically tested 20 species of bamboo to date, recommending 16 species for structural use. Dendrocalamus strictus is among these 16 recommended species.

The successful integration of bamboo into concrete structures relies heavily on achieving a robust bond between the bamboo and the concrete matrix. One approach to enhancing this bond

Table 1. Physical and Mechanical Properties of D. strictus

	Properties	IS code values [5]	Experimental values [6]
In Air Dry condition	Maximum compressive strength [N/mm²]	69.1	65.14
	Modulus of elasticity [N/mm²]	$15 \cdot 10^3$	$12.3 \cdot 10^3$
	Modulus of rupture [N/mm²]	119.1	111.6
	Density [kg/m³]	728	783

is by incorporating grooving patterns in the bamboo elements [8]. Grooving, involving a deliberate alteration of the surface geometry of the bamboo, has the potential to influence the mechanical interlocking and adhesion between bamboo and concrete. Understanding the effects of different grooving patterns on composite bond strength is crucial for optimising the performance and durability of BRC structures [8]. This study explores the intricate relationship between grooving patterns and composite bond strength in bamboo-reinforced concrete. By systematically examining various grooving techniques and their impact on the interfacial interactions between bamboo and concrete, we aim to provide valuable insights contributing to the development of guidelines for designing and constructing BRC structures. The research not only addresses the technical aspects of grooving but also underscores the broader implications for sustainable construction practices and the promotion of eco-friendly building materials. As the construction industry continues to evolve towards more environmentally conscious solutions, the findings of this investigation are poised to play a pivotal role in shaping the future of bamboo-reinforced concrete applications.

In this study, the bond between bamboo and concrete is examined through a pull-out test. This test involves evaluating the bond strength between grooved bamboo strips and the concrete matrix within a bamboo-reinforced concrete cylinder. It is essential for assessing the integration of bamboo and concrete, as well as the effectiveness of grooving patterns in enhancing composite bond strength. A combination of mechanical and chemical mechanisms is employed to improve the bonding properties of bamboo strips with concrete. Various grooving patterns applied to bamboo strips facilitate mechanical action. Additionally, two different chemical treatments, bond-tite adhesive and bituminous paint, are utilised to investigate chemical action.

2. Literature review

Traditional methods of selecting engineering materials must now consider additional factors beyond strength, efficiency, and cost, such as environmental impact and design flexibility. Natural bamboo emerges as a valuable engineering material, offering potential as a reinforcing material for structural applications due to these added qualities [9]. A recent study by Anusha et al. [10] highlights the construction industry's significant contribution to environmental pollution and resource depletion. In developing countries, where the demand for affordable housing is high, the search for sustainable and cost-effective building materials is paramount. The study suggests that bamboo and polypropylene bands can effectively reinforce concrete beams, presenting several advantages. Both bamboo and polypropylene are renewable resources with lower environmental footprints than steel. Moreover, they are notably more cost-effective than steel, rendering them suitable for low-cost housing projects. Additionally, their lighter weight compared to steel reduces the overall structural load. Bamboo boasts high tensile strength and stiffness, while polypropylene bands offer excellent shear reinforcement. The study indicates that using bamboo and polypropylene bands can reduce construction costs by up to 85 % compared to steel reinforcement.

A robust bond is vital for effectively transferring load between reinforcement and concrete. Research has revealed that untreated bamboo splints exhibit poor bonding with concrete [11]. Previous studies utilising bamboo-reinforced beams have encountered challenges, largely due to the weak connection between bamboo and concrete [3, 12]. Improving the bond between bamboo and concrete is imperative for enhancing the performance of bamboo-reinforced concrete (BRC) beams. A study by Sayed et al. [13] underscores the potential of surface treatment and corrugation techniques in enhancing bond strength. They propose that BRC beams show promise as a sustainable alternative to steel-reinforced concrete (SRC) beams, but further research and development are necessary to address challenges and optimise their performance.

Khatib and Nounu [8] investigated the potential use of grooved bamboo as reinforcement in concrete. They conducted experimental tests on concrete beams reinforced with either steel bars or grooved bamboo strips, comparing their mechanical properties such as load-carrying capacity, deflection, and crack patterns. The results indicated that the bamboo-reinforced beams had a similar load-carrying capacity to the steel-reinforced ones but exhibited greater ductility and energy absorption, attributed to bamboo's tough and flexible nature. They also discussed the challenges and opportunities of using bamboo as a sustainable and eco-friendly alternative to steel reinforcement in construction, emphasising the need for further research and standardisation in this field. Azadeh and Kazemi [14] introduced novel methods to enhance the bond strength between bamboo and concrete. They explored various grooving patterns on bamboo culms and their effects on the bond strength between bamboo and concrete. The study conducted experimental tests on bamboo-concrete composite samples with different grooving patterns. The results demonstrated that appropriate grooving patterns on the bamboo surface can significantly enhance the bond strength between bamboo and concrete.

