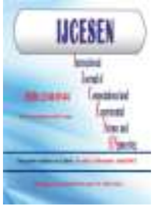
International Journal of Computational and Experimental Science and ENgineering
(IJCESEN)

Vol. 10-No.4 (2024) pp. 1801-1813
http://www.ijcesen.com

ISSN: 2149-9144

Research Article



Assessment of Bond Strength in Bamboo-Reinforced Concrete

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Article Info:

DOI: 10.22399/ijcesen.498
Received : 09 October 2024
Accepted : 15 December 2024

Keywords :

Bamboo,
Bamboo-reinforced concrete,
Concrete,
Bond strength,
Pull-out test ,

Abstract:

Bamboo, a sustainable and eco-friendly material, has been utilized in construction for centuries. With the increasing focus on green building practices, bamboo is gaining recognition as a feasible option for reinforcing concrete. Its affordability and high strength-to-weight ratio have sparked significant interest. However, natural bamboo faces challenges such as poor compatibility with concrete, and insufficient stiffness, which hinder its widespread use. Additionally, the dimensional instability of bamboo due to moisture and temperature fluctuations can result in de-bonding, significantly weakening bond strength. To overcome these limitations, improving the inherent properties of bamboo through various treatments is crucial for its effective application as concrete reinforcement. This paper comprehensively reviews multiple techniques used to incorporate bamboo into concrete, comparing bond strength results and analyzing the factors that influence bond performance. The review identifies optimal solutions for the effective use of bamboo as a sustainable reinforcement in construction.

1. Introduction

Concrete is a frequently employed construction material for its durability, adaptability, and moldability in various shapes. However, its tensile strength is relatively low, necessitating reinforcement to improve its structural performance [1,2]. Traditionally, steel has been the primary material for reinforcing concrete due to its high tensile strength and compatibility with concrete. However, the environmental impact of steel production, coupled with its rising cost and susceptibility to corrosion, has prompted the exploration of alternative materials for reinforcement [3]. As a result, bamboo is emerging as a sustainable alternative [4].

Bamboo, a natural composite material with high tensile strength and a rapid growth rate, has been traditionally used in construction across many cultures, particularly in Africa, Latin America, and Asia. Its potential as a sustainable reinforcement material in concrete structures has gained increasing attention from researchers over the past few decades [5,6]. Bamboo offers unique properties, such as its high strength-to-weight ratio, flexibility, and low cost, which make it an attractive alternative to steel, particularly in regions where bamboo is readily available [7].

Although bamboo has significant potential as a reinforcement material, it faces several challenges. One of the main challenges is the variability in bamboo properties due to differences in species, age, and growing conditions, which can lead to inconsistent bond performance in concrete. The organic nature of bamboo, its anisotropic properties, and its tendency to swell in the presence of moisture present unique challenges for bonding with concrete [8]. The bamboo-concrete bond significantly influences the efficacy of bamboo-reinforced concrete structures. A strong bond is necessary to ensure efficient stress transfer from the concrete to the reinforcement, enabling the composite action of the structure [9,10]. In contrast, the bond strength in steel-reinforced concrete is well-established, with numerous studies identifying key factors that influence it, such as rebar properties, concrete type, and bonding test methods [11]. The bond strength of bamboo is significantly affected by its water absorption capacity and the dimensional alterations influenced by moisture and temperature fluctuations. The bamboo absorbs moisture and swells during the concrete casting and curing process, as illustrated in figure 1(a). This swelling causes the bamboo to exert pressure on the surrounding concrete, as depicted in figure 1(b). After the curing period, the bamboo releases the absorbed water and shrinks back to almost its original size, resulting in the formation of voids around it, as depicted in figure 1(c). The swelling and shrinking effects in bamboo can be mitigated by employing an appropriate surface treatment [12,13].

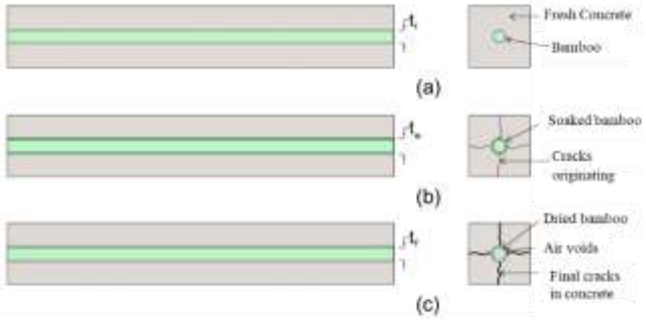

Figure 1. *Illustrates the performance of untreated bamboo when used as reinforcement in concrete: (a) fresh condition, (b) curing stage, and (c) hardened condition*

