Javadian, A. A. Wielopolski, M.B., Smith, I.F.C. and Hebel, D.E. "Bond-behavior study of newly developed bamboo-composite reinforcement in concrete", Construction and Building Materials, 2016, doi10.1016/j.conbuildmat.2016. 06.084

Bond-behavior study of newly developed bamboo-composite reinforcement in concrete

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Abstract

Bamboo is a rapid growing, affordable and available natural resource in many developing countries. It is potentially superior to timber and to construction steel in terms of its weight to strength ratio. A new technology has been developed in this research to preserve the mechanical properties of bamboo and to enhance physical characteristics through composite action for application in structural concrete. The goal of present work is to investigate the bonding properties of a newly developed bamboo-composite reinforcement in concrete through pull-out testing. Various coatings are applied to determine bonding behavior between concrete and newly developed bamboo-composite reinforcement. The results of this study demonstrate that bamboo-composite reinforcement without coating develops adequate bonding with the concrete matrix. However an epoxy based coating with sand particles could provide extra protection without loss of bond strength.

Keywords

Bamboo composite; Reinforcement; Pull out; Bonding; Concrete

Introduction

Today, the world is facing the highest population growth rate it has ever experienced. With it, enormous urbanization rates are reported, especially in developing territories. To satisfy the immense demand for construction materials, the traditional understanding on how to build shelter and infrastructure is no longer sufficient. Either materials are finite or they are not available in the locations where they are needed. For instance only two out of 54 African nations produce steel in notable quantities. Using steel as reinforcement has disadvantages. High costs of production, lack of renewability and corrosion in concrete are disadvantages that are usually associated with using steel reinforcement. New strategies favor cultivating required materials instead of mining them. Proposals are emerging to replace steel with renewable, low-cost and sustainable forms of reinforcement that can be found locally. Organic materials such as jute, sisal, coconut coir and date palm are among some of the alternatives that have been used to replace steel. However, the tensile capacity of these materials is often too low when compared with steel [1-4].

Among possible alternative materials, bamboo is an organic alternative which grows in the tropical zones, an area that coincides closely with the developing countries where the highest rates of urbanization and population growth can be found. Bamboo is gaining attention as an alternative for steel since most developing countries could benefit economically by its use in construction. It could strengthen local value chains, bring jobs and trade as well as lower dependency on international markets through meeting construction demands locally. From technical perspective, bamboo is a fast growing grass, which can grow up to one meter a day and can reach its maximum strength in 3 years. Some species of bamboo have shown tensile capacities of more than 400 MPa and single bamboo fibers can reach a tensile strength as high as 1000 MPa[5-8].

Several studies have been carried out on the use of raw bamboo as reinforcing material to replace conventional steel. In 1950, Glenn conducted research into using natural raw bamboo as reinforcement in concrete structures [9]. Using small diameter culms and bamboo splits, he demonstrated that although the application is feasible in principle, there were disadvantages regarding insect and fungus attacks, shrinking and swelling.

Ghavami has undertaken more recent work in this field. He completed a series of mechanical tests on several species of bamboo in order to find the most appropriate for use as reinforcement in lightweight concrete beams [10, 11]. Concrete beams with raw bamboo as reinforcement showed an increase in the ultimate-load behavior compared to beams reinforced with steel bars[11]. Nevertheless, the long-term durability of bamboo in concrete beams was not studied.

Terai and Mianmi studied use of raw bamboo as reinforcement in concrete beams and columns [12]. They found a similar fracture behavior to steel-reinforced-concrete beams and columns. Although several other studies involved use of natural raw bamboo to replace steel reinforcement in concrete walls, beams and slabs none addressed the challenges related to durability of raw bamboo reinforcement [13, 14].

Lima Junior et al. used bamboo culms filled with concrete as structural column. The ultimate load capacity of the column was 50% lower than that of a column made only with bamboo culm [15]. Long-term durability and bonding behavior of the culm in the concrete matrix were not discussed.

The difficulty associated with durability of raw bamboo is that it absorbs water from the surrounding environment through fine cracks in concrete. This results in swelling of the bamboo. Swelling occurs when there is sufficient time for water to reach the bamboo before the concrete cures. It is then absorbed by the bamboo microstructure, which induces an expansion of the bamboo reinforcement and promotes internal local stress in the concrete surrounding the bamboo. Over a long period of time, the consequences are brittle splitting failure in concrete can result in sudden collapse. Figure. 1 shows the swelling problems associated with using raw bamboo in concrete.

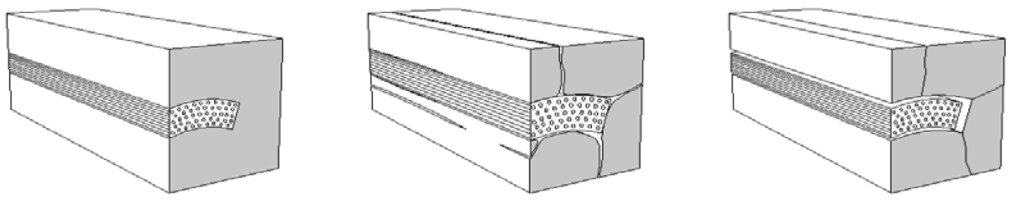

Figure1 Swelling of raw bamboo reinforcement in concrete and the micro cracks followed by the expansion of raw bamboo

In addition to water absorption of raw bamboo, chemical decomposition of the bamboo fibres, accelerated by the alkaline environment of the concrete matrix, is another reason for the loss of mechanical properties of raw bamboo over time. Pacheco-Torgal & Jalali reviewed the works on natural fibre degradation in cementitious matrix and concluded that chemical decomposition is due to the high alkaline environment which dissolves the lignin and hemicellulose phases, thus weakening the fibre structure [16].