In a recent study, Tazowar et al. [8] explored methods to enhance the bond performance of BRC through surface treatment and the application of various corrugation patterns to bamboo strips. Poor bonding represents a significant limitation of BRC, jeopardising its performance and structural integrity. The study revealed that creating grooves or patterns on the bamboo surface improves mechanical interlocking with the concrete. Results demonstrated that, compared to plain bamboo, bond strengths significantly increased by 46 % for rectangular, 85 % for V-notch, and 81 % for trapezoidal corrugation patterns. This research introduces a novel and effective approach to address a key challenge in utilising bamboo as a sustainable reinforcement material. It facilitates broader adoption of BRC in construction, promoting eco-friendly and resource-efficient building practices.

Kute and Wakchaure [15] investigated the utilisation of bamboo as reinforcement in concrete by assessing several of its engineering properties, including tensile strength, compressive strength, bond strength with concrete, and modulus of elasticity. They conducted a series of laboratory tests on concrete specimens reinforced with bamboo strips of various dimensions and orientations, comparing their performance with that of steel-reinforced specimens. The results indicated that the bamboo-reinforced specimens exhibited lower compressive and tensile strengths than the steel-reinforced ones. However, they displayed higher energy absorption and toughness, attributed to the fibrous and ductile nature of bamboo. The authors also proposed measures to enhance the bond strength between bamboo and concrete, such as employing chemical treatments, roughening the bamboo surface, and optimising the concrete mix design.

In summary, the literature review underscores the significance of enhancing the bond between bamboo and concrete to fully realise the potential of BRC as a sustainable and competitive construction material. The bond between bamboo and concrete plays a pivotal role in determining the performance and structural integrity of BRC structures.

3. Experimental programme

3.1. Characteristics of bamboo strips

According to IS 15912 – 2018 [5], solid bamboos or bamboos with thicker walls and closely spaced nodes are generally deemed suitable for structural purposes [5]. The bamboo samples used in the investigation were aged between 4 and 5 years, representing the stage at which bamboo species exhibit optimal mechanical and physical properties [16]. Dendrocalamus strictus, locally known as manvel, is a medium-sized bamboo characterised by culms ranging from 8 m to 20 m in height and 25 to 80 mm in diameter. Internodes measure between 300 to 450 mm in length and 8 mm to 15 mm in thickness. Culms are hollow in moist conditions but nearly solid when dry. During collection, bamboo culms are carefully selected to ensure straight and undamaged geometry, resulting in final samples with evenly distributed fibres (with the fibre concentration being highest at the outer surface compared to the inner region). This meticulous process yields high-quality samples with favourable physical and mechanical characteristics.

To safeguard against termite and pest infestation, cleaned bamboo culms are immersed in a 6 % boric acid solution for 72 hours. After this treatment, the culms are removed from the solution and left to dry for five days at a temperature of 35 °C [11]. Subsequently, the cleaned and air-dried bamboo culms are cut into strips with uniform thickness and rectangular cross-sections. Finally, these bamboo strips are coated with chemicals to minimise moisture absorption within the concrete.

3.2. Grooving of bamboo strips and surface treatments

According to IS 15912-2018 [5], bamboo intended for concrete reinforcement should be initially halved and then split into four parts. Strips measuring between 20 mm to 25 mm in width, with a minimum thickness of 9 mm, are recommended for use as reinforcement in concrete. These strips should be plain along their length and approximately rectangular in cross-section. The mechanical interaction at the interface between bamboo and concrete is the primary source of bonding between plain treated bamboo and the concrete surface. The external coating (adhesive) applied to the bamboo surface not only renders it impermeable but also initiates adhesion with the surrounding concrete. However, this bond strength may be insufficient to facilitate composite action between the two materials under high structural loads. Introducing modifications at the bamboo-concrete interface can meet additional bond strength requirements. In this study, to enhance the mechanical interaction between bamboo and concrete, three different grooving patterns were selected to investigate the bonding behaviour between grooved bamboo strips and concrete. These patterns, depicted in Figure 1, include rectangular, semi-circular, and V-notch grooves.

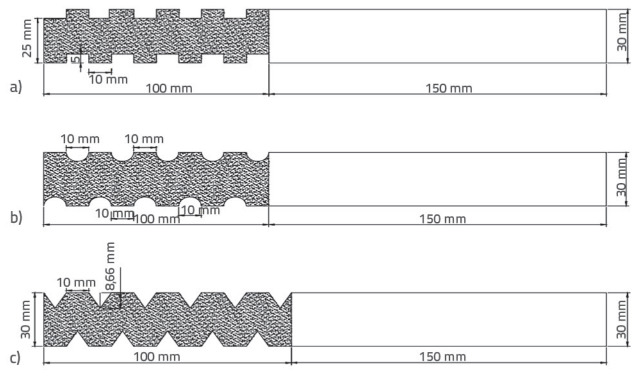

Figure 1. Various types of groove patterns: a) rectangular; b) semi-circular; c) V-notch

To maintain the inherent qualities of the raw bamboo strip, grooves are cut across the thickness and along the length of the bamboo strips. However, manual creation and processing of grooved bamboo samples can be slow and inefficient. Manual grooving poses challenges in achieving consistent groove size and depth across all bamboo samples. Variability in pressure applied, tools used, and the skill level of the individual creating the grooves can lead to irregular distributions and shapes. Manual grooving typically demands skilled craftsmanship and is labour-intensive. The speed and efficiency of the process are limited by the physical abilities of the operator, resulting in a slow production rate that is impractical for large-scale manufacturing. To address this challenge, different carpentry tools and a lathe machine are utilised to create various grooves, as illustrated in Figure 2. The use of a lathe machine facilitates the creation of grooves in a shorter period of time.

