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RESEARCH ARTICLE

Investigation of the bond between bamboo and ribbed steel reinforcements and the surrounding concrete by pull-out test

Abraham Ayamga-Annia[1*] . Jonny Osei Kofi[1] . Charles Antwi Boasiako[1]

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Abstract: Traditional housing did not use expensive materials like steel reinforcement, yet some have outlived sandcrete or mud-brick housing. One means to build at a low cost is to supplement high-cost materials with low-cost types, which have comparable strength. This study compares the bond between bamboo (*Bambusa vulgaris and Bambusa vittata*) reinforcement as well as ribbed steel enforcement and the surrounding concrete by pull-out test. Bamboo specimens were split and cut into the dimensions of 600 mm × 20 mm ×10 mm. Sixty (60) samples of each of the two varieties were prepared, thirty (30) were coated with tar oil as waterproof agent to a length of 200 mm and embedded into fresh concrete samples and allowed to cure, while another 30 did not receive any coating. Thirty (30) specimens of 12.5 mm diameter of ribbed steel rods of length 60 mm were used as control Materials for the pull-out test were also embedded in the centre of 150 mm concrete cubes and left to cure for 28 days. The load required to pull the steel rods from concrete (5.49±0.22 kN) was greater than those for both coated *Bambusa vulgaris and Bambusa vittata* (1.67±0.11 kN – 1.67±0.12 kN) and uncoated *Bambusa vulgaris and Bambusa vulgaris vittata* (2.04±0.14 kN– 2.14±0.19 kN) bamboo. The differences were significant ($p<0.05$). The pull-out was also conducted in conformity with the Bureau of Indian Standard (IS) 2770: 1997.

**Corresponding Authors*

[1] Department of Wood Science and Technology, Kwame Nkrumah University of Science and Technology - Ghana.
✉ abrahamayamgaannia@gmail.com

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Introduction

Concrete is widely used as the foundation for infrastructure because it is economical, readily available and has suitable building properties such as its ability to support large compressive loads. However, its use is limited because it's low tensile strength. For that matter, it is reinforced, and one of the popular reinforcing bars is steel. (Luecke *et al*., 2005) reported that steel has a relatively high tensile strength, as high as 792 N/mm^2. Comparatively, the tensile strength of woody bamboo is high and can reach 370 N/mm^2 (Kaur, 2018). These complement the low tensile strength of concrete (Madandoust *et al*., 2017). In many countries, none or very little steel reinforcement is used in construction. Steel reinforcement at some point may no longer be available. Even today, there exists a need for more economical and readily available substitute reinforcements for concrete. In some developing countries, many buildings are constructed only with sandcrete or mud-bricks. These buildings have little hope of standing natural disaster such as an earthquake, constant flooding and heavy storms. Steel reinforcement would be an ideal solution, but cost is a considerable problem. For that matter, there has been a way for constantly seeking for new materials to address this challenging. According to (Muhtar *et al*., 2020), bamboo is one of the most suitable materials to substitute for reinforcing bars in concrete. Due to its low Modulus of Elasticity (MOE), bamboo can crack and deflect more than steel reinforcement under the same conditions. .

Therefore, it is necessary that information on its strengths and weaknesses be known. Bamboo's high tensile strength makes it an alternative material to steel in tensile-loading applications. This is due to the fact that the ratio of tensile strength to the specific weight of bamboo is six times greater than that of steel (Rahim *et al*., 2020).

The mechanical properties vary with the height and age of the bamboo culm. The optimum strength value occurs between 3 and 4 years. The strength gradually decreases up to 12 years old (Ren *et al*., 2014). Therefore, considering bamboo age before harvesting for construction purposes is very important.

Bamboo is a giant grass. Its culm is a cylindrical shell divided by transverse woody diaphragms at nodes and has some intriguing properties such as high strength in the direction parallel to the fibres, which run along the long axis of the culm. It has low strength in a direction perpendicular to the fibres. The density of fibres in the cross-section of a bamboo shell varies with thickness as well as height (R., 2014). Its abundance in tropical and subtropical regions makes it an economically advantageous material as a substitute for steel for reinforcement (Tripathi & Bhalerao, 2021). Some positive aspects such as a lightweight design, better flexibility, and toughness due to its thin walls with discretely distributed nodes and its great strength make it a good construction material (Sahana *et al*., 2018). Bamboo is easily accessible as it grows in almost every tropical and subtropical region. As a result of this, it lowers the cost of construction and increases the strength of the buildings that would otherwise be unreinforced (Adier *et al*., 2023; Emamverdian *et al*., 2020; Kaur, 2018).