To overcome these issues, researchers investigated methods to control the mechanical properties and physical behavior of bamboo. One of these methods was treatment of raw bamboo with various types of coating. This method has been investigated for many years by many researchers, from the early stages of research into use of raw bamboo in construction [17-21].

Coatings such as water-based paints or bitumen were used to prevent the water ingress to bamboo reinforcement in concrete. Unfortunately, such coatings only last for the first few years of service. They are sensitive to damage due to improper handling. Studies on the long-term durability and feasibility of such coatings are not available.

Bonding between bamboo and concrete is another important factor, especially when there is loading on the concrete member. The bond between reinforcement bars and concrete matrix is developed principally through main mechanisms; adhesion to the concrete matrix; development of residual compressive stress due to concrete shrinkage at the interface of reinforcement and concrete; and friction due to surface roughness of reinforcement bars. Bonding establishes a shear resistance at the concrete matrix interface with reinforcement. Ghavami studied bonding properties of treated and untreated raw bamboo splits in concrete [11]. The study showed that a two-component epoxy resin coating enhances the bonding of raw bamboo reinforcement up to 5 times compared with uncoated bamboo and steel.

To overcome the problems related to the use of raw bamboo reinforcement, such as swelling and chemical decomposition, a new class of materials, called natural fibre composites is under development. Advantages of natural fibre composites over their traditional synthetic fibre composites include their abundance, renewability, and low production costs. This research focuses on the application of newly developed bamboo-fibre-reinforced composite materials to replace conventional steel reinforcement in structural concrete.

In this study, bamboo fibres are first obtained by processing entire bamboo culms. The fibres are then added to a two-component epoxy resin system and then pressed into high tensile strength composite materials using a hot-press fabrication technology. The process yields a bamboo composite material which is densely compressed. The newly developed bamboo-composite materials are cut into different sizes for the use in concrete as reinforcement.

Preliminary physical and mechanical tests have been carried out to evaluate the suitability of bamboo-composite materials for concrete reinforcement. The key factor for implementation is the bonding of reinforcement bars to concrete. Adequate bonding between bamboo-composite reinforcements and the concrete matrix ensures a stable load transfer between the two materials.

To understand the bonding behavior of the newly developed bamboo-composite reinforcement in concrete, series of pull-out tests were carried out to find a suitable technique to enhance the bonding between concrete matrix and bamboo-composite reinforcement.

Several types of coating were applied on the surface of the bamboo-composite reinforcements to investigate bonding behavior with concrete matrix. The coatings and their chemical composition are discussed in experimental procedures. Normal strength concrete with 20MPa compressive strength was used throughout this study.

Materials and Methods

General characteristics of newly developed bamboo-composite reinforcement

The bamboo species employed within this study was a 4-year-old *Dendrocalamus asper*, which was harvested in the Bali island of Indonesia and is known locally as *Petung Putih*. At this age, the performance of *Dendrocalamus asper* is known to be at its highest level. Another characteristic is a high concentration of vascular bundles at the outside surface of the culm walls. The average density of *Dendrocalamus asper* having a moisture content of around 8% is 0.78 g/cm^3. The average tensile strength is 320 MPa, average elastic modulus is 21 GPa and average flexural strength is 150 MPa.

The raw bamboo culm was first boiled in water to eliminate natural starches and sugar and keep insects away. While Borax (sodium borate) has been used, this method is known to have potential health hazards when is used over long periods [22]. Boiling in water is friendly safer method that also softens the lignin and loosens the bond between lignin and cellulose fibres. After boiling, raw bamboo was processed into 700 mm long strips with thicknesses of 5 to 8 mm. The bamboo strips were dried in an oven for 24 hours to stabilize the moisture content to less than 10%. The raw bamboo used in this study represented an average fibre collection from middle and lower sections of the bamboo culm in nearly equal ratios with both inner and skin sections included. Bamboo composite materials were prepared by using a two-component epoxy resin as matrix.

The composites were prepared by pre-aligning the epoxy-impregnated strips into a layered structure and then placing them it into the mold of a hot press. Temperature and pressure of hot press were set to 80˚C and 7 MPa respectively. These settings were established iteratively through a 3-month study that recorded tensile properties of the composite samples. Finally, the composites were cured in a curing room for 12 hours at 40˚C and a humidity of 80%.

Tensile strength and elastic modulus of bamboo composite samples were measured according to ASTM D3039; standard test method for tensile properties of polymer matrix composite materials [23]. The average density of the composite was determined to 1.22 g/cm^3. The average tensile strength of the composite used in this study was 295 MPa and the average elastic modulus is 37 GPa. Tensile tests were carried out using a Shimadzu AG-IC 100 kN machine in accordance with the ASTM D3039 standard at a loading rate of 1 mm/min [23].

