Advances in Concrete Construction, *Vol. 7, No.* 3 *(2019) 191-201*
DOI: https://doi.org/10.12989/acc.2019.7.3.191

Experimental study on improving bamboo concrete bond strength

Pankaj R. Mali* and Debarati Datta[a]

Department of Applied Mechanics, Visvesvaraya National Institute of Technology, Nagpur-440010, Maharashtra, India

(Received April 17, 2018, Revised March 13, 2019, Accepted March 28, 2019)

Abstract. Bamboo concrete bond behaviour is investigated through pullout test in this work. The bamboo strip to be used as reinforcement inside concrete is first treated with chemical adhesive to make the bamboo surface impermeable. Various surface coatings are explored to understand their water repellant properties. The chemical action at the bamboo concrete interface is studied through different chemical coatings, sand blasting, and steel wire wrapping treatment. Whereas mechanical action at the bamboo concrete interface is studied by developing mechanical interlock. The result of pullout tests revealed a unique combination of surface treatment and grooved bamboo profile. This combination of surface treatment and a grooved bamboo profile together enhances the strength of bond. Performance of a newly developed grooved bamboo strip is verified against equivalent plain rectangular bamboo strip. The test results show that the proposed grooved bamboo reinforcement, when treated, shows highest bond strength compared to treated plain, untreated plain and untreated grooved bamboo reinforcement. Also, it is observed that bond strength is majorly influenced by the type of surface treatment, size and spacing of groove. The changes in bamboo-concrete bond behavior are observed during the experimentation.

Keywords: surface treatment; pull-out test; bamboo reinforcement; bond strength; semicircular groove; mechanical interlock

1. Introduction

In the present scenario majority of the infrastructure and housing structures are RC structures around the globe. Most common and widely used materials in RC structures are steel and concrete because of their excellent structural properties, durability and ease in construction. In last two decades, the use of these materials have risen exponentially causing their production rate to increase making them a costly building material. The resources available are limited in nature and the manufacturing of cement and steel involves emission of harmful gases like CO_2 in the natural atmosphere. Considering such limitations of conventional materials the research for an alternative ecofriendly, renewable material has been going on since 1960. Many alternative construction materials have been explored, as either partial or full replacement to reinforcing steel, majority of them are type of synthetic fibres. Amongst natural fibres, bamboo is very popularly known for its promising engineering properties.

However, more research is required to improve its structural behaviour, especially when it is used inside concrete. The amount of CO_2 released in the atmosphere is about 50 times higher in steel production compared to bamboo, which consumes 1-tonne of CO_2 during its growth (Xiao *et al.* 2003, Sharma *et al.* 2014). Being the fastest growing renewable, eco-friendly material, it could be a very good and a sustainable alternative to conventional steel reinforcement.

From a technical perspective, bamboo is a fast-growing grass. It has a high strength to weight ratio compared to reinforcing steel. The bamboo species used in the present work is Bambusa arundinacea (*B. arundinacea*) the tensile strength to weight ratio of conventional 6 mm diameter steel bar is 113 per meter length and for *B. arundinacea*, it is 645, which is 5.7 times more, based on equivalent area of 6 mm diameter steel bar. Bamboo reaches its optimum strength in 3 to 4 years and attains complete maturity in 5 years. Like a steel bar, it can take both tension and compression, whereas many other materials cannot withstand compressive loading. However, being an organic material, durability of the material is a concern for bamboo as reported by Imadi *et al.* (2014).

Many researchers have carried out their experimentation on the feasibility of using bamboo as alternative reinforcement in structural concrete. Use of raw bamboo either full culm or in the form of main reinforcement inside concrete splints has two major disadvantages. First one is the durability of bamboo over a considerable period of time inside structural concrete leading to weakening and splitting of bamboo fibres due to water absorption. Second is a loss of bond between bamboo and concrete due to inadequate chemical and mechanical action at the interface. Many researchers have addressed the above issues. To overcome the durability of bamboo concrete bond many attempts had been made. Various chemical coatings had been used to make bamboo surface impermeable to surrounding moisture inside concrete. A few important works have been discussed below to study the bond behavior of bamboo reinforced concrete.