Research on bamboo-reinforced concrete (BRC) has revealed that untreated bamboo exhibits poor adhesion with concrete, primarily due to its smooth surface and a waxy outer layer known as the cuticle. To address these issues, researchers have explored various surface treatments and modifications to strengthen the bond strength of bamboo-reinforced concrete, aiming to improve the performance and reliability of BRC in construction applications. These treatments include mechanical roughening and coating bamboo with waterproofing and bonding agents. Each of these methods aims to improve the surface roughness of the bamboo or its chemical compatibility with concrete, thereby enhancing the mechanical interlock and the adhesive bond [14,15,16,17].

To assess bond strength, numerous researchers have conducted pull-out tests. The test is conducted on a Universal Testing Machine (UTM), where specimens are loaded at controlled displacement rates with uniaxial tensile loading. Load and deformation readings are recorded at regular intervals of deformation until failure occurs [18]. Figure 2 represents a schematic diagram of Pull-out samples and forces related to them.

The loading setup for the pull-out test is shown in figure 3. An equilibrium of resistive forces (R) and applied force (P) in the axial direction results in Equation 1

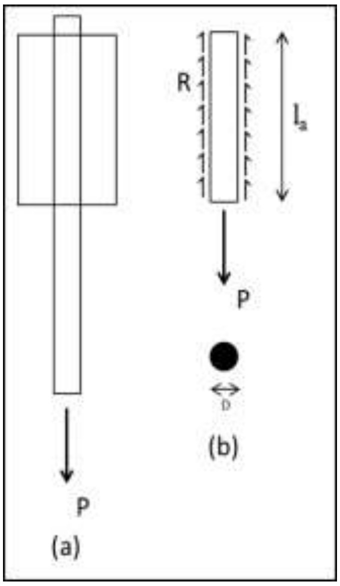

Figure 2. *Schematic representation of (a) Pull-out samples (b) Forces related to bond*

$$P = \tau . \mathrm{p} . \mathrm{la} \tag{1}$$

Where, τ = bond stress (MPa); P = pullout applied through the UTM (N); l_a = Bamboo embedment length (mm); and p = perimeter of bamboo (mm)In addition to experimental studies, analytical and numerical models are established to forecast the bond behavior of bamboo-reinforced concrete. These models offer enhanced insight into bond behavior, ultimately contributing to the better design of bamboo-reinforced concrete structures. The results from these studies have been promising, indicating that with appropriate treatment and design, bamboo can be a viable alternative to steel in reinforced concrete structures. Despite the promising results from various studies, the bond behavior of bamboo-reinforced concrete remains an area of ongoing research, with several challenges yet to be fully addressed [19,20,21]. This review synthesizes existing research on the bond behavior of bamboo-reinforced concrete, focusing on factors influencing bond strength, surface treatment effectiveness, and predictive numerical models. By providing a comprehensive overview, it aims to support efforts to promote bamboo as a sustainable reinforcement material in concrete construction.

2. Bamboo as construction material

Bamboo, a giant woody grass from the Poaceae family, includes over 1,250 species. Bamboo is renowned for its rapid growth, sustainability, and renewability, with some species growing up to 91 cm per day, according to Guinness World Records. When evaluating the energy needed for bamboo production, it is significant to note that bamboo is 50 times more energy efficient than steel. The production of each bamboo ton necessitates consuming approximately a ton of atmospheric CO_2. Its capacity to absorb carbon and release oxygen contributes to its viability as a sustainable option for mitigating greenhouse gas emissions [22]. Furthermore, bamboo presents a lower carbon footprint in comparison to steel [23]. Moreover, bamboo possesses a considerable tensile strength, as illustrated in table 1, which presents a comparison between the properties of steel and bamboo. Bamboo weighs six times less than steel, making it a lightweight material with a high strength-to-weight ratio [24]. Bamboo can resist both tensile and compressive forces, much like steel bars. Employing bamboo as a concrete reinforcement makes it feasible to overcome the limitations associated with steel, while simultaneously fostering sustainability and generating economic advantages for developing nations [25,26].

3. Factors Affecting Bond Strength

The data collected from the literature include concrete strength, treatments provided to increase the bond, specimen details, bamboo species used, tensile strength, bond strength results, and observed failure modes. All these data are presented in table 2. The factors affecting the bond strength between bamboo and concrete, such as the surface characteristics of the bamboo, the type of concrete mix, and the properties of bamboo as illustrated in figure 4, are discussed.