These grooved bamboo strips are employed as reinforcement within concrete cylinders for conducting pull-out tests to determine the grooving profile that fails at maximum load. The pull-out tests are conducted in accordance with IS 2770 (Part I) - 1967 [17].

A primary drawback of utilising bamboo as reinforcement in concrete is its propensity to absorb moisture from the concrete. This leads to dimensional changes in the bamboo, significantly impacting the bond behaviour between bamboo and concrete, as depicted in Figure 3 [18].

Figure 2. Lathe machine and a display of slot creation

From the table above, it is evident that Bitumen (VG-30) and Bituminous Paint are more cost-effective compared to other chemicals. Bituminous paint is readily available and treating bamboo strips with it is simpler compared to Bitumen (VG-30). As the primary objective is to minimise construction costs, bituminous paint is selected for treating the bamboo splints. It reduces water absorption by 75 %, with only a 10 % impact on bond stress [15]. Additionally, Bond Tite adhesive has been utilised to facilitate comparison with previous studies.

To address this issue, two types of chemical treatments, namely bituminous paint (commonly known as black Japan) and bond tite adhesive, are employed to decrease the water absorption capacity of bamboo splints. Mali and Datta [11] investigated various chemical treatments and determined that bond tite adhesive yielded the best results in reducing water absorption and enhancing the bond strength between bamboo and concrete. In the current study, the economic aspects of different treatments have been considered. Table 2 presents the approximate costs of various chemical treatments based on available market information.

Table 2. Cost of different chemical treatments

Sample No.	Chemical treatments	Cost [EUR]
1	Bituminious paint (Black Japan)	1.1 per litre
2	Bond Tite	18.7 per kg
3	Triflor PUAL lacquer	1.5 per litre
4	Araldite	12.1 per kg
5	Strepoxy	8.2 per kg
6	Bitumen (VG-30)	0.6 per kg
7	EPI BOND - 21	6.6 per litre

Ensuring that the chemical action of these coatings does not impact the internal structure of the bamboo fibres is imperative. The bamboo strips are uniformly coated with a thin layer of these chemicals, using carpentry tools and a paintbrush. This process ensures that the surface is evenly coated with the final adhesive layer, maintaining water resistance and facilitating chemical bonding with the surrounding concrete. Finally, the bamboo splints undergo a sandblasting process. Figure 4 illustrates the treated grooved bamboo splints. The chemicals utilised is described as:

- ·Bituminous paint: Composed of an asphaltic base dissolved in naphtha or turpentine, occasionally with the addition of varnish components like linseed oil. This paint, with its bituminous black colour, has a solvent base for waterproofing and weatherproofing various materials including steelwork, asphalt, wood, concrete, and water storage tanks. Upon drying, it forms an odourless, taint-free bituminous coating that is waterproof, weatherproof, and corrosion resistant.
- Bond-tite: A two-component epoxy adhesive system renowned for its exceptionally high impact resistance and shear strength. It offers greater coverage than standard epoxy adhesives and is suitable for outdoor applications due to its all-weather and UV resistance. Additionally, it requires less clamping time and has a longer pot life, making it ideal for large surface applications and improving productivity. Bond-tite can be used to bond a variety of materials such as metals, ceramics, wood, leather, rubber, marble, and glass, whether similar or dissimilar.

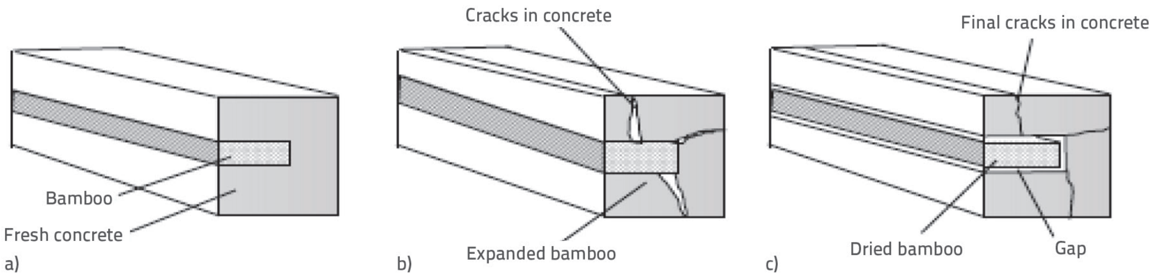

Figure 3. Bamboo performance in concrete: a) Bamboo in concrete; b) Bamboo during concrete curing (with developed cracks); c) Visible voids and cracks in concrete after curing [18]