∗Corresponding author, Ph.D. Student
E-mail: pankaj04.m@gmail.com
[a]Assistant Professor
E-mail: debaratidatta@apm.vnit.ac.in

http://www.techno-press.org/?journal=acc&subpage=7
ISSN: 2287-5301 (Print), 2287-531X (Online)

Fang and Mehta (1978) used bamboo as a reinforcement in concrete and did further research to study bond characteristics using Sulphur sand surface treatment. Sulphur impregnation improves the natural weaknesses of bamboo culm as used for the engineering application. It is concluded that using Sulphur-sand coating the bond strength has increased compared to that of raw bamboo specimens. However, long-term swelling and shrinkage effects are not discussed. Ghavami in 1995 and 2005 have explored the water repellent characteristics of two types of surface coating. These are Negrolin and Sikadur -32 gel. It is reported that these adhesives also contributes in the process of enhancing the bond strength.

Sakaray *et al.* (2012) made a comparison of bond strength among treated, untreated bamboo and steel HYSD reinforcement. This study reported that when bamboo was placed with a waterproof material irrespective of its type marginal increase in bond strength has occurred. Agrawal *et al.* (2014) performed pull-out tests on chemically treated bamboo samples. They used different sealant materials. Amongst these adhesives used, samples coated with Sikadur 32 Gel exhibited highest bond strength. The durability of this coating under the alkaline environment of concrete needs further studies. Javadian *et al.* (2016) had used a new class of bamboo composite material. Bamboo composite materials were prepared by using a two-component epoxy resin as matrix. In addition to this, fine and coarse sand particles were used to enhance the bond strength. It is observed that bond strength of coated bamboo composite and uncoated bamboo composite are comparable. The long-term durability effects on the suggested bamboo composite with the change in water content of design mix concrete needs to be observed.

The natural chemical composition of bamboo is known to consist of cellulose, hemicellulose, lignin, ash and other extractives Saikia *et al.* (2015). Bamboo surface coated with chemical adhesive coatings alone may not be sufficient to preserve the natural chemical composition of bamboo over a period of time. Chemical action of these coatings has limited effect on bond strength. Additional, increase in bond strength may require processing of raw bamboo and addition of mechanical action. Ghavami (1995) and (2005) in their pull-out experiments used 1.5 mm circular steel wire along with chemical coating. The steel wire is wrapped all around the bamboo surface to generate some additional friction with surrounding concrete. The results of tests have shown an increase in bond strength.

In addition to surface treatment of various chemical adhesives, natural oil, attempts have also been made to manufacture bamboo composites of standard/required sizes by processing bamboo fibres with certain adhesives. Thermo mechanical and biochemical treatments have been done on bamboo and its fibres in order to reduce the shrinkage and enhance their mechanical properties. An attempt had also been made to configure concrete mix to avoid moisture absorption action of bamboo splints embedded inside the concrete. (Zhang *et al*. 2013, Pacheco-Torgal and Jalali 2011, Pallav Saiki *et al*. 2014, Sharma *et al*. 2014, Javadian *et al*. 2016, Chaallal and Benmokrane 1993, Tripura and Sharma 2014, Mathur 2006, Ganesan *et al.* 2018) Several researches were also done to incorporate mechanical interlock at the bamboo concrete interface. For instance, Schneider in 2014 had carried out the research based on pull-out tests samples treated with Thomsons waterseal. Bamboo strip with naturally available diaphragm were tested to study the effect of diaphragm on bond strength. It is found that there is the clear effect of the diaphragm (node) on bond strength as the specimen with one diaphragm had a bond strength of 106 psi and that without any diaphragm had the strength of 59 psi. Terai and Minami (2012) used a full-size bamboo culm as reinforcement rod in concrete along with the chemical action of synthetic resin and synthetic rubber. Slotting on the bamboo surface at different spacing is used. The results show that there is an increase in bond strength after coating. However, the effect of slotting does not have a significant impact on the bond strength of bamboo samples. Azadeh and Kazemi (2014) focused on corrugations made on bamboo strip along with surface treatment. The effect of rectangular shape corrugations made opposite to each other on a bamboo strip were tested to study its effect on bond strength. It is reported that the negative effect of shrinkage, thermal expansion, stress concentration in a raw bamboo strip due to presence of nodes and wedging effect on bond strength can be significantly reduced by the use of corrugated bamboo profile. Authors concluded that bond strength can be enhanced by the use of such corrugated bamboo strips even without using surface treatment. However, the influence of such corrugations on mechanical properties of the raw bamboo strips is unclear from the research. In another study made by Khatib and Nounu (2017) it is reported that corrugations made (Staggered pattern) on the plain bamboo profile resulted in enhanced bond strength. Authors have used Linseed oil along with sand particles as surface treatment. The corrugated bamboo strip profile consist of rectangular corrugations. Corrugations were of 1 mm and 2 mm depth and four different patterns of corrugation with three spacing: corrugation size (B: A) ratios (1:1, 1·5:1and 1:1·5) were investigated. Authors concluded that circular arc shape corrugations (10 mm diameter) with 2 mm depth of projections treated with Linseed oil were more effective than other bamboo strip of 1 mm depth of projection in enhancing bond strength. However, the proposed surface treatment without steel wire wrapping may not result in adequate skin friction.