The base of the culm has a more uniform fibre distribution than the middle or the top. This is because bamboo is subjected to maximum bending stress due to wind at the top portion of the culm. bamboo strength is greater than most timber products (Adier *et al*., 2023; Dange & Pataskar, 2017; Koko & Dakur, 2019; Zong *et al*., 2023).

One major problem with bamboo is that since it is a living material, it is subject to fungal and insect attacks (Liese & Tang, 2015; Sulaeman *et al*., 2017). It is more prone to insect attack than trees and other grasses due to its high content of nutrients such as starch. In order to combat this, it becomes necessary to treat the bamboo to protect it from the environment and bio-degradation (Kaur *et al*., 2016).

Bamboo is used in a wide variety of applications such as housing and construction of furniture, bicycle frames and motorbike helmet. A decent shaft for a spear or stick for fighting in the marshal could be made from bamboo. In China, bamboo is beginning to gain exposure as flooring and paneling (Lee & Liu, 2003).

The success of this project would have a positive effect on the bamboo reinforcement since most houses are built without any reinforcement based on the high cost of steel. The study would also contribute to the existing knowledge on bamboo utilization since most bamboo, especially in our villages, is cut down and left to destroy. It would also create jobs for people in the bamboo industry from the processing to the production stage.

Literature review

Introduction

This literature review explores the bond between bamboo and ribbed steel reinforcements in concrete, focusing on the challenges and opportunities of incorporating bamboo as a sustainable alternative. It aims to optimize the structural performance of bamboo-reinforced concrete, promoting innovation and sustainability in the construction industry.

Some bamboo in Ghana

Ghana, covering 238,533 square kilometers, has 300,000 ha of bamboo growing areas, particularly in the Moist Evergreen Forest Area (Bahru & Ding, 2021; Tekpetey, 2016). Bamboo resources are processed for handicrafts, scaffolding, paneling, flooring, and furniture. *Bambusa vulgaris* accounts for 90-95% of the country's resources. The common ones are *Dendrocalamus strictus, Oxytenanthera abyssinica, Bambusa arundicnacea, B. vulgaris, B. perveriabilis, B. multiplex and B. nana* (Rahangdale, n.d.; Tekpetey, 2016). These species are mostly found in botanical gardens and some private plantations around the forest zones of Ghana. Among the species, *Bambusa vulgaris* forms about 90-95% of bamboo resources in the country (Bahru & Ding, 2021). However, according to to (Tekpetey, 2016), the Bamboo and Rattan Development Programme (BARADEP) Secretariat of the then Ministry of Lands, Forestry and Mines facilitated the distribution of eighteen (18) exotic bamboo species imported from Hawaii into the country by the Opportunity Industrialization Centre International (OICI).

Bamboo utilisation as a building material

Roofing, Trussing, Foundation, Scaffolding and Flooring

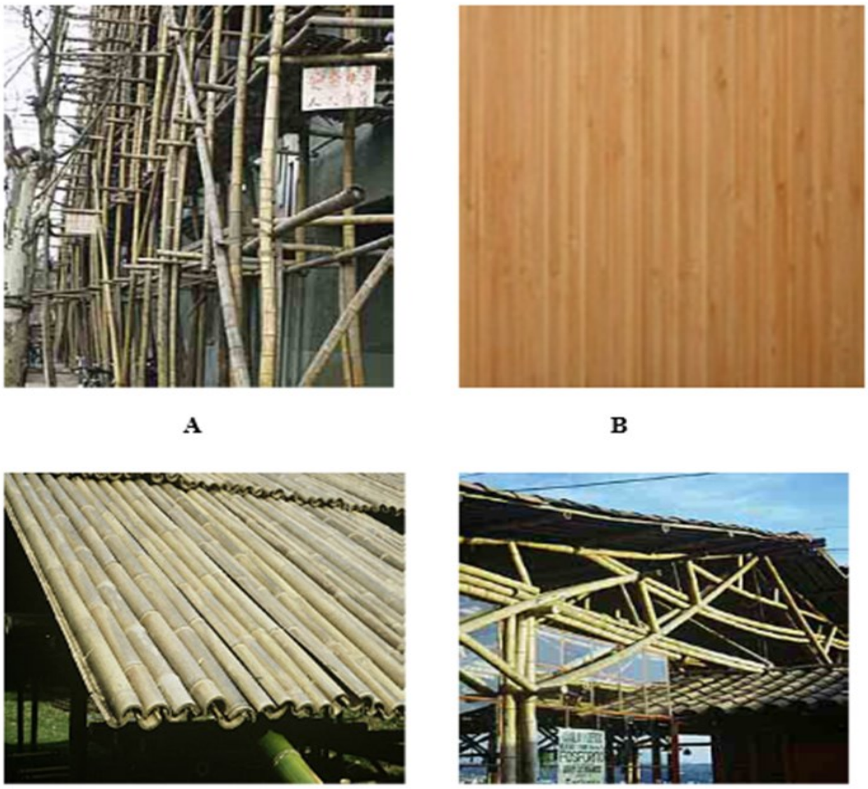
Bamboo roofing materials have been used in various cultures for centuries, but their interlocking split design attracts moulds and fungi, reducing their lifespan. Research by (Sassu *et al*., 2014; Ubolsook & Thepa, 2011) reveals examples of bamboo tile, shingle, and thatch roofing.