The samples for the pull-out experiment were prepared by fabricating five composite boards of 1800 mm length and 200 mm width.

Bamboo-composite reinforcement

The bamboo-composite samples were cut into half dog-bone shaped bars of 10mm by 10mm squared cross sections. The dog-bone shape of the grip ensured that the risk of slippage during the test was minimized based on previous experience from tensile-test setups. Figure 2 shows the samples for the pull out test.

Figure 2 Pull out samples

Bonding length of 200mm and 10 chemical and mechanical bonding methods were considered in this study. The chemicals and coatings used in this study are explained below. A total of 75 samples were prepared.

In addition to the samples that were coated on the surface and placed into the normal concrete mix, a water-based epoxy system was also directly added to the normal concrete mix to study bonding enhancement through increasing the viscosity of the concrete without addition of any coating on the surface of the bamboo composite samples. The water-based epoxy matrix was added into concrete in one mix with 25 % wt. of cement and one with 10% wt. of cement.

Five samples were used for each water-based epoxy concrete mix with no coating on the samples surface.

To increase the friction, sand was also added on top of selected coatings and compared with results obtained with the coatings without sand. The following coatings were applied;

- Moisture seal; a two part water based epoxy coating [24]

  Moisture Seal is a two-component, water based epoxy waterproof vapor barrier membrane. The two parts were mixed in a 1:1 ratio. The coating was applied on the reinforcement bars one day before concrete pouring in order for the curing process to be completed.

- Enamel Coating; a two-part epoxy resin coating [25]

  Enamel Coating is resistant to a wide range of chemicals. The coating was applied on the surface of reinforcement bars just before concrete pouring to be cured with the heat of hydration from concrete and provide a better bonding with both bamboo-composite reinforcement and concrete matrix while curing takes place inside the mix.

- ExaPhen coating; a Bio-based epoxy resin system [26]

  Exaphen coating is a two-part epoxy resin formulation which has a high moisture and chemical resistance. After mixing the resin with the hardener the coating was applied on the surface of the reinforcement bars. It cured for two days in a curing oven at a temperature of 45^{o}C and relative humidity of 80%.

- Truegrip BT and EP; a two part epoxy resin based surfacing system [27]

Truegrip BT and EP can be used together with concrete matrix. They are resistant to wide range of chemicals. The coating was applied on the surface of the reinforcements two days prior to casting of the concrete samples.

Two particle sizes for the sand coating were used; fine silica sand with particle sizes between 0.20 mm and 0.30 mm and coarse silica sand with particle sizes of 0.70 mm to 1 mm.

All coatings have been applied to the surface of the bars one to two days before casting to ensure sufficient time for curing. As mentioned above, the enamel coating was applied 30 mins prior to the casting of the concrete, in order to use the heat of hydration for curing and create direct bonding with the concrete matrix. Figures 3 to 7 show the coatings used in this study.

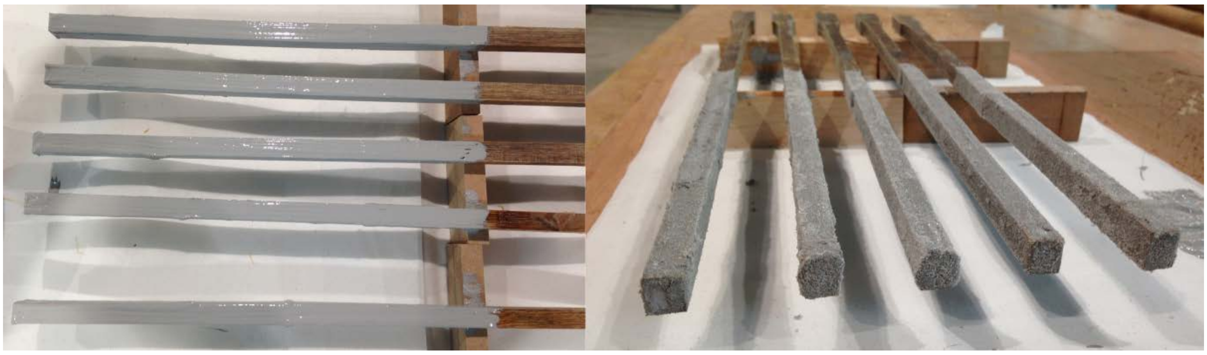

Figure 3 Moisture seal water based coating applied on the surface of reinforcement; Left-without sand particles; Right-with fine sand particles