3.1 Surface treatments of Bamboo

The smooth surface of bamboo poses a significant challenge in achieving strong bond strength. The treatments applied are primarily divided into two categories: chemical treatment, which involves the use of adhesives, and mechanical treatment, which includes techniques like notching, corrugation, and the use of steel wire, etc.

Chemical Treatments

Various researchers have suggested chemical treatments to increase bond strength and make bamboo surfaces impermeable. These treatments include bitumen asphalt emulsion [43], sulfur [44], varnish [41], Sikadur 32 gel [12,30], negrolin [9], SJK-61 epoxy mortar [45], Bondtite [16], tack coat [35], water-based epoxy coating [33], Algicoat RC-104 [36], Araldite [21], linseed oil [37], and Sikadur 32-LP [20]. Kute and Wakchaure investigated various treatment techniques to improve the properties of bamboo used as reinforcement in concrete [15]. These techniques included binding wire, oil, bituminous paint, zeolite powder, bitumen, kerosene, and combinations thereof. Their findings indicated that applying bituminous paint and zeolite powder, especially in the presence of a node, significantly enhanced the bond performance of bamboo-reinforced concrete. Agarwal et al. utilized different adhesives including Anti Corr RC, Tapecrete P-151, Araldite, and Sikadur 32 Gel and in the experimental work to examine their impact on the bond strength at the bamboo-concrete interface [30]. It was determined that Sikadur 32 gel results in the strongest average bond strength between bamboo and concrete [12,30].

Table 1. *Comparative Analysis of Bamboo and Steel Properties*

Property	Bamboo	Steel
Density (kg/m^3)		7850
	(640–758) for different species in air-dry condition [27]	
Modulus of Elasticity (GPa)		200 [29]
	(6.06–21.41) for different species in air-dry condition [27]	
Compressive Strength (MPa)		130 for Mild Steel [29]
	(53.4–69.9) for different species in air-dry condition [27]	
Tensile Strength (MPa)	(114–321) for different species [27]	140 (up to 20 mm dia.) and 130 (over 20 mm dia.) for Mild Steel [29]
Factor of Safety limit state of collapse	3.5 [28]	1.15 [29]

Figure 3. *Loading setup for pull-out test [21].*

***Table 2**. Bamboo-reinforced concrete bond strength achieved by several researchers*

Author	**Species**	**Bamboo Tensile Strength (MPa)**	**Concrete Mix Design / Concrete strength**	**Sample size and embedded length**	**Treatments to increase bond**	**Bond strength (Mpa)**		**Failure mode**
						No node	**with node**	
[20]	Bambusa balcoa	114	1: 1.68:3.21 w/c 0.52	Concrete cube of 150 mm and bamboo 650 mm length, 100% embedded	Sikadur 32-LP and medium sand sprayed	2.2	**2.7**	Bond breakage at the resin bamboo interface
[30]	Muli Bamboo	185.93	20 MPa	Concrete cylinder 100 mm x 200 mm, 50% embedded	Without treatment	0.13		Slippage of bamboo strips
					Araldite coating	0.23		
					Araldite coating + thin wire winding	0.54		
					Tapecrete P 151	0.1		
					Anti Corr RC	0.16		
					Sikadur 32 Gel	0.59		
[16]	B. arundinacea	150	1:2.46:4.07 w/c 0.55	Concrete cylinder 100 mm x 200 mm, 50% embedded	No treatment	0.14		
					Plain bamboo with a 1mm steel wire wrapped			
					Triflor PUAL lacquer	0.21		Bond Failure
					Bondtite treatment	1.4		
					Araldite	0.84		
					Strepoxy	1.37		
					Bitumen (VG-30)	0.22		
					EPI BOND -21	1.2		
					Grooved and no chemical treatment	0.49		Bond failure with partial groove failure
					Semicircular grooved with 1mm steel wire wrapped			
					Triflor PUAL lacquer	1.04		Groove Failure of bamboo
					Bond tite treatment	2.35		
					Araldite	1.44		
					Strepoxy	1.88		
					Bitumen (VG-30)	0.97		
					EPI BOND -21	1.54		
[5]	Bambusa Vulgaris Vittata	135.5	1:1.34:1.8 w/c 0.5	Concrete cylinder 150 mm x 300 mm, 50% embedded	No treatment		0.667	
	Bambusa Heterostachya	215.9			No treatment		0.345	
[12]	Dendrocalamus giganteus	119.02	1:3.22:0.78 with w/c 0.55	Concrete cylinder 150 mm x 300 mm, 100% embedded	No treatment	0.52	1.2	
					Negrolin + sand	0.73	1.55	
					Negrolin + sand + wire	0.97	1.8	
					Sikadur 32-Gel	2.75		
[31]	Dendrocalamus Asper	126.68	1:1.8:2.8	Concrete cylinder 150 mm x 300 mm, 66.67% embedded	No treatment	1		
					Hose Clamp 10 cm	1.08		Bond-slip failure
					Sikadur 752 + Sand	2.25		Bond-slip failure