Bamboo trusses, typically in a triangle shape, provide a suitable alternative to Western-style roofs. They are made from culms with 75-100 mm outer diameters and should be coated in plaster for fireproofing.

(Sharma *et al*., n.d.) recommends large diameter, thick walls, and close nodes for bamboo foundation and supporting posts in low-cost houses. If large bamboo is unavailable, smaller, thicker ones can be combined.

Bamboo poles have been used as scaffolding since ancient times, first introduced in Hong Kong in the 1800s. Ideal for multi-story buildings and working platforms for masons, bamboo's resilience, shape, and strength make it a versatile material (Adier *et al*., 2023; Chaowana *et al*., 2021; Mimendi, 2021).

Bamboo culms offer superior resilience compared to conventional timber for floor beams, which can be covered with small culms, strips, or bamboo boards. Bamboo plastic composites, a technology using bamboo fiber and plastic, offer higher water resistance and dimensional stability (Kumar *et al*., 2017; Sylvayanti *et al*., 2023).



A B C D

Source: Picture by Researcher

Fig 1: The various uses of bamboo: Bamboo scaffolding (A) , Bamboo board (B), Bamboo tile roofing (C) and Bamboo trusses (D).

Bamboo housing

Bamboo houses, dating back to the pre-ceramic period in Asia, are affordable, easy to construct, detachable, and have good insulation. They are environmentally friendly and have better earthquake resistance. Bamboo construction is sustainable, as it helps prevent deforestation. Research in Costa Rica found that only 70 ha of bamboo plantation is sufficient to build 1,000 bamboo houses per year. It requires only 30 MJ/m^3 per N/mm^2 compared to concrete, steel and timber, that require 240, 500 and 80 MJ/m^3 per N/mm^2 respectively. Studies show that processing of bamboo requires only one-eighth of the energy that concrete needs to create a building material of the same capacity. In comparison to steel bamboo needs only one-out-of-fifth of the amount of energy for processing (Li *et al*., 2017; Madhushan *et al*., 2023). These affordable, quality prefabricated houses can be used for relief during natural disasters.

Mechanics of reinforced concrete of steel

Concrete is a durable and versatile construction material, but it has inherent weaknesses, particularly in tension, which can cause cracking. To address this, reinforcements like steel, fibers, glass fibers, plastic fibers, or bamboo are added to carry tensile loads. Concrete offers superior fire resistance and can gain strength over time through "curing." Its versatility makes it a preferred choice in construction, including architectural structures, foundations, pavements, bridges, motorways, runways, parking structures, dams, pools, pipes, and even boat construction (Ahmad *et al*., 2022; Anas *et al*., 2022; Sanjeev & Nitesh, 2020).

Bamboo reinforcing in concrete

Bamboo is a cost-effective and high-tensile strength reinforcement material in concrete due to its lower price compared to steel. The ratio of tensile stress in bamboo is 8:2, and the mass per volume is 16:1. However, bamboo has a weak bond with concrete, as it absorbs water and swells when poured around it. This can break the concrete when it hardens and dries. Researchers have proposed solutions to overcome this issue.

Selection and preparation of bamboo for reinforcement

Bamboo selection and preparation for construction projects involve harvesting, treatment, and preservation to ensure structural integrity and longevity. Below is a general outline of the steps;

Harvesting and Treatment of the Bamboo: Bamboo should be harvested between 3 to 5 years old, using a sharp tool to cut the pole without harming the remaining plants. Select mature culms with uniform diameters and avoid pests and decay during the dry season. Bamboo should be treated to enhance resistance to insects, fungi, and weathering using environmentally friendly methods like boron salt solutions and pressure impregnation. Seasoning the bamboo helps reduce moisture content and fully absorb the chemicals used.

Cutting and Shaping with Quality Control measures: Cut bamboo into suitable shapes for reinforcement, considering project requirements, and ensure clean cuts free from splinters or cracks to prevent weakening.

Quality control is crucial for bamboo reinforcement in concrete structures, ensuring structural integrity and longevity. To prevent wetness, design buildings with unrestricted airflow for quick drying, despite potential burden on creativity. This long-term investment benefits the building's performance.