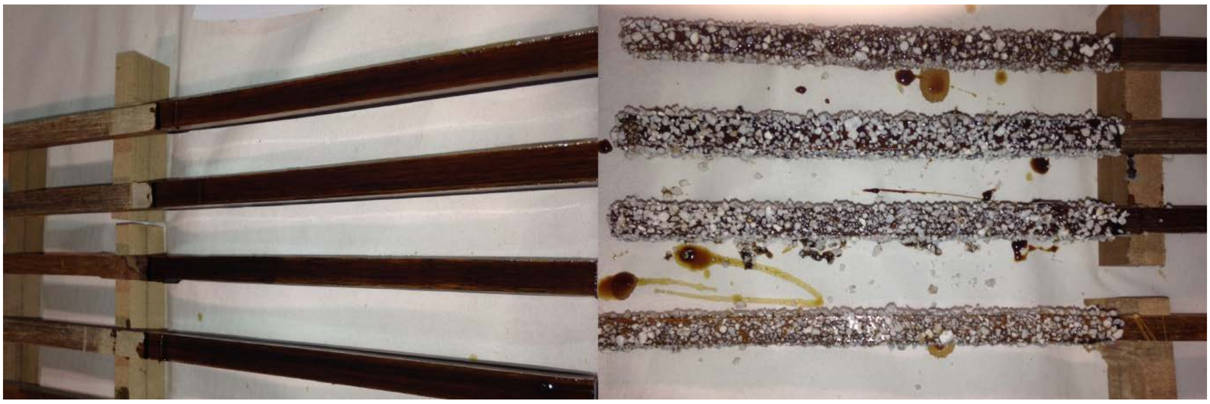

Figure 4 Truegrip BT coating applied on the surface of reinforcements;

Left-without sand particles; Right-with coarse sand particles

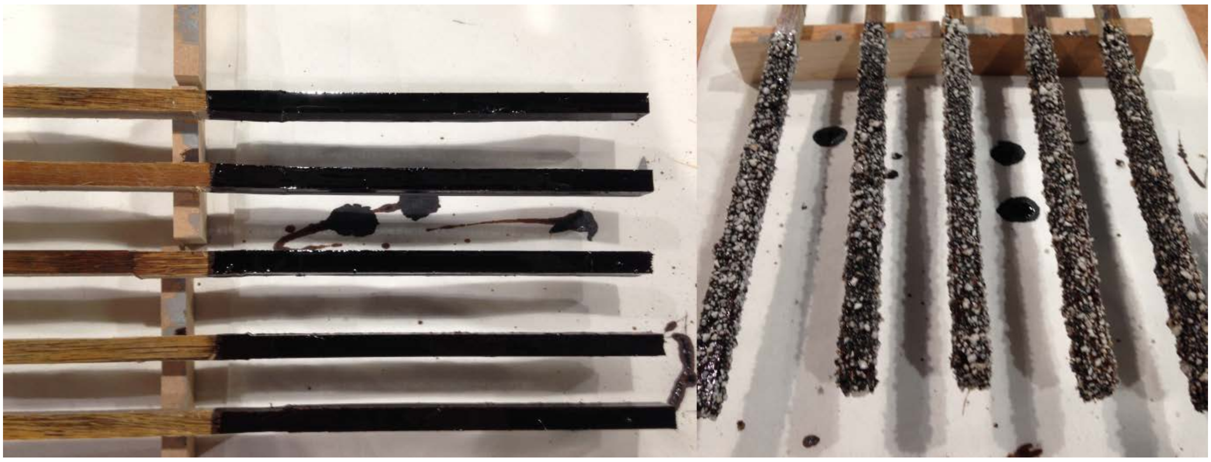

Figure 5 Truegrip EP coating applied on the surface of reinforcements;

Left-without sand particles; Right-with coarse sand particles

Figure 6 ExaPhen bio-based coating applied on the surface of reinforcements;

Left-without sand particles; Right-with coarse sand particles

Figure 7 Enamel coating as applied on the surface of reinforcements 30mins before casting the concrete

Concrete sample preparation

Normal strength concrete of grade 20MPa with Ordinary Portland Cement (OPC) was used for this study. To minimize the effects of the mechanical properties of the concrete matrix, only one type of concrete mix was used in this study. The concrete mix for a volume of 1 m^3 concrete is shown in Table 1.

Table 1 Concrete mix proportions

Water (kg/m^3)	182
Cement (kg/m^3)	280
Sand (kg/m^3)	850
20mm Aggregates (kg/m^3)	1050
Water/Cement	0.65
Density (kg/m^3)	2362
Slump (mm)	100

Cylinders of 300 mm height and 150 mm diameter were used to prepare the pull-out specimens. The concrete mix was prepared by a 60L laboratory mixer.

For each batch of casting, a slump test was performed according to ASTM C143 to control the quality of concrete [28]. The slump test for all the batches was between 110 mm and 95 mm.

Bamboo-composite bars were placed in the center of the cylinders and at the specified embedment length of 200 mm. The cylinders were cured in a curing room for 24 hrs. before opening the molds. The concrete samples were cured in curing room for 28 days before testing. To monitor the strength of the concrete samples, 7-day and 28-day compressive strength tests were performed by casting concrete cubes together with the cylinders. The average 7-day compressive strength of the concrete cubes was 17 MPa and the average 28-day compressive strength for all the samples was 20 MPa.

Tensile strength and elastic modulus of the concrete used in this study were 3.5MPa and 25GPa respectively.

Testing methodology

Pull out tests have been carried out by fabricating a custom-made insert for the Shimadzu UTM machine of type AG-IC 100kN. The insert is made from hardened steel and secures the position of the concrete cylinder during the test when the bar is being pulled out by the machine. The standard tensile grip can be used for this test due to the half-dog-bone shape. The loading rate was 2mm/min. The rate was adjusted to the setup used for tensile strength testing of the bamboo composite samples. Tests have been performed at a temperature of 23^{o}C and a relative humidity of 65%. Figure 8 shows the specimen and test set-up. Before the test, a strain gauge was also attached to the exposed section of the bamboo-composite bar to measure the strains outside concrete matrix as well as modulus of elasticity. This helped to identify any bond slippage due to the pull-out forces rather than a tensile failure during the test. The strain gauge is an Epsilon axial extensometer with a gauge length of 80 mm, which is directly connected to the UTM machine during the test.