From the past research work, it is found that there exists lack of adequate bonding between bamboo concrete interface. Many researchers have addressed this issue. All above mentioned researchers have worked on a variety of surface treatments by using chemical coats and changing bamboo surface condition or processing bamboo fibres etc. The above treatment techniques had improved the bond and water absorption issue through chemical action. Yet there are limitations on type of chemical coating to be adopted. These treatments have certain limitations as they can enhance bond strength up to a certain limit, which may not be adequate under heavy structural loading. In addition, environmental impact and their availability of various chemical treatments used in previous work has not been discussed adequately. Mechanism and methodology studied to incorporate mechanical action by modifying natural bamboo profile needs further investigation.

In present work, bond mechanism between bamboo-concrete interface has been investigated by using a combination chemical and mechanical action. Mechanical action is incorporated in the bond mechanism by using the new grooved bamboo reinforcement. Effectiveness of a newly developed grooved pattern of bamboo reinforcement against the conventional plain bamboo strip reinforcement is verified. To achieve adequate chemical action the effect of various surface treatment on bamboo reinforcement have been analyzed. The experimentation includes a series of pullout tests performed on a universal testing machine (UTM). These pull-out samples include plain bamboo splints and grooved bamboo splints, M20 grade of concrete and 6 different chemical treatments.

2. Materials and methods

The experimentation has been carried out in the following steps-

- Characterisation of Bamboo Species.
- Developing corrugated bamboo strip profile
- Surface Treatment and procedure
- Concrete Sample preparation

2.1 General characteristics of bamboo reinforcement

There are around 100 bamboo species exist in the Indian subcontinent. However, only few (16) of them are used in various structural applications. NBC India (2005) classifies these species into three groups (A, B, C) based on their strength characteristics in wet and dry condition. Some of the notable species from each group are Bambusa vulgaris (*B. vulgaris*), Bambusa arundinacea (*B. arundinacea*), and Dendrocalamus strictus (*D. strictus*). Strength characteristics of these species vary depending in which climatic and geographic conditions the bamboo culm has grown up.

In the present work, two bamboo species namely *B. arundinacea* and *D. strictus* are tested for important engineering properties, as they are widely available in the local region. Based on the test results it was decided, to use *B. arundinacea* as it is found suitable than other species in terms of its mechanical and physical properties. Katang is the regional name used for *B. arundinacea*. National Building code of India (NBC-2005) have also mentioned its use for construction purposes.

The bamboo samples chosen for study were between 4 to 5 years of age. At this age, this species shows the highest performance in terms of its mechanical and physical characteristics. (Xiao *et al.* 2013, Lima *et al.* 2008). The bottom one-third portion of these bamboo culms possesses a diameter ranging from 50 mm to 150 mm with wall thickness of 8 mm to 15 mm compared to those of upper and middle one-third portion, which are of lower culm dimeter and less wall thickness. The density is very high because bamboo samples used in the present work are mainly from the bottom region of a well grown up bamboo culm. The average density value obtained for the chosen bamboo samples was 1125 kg/m^3. While harvesting bamboo culm, it is ensured that the overall geometry is straight enough and free from fungus or damage, so the final samples represent well distributed fibres (the fibre concentration of bamboo culm was maximum at the outside surface of the culm compared to the inside region). This exercise helped to select good samples representing good physical and mechanical properties (Sharma *et al.* 2014, NBC-2005).