Fig 2. Specimens coated at the bonded length ready to receive concrete

Materials and methods

This research was designed for pull-out test for coated (with tar oil) and uncoated bamboo *Bambusa vulgaris and Bambusa vittata* in concrete at their bonded lengths (part of bamboo perpendicularly embedded at the centre of the wet concrete to the depth of 150 mm for it to cure).

Harvesting of bamboo

Matured culms of *Bambusa vulgaris (B. vulgaris*) (green bamboo) *and Bambusa vittata (B. vittata*) (yellow bamboo) were harvested between 3 to 5 years old at the Botanic Garden of K.N.U.S.T in the dry season (January). The water content was 72.12 % due to the lower relative humidity, which gave small room for attack by bio-degraders such as insects and bacterial fungi. Two (2) healthy matured culms of *B. vulgaris* and *B. vittata* were harvested. Culms of each variety were harvested in a single clump at the length of 7 m. Maturity was determined by the absence of culm-sheaths, dull and non-glossy surface due to the growth of lichen on the epidermis and absence of branching from the lower two-third of the culm. Each culm was harvested at the 3rd or 4th nodes. The top, middle and butt portions of the culms were cut into 5 internodes (about 2 m) each and labelled for easy identification for the test. The culms were cross-cut and sectioned to the various dimensions for various tests. The culms walls thickness range from 10-13 mm. The specimen was positioned vertically on raised dry floor and leaned against the wall from an angle of about 75^{o} to the horizontal. They were then left to dry for eight (8) weeks to a moisture content of 13%.

Treatment of bamboo against Bio-degraders

Prophylactic treatment was done by submerging the samples in sunpyrifos preservative solution (10 ml in 10 lt of water) for a period of 24 hours. Penetration was by capillary action.

Preparation of specimen for pull-out test

Each sample was freshly prepared and embedded in concrete to a depth of 150 mm and allowed to set and cure. The test was conducted to compare the bamboo sample with steel in terms of interfacial strength between them and the concrete block. Each variety of bamboo (i.e. *B. vulgaris* and *B. vittata)* was split and cut into the dimensions of 600 mm ×20 mm×10 mm as the specimens for reinforcement. Sixty

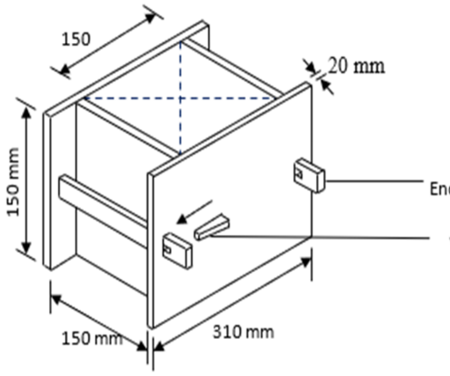


Fig 3. Isometric view of the mould box for casting of concrete cubes

(60) samples of each of the two varieties were prepared, thirty (30) were coated with tar oil as water-proof agent to a length of 200 mm (Fig.2) and embedded into the fresh concrete sample and allowed to cure, while another 30 did not receive any coating. Thirty (30) specimens of 12.5 mm diameter of ribbed steel rods of 60 mm in length were used as the control.

Preparation of formwork /moulding boxes

Wooden formwork/moulds boxes of inner dimensions 150 mm × 150 mm ×150 mm were constructed (Fig. 3 and 4) using 20 mm thick obeche (wawa) board. The inner surfaces were oiled before the concrete was poured. The purpose of the formwork was to support and give the freshly poured concrete the required shape after curing in conformity with IS 2770: 1997.