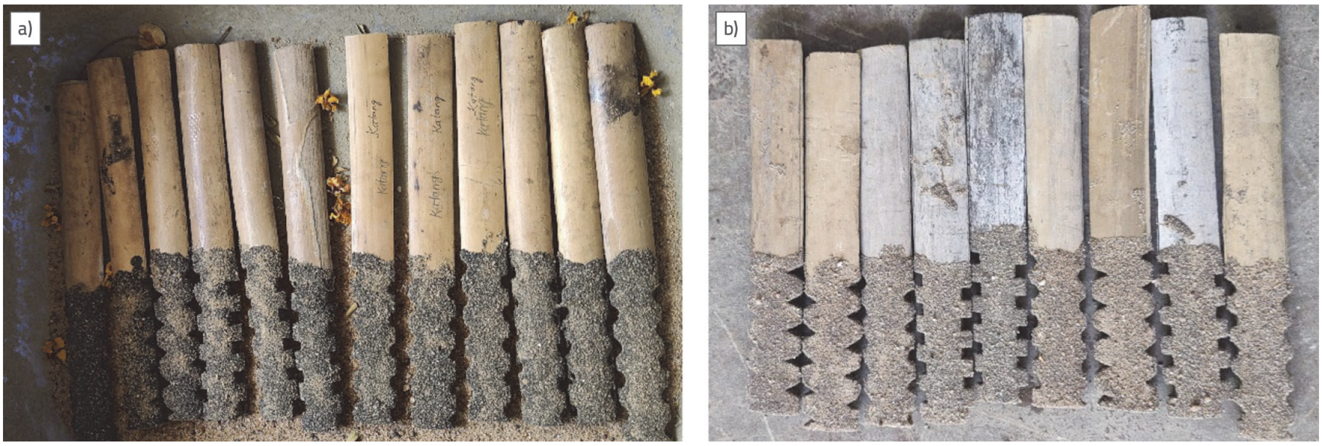

Figure 4. Treated bamboo splints: a) bituminous paint; b) Bond Tite

3.3. Preparation of pull-out test specimen

In this study, M 20 grade concrete (equivalent to C 16/20 as per Eurocode 2) is utilised. The average compressive cube strength at 7 and 28 days was 18 MPa and 29 MPa respectively. Ordinary Portland cement (OPC) of 53 grade was employed. Specimens are cast using a pull-out casting assembly in a cylindrical steel mould measuring 100 mm in diameter and 200 mm in height. Figure 5.a illustrates a schematic diagram depicting grooved bamboo splints in a cylindrical mould, while Figure 5.b displays the actual pull-out test specimen. Table 3 lists the details of the test specimens with different grooving patterns.

3.4. Testing of samples

The pull-out test is a standard method used to assess the bond strength between reinforcement bars (rebar) and concrete in reinforced concrete structures. This test evaluates the effectiveness of the bond between the reinforcing steel and the surrounding concrete, which is essential for the structural integrity and performance of the concrete elements.
In this study, pull-out tests are conducted on various samples using a universal testing machine (UTM) with a 600 kN capacity, equipped with the ability to apply displacement control loading. An assembly is created to properly position the specimen in the UTM, as illustrated in Figure 6.

Figure 5. a) Schematic representation of pull-out sample; b) Actual pull-out test specimen

Table 3. Details of test specimen

Chemical treatment	Grooving pattern	Abbreviation	No. of samples
(a) Bond Tite	Rectangular (R)	BO - R	5
(b) Bituminous paint		BA - R	5
(a) Bond Tite	Semi-circular (S)	BO - S	5
(b) Bituminous paint		BA - S	5
(a) Bond Tite	V - Notch (V)	BO - V	5
(b) Bituminous paint		BA - V	5

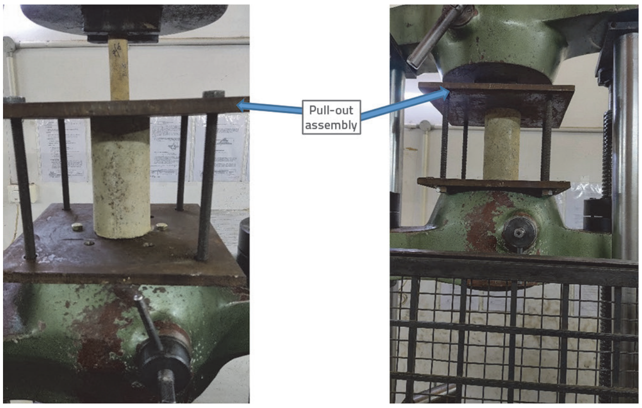

Figure 6. UTM with test sample

The assembly is constructed from hardened steel, ensuring the secure retention of the sample without exhibiting any internal deformations, thus maintaining its proper position throughout the pull-out test process.

The gripping arrangement employed to secure the bamboo strip at the loaded end is designed to prevent the bamboo strips from being crushed at the gripping region. A loading rate of 6 mm per minute (0.1 mm per second) is applied at intervals. The control unit attached to the UTM records the relevant displacements at each load stage.

4. Results and discussions

4.1. Peak load results

All specimens undergo testing under uniaxial tensile loading. Prior to testing the main pull-out samples, a few trial samples are tested in the same UTM to identify and mitigate the effects of initial slip and crushing of bamboo at the grip location. No crushing or slipping occurs at the grip. This exercise ensures that machine compliance is considered when determining the response to applied load and displacement from the pull-out samples at each load step. After the test concludes, the final displacement is confirmed by physically measuring the actual slip of the bamboo strip that occurred in the failed samples (measured from the top surface of the concrete cylinder).