Table 1 Mechanical properties of *B. arundinacea*

S.N.	Type of test	Parameter	*B. arundinacea*
1	Tension	Young's Modulus (MPa)	7560.00
		Stress at peak (MPa)	200.00
		Peak displacement (mm)	2.71
2	Compression	Compressive strength (MPa)	65.10
3	Static bending	Flexural strength (MPa)	90.42
4	Shear	Shear strength (MPa)	7.20

Table 2 Physical properties of *B. arundinacea*

S.N	Type of test	Location/Position of Culm	*B. arundinacea*
1	Moisture content (%)	Middle	25.56
2	Shrinkage (%)	Length	0.06
		Diameter	3.28
		Thickness	3.28
3	Density (kg/m^3)	Top	888.80
		Middle	1125.00
		Bottom	1142.85

These cleaned bamboo culms are then soaked in 6% boric acid solution for 72 hrs to prevent the attack of termites and insects. After removing the culms from solution, they are allowed to dry under moderate (35℃) temperature for 5 days. The moisture content and density of these culms is found to be 25% and 1125 kg/m^3. Further, these cleaned and air-dried bamboo culms are then converted into strips of uniform thickness and rectangular cross section. IS: 6874 (2008) and ISO 22157 (2004) have given guidelines to determine the important physical and mechanical properties. The average value of each property are mentioned in Table 1 and Table 2. At last, these suitable bamboo strips are used in surface treatment procedure to eliminate shrinkage inside structural concrete.

2.2 Newly developed bamboo reinforcement pattern

The conventional bamboo strip is plain along the length and possesses rectangular cross-section area approximately as shown in Fig. 1(a) where, L_d is the embedded length and b is width of bamboo strip in mm. The bonding between plain treated bamboo and concrete surface is mainly because of the chemical interaction at bamboo and concrete interface. This externally applied coating (adhesive) on the bamboo surface not only make the bamboo (strip) surface impermeable but also develops initial adhesion with the surrounding concrete. This chemical action is responsible for bond between bamboo and concrete. However, under

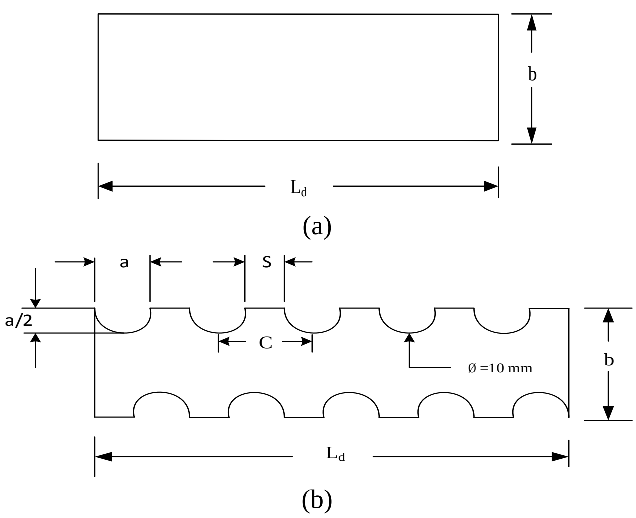


Fig. 1 Untreated (a) Regular plain rectangular bamboo strip and (b) Semicircular grooved rectangular bamboo strip

heavy structural loading this bonding may not be adequate to form a composite action between the two materials in contact. The additional bond strength requirement can be fulfilled by incorporating mechanical action at the bamboo concrete interface. This mechanical action is made possible through bamboo concrete interlocking. Bamboo strips are grooved across the thickness and along the fibre length such that original properties of the raw bamboo strip remains intact. This untreated grooved bamboo strips are used inside concrete cylinder as reinforcement for pull out tests to study the effectiveness of mechanical interlock. The parameters like groove shape, size, its spacing, and amount of embedded length are decided based on the results of trial pull out tests. Three types of groove shapes V-notch, rectangular and semicircular are tried before arriving at the most effective shape. Three embedded lengths of 50, 75 and 100% of cylinder height and with three groove size to its spacing ratios (a: S) equal to 1:1, 1:2, 1:3 were tested. From observations, semicircular shape groove pattern with 50% embedded length and a: S ratio of 1:1 is found to be most effective in enhancing bond strength through mechanical interlock.

The final groove pattern of bamboo reinforcement consists of creating a semicircular shape groove of 10 mm diameter on the edge, i.e., along the thickness of bamboo strip as shown in Fig. 1(b) with the help of carpentry lath machine and associated tools. Where *a*, *S* and *C* are diameter of semicircular groove, clear spacing between the adjacent grooves and center to center spacing of grooves respectively. The effect of various chemical coatings on plain as well as grooved bamboo surface is then investigated further.

2.3 Surface treatment and procedure

The overall surface treatment is affected by three major factors i) Adhesion ii) Water repellent property of chosen substance iii) Topography of Bamboo-Concrete interface (Ghavami 1995).