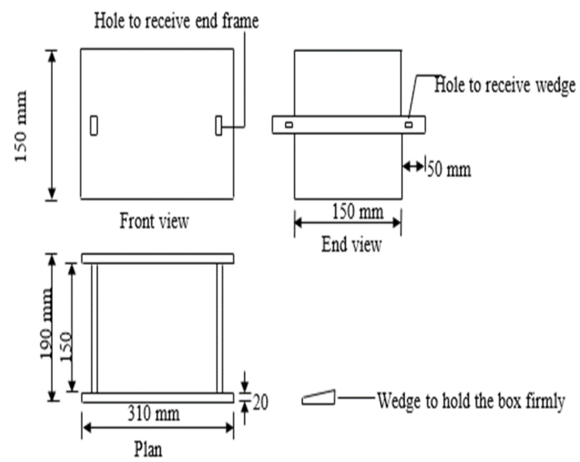


Fig 4. Orthographic projections of the mould box

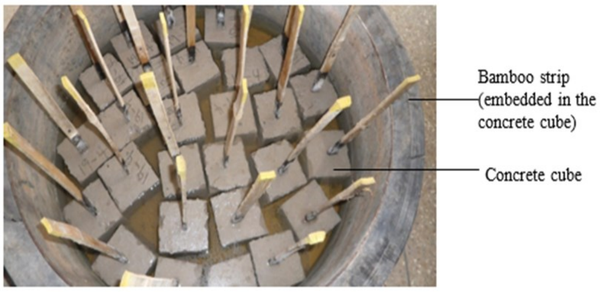


Fig 5. Curing of concrete cubes with embedded bamboo strips

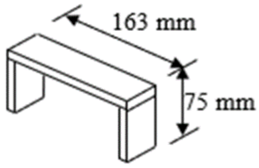


Fig 7. A restrainers to secure the concrete cubes during pull-out test

Mixing and casting of concrete into mould boxes

The wet concrete mix of cement (Portland brand), fine aggregate (sand), coarse aggregate (18 mm gravel) and water (in a ratio of 1:2:4 respectively), were poured into the moulds and agitated on the side by knocking on the walls with rubber mallet in order to remove all the air pockets that were created during the casting. The center of the concrete cube was determined by the intersection point of the two diagonal lines drawn across the concrete box (Fig. 2). After 24 h the cubes were removed from the mould box and cured in water for 28 days (Fig. 3) in accordance with BS 882 (1992).

Design and construction of concrete holder for the pull-out test

A concrete holder was designed, fabricated and attached to a manual tensile test machine (T.16) in order to perform the "pull-out" test at the Mechanical Engineering Laboratory of KNUST. The concrete holder was constructed as follows:

i. Two stainless steel plates of 152 mm × 150 mm × 5mm were cut with a flat cold chisel for two opposite sides of the holder.

i. Another two plates of 162 mm × 150 mm × 5 mm were also cut for another two opposite sides of the holder

iii. All four pieces were welded together to form a four-sided container of 152 mm^2 as an internal dimension (Fig. 6A).

iv. After welding the four plates together, another two pieces of metal plates (162 mm^2 and 100 × 50 × 5 mm) were also cut and welded together (Fig. 6B). The function of the tail was to hold by the lower jaw for pull-out.

v. After that two each of 163 × 40 × 5 mm and 75 × 40 × 5 mm plates were also cut and welded together (Fig. 7) to act as restrainers to the concrete cube during the pull-out test.

vi. Four holes were drilled at the two sides of the container to support the restrainers (fig. 8A) to secure the concrete cube during the test.

vii. Each side of the restrainer was also drilled to receive a bolt to hold the concrete in place (fig. 8B).

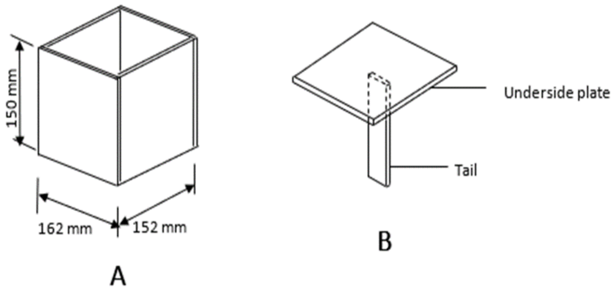


Fig 6. A - Four Pieces of metal plates welded together, B - Tail welded perpendicularly to the underside plate to help the lower jaw for pull-out

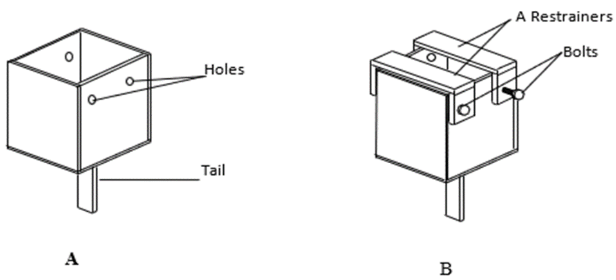


Fig 8. Set-up for pull-out strength test; A: Holes created at side of the container to receive restrainers, B - Restrainers secured to the container by bolts