In the concrete, it is assumed that the bond stress distribution will remain constant along the embedded length. After testing the samples, it is observed that bamboo strips with a rectangular grooving pattern are the most effective among the three types tested. The rectangular grooving pattern has shown the most favourable combination of properties under the given testing conditions. It is noted that the rectangular grooving of bamboo strips enhances the mechanical properties of the bamboo reinforcement, offering better performance in terms of strength, flexibility, and other relevant factors.

The rectangular pattern strip samples are observed to fail at higher loads. Table 4 displays the average peak load values at which all three patterns—rectangular, semi-circular, and V-notch—treated with bond tite and bituminous paint fail.

From Table 4, it is evident that rectangular grooved bamboo strips treated with bond tite adhesive display the highest failure load among all other grooved bamboo strips, reaching 22.02 kN. Additionally, rectangular bamboo strips treated with bituminous paint demonstrate a relatively high failure load of 13.83 kN compared to other grooving patterns with the same coating. Corresponding deflection and linear stiffness values are also provided in Table 4. These observations indicate that different grooving patterns and the choice of treatment (bond tite or bituminous paint) significantly influence the structural performance of bamboo.

Further analysis of the load-displacement curves can offer insights into the behaviour of the bamboo under different grooving patterns, aiding in understanding factors such as stiffness, ductility, and failure modes. Load-displacement curves are plotted for all three grooving patterns treated with bond tite and bituminous paint, as depicted in Figure 7.

The conclusions drawn from the load-displacement curves offer valuable insights into the structural behaviour of bamboo strips under various grooving patterns and treatments. The curves show that rectangular grooved bamboo strips display the highest peak load among the three types of grooving patterns. However, the load-carrying capacity sharply drops after reaching the peak load, indicating low ductility. Ductility refers to a material's ability to deform before failure, and the sudden decrease in load suggests that the material may not undergo significant deformation before failure.

Additionally, the load-carrying capacity of bamboo strips with semi-circular and V-notch grooves is observed to be lower than that of the rectangular pattern. Despite the lower peak load, these grooving patterns demonstrate better ductility. The load-displacement curves suggest that these bamboo strips can undergo more deformation before failure, indicating a more ductile response.

Table 4. Results of different samples at peak load

S. No	Samples	Average peak load [kN]	Deflection [mm]	Linear stiffness [kN/m]
1	BA - R	13.83	19.9	694.97
2	BO - R	22.02	22.6	974.34
3	BA - S	9.67	22.2	435.59
4	BO - S	14.71	25.2	582.81
5	BA - V	9.30	14.1	659.57
6	BO - V	12.67	16.6	763.25

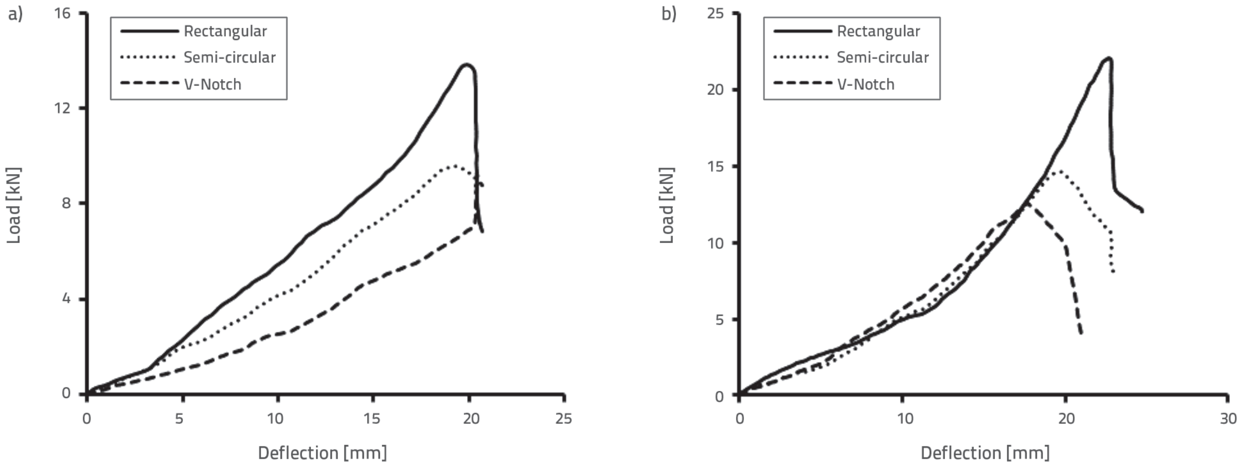

Figure 7. Load-deflection curve: a) for samples treated with bituminous paint; b) for samples treated with Bond Tite

It was noticed that creating bamboo strips with a rectangular grooving pattern is easier compared to semi-circular and V-notch patterns. This aspect holds importance for practical applications, particularly in regions where ease of fabrication is critical. Regarding the treatment of bamboo strips, those treated with bituminous paint are considered for further research. This choice stems from its affordability and ready availability in the Indian market, making it a practical option for large-scale applications. Since the primary goal of this study is to reduce construction costs without compromising structural integrity, bamboo strips treated with bituminous paint are prioritised for further investigation. Bond-tite adhesive is more expensive than bituminous paint, as indicated in Table 1. This cost disparity is crucial in decision-making for large-scale projects or applications where material expenses are significant. Additionally, treating bamboo strips with bituminous paint is straightforward: the strips are placed in a large container filled with the paint. This method simplifies the treatment process and enables the simultaneous treatment of multiple bamboo strips, facilitating mass production. The cost-effectiveness of bituminous paint and the simplicity of its treatment process make it a practical choice for projects with budget constraints or those requiring large quantities of treated bamboo strips. The ease of bulk production through the container-based treatment method renders bituminous paint a viable option for applications necessitating a substantial volume of treated bamboo.