The newly developed grooved pattern will provide additional mechanical resistance in a plane, which is parallel to the width of the bamboo strip. This is because of the presence of semicircular grooves along the thickness. The chemicals adopted in the surface treatment procedure are selected based on the specifications regarding their chemical constituents and chemical action mentioned in their technical data sheet. This includes water repellent characteristics of the chemicals with wood surface and their availability. The manufacturing of Bond Tite chemical adhesive does not have any hazardous impact on the surrounding atmosphere in the form of harmful gas emissions. Being a versatile adhesive it is easy to use and can function in any weather conditions. (Ref. Technical data sheet). Thermal properties of this epoxy chemical are excellent as its safe working temperature range is -20°C to 100°C. Also water absorption of this chemical is very low i.e., only 0.12% to 0.15% for 7 days at 25°C. (Ref. Technical data sheet) making it ecofriendly.

The first letter indicates the type of adhesive used for coating; the second letter is either *P* or *G*. Here *P* is for the conventional plain type of bamboo strip reinforcement, and *G* is for newly proposed grooved bamboo reinforcement,

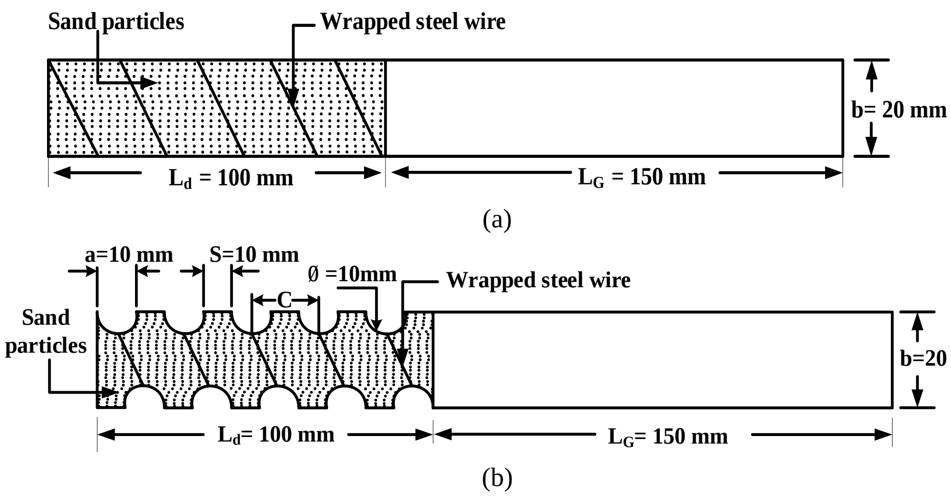


Fig. 2 (a) Treated plain and (b) Treated semicircular grooved bamboo strip

Table 3 Details of surface treatments used

S.N.	Type of Coating	Type of Concrete	Sample Identification		No. of Samples
			Plain	Groove	
I	Triflor PUAL lacquer	Design concrete mix	AP	AG	5
II	Bond Tite	Design concrete mix	BP	BG	5
III	Araldite	Design concrete mix	CP	CG	5
IV	Strepoxy	Design concrete mix	DP	DG	5
V	Bitumen (VG-30)	Design concrete mix	EP	EG	5
VI	EPI BOND -21	Design concrete mix	FP	FG	5

while the number, at last, indicates the sample number in that particular category. The untreated bamboo reinforcements (control) specimens are identified by GP and GG.

It is ensured that chemical action of these coatings does not influence the internal fibre structure of bamboo. The complete surface treatment is carried out in two-steps at a temperature of 25℃ and a humidity of 50%. In the first step, solution of given chemical coating is prepared as per the standard proportion mentioned. A thin layer of this coating solution is applied to the bamboo strips uniformly. A specially prepared mould made of steel and a putty knife (carpentry tool) is used while applying various chemical coatings over the bamboo surface. This ensures that the final layer of adhesive coating is uniform throughout the surface. This coating will ensure that the bamboo strip remains water repellent and helps in chemical adhesion with surrounding concrete.

After applying the adhesive coating on the surface of bamboo, a thin circular steel wire of 1 mm diameter and 415 MPa yield strength is wrapped throughout the coated bamboo surface in a helical manner (ribbed shape). The wrapped steel wire will provide additional mechanical resistance along with that of groove action. At last, the coated specimens are subjected to sandblasting process; where sand particles used in the process are of size 1 mm to 3 mm. The schematic representation of treated plain and grooved bamboo reinforcements are shown in Fig. 2(a) and 2(b) respectively, where L_d and L_G are embedded and grip length of the bamboo strip, inside and outside of the concrete cylinder respectively.