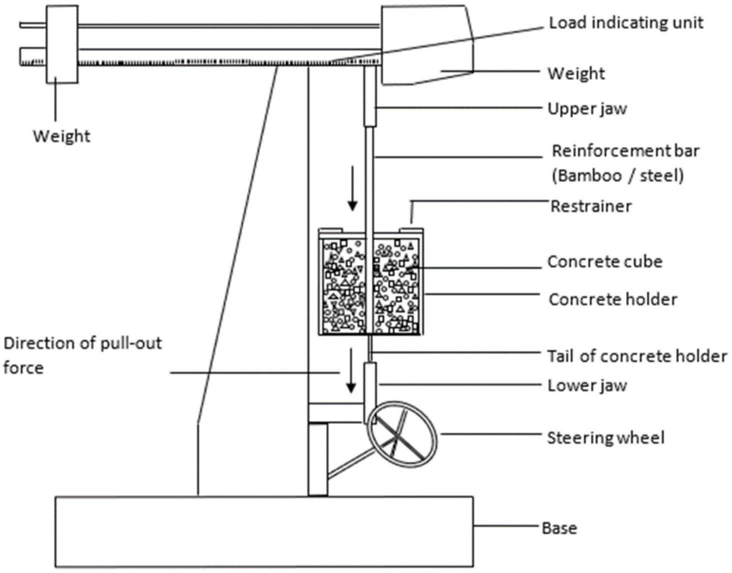


Fig 9. Schematic diagram of manual tensile machine

Set-up for pull-out strength test

The reinforcement bar was gripped by the upper jaw of the testing machine with the concrete secured in the concrete holder. The lower jaw was connected to the tail of the holder (Fig. 8B). The lower jaw derived its pulling power from the steering wheel by turning it clockwise. As the lower jaw pulled the holder downwards by gradually applying axial load, it automatically pulled the concrete from the reinforcement. At an extension (jump) of every 2.54 mm (from the load indication unit), a load was gradually applied until the concrete finally lost its bonding strength from the reinforcement bar by cracks or slipped out. The applied load of one extension may defer from the other depending on the bonding ability of the concrete. Loads were recorded in kilonewtons (kN) in conformity with IS 2770.

Fig 10. Manual tensile machine (T.16) used for the pull-out test

Results

Data presentation and Analysis

The data were presented in figures and tables. Excel analysis tool pack was used to run the 't-Test, ANOVA and LSD

Pull-out load for ribbed steel, coated and uncoated *B. vulgaris, B. vittata*

A manual tensile test machine (T.16) was used to conduct the pull-out test. The load required to pull the ribbed steel rods from concrete (5.49±0.22 kN) was greater than those for both coated (1.67±0.11 kN – 1.67±0.12 kN) and uncoated bamboo (2.04±0.14 kN – 2.14±0.19 kN) (Figure 1.3). The differences were significant ($p<0.05$). Pull-out load for the bamboo varieties were in this order: *Bambusa vittata* (uncoated) (2.14±0.19 kN) >*Bambusa vulgaris* uncoated (2.04±0.14 kN) >*B. vit.* (coated) (1.67±0.12kN) >*B. vul.* (coated) (1.67±0.11 kN). A significant difference ($p<0.05$) existed between *B. vit* (coated) and *B. vit* (uncoated). For the coated bamboo (*B. vul* and *B.vit),* there is no significant difference between them but with a statistical difference of 0.11 kN. Likewise, there is no significant difference between the uncoated bamboo (*B. vul* and *B. vit)* but a statistical difference of 0.17 kN.

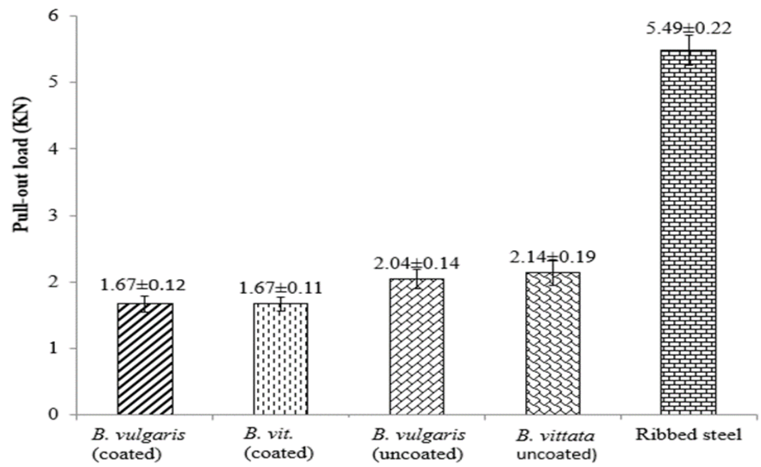


Fig 11. Pull-out load for reinforced bamboo (coated and uncoated) and ribbed steel as reinforcement in concrete