					Sikadur 752 + Sand + Hose Clamp 15 cm	3.25		Bond and concrete cone failure
					Sikadur 752+ Sand + Hose Clamp 20 cm	3		
[32]		82	1:1.49:3.4	Concrete cylinder 150 mm x 300 mm, 100 % embedded	No treatment		0.16	Slippage
					semi-circular corrugation		0.286	Breakage of bamboo
					2mm diameter wire wrapped		0.185	Slippage
[15]	Dendrocalamus strictus	321	1: 1.47: 2.33 w/c 0.45	Concrete cube of 150 mm and bamboo 750 mm length embedded 100%	No treatment	0.73	0.9	
					Binding wire wound	1.06	1.25	
					Oil painted	0.48	0.69	Slipping at low load
					Oil painted, with zeolite powder	0.71	0.93	
					Bitumen and kerosene	0.63	0.79	
					Bitumen + kerosene, zeolite powder	0.88	1.11	
					Bituminous Paint with zeolite powder	1.06	1.19	
[33]	Dendrocalamus asper	320	1:3.03:3.75 w/c 0.65	Concrete cylinder 150 mm x 300 mm and bamboo embedded 66.67 %	No treatment	3.61		Bamboo tensile failure
					Water based epoxy coating	3.47		
					Water based epoxy coating + fine sand	3.65		
					Water based epoxy coating + coarse sand	3.61		
					TrueGrip EP	3.3		
					TrueGrip EP + coarse sand	3.45		
					Exaphen	3.36		
					Exaphen with coarse sand	3.46		
					Enamel Coating	3.4		
					TrueGrip BP	2.42		Bond failure
					TrueGrip BP + coarse sand	2.62		
			Cement Epoxy in concrete mix by 25% weight of cement		No treatment	3.52		Bamboo tensile failure
[34]		202	20 MPa	Concrete cube of 150 mm				
				embedded 33.33%	No treatment	0.61		
				embedded 50%	No treatment	0.625		
				embedded 66.6%	No treatment	0.65		
				embedded 33.33%	Sikadur	1.35		

				embedded 50%	Sikadur	1.36		
				embedded 66.6%	Sikadur	1.34		
[10]	Bambusa bambos	26.74	1:2.37:4.34 w/c 0.5	Concrete cylinder 100 mm x 200 mm and bamboo embedded 50%	No treatment	0.16		Slippage of the bamboo strip
					Araldite	0.31		
					Araldite with wire	0.5		
[35]		169.27	32.95 MPa	Concrete cylinder 150 mm x 300 mm 50% embedded	No treatment	1.87		
					Tack coat	2		
[36]	Moso bamboo	125	1:1.5:3 w/c 0.54	Concrete cylinder 150 mm x 300 mm				
				embedded 86.6%	No treatment	1.1		
					Algicoat RC-104	1		
				embedded 66.6%	No treatment	1.3		
					Algicoat RC -104	1.16		
				embedded 50 %	No treatment	1.62		
					Algicoat RC -104	1.64		
[21]	Bambusa Balcooa	135	22.4 MPa	Concrete cylinder 100 mm x 200 mm				
				50% embedded	No treatment	0.93		Most samples fail in bond and a few fails in tensile and splitting failures
					Araldite treated	1.24		
					Rectangular corrugated	1.35		
					V-notch corrugated	1.68		
					Trapezoidal corrugated	1.69		
				100% embedded with 100 mm debonding	No treatment	0.92		
					Araldite treated	1.19		
					Rectangular corrugated	1.34		
					V-notch corrugated	1.7		
					Trapezoidal corrugated	1.63		
[37]	Moso bamboo		1: 1.7: 3 w/c 0.5	Concrete cube of 150 mm	No treatment	0.9		
					Treated with linseed oil	1.11		
					No chemical treatment and Corrugated 1 mm Projection	1.46		
					Corrugated 1 mm Projection (1:1) and treated with linseed oil	1.48		
					No chemical treatment and corrugated 2 mm Projection	1.61		
					Corrugated 2 mm Projection (1:1) and treated with linseed oil	2.79		
					Corrugated 2 mm Projection (1:1.5) and treated with linseed oil	2.92		
					Corrugated 2 mm Projection (1.5:1) and treated with linseed oil	2.14		
[13]	oxytenanthera abyssinica	300	31.2 MPa	Concrete cylinder	surface roughened	0.33	0.98	
			35.7 MPa		surface roughened	0.6	1.88	
			44.3 MPa		surface roughened	1.13	2.04	