The overall matrix of pull out samples includes majorly two categories i.e., plain and grooved bamboo profile specimens. Each of this category includes treated and untreated specimens. The treated specimen is the one, which is having a chemical coating, steel wire wrapping and sandblasting. The combined effect of wrapped wire and sand particles treatment helps the bamboo reinforcement embedded inside the concrete to develop initial friction followed by the initiation of bamboo concrete interlocking. The two patterns of bamboo reinforcement specimens are given identification, which includes two letters followed by a number.

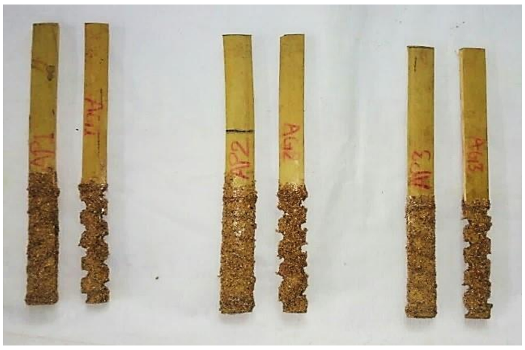


Fig. 3 Triflor PUAL lacquer coating with sand particles

Fig. 4 Bond-Tite coating with sand particles

The various types of coatings mentioned in Table 3, are described below.

I. Triflor PUAL lacquer is a single polymer coat from Pearl coating, Pune, Maharashtra, India under the trade name lacquer . A thin layer of the polymer liquid is applied to the bamboo reinforcement surface. The specimens are allowed to dry for 24 hours before casting. The samples are as shown in Fig. 3 (AP and AG).

II. Bond-Tite is a two-component based high strength adhesive from Resinova Chemie Limited, Kanpur, Uttar Pradesh, India, under the trade name Astral adhesives. The two-component part A and part B of this adhesive are mixed in equal volume. The samples are as shown in Fig. 4 (BP and BG).

III. Araldite Standard is a multipurpose, two components adhesive from Huntsman International (India) Private Limited. The solution is prepared by mixing equal proportion of two components by weight. The samples are as shown in Fig. 5 (CP and CG).

IV. Strepoxy systems is a two-component epoxy resin from speciality reinforced matrix private limited from, Thane, Maharashtra, India, under the trade name FRP composites. It is prepared by mixing base to a saturant agent in a ratio of 1:20 by weight. The two components are stirred until the solution generates slight heat. The samples are as shown in Fig. 6 (DP and DG).

V. Bitumen of viscosity grade 30 obtained by the process of petroleum distillation, in a solid state was procured from a local government agency, Nagpur, Maharashtra India. It is subjected to a heat treatment untill the melting point is reached. A thin layer of liquid solution is applied evenly to the bamboo surface and

Fig. 5 Araldite coating with sand particles

Fig. 6 Epoxy coating with sand particles

Fig. 7 Bitumen (VG-30) coating with sand particles

allowed to dry for 24 hours. The samples are as shown in Fig. 7 (EP and EG).

VI. EPI bond -21 is a two-component epoxy resin conforms to ASTM-C-1059-86 Type II manufactured by Krishna Conchem Products Pvt. Ltd. (KCPPL) Thane, Maharashtra, India. It is prepared by mixing base to curing agent in the ratio of 2:1 by weight thoroughly. The specimens are allowed to dry for 24 hours before casting. The samples are as shown in Fig. 8 (FP and FG).

2.4 Concrete sample preparation

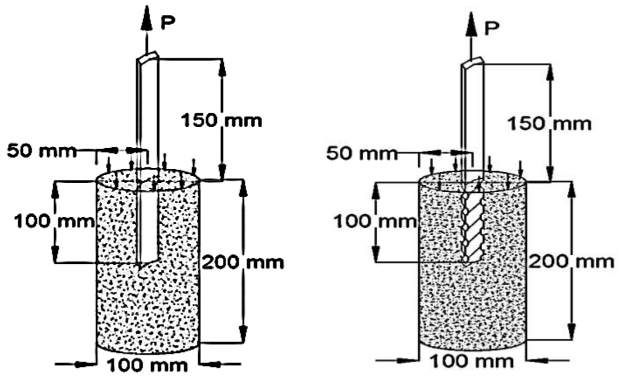
2.4.1 Selection of type of concrete

Concrete is a common part of this work, therefore only one grade of concrete M 20 is used (Reis 2006). The mix design and testing of concrete samples are carried out as per the guidelines of IS 10262 (2009) and IS 456 (2000). After making trial mix proportion the final mix obtained is shown