4.2. Result of bond strength

Calculating bond stress is crucial for determining the effectiveness of force transmission between the bamboo and the surrounding concrete. A robust bond facilitates efficient load transfer and strengthens the structural integrity of the composite material. Bond stress is calculated using the shear force per unit nominal surface area of the reinforcing bamboo strip. This stress acts parallel to the bamboo strip at the interface with the surrounding concrete. The relationship between pull-out load and bond resistance for plain bamboo strips is expressed by Equation (1).

$$P = \tau_{bp} \cdot (2b + 2t) \cdot L_d \tag{1}$$

where P is pull-out force applied through the UTM (kN), L_d is embedding length of bamboo strips in mm, b and t are width and thickness of bamboo strips in mm and τ_{bp} is average bond stress in N/mm^2.

The experiment results indicate that bamboo strips with rectangular grooves outperformed other grooving patterns. This pattern is, therefore, chosen for further consideration in calculations. The pull-out force mechanism involves both adhesion and friction between the bamboo and the surrounding concrete. Adhesion refers to the molecular attraction between the materials, while friction is the resistance to relative motion at the interface. The mechanical interlock provided by the rectangular grooves enhances the pull-out resistance. The grooves physically engage with the concrete, creating a mechanical bond that resists pull-out forces. The geometry of the bamboo strips, specifically the rectangular grooves, is a key factor in determining the pull-out force. The dimensions and arrangement of the grooves influence the overall interaction with the surrounding concrete. Equation (2) establishes a relationship between the theoretical pull-out load and internal bond resistance. This equation quantifies the pull-out force based on factors such as groove dimensions, material properties, and the nature of the bond.

$$P_{theoretical} = \{[(s \cdot n \cdot t) + (2 \cdot w \cdot L_d)] \cdot \tau_{bp}\} + [(a \cdot n \cdot t) \cdot \tau_{bs}] \tag{2}$$

where τ_{bp} is bond strength between plain bamboo and concrete in N/mm^2, τ_{bs} is shear strength of bamboo specimen along the grain (11.02 N/mm^2) [19]. Here, s denotes the size of grooves in mm, 'a' is the distance between adjacent grooves in mm and n is number of grooves. L_d is the length of bamboo embedded within the concrete cylinder in mm, w and t is effective width and thickness of bamboo strips in mm. Figure 8 shows details of rectangular grooved bamboo strip.

Understanding the relationship between the theoretical pull-out load and internal bond resistance is crucial for designing bamboo-reinforced structures. It offers insights into the factors influencing

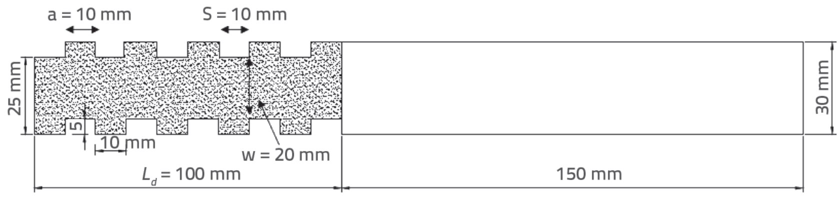

Figure 8. Details of the rectangular grooved bamboo strip

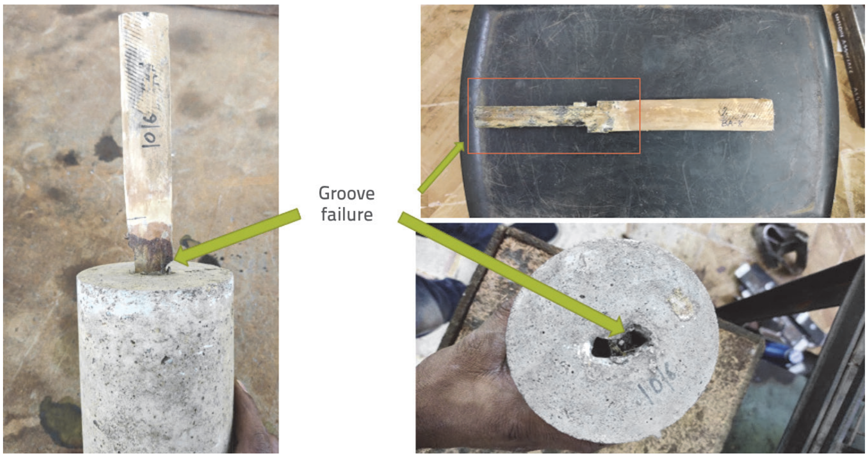

Figure 9. Groove failure of the bamboo strips

the pull-out force and enables optimisation in structural applications. The geometry of the rectangular grooves plays a pivotal role in the pull-out force mechanism. Table 5 presents calculations of experimental and theoretical ultimate loads according to equation (2). The values of τ_{bp} for BO-R and BA-R are taken as 1.48 MPa [11] and 0.66 MPa [15], respectively.