			37 MPa		surface roughened		1.93	
					surface roughened & 1 coat of bitumen + sand		2.47	
			30.4 MPa		surface roughened+ 2 coat of bitumen		2.39	
					surface roughened+ 2 coat of bitumen + sand		2.6	
[38]	Arundinaria Amabilis	84.7	1:1:6 w/c: 0.62	Concrete cylinder 150 mm x 300 mm, 100% embedded	Spar varnish coated + fine sand	1.49	2.16	
[39]		197	10MPa	Concrete cube 200 mm, 85% embedded	No treatment	0.66		
					Synthetic Resin (Brush Coating)	1.34		
					Resin (Spray Coating)	1.25		
					Synthetic Rubber (Spraying)	1.18		
[40]	Moso bamboo	117	30 Mpa	Concrete cube 150 mm and bamboo embedded 80%		Bamboo splint	Half round	
					Plain	0.45	0.56	slippage of bamboo
					Oil Paint	0.5	0.6	
					Oil Paint + sand	0.58		
					Oil Paint & wire in one direction	0.8	0.89	
					Oil Paint & wire in cross	0.87	1.12	
						Square cross section	Round cross section	
[41]	Petung	161	15 Mpa	Concrete cylinder 150 mm x 300 mm and bamboo embedded 50 %	No treatment	0.62		
					Varnish	2.22	1.7	
					winding wire	1.9	1.49	
	Wulung	168			No treatment	0.62		
					Varnish	1.33	1.12	
					winding wire	0.95	0.98	
[42]	Moso Bamboo	125		Prisms with 100 mm square cross-sections and length 400 mm and diameter				
			21 Mpa	Dia. 15.5 mm	rubber coating		0.7	
			19 Mpa	Dia. 16.9 mm	rubber coating		0.96	
			13 MPa	Dia. 19.5 mm	rubber coating		0.99	
			6 MPa	Dia. 13 mm	rubber coating		0.26	
				Dia. 15.2 mm	rubber coating		0.47	
				Dia. 22.4 mm	rubber coating		0.24	

Javadian et al. studied the bond behavior of newly developed bamboo-composite reinforcement in concrete [33]. Their research found that the bamboo composite, when treated with a water-based epoxy and fine sand as shown in figure 5, exhibited favorable bonding characteristics, making it a viable alternative to traditional steel reinforcement. The introduction of sand particles serves to augment the adhesion between the bamboo and the concrete, primarily by intensifying the frictional forces between the sand particles and the irregularities present on the cured concrete surface [33]. Wang et al. conducted pull-out loading tests on surface-modified bamboo and concrete [45]. Their findings highlighted that the bond strength improved up to 25 times when epoxy mortar (EM) was used for surface modifications compared to untreated bamboo. This study evaluates the bond strength among various specimens, revealing that epoxy-treated and sand-coated bamboo specimens exhibited highest bond strength [46]. The bond strength increased with the increasing thickness of the paint. The bond between the splints and concrete was better when the splints were painted with two coats of paint [13].

Mechanical Treatments

Several studies have also been conducted to incorporate mechanical interlock by adding