Fig. 8 EPI BOND -21 coating with sand particles

Table 4 Properties of the concrete

Mix Proportion C: S: A	Compression (MPa)			Tensile strength (MPa)	Flexural strength (MPa)	Specific weight (kN/m^3)	Slump (mm)
	Strength	Elastic modulus	Design strength				
1:2.46:4.07 at water to cement ratio of 0.55	28	24000	20	2.35	4.70	24.00	45.00



(a) (b)

Fig. 4 Schematic representation of Pull-out samples for (a) Plain and (b) Grooved bamboo reinforcement

in Table 4. The concrete of this mix is further tested for its compressive test and other important properties. The average cube strength of each batch of concrete at the age of 7 days and 28 days was 19 MPa and 28 MPa respectively. Final mix proportion along with other important properties are shown in Table 4. To ensure adequate bamboo-concrete interlocking the volume of coarse aggregate is splitted into two different nominal sizes. This includes 20 mm and 10 mm size aggregate in the ratio of 70:30. The cement used is OPC (Ordinary Portland Cement). After 28 days curing of concrete specimens these are tested for compressive as well as other important properties, the test results are mentioned in Table 4.

2.4.2 Pull-out test sample

Concrete compressive strength used during each batch of casting cylinders is checked by casting cubes for each batch separately and tested for their 7 days and 28 days strength. The average compressive strength of cube at 7 days age was 19 MPa and that of 28 days was 28 MPa for each batch. The schematic representation of pull-out operation in plain, as well as grooved bamboo samples is shown in Figs. 9(a) and 9(b)

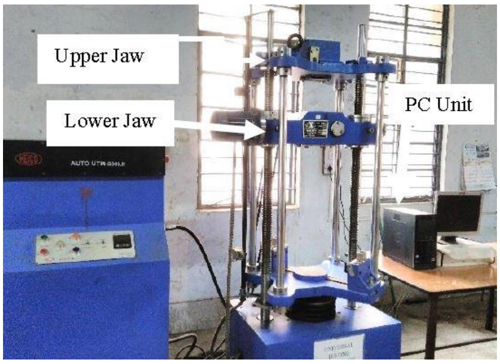


Fig. 10 UTM used during pull-out testing


Fig. 11 Pull-out sample placed inside UTM

respectively. The specimens are cast in the cylindrical steel mould of diameter 100 mm and height 200 mm using the pull-out casting assembly.

The test samples are divided into seven categories. One is uncoated control category; other six are based on different types of coatings used for surface treatments. Each category consists of 10 specimens, which are subdivided into plain bamboo and grooved bamboo samples. Therefore, in each category, there are five plain test samples and five grooved test samples. After casting is over, the cylindrical moulds are kept for 24 hours in laboratory allowing concrete to have an initial setting. Samples are demolded after 24 hours and kept inside the curing tank for 28 days under normal temperature. Once the curing period is over the samples are further used for Pull-out test.

2.5 Testing methodology

A series of pull-out tests are performed on concrete cylinder samples using UTM. A servo-hydraulic machine having 100 kN capacity with a feature of applying displacement control loading as shown in Fig. 10 was used. A specially prepared assembly is used to mount the pull-out samples inside the UTM in the correct position. Assembly is manufactured with a hardened steel material, which holds the sample without showing any internal deformations, and maintains the correct position of the sample during pull-out operation. The sample is placed inside the set up prepared for the pull-out test as shown in Fig. 11. It is ensured that loading head, specimen, and fixed bottom support are symmetrical in one vertical plane. The gripping arrangement used for holding bamboo strip at the loaded end is same as used in during tensile testing of bamboo strip specimens which, prevents the crushing of bamboo strips at gripping region. The load is gradually applied at the interval of 0.1 mm/Sec and at each load step; control unit attached to the UTM as seen in Fig. 10 records corresponding displacement (slip of bamboo strip in mm).