From the table above, it is concluded that rectangular grooved bamboo strips treated with bond tite exhibit higher bond strength than rectangular bamboo strips treated with bituminous paint. Both samples have experimental ultimate load (P_{EG}) and theoretical ultimate load (P_{TG}) ratios close to 1, indicating that the experimental ultimate loads are relatively consistent with the theoretical expectations. This suggests that the bond strength in both samples is reasonably close to the predicted values. The grooved bamboo strips show enhanced mechanical resistance compared to plain bamboo strips. This improvement is attributed to the presence of grooves, which likely enhance the bond strength and load-carrying capacity of the bamboo-concrete composite. The maximum mechanical resistance is achieved because all the grooves simultaneously participate in resisting the applied forces. This implies a collective and synergistic effect of the grooves, working together to provide optimal structural performance.

All samples failed owing to the successive failure of grooves, as depicted in Figure 9. This indicates that the failure mode is associated with the performance of these grooves, suggesting the critical role played by the grooves in the overall failure mechanism. Figure 9 illustrates the failure pattern observed during the experiment, depicting the progression of groove failure and the overall behaviour of the bamboo strips embedded in concrete.

In some samples, partial groove failure occurs during the pull-out test, which could be attributed to variations in material properties, load distribution, or other factors influencing the performance of individual grooves.

The observation of successive groove failure highlights the importance of grooves in maintaining the structural integrity of the bamboo-concrete composite. The failure mechanism is predominantly associated with the grooves, and understanding how and why grooves fail can guide further research into optimising grooved bamboo strips for enhanced performance.

It was seen that the chemical treatment with bituminous paint reduces the water absorption capacity of bamboo strips, which is desirable for construction purposes. Water absorption can

Table 5. Pull-out load results for grooved bamboo strips

Plain bamboo-concrete bond strength (τ_{bp}) [N/mm²]	Sample	Theoritical ultimate load P_{EG} [kN]	τ_{bp} [kN]	P_{EG} / P_{TG}	Bond strength [MPa]
1.48	BO-R	22.02	21.38	1.03	1.94
0.66	BA-R	13.83	15.64	0.88	1.41

Table 6. Comparison of the bond strengths of steel and bamboo reinforcements

Grade of concrete	M 20 (C 16/20)	M 20 (C 16/20)	M 20 (C 16/20)	M 20 (C 16/20)
Reinforcement type	Plain steel reinforcement (IS 456)	Ribbed steel reinforcement (IS 456)	Rectangular grooved bamboo reinforcement (bituminous paint)	Rectangular grooved bamboo reinforcement (bond tite)
Design bond stress [MPa]	1.2	1.92	1.41	1.94

cause swelling, warping, and degradation of bamboo over time. By reducing water absorption, the treated bamboo becomes more resilient to environmental conditions. The application of bituminous paint helps mitigate significant dimensional changes in bamboo during concrete curing, suggesting that treated bamboo experiences less expansion or contraction compared to untreated bamboo. Treated bamboo with bituminous paint is expected to demonstrate improved stability and longevity, rendering it a more reliable material in construction applications.
Table 6 compares the actual bond stress of treated rectangular grooved bamboo strips to that of plain and ribbed steel reinforcement, following IS 456:2000 [20]. Both bituminous paint and bond tite-treated rectangular grooved bamboo exhibit higher design bond stress than traditional steel reinforcements. This indicates that grooved bamboo may provide competitive bond strength in concrete structures.

5. Conclusions

This investigation focuses on the bamboo-concrete bond action through pull-out tests. Mechanical and chemical actions are employed to enhance the bond between bamboo and concrete, investigating three different grooving patterns: rectangular, semi-circular, and V-notch. It is observed that rectangular pattern bamboo strips fail at higher loads. Bamboo strips are chemically treated with bond tite adhesive and bituminous paint, along with sandblasting, to reduce the water absorption capacity of bamboo. This chemical treatment enhances the bond between bamboo and concrete, achieving bond strengths of 1.94 MPa and 1.41 MPa using bond tite and bituminous paint, respectively. The primary aim of this study is to minimise construction costs. After comparing the cost of both chemicals, it is recommended to use bituminous paint for treatment as it is cheaper than bond tite and suitable for mass production of treated bamboo strips. The design bond stress values for rectangular groove samples are comparable with those suggested by IS 456:2000 for plain and ribbed steel bars with M20 (C 16/20 as per Eurocode 2) grade concrete. This investigation mainly focuses on the bonding between bamboo and concrete. Further research could explore the optimisation of bamboo treatment methods to enhance bond strength, considering factors like cost-effectiveness and environmental sustainability. Investigating the long-term performance of bamboo-reinforced concrete structures could provide insights into the durability and effectiveness of bamboo as a reinforcement material. Nonetheless, this research has demonstrated that the bond performance is greatly enhanced by the proposed grooved pattern of a bamboo strip with bituminous paint as chemical treatment.