Compression tests of the cubes after seven and 28 days of curing were also performed with a Shimadzu UH-500kN with a loading rate of 1 mm/min.

Figure 8 Pull-out test set-up

Results and Discussion

A schematic representation of the forces related to the bond strength between the concrete and the bamboo-composite reinforcement is shown in Figure 9. *P* is the pull out force applied through the UTM machine in kN, l_a is the embedment length in mm, τ is the bond strength in MPa, *a* and *b* are the cross sectional dimensions of the composite bar in mm.

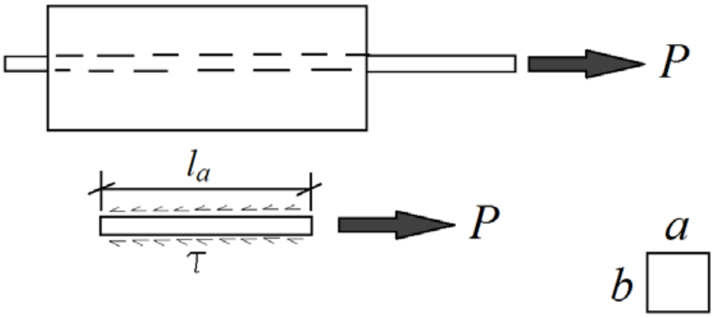

Figure 9 Bond strength of bamboo-composite bar and concrete

Equilibrium leads to the following:

$$\tau.(2a + 2b).l_a = P \quad (1)$$

From Eq.1, the bond strength is determined using Eq.2:

$$\tau = \frac{P}{(2a+2b).l_a} \quad (2)$$

Table 2 summarizes the characteristics of the bamboo-composite bars used in this study. All bamboo-composite bars had a cross section of 10mm x 10mm and an embedment length of 200 mm.

Table 2 Pull out samples general properties

Batch	Type of concrete	Type of coating
1	Normal concrete mix	No coating
2	Cement Epoxy in concrete mix by 25% weight of cement	No coating
3	Cement Epoxy in concrete mix by 10% weight of cement	No coating
4	Normal concrete mix	Water based epoxy coating
5	Normal concrete mix	Water based epoxy coating with fine sand
6	Normal concrete mix	Water based epoxy coating with coarse Sand
7	Normal concrete mix	TrueGrip EP
8	Normal concrete mix	TrueGrip EP with coarse Sand
9	Normal concrete mix	TrueGrip BP
10	Normal concrete mix	TrueGrip BP with coarse Sand
11	Normal concrete mix	Exaphen
12	Normal concrete mix	Exaphen with coarse Sand
13	Normal concrete mix	Enamel

Figure 10 shows the typical load-deflection curve for samples with tensile mode of failure where the bamboo-composite bar breaks before any bond failure. As it can be seen from the curve, bamboo-composite bar has a linear elastic behavior until it breaks due to tensile failure. This mode of failure indicates that there is sufficient bonding between bamboo-composite bar and concrete. Furthermore it shows that the bonding strength exceeds the tensile capacity of bamboo-composite bar. Figure 11 shows the load-deflection curve when the failure is due to bonding mechanism failure between bamboo-composite bar and concrete matrix. According to figure 11, the sample exhibits a linear elastic behavior before it slips due to bonding failure and the curve develops into a plateau. Eventually bamboo-composite bar pulls out of the concrete cylinder due to complete bond failure which can be seen from the load-deflection curve where the curve is descending. There was no concrete splitting failure mode observed for the samples during the testing.