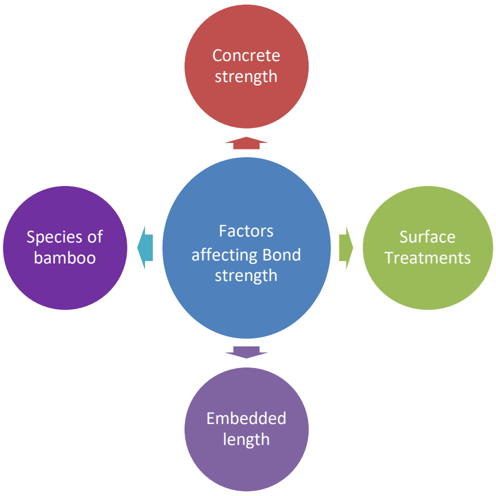

Figure 4. *Factors affecting bond strength of bamboo in concrete*

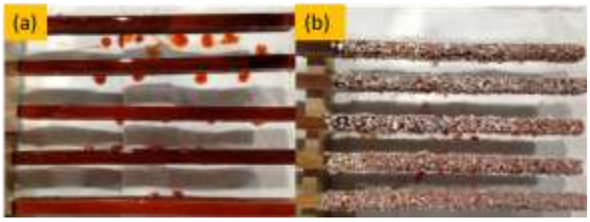

Figure 5*. ExaPhen coating applied on the surface of bamboo; (a) without sand particles; (b) with coarse sand particles [33]*

corrugations, using steel wire, or installing hose clamps on the bamboo surface. In the study conducted by Khatib and Nounu, the application of corrugated bamboo as reinforcement in concrete is explored [37]. Their findings suggested that corrugated bamboo splints with 2 mm Projection with spacing ratios (a: S) 1:1.5 and treated with linseed oil could achieve 3.24 times better bond performance compared to smooth bamboo [37]. Additionally, corrugation can minimize the wedging effect by altering the stress transfer mechanism between bamboo and concrete and improve overall bond strength [47]. The highest bond strength achieved was 1.94 MPa using Bond Tite adhesive and a rectangular grooved pattern [48]. A study was performed by Tazowar using 3 types of corrugation patterns, such as V-notch corrugation, trapezoidal corrugation, and rectangular corrugation as shown in figure 6. Among these V-notch corrugation emerged as the most prominent. It boasts an impressive enhancement of approximately 85% and 43% compared to plain and epoxy-treated bamboo, respectively [21]. In the study conducted of Mali [16], three different groove shapes rectangular, semi-circular, and V-notch as shown in figure 7. Results revealed that combination of semi-circular grooved bamboo with a chemical coating of Bond Tite yields the maximum pull-out strength, up to 16 times more than untreated plain bamboo reinforcement. Qaiser et al. conducted an experimental study on the bond behavior of bamboo, comparing the bond properties of plain bamboo strips, semi-circular grooved bamboo strips, and wired bamboo strips. Observations suggest that a semi-circular grooved sample as shown in figure 8 enhances bond strength the most [32]. The study by Awalluddin et al. found that fly ash geopolymer concrete specimens reduce bond breakage due to the swelling and shrinkage of bamboo, resulting in higher bond strength compared to Ordinary Portland cement concrete specimens [49]. Additionally, the results showed that galvanized iron (G.I.) rolled wire bamboo specimens outperformed corrugated and plain bamboo specimens [49]. Improved bonding effect and minimized slip effects with notched bamboo reinforcement [50]. Similarly, Muhtar et al. utilized hose clamps as shown in figure 9, to increase bond stress and slip resistance, demonstrating a simple yet effective method to enhance the performance of bamboo-reinforced concrete [31].

3.2 Concrete Mix Design

The composition of the concrete mix can also significantly affect the bond strength. The bond strength of concrete is directly proportional to the compressive strength of concrete. When bamboo is pulled out from the concrete, it exerts pressure on the concrete. As the concrete breaks down, the slip increases, leading to a reduction in bond strength. Consequently, the stronger the concrete, the greater the bond strength [13]. In the experimental study by Terai [42] various concrete strengths of 6, 13, 19, and 21 N/mm² were tested. The results showed that the initial bond stress does not have a significant correlation with concrete strength, but the maximum bond strength generally increases as concrete strength rises.

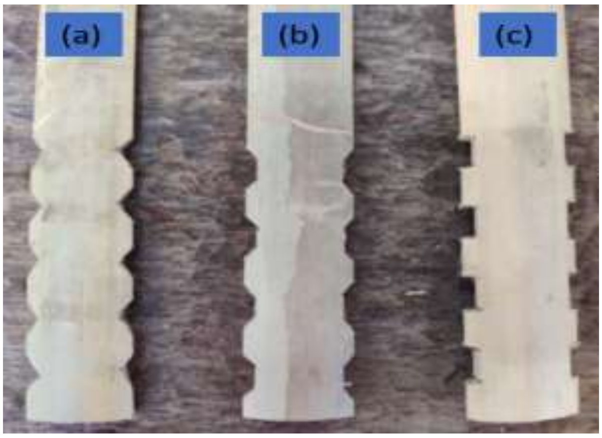

Figure. 6. *Bamboo strip with corrugations (a) V Shape (b) Trapezoidal (c) Rectangular [21].*