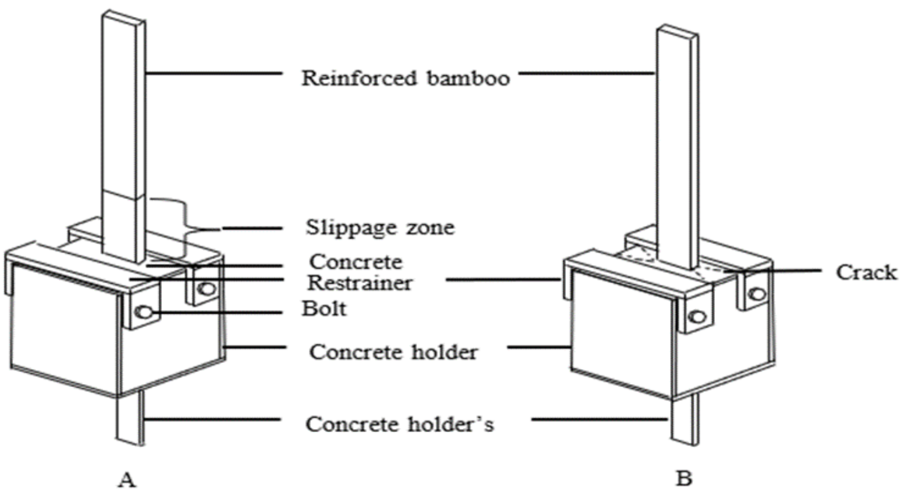


Fig 12. (A): Failure of the pull-out test due to the slipping of the bamboo out of the Concrete (B): Failure of the pull-out test due to the splitting of the concrete

Discussion

Pull-out load for bamboo and steel

According to (Hong & Park, 2012; Parameswaran *et al*., n.d.), a bond in reinforced concrete refers to the resistance of surrounding concrete against pulling out of reinforcing bars. Anchorage bond is developed parallel to the direction of force over a contact surface in order to induce stress in rebars. If the bond resistance is inadequate, slipping off the reinforcing bar occurs and weakens the strength of the reinforced concrete. Sudden loss of bond between rebars and concrete in anchorage zones causes brittle failure which could lead to the collapse of structural, portraying the building construction industry in bad shape. Bond is necessary not only to ensure an adequate level of safety but also to control structural behaviour along with sufficient ductility (Al-Rousan & Alkhawaldeh, 2021; Gangolu *et al*., 2007; Yang *et al*., 2023). Thus, the bond strength of concrete-reinforced beams is a critical parameter that influences the overall performance of such beams.

Pull-out load of the samples from concrete ranged from 1.67±0.11kN (for coated *B. vulgaris*) to 5.49±0.22 kN (for ribbed steel rods) (Figure 10). Those for the other samples decreased as: 2.14±0.19 kN(uncoated *B. vittata*) > 2.04±0.14 kN (uncoated *B. vulgaris*) (Fig. 10). There were significant differences ($p<0.05$) in the pull-out load of the samples. This primarily could be due to varied bonding interactions (adhesive properties of the cement matrix, the compression friction forces on the surface of the rebar, and the shear resistance of concrete due to the surface texture of the rebar) and the strength between the reinforcement materials and the concrete (Kim *et al*., 2013; S & Rajendran, 2022). The dimensional changes of bamboo (i.e., those uncoated with water repellents) due to moisture and temperature variations influence greatly the bonding interactions. During the casting and curing of concrete, the reinforcing bamboos absorb water and expand. This led to the swelling of the bamboo, which pushes the concrete away and weakens the bond of the reinforced beam (Ghavami, 2005). Then during curing, the bamboo loses the moisture imbibed during casting and shrinks back almost to its original dimensions. This results in voids being created around it. Differential thermal expansion of bamboo with respect to concrete may also lead to cracking of the concrete during service life (Ghavami, 2005; Huang *et al*., 2017). The swelling and shrinkage of bamboo in concrete is a serious limitations in their use as a substitute for steel in concrete rebars (Archila *et al*., 2018; Sabnani, n.d.). They also identified that ribbed steel bars, on the other hand, did not absorb water during casting and shrank during curing. This property makes them preferred as rebars, as they are more dimensionally stable. They may however, expand when heated. This can also lead to cracks in the concrete reinforced beam (Topçu & Karakurt, 2008). The effect of these bond interactions could be seen from the results of this study where, a pull-out load of the samples from concrete was greatest for ribbed steel rods (5.49±0.22 kN) and least for coated *B. vulgaris* (1.67±0.11kN) (Fig. 10).

Generally, it was observed that the load required to pull the ribbed steel rods from the concrete was greater (5.49±0.22 kN) than those for both coated [1.67±0.11kN (*B. vulgaris*) and 1.67±0.12 kN (*B. vittata*)] and uncoated bamboo [2.04±0.14kN (*B. vulgaris*) and 2.14±0.19 kN (*B.vittata*)] (Fig.10). This could be due to the ribbed nature of the steel rod (i.e., steel rod manufactured by controlled cold twisting of hot rolled bar with projections on its surface known as ribs), which created more resistance and shear within the concrete resulting in more force to pull it out (Leramo *et al*., 2018; Luecke *et al*., 2005; Xiao, 2018). The greater pull-out force recorded for ribbed steel rod could also be attributed to the fact that it is more dimensionally stable (*(PDF) PULL OUT BOND STRENGTH OF REINFORCING STEEL BARS IN SCC*, n.d.). It does not imbibe moisture during casting to swell and shrink during curing. Thus, voids were not created between the steel rod and the concrete which led to greater bond strength. For uncoated bamboos, voids left between the bamboos and concrete, due to swelling and shrinkage during casting and curing respectively, could account for its poor pull-out strength [2.04±0.14kN (for *B. vulgaris*) and 2.14±0.19 kN (for *B. vittata*)] (Fig. 10). Coated bamboos recorded the least pull-out force [1.67±0.11kN (for *B. vulgaris*) and 1.67±0.12 kN (for *B. vittata*)] (Figure 10). This can be attributed to their smooth surfaces, which did not promote good bonding between the bamboo and concrete as bonding interaction was poor (Archila *et al*., 2018).