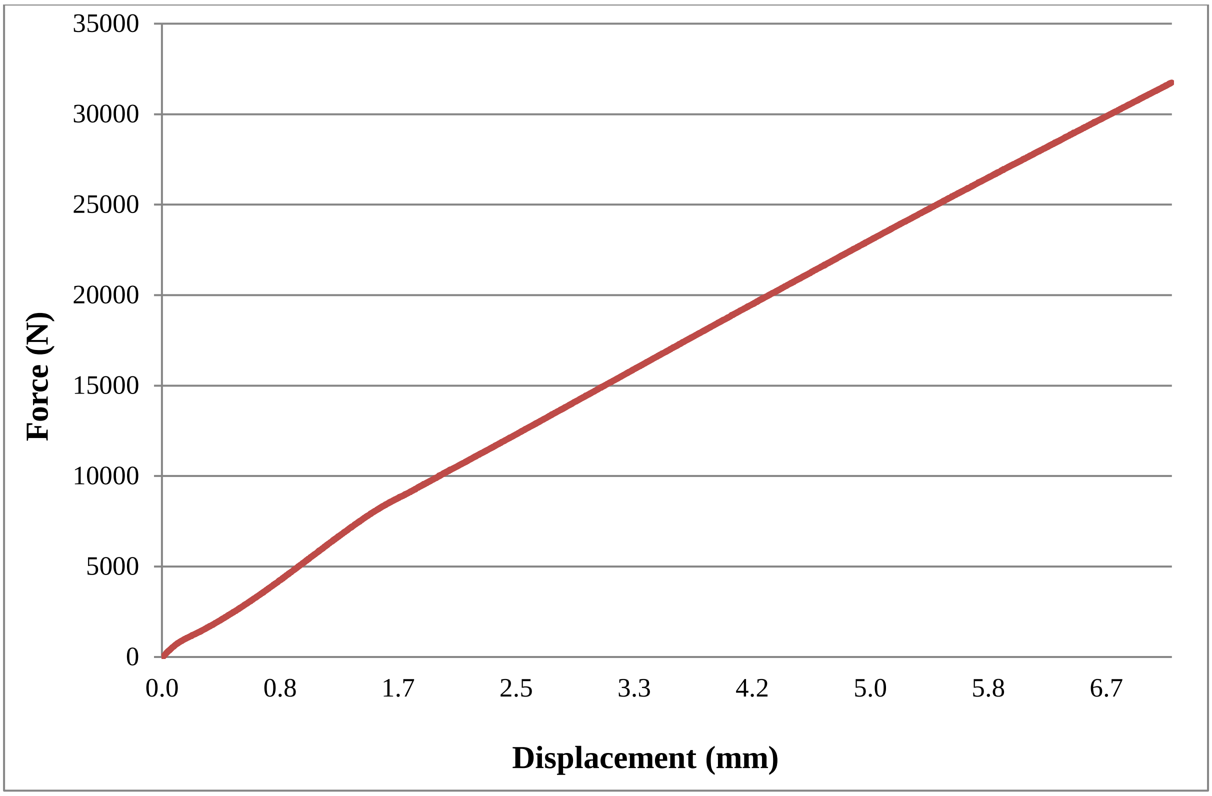

Figure 10 Typical load-displacement curve for a tensile failure mode

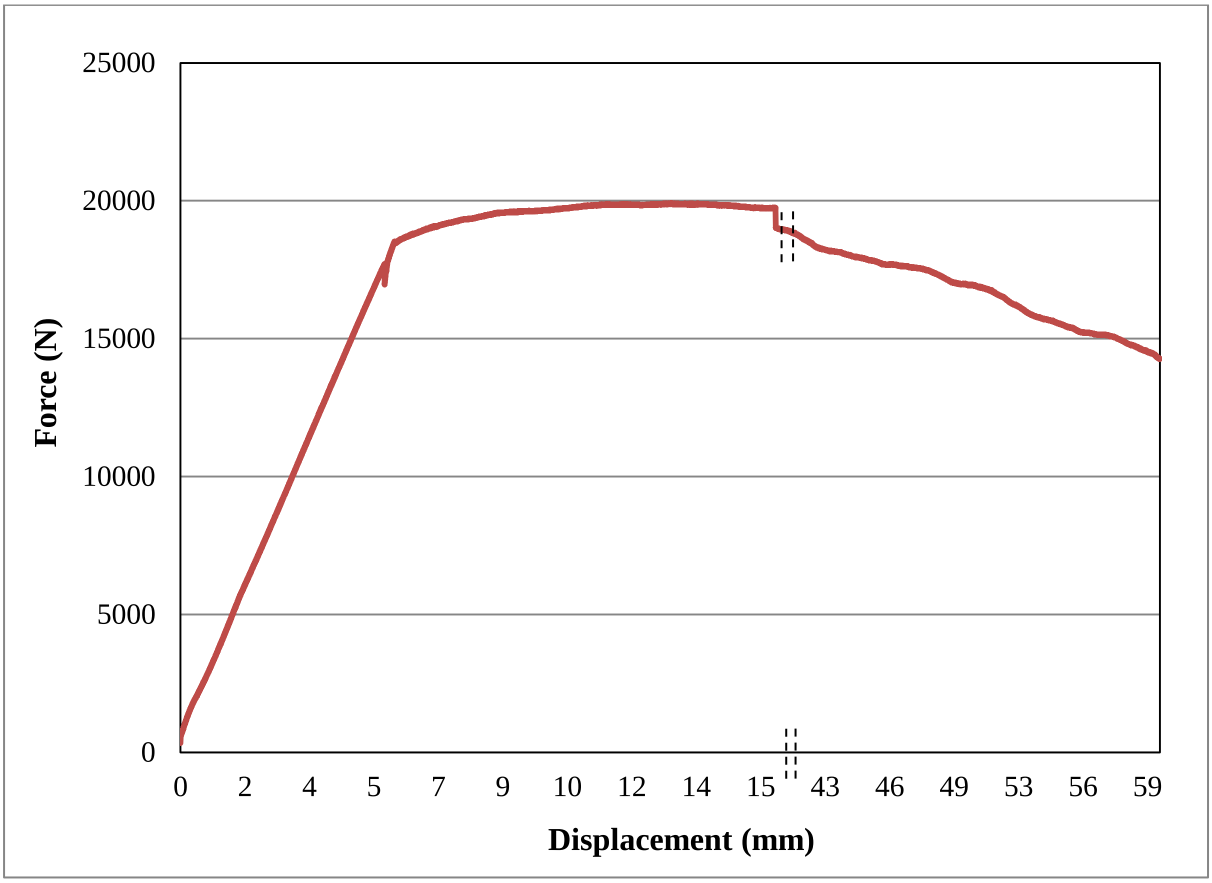

Figure 11 Typical load-displacement curve for the bond failure mode

Figure 12 shows sample of bamboo-composite bar with 300 mm embedment length which slipped due to insufficient bond strength with concrete matrix. The applied stress exceeds the bond strength of the bar and eventually overcomes the friction forces between concrete matrix and the bar. Figure 12 correlates with load displacement curve shown in Figure 11.The tensile mode of failure is shown in Figure 13.