Figure 7. *Bamboo specimens with Bond tite coating and sand particles [16].*

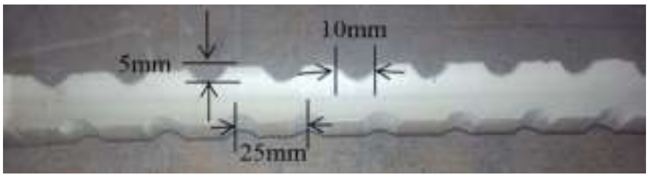

Figure 8. *Bamboo specimen with semi-circular corrugations [32].*

Figure 9. *Bamboo with hose clamps and layer of Sikadur-752 [31]*

3.3 Properties of bamboo

Presence of node

Many researchers have thoroughly investigated the impact of the presence of nodes in bamboo used as reinforcement, and it was found that the bond strength in concrete was enhanced by the inclusion of bamboo nodes, as they provided mechanical interlocking at these points. In comparison, the internodal sections yielded relatively lower bond strength than the nodal sections. This improved the overall integrity of the concrete structure, making it more resistant to tension and shear forces. In addition, the bamboo nodes also provided additional reinforcement, making the structure stronger and more able to withstand external forces [12,38]. In the study conducted by Kankam and Perry it was found that the ultimate bond strength between bamboo and concrete depends on the presence of nodes, concrete compressive strength, bamboo surface roughness, and the number of waterproofing paint coats applied [13]. Similarly, Ghavami observed that using nodal samples resulted in up to a 100 % increase in bond strength [9]. Al-Fasih et al. [5] demonstrated significant differences in the bond strength between bamboo species and concrete, underscoring the importance of species selection in achieving optimal results [5]. The study conducted by Kute and Wakchaure examined the trend of bond strength of bamboo specimens with nodes and without nodes, and it was found that nodal samples have higher bond strengths for all kinds of chemical treatments by 15 % -22 % [15].

Aspect ratio of bamboo

To determine the effects of the aspect ratio (width/thickness) of the bamboo strips Mondal et al. [20] conducted pullout test, with different aspect ratios. The test results revealed that bond strength is greatly influenced by the aspect ratio of bamboo strips: as the aspect ratio decreases, the bond strength increases. Therefore, it can be stated that the size of bamboo strips has a significant impact on the bond stress. A recent study by Terai evaluated the bond properties of bamboo reinforcement using various diameters of bamboo [42]. It was found that the bond strength exhibits an upward trend as the diameter increases up to around 18 mm; however, it decreases with a subsequent increase in diameter [42]. Moreover, Wairagade and Sonar conducted a pullout test on bamboo splints and half bamboo culms, and their results revealed that half bamboo culms possess greater bond strength than bamboo splints [40]. The study examines the impact of using split and whole bamboo as concrete reinforcements. The findings demonstrate the potential of treated split bamboo as a viable substitute for steel reinforcement. Additionally, the results highlight that the bond between concrete and bamboo plays a crucial role in determining the strength of bamboo-reinforced concrete [51]. The impact of bamboo varying diameters on bond strength was examined by Terai [42]. The result revealed that bond strength exhibits an upward trend as the diameter increases up to around 18 mm; however, it experiences a decline with a subsequent increase in diameter.

Bamboo type

The bond-slip response of bamboo is minimally affected by the tensile modulus, suggesting that the species of bamboo has no bearing on the bond between bamboo and concrete [20]. Al-Fasih et al. demonstrated significant differences in the bond strength between bamboo species and concrete, underscoring the importance of species selection in achieving optimal results [5]. Zhou et al. Investigated bond properties with different types of bamboo bars, highlighting the superior performance of restructured bamboo with notches and changed failure mode from pull-out to shear [52].

Embedded length of Bamboo

Mali and Datta tested bond strength using three embedded lengths: 50%, 75%, and 100% of cylinder height and found that the 50% embedded length proved to be the most effective [16]. Sakaray et al. conducted an experimental study on a bond with three different embedded lengths of 86.67%, 66.67%, and 50% and found that as the embedded length decreases, bond strength increases to a certain limit, then decreases and the highest bond value is found at an embedment length of 50% [36]. The bond value increases over 60% using the embedded length of 50% in comparison to 86.67% [36]. To determine the effect of embedded length, Mishra et al. performed an experimental study using a pull-out test, the concrete cube of 150 mm was used, and bamboo strips were penetrated at different depths of 33.33%, 50%, and 66.66% in the concrete cube [34]. The results revealed that the bond stress remained unaffected by the penetration depths as long as the penetration length exceeded the adherence length.