REFERENCES

[1] Ameen, M.S., Datta, D.: Bamboo as reinforcing material in concrete structures: A literature study, GRADEVINAR, 75 (20238 8), pp. 803–818. https://doi.org/10.14256/JCE.3681.2022

[2] Dixit, A., Puri, V.: Bamboo bonding in concrete: A critical research, International Journal of Innovative Technology and Exploring Engineering, 8 (2019) 11, Special Issue, pp. 323–334.

[3] Ghavami, K.: Bamboo as reinforcement in structural concrete elements, Cem Concr Compos, 27 (2005) 6, pp. 637–649, https://doi.org/10.1016/j.cemconcomp.2004.06.002.

[4] Sharma, B., Gatóo, A., Ramage, M.H.: Effect of processing methods on the mechanical properties of engineered bamboo, Constr Build Mater, 83 (2015), pp. 95–101, https://doi.org/10.1016/j.conbuildmat.2015.02.048.

[5] Indian Standard Specifications for Code of Practice for Structural Design using Bamboo, IS 15912-2018, Bureau of Indian Standards, New Delhi, 2012.

[6] Correal, J.F., Echeverry, J.S., Ramírez, F., Yamín, L.E.: Experimental evaluation of physical and mechanical properties of Glued Laminated Guadua angustifolia Kunth, Construction and Building Materials, 73 (2014), pp. 105–112. https://doi.org/10.1016/j.conbuildmat.2014.09.056

[7] NBC (2005), National Building Code of India, Group-2, Part 6 Section 3B, Bureau of Indian Standards, New Delhi, India.

[8] Tazowar, M., Siddique, A.F.A., Ahmed, I.: A novel approach for enhancing the bond performance of bamboo reinforced concrete by surface treatment and corrugation, Construction and Building Materials, 409 (2023), https://doi.org/10.1016/j.conbuildmat.2023.133728

[9] Khatib, A., Nounu, G.: Corrugated bamboo as reinforcement in concrete, Proceedings of the Institution of Civil Engineers: Structures and Buildings, 170 (2017) 4, pp. 311–318, https://doi.org/10.1680/jstbu.16.00067

[10] Anusha, M., Surendra, H.J., Dhar, N., Choudhary, M., Khan, I.A., Pasha, S.F.A.: Enhancing sustainability of polypropylene band and bamboo-reinforced structural elements for rural low-cost housing. Environment, Development and Sustainability, (2022) https://doi.org/10.1007/s10668-022-02864-9

[11] Mali, P.R., Datta, D.: Experimental study on improving bamboo concrete bond strength, Advances in Concrete Construction, 7 (2019) 3, pp. 191–201, https://doi.org/10.12989/acc.2019.7.3.191.

[12] Agarwal, A., Nanda, B., Maity, D.: Experimental investigation on chemically treated bamboo reinforced concrete beams and columns, Comput Chem Eng, 71 (2014), pp. 610–617, https://doi.org/10.1016/j.conbuildmat.2014.09.011.

[13] Sayed, U., Dauletbek, A., Xin, X., Lorenzo, R., Li, H.: A Review on the Mechanical Behaviour of Bamboo Reinforced Concrete Beams, In Journal of Renewable Materials, Tech Science Press, 10 (2022) 12, pp. 3629–3657, https://doi.org/10.32604/jrm.2022.022624

[14] Azadeh, A., Kazemi, H.H.: New approaches to bond between bamboo and concrete, Key Engineering Materials, 600 (2014), pp. 69–77, https://doi.org/10.4028/www.scientific.net/KEM.600.69

[15] Kute, S.Y., Wakchaure, M.R.: Performance Evaluation for Enhancement of Some of the Engineering Properties of Bamboo as Reinforcement in Concrete, Journal of The Institution of Engineers (India): Series A, 94 (2013) 4, pp. 235–242, https://doi.org/10.1007/s40030-014-0063-1.

[16] Lima, H.C., Willrich, F.L., Barbosa, N.P., Rosa, M.A., Cunha, B.S.: Durability analysis of bamboo as concrete reinforcement, Materials and Structures/Materiaux et Constructions, 41 (2008) 5, pp. 981–989, https://doi.org/10.1617/s11527-007-9299-9.

[17] Indian Standard Specifications for Methods of Testing Bond in Reinforced Concrete, IS 2770 (Part 1), Bureau of Indian Standards, New Delhi, India, 1967.

[18] Mondal, B., Maity, D., Patra, P.K.: Bond Behavior between Bamboo and Normal-Strength Concrete: Experimental and Numerical Investigation, Practice Periodical on Structural Design and Construction, 27 (2022) 3, pp. 1–11, https://doi.org/10.1061/(asce)sc.1943-5576.0000715

[19] Chand, N., Shukla, M., Sharma, M.K.: Analysis of mechanical behaviour of bamboo (Dendrocalamus strictus) by using FEM, Journal of Natural Fibers, 5 (2008) 2, pp. 127–137, https://doi.org/10.1080/15440470801928970

[20] Indian Standard Specifications for Code of Practice for Plain and Reinforced Concrete, IS 456-2000, Bureau of Indian Standards, New Delhi, 1987.