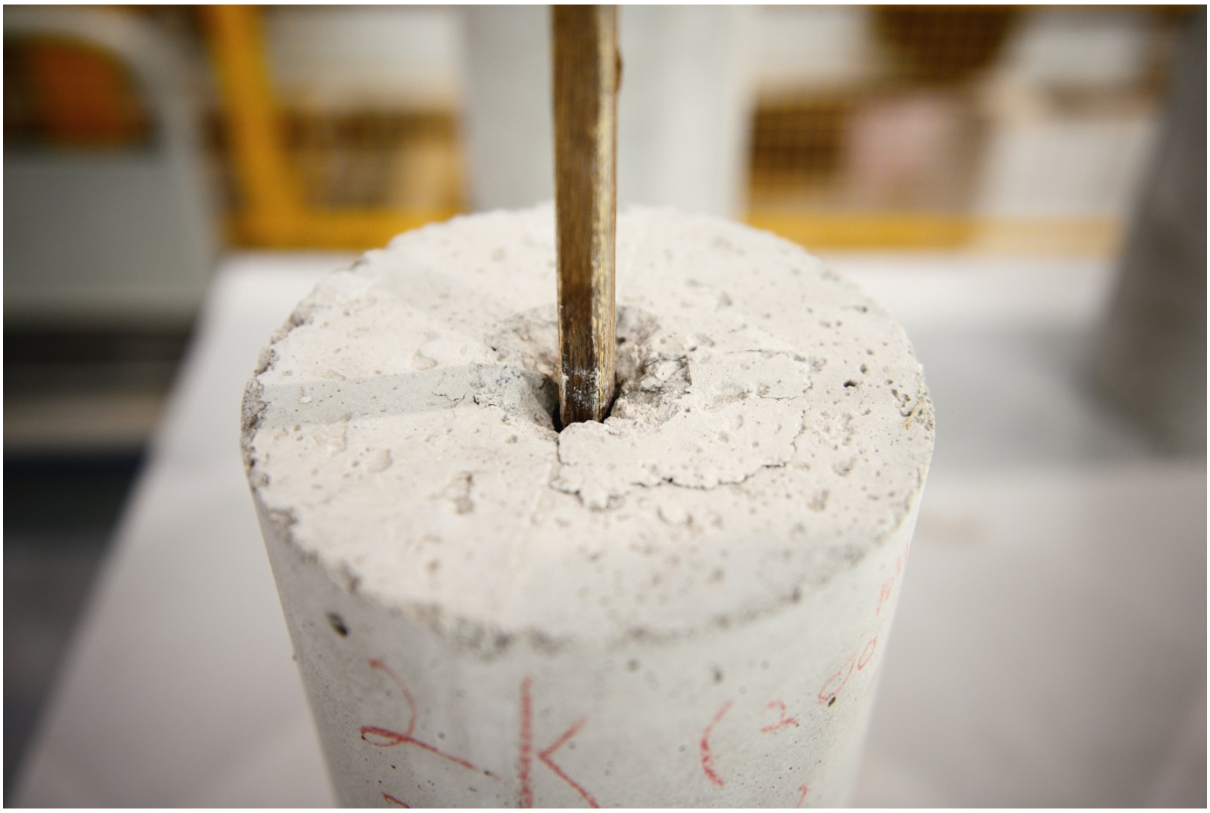

Figure 12 Bond failure and slippage of bamboo-composite bar from concrete matrix

Figure 13 Tensile failure of bamboo-composite bar

Table 3 summarizes the results of the pull-out tests with the average bond strength and mode of failure, either tensile or bond failure, obtained for each batch of specimens. The standard deviations for each batch of specimen are also displayed in Table 3. The fine sand coating was used only with the moisture seal water-based coating to compare its effect with coarse sand. As can be seen from Table 3, the difference in bonding strength with the coarse sand coating and the fine sand coating is not significant. Samples of water based epoxy with fine sand coating had an average bond strength of 3.65 MPa while the average bond strength for samples with water based epoxy and coarse sand was 3.61 MPa, a difference of less than 1.5%. The remaining coatings were applied with coarse sand only. The general aim of the sand coatings was to determine whether the sand particles can help to increase the bond strength between the bamboo-composite bars, the coating and the concrete.