4. Analytical models to predict bond strength of bamboo

Analytical models play a crucial role in predicting the bond strength of bamboo when used as reinforcement in concrete structures. These models help in understanding the interaction between bamboo and concrete, enabling more accurate design and optimization of bamboo-reinforced concrete elements. The study by Puri et al. introduced an integrated approach that combines experimental and statistical methods to predict and optimize the bond strength between bamboo and mortar. Among the various factors examined, bamboo treatment and curing age were identified as the most critical in influencing bond strength development. Statistical models accurately predicted bamboo-mortar bond strength [53]. An ABAQUS model capable of simulating pull-out tests was created using surface-based cohesive interactions to represent the bond interface between the bamboo and concrete. Experimental data closely matched results from the FE model on bond stress versus slip [20]. Figure 10 presents the FE model for the pull-out test specimen and the observed strain results. In the study conducted by Tazowar et al., a theoretical framework was developed to describe the bonding mechanisms between corrugated bamboo and concrete, which was then validated with experimental data. The theoretical model exhibited higher accuracy, achieving a 95.6% success rate in predicting rectangular corrugated samples without any debonding [21]. In the research conducted by Khatib, the finite element model was developed using ABAQUS software, which provides a sophisticated tool for predicting bond strength in bamboo-reinforced concrete by considering factors such as embedment length, material properties, and cracking behaviour [37]. The findings from the model suggest that corrugated bamboo reinforcement can achieve serviceability equivalent to up to 1% steel-reinforced concrete [54].

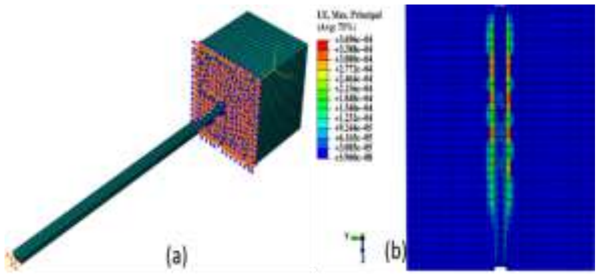

Figure 10 *(a) FE model of the pullout specimen with applied boundary conditions and loading (b) Strain observed in pull-out specimen [20]*

5. Failure Modes

Three major failure modes were identified in the database: pull-out or slippage of bamboo, bond failure, and bamboo tensile failure as shown in figure 11. The data collected from the literature indicate that most samples failed due to the slippage of bamboo, likely resulting from an inadequate bond between the bamboo and concrete. Only a few samples failed due to the tensile failure of bamboo, suggesting that bamboo possesses significant tensile strength. In contrast, bond failure was observed in some cases, indicating a partial or complete loss of adhesion between the bamboo and concrete. This type of failure emphasizes the critical role of effective surface treatments including chemical and mechanical treatment to ensure a strong bond. The occurrence of bond failure underscores the need for further research into optimizing the interface between bamboo and concrete, as well as improving the consistency of bond strength across different specimens. Addressing these issues could significantly enhance the overall structural performance of bamboo-reinforced concrete [15,16,20,30,48].

6. Conclusions

This review highlights the following key conclusions:

Figure 11. *Failure modes observed during pull-out test (a) Tensile failure of bamboo [33] (b) Slippage of bamboo [30] (c) Bond failure with concrete splitting [21]*

- Untreated bamboo exhibits low bond strength with concrete, primarily due to its smooth surface and higher water absorption, leading to dimensional instability and bond weakening.
- Chemical and mechanical treatments significantly improve bamboo-concrete bond strength by enhancing adhesion, friction, and interlocking, while reducing the effects of water absorption.
- Sikadur 32 mixed with sand particles is particularly effective among chemical treatments for increasing bamboo-concrete bond strength.
- Among various mechanical treatments, the grooving technique has proven to be the most effective in enhancing bond strength.
- Bond strength increases with higher concrete compressive strength and the presence of nodes. However, bond strength exhibits a nonlinear relationship with embedment length and bamboo species.
- The failure mode observed in most samples was the slippage of bamboo during pull-out tests, indicating a poor bond between bamboo and concrete.
- Analytical models align well with experimental data and are crucial for optimizing design, improving reliability, and ensuring the structural integrity of bamboo-reinforced concrete.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
- **Acknowledgement:** The authors declare that they have nobody to acknowledge.
- **Author contributions:** The authors declare that they have equal rights on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data supporting the findings of this study are included in the manuscript.

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