For the coated and uncoated bamboo samples, the failure was mainly due to the slipping of the bamboos out of the reinforced beam but on a few occasions splitting of the concrete (Fig. 11B). This was inconsistent with the findings by (Javadian *et al*., 2016) that bamboo comes out smoothly from concrete during pull-out tests due to bond failure. This bond failure is chiefly due to poor bonding between the bamboo and the concrete due to voids created between the two materials during the swelling and shrinking of the bamboo during casting and curing respectively (Ghavami, 2005). Their smooth surfaces do not promote the shear resistance of concrete on bamboo (rebars) (Ghavami, 2005). This makes bamboo a less suitable material to use as a rebar. Ribbed steel rods are more dimensionally stable and possess greater shear resistance than the bamboo rebars, thus, it would perform better as a rebar. Splits (pull-out failure), which occurred in some of the uncoated bamboo reinforced concretes were a result of the high shear strength between the bamboo and the concrete (Ka *et al*., 2018; Zhang *et al*., 2023). This is because the uncoated bamboo could imbibe the moisture from the freshly poured concrete, which caused it to swell and shrink during curing (Javadian *et al*., 2016). This could lead to the creation of voids inside the concrete and lead to a weak bond formation in the concrete since the outer layer of the bamboo is smooth (Javadian *et al*., 2016). On the part of the coated bamboo, the waterproof agent (tar oil) was used to protect the bamboo from imbibing the concrete's moisture. The oily nature of the waterproof agent (i.e., tar oil), however, resulted in a weak bond between the bamboo and concrete. This is because the oil between the bamboo and the concrete hindered the bond formation between the two materials (bamboo and concrete) (Ahmad *et al*., 2023).

It is to be appreciated that the pull-out test is generally conducted to obtain accurately the carrying capacity of the flexural strength of the knit bamboo reinforced concrete beam. This is more determined by the bonding strength than the tensile strength of reinforcement in concrete (Dewi & Soehardjono, 2013). Bond stress is the shear stress on the surface of the concrete, where the load transfer occurs between the reinforcement material and the surrounding concrete to modify the stress of the reinforcing material (Irshidat, 2021; Siempu & Pancharathi, 2018; Xing *et al*., 2015). This bonding is effectively distributed and it allows two materials to form a composite structure. Furthermore, (Xing *et al*., 2015; Zhang *et al*., 2023) reported that bond strength is caused by the shear interlock between the reinforcement and the concrete. This could be seen in the results of this study where ribbed steel rods due to their nature (which promotes shear interlocking) had the greatest pull-out force (5.49±0.22kN) (Fig. 10) whiles bamboo (coated or uncoated) with a smoother surface, which leads to poor shear interlocking had the weakest pull -out strength (uncoated bamboo: 2. 04±0.14kN–2.14±0.19kN. and coated bamboo: 1.67±0.11kN–1.67±0.12kN) (Fig. 10). It means a combination of the ability between the reinforcement and the concrete that covers it can cause weak bonding between the rebars and the concrete. Thus, the greater pull-out force required to pull the ribbed steel rods from the concrete (5.49±0.22 kN) could be due to the better shear interlocking between the steel rods aided by the ribbed nature of the steel with the concrete.

Conclusions

The bond strength of the ribbed steel in concrete was stronger than the bond strength of the bamboo in concrete. This is due to the ribbed nature of the steel which promotes good friction between the concrete and the ribbed steel.

The waterproof agent (tar oil) applied on the coated bamboo for the pull-out provided poor bonding between the concrete and the bamboo therefore causing less friction between the two which could cause structure failure in future.

The uncoated bamboo absorbed water from the fresh concrete, which resulted in the swelling of the bamboo, and created a gap between the interface of the bamboo and the concrete after shrinkage. This leads to poor bonds.

Base on the results gathered, bamboo can be considered as a reinforcement material in certain situations, but it's essential to carefully evaluate the specific project requirements, structural needs, and available treatment methods. In this case, local building code and standards must be complied when considering the use of bamboo in construction.

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