Table 3 Bond strength values for bamboo-composite bars (MPa)

Batch	Type of concrete	Type of coating	Bond Strength (MPa)	Failure Mode
1	Normal concrete mix	No coating	3.61±0.23	Bamboo tensile failure
2	Cement Epoxy in concrete mix by 25% weight of cement	No coating	3.52±0.28	Bamboo tensile failure
3	Cement Epoxy in concrete mix by 10% weight of cement	No coating	2.75±0.11	Bond failure
4	Normal concrete mix	Water based epoxy coating	3.47±0.16	Bamboo tensile failure
5	Normal concrete mix	Water based epoxy coating with fine sand	3.65±0.10	Bamboo tensile failure
6	Normal concrete mix	Water based epoxy coating with coarse Sand	3.61±0.14	Bamboo tensile failure
7	Normal concrete mix	TrueGrip EP	3.30±0.24	Bamboo tensile failure
8	Normal concrete mix	TrueGrip EP with coarse Sand	3.45±0.33	Bamboo tensile failure
9	Normal concrete mix	TrueGrip BP	2.42±0.41	Bond failure
10	Normal concrete mix	TrueGrip BP with coarse Sand	2.62±0.23	Bond failure
11	Normal concrete mix	Exaphen	3.36±0.27	Bamboo tensile failure
12	Normal concrete mix	Exaphen with coarse Sand	3.46±0.19	Bamboo tensile failure
13	Normal concrete mix	Enamel	3.40±0.20	Bamboo tensile failure

From the results of water based epoxy coating, TrueGrip EP, TrueGrip BP and Exaphen coating, it is observed that adding sand to the coating; either fine or coarse particles marginally improves the bonding between the concrete and the bamboo-composite bars. The sand particles increase the bonding between the bamboo-composite bars and the concrete aggregates due to the enhancement of friction between the sand particles and the rough cured concrete surface surrounding the composite bars. When the bamboo-composite bar is pulled out of the concrete cylinder, friction due to interlocking mechanism between sand particles and concrete aggregates – especially fine and large aggregates prevents slippage. When the pull-out force overcomes this friction then tensile capacity of the bamboo-composite bar is activated. With further increasing pull-out force, tensile failure of the bamboo-composite bar occurs (Figure 13). However, if the pull-out force exceeds the friction forces but not the tensile capacity of the bamboo-composite bar, then the bar will slip completely from the concrete cylinder which is shown in Figure 12.

Remarkably, the bamboo-composite bar with an embedment length of 200 mm without any coating has shown a similar bond strength as compared with the bars coated with the moisture seal water based epoxy and coarse sand. The highest bond strength of 3.65 MPa was observed in samples coated with water based epoxy coating and fine sand and followed by samples with water based epoxy coating and coarse sand with bond strength of 3.61 MPa. Addition of 10% wt. water based epoxy to the concrete mix resulted in bond strength of 2.75 MPa. Adding 25% wt. water based epoxy to the concrete mix resulted in a bond strength of 3.52 MPa which is comparable to samples coated with water based epoxy and Exaphen coating with coarse sand. Samples with the TrueGrip BP coating with and without sand had the lowest bond strength among the samples with coating and did not reveal any superior bond strength compared with the rest of the coated samples. However the bond strength increased from 2.42 MPa with no sand to 2.62 MPa with coarse sand; an increase of 8.2%. Bars coated with Exaphen have shown average bond strength of 3.36 MPa. Adding sand to the Exaphen coating improved the bond strength to 3.46 MPa, which was almost similar to the average bond strength value of samples with water based epoxy coating and TrueGrip EP with coarse sand. The enamel coated reinforcement had average bond strength of 3.40 MPa, similar to the Exaphen coating. Comparing the samples with no coating, enamel coating did not improve the bond strength.

The bamboo-composite bar develops a strong bond with concrete when the concrete is cured and hardened. The average bond strength of bamboo-composite bars without coating and an embedment length of 200 mm was as good as water based epoxy coating with fine sand. To maintain the bond in the long term, addition of a coating and sand provides advantages. The coatings applied in this study have long-term resistance to the alkaline environment in concrete, which protects the bamboo-composite bars and maintains the bonding between concrete and composite reinforcement. Addition of sand particles to the coating enhances the bonding by increasing the mechanical interlocking between concrete matrix and bamboo-composite bars. As it was mentioned earlier, the difference between coarse and fine sand particles in developing bond strength is not statistically significant since both particle sizes improve the bonding through friction similarly as shown in Table 3. The bond strengths of bamboo-composite bars with and without coating were similar to the bond strength of plain glass fiber reinforcement in normal strength concrete [29-31]. However the bond strength is only 80% of the bond strength of plain steel reinforcement in normal grade concrete with similar embedment length used in this study[32, 33].

Conclusions

Bamboo-composite material was produced with a new technology to be used in concrete structures to replace steel reinforcement. To evaluate the bonding properties of bamboo-composite reinforcement to concrete, several coatings were studied. Chemical and mechanical bonding behavior were observed during this study. The composite reinforcement having 200 mm embedment length with no coating has a bond strength that is comparable to coated reinforcements. Addition of fine sand particles to water based epoxy coating has shown little effect on enhancement of the bonding between bamboo-composite reinforcement and the concrete matrix. Nonetheless to protect the bond against the chemical reaction in concrete matrix for longer period of time, it is desirable to coat the bamboo-composite reinforcement with water based epoxy coating and fine sand particles. Since there is no significant difference between fine sand and coarse sand, either coating can be used to improve the bond strength. The long-term bonding behavior against conditions such as alkaline environment of concrete or acid rain and exposure to sunlight is the subject of ongoing research.

Acknowledgement

The authors would like to thank Singapore ETH Centre, ETH Global and Sawiris Foundation for Social Development for supporting this research.

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