Before testing the main pull out samples few trial samples are tested in the same UTM in order to identify and eliminate the effect of initial slip and crushing of bamboo at grip location. This exercise is done to ensure that at each load step the response of corresponding load and displacement are received from the pullout samples only by considering machine compliance. The readings of load and deformation were recorded by a calibrated electronic control system attached with a host PC. The specimens are loaded till the bamboo starts slipping from the concrete cylinder. The displacement obtained during the test is again verified by measuring the actual slip of bamboo strip occurred (measured from the top surface of concrete cylinder) of the failed samples at the end of the test.

3. Test results and discussions

Total 70 pull out samples are tested under uniaxial tensile loading. The distribution of bond stress is assumed constant throughout the embedded length inside the concrete (average shear stress distribution at the interface). In a reinforced concrete composite material, development of boning mainly depends on two major factors i) Adhesion and friction due to adhesive coating between Reinforcing steel-concrete interface and ii) Nature of mechanical interlock, between the surfaces of two materials.

The first type of mechanism is very commonly seen in bamboo strip (chemically treated) with a rectangular cross section and having plain surface along its length embedded inside concrete. Whereas in the second type, groove concrete interlocking and ribbed action of wrapped steel wire together is aimed at imparting additional anchorage between the two surfaces in contact.

In the present calculations bond stress is taken as the shear force per unit nominal surface area of reinforcing bamboo strip (embedded in concrete). The stress is acting at the interface between bamboo and surrounding concrete and along the direction parallel to the bamboo strip. In case of the plain bamboo specimen, the bond force is because of friction between concrete and surface coating. In order to determine bond stress developed, equilibrium between applied pull out load and bond resistance generated is considered and it is given by Eq. (1). Whereas Eq. (2) gives bond stress value.

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

$$\tau_{bp} = \frac{P}{(2b+2t)\times L_d} \quad (2)$$

Now in the case of a newly proposed grooved bamboo reinforcement, the pull-out force mechanism is generated because of the resistance offered by adhesion and friction as well as due to mechanical interlock of semicircular grooves with concrete. Based on the geometry of the grooved bamboo specimen as shown in Fig. 2(b), the equilibrium is assumed between pull out load and internal bond resistance, which can be given by Eq. (3).

$$P_{theoritical} = \left\{\left[\tau_{bp} \times (2b + 2t) \times L_d\right] + (\tau_{bs} \times t \times s) \times 2 \times \left(\frac{L_d}{c}\right)_f \right\} \quad (3)$$

$$\tau_{bg} = \frac{P}{A_{net}} \quad (4)$$

Where τ_{bp} and τ_{bg} are the bond strength of a plain and grooved bamboo specimen in N/mm^2 respectively. And τ_{bs} represents the shear strength of a bamboo specimen along the grain in N/mm^2 as mentioned in Table 1. Here's' is the spacing of semicircular grooves or end to start distance between two adjacent grooves. *C* is centre-to-centre spacing of successive grooves, L_d is embedded length of bamboo inside the concrete cylinder in mm, *b* and *t* are cross-sectional dimensions of rectangular bamboo samples in mm as shown in Fig. 1(a) and 1(b). The term $(L_d/c)_f$ represents number of grooves that have been sheared off/failed. The last term in Eq. (3) $\left[(\tau_{bs} \times t \times s) \times \left(\frac{L_d}{c}\right)_f\right]$ represents shear resistance of a groove in N/mm^2. $\boldsymbol{\tau_{bg}}$ is calculated using a ratio of pull-out force by the net surface area of a grooved bamboo reinforcement as given by Eq. (4). The calculation of net surface area in contact with surrounding concrete is done as per Eq. (5).

$$A_{net} = \left\{[(2b + 2t) \times L_d] - \left[2 \times \left(\frac{L_d}{c}\right)_i \times \left(\frac{\pi d^2}{4} + d \times t\right)\right] + \left[\left(\frac{\pi dt}{2}\right) \times 2 \times \left(\frac{L_d}{c}\right)_i\right]\right\} \quad (5)$$

Where, *d* is diameter of a semicircular groove in mm and $\left(\frac{L_d}{c}\right)_i$ is total number of grooves present on each side of the bamboo reinforcement before test. Table 5, shows the average of maximum pullout load sustained by samples for different surface treatment in plain as well as grooved bamboo reinforcement (P_{EP} and P_{EG}). The calculation of theoretical pullout load in grooved bamboo samples (P_{TG}) is done as per Eq. (3) considering the along fibre shear strength of bamboo strip for each type of surface treatment. It can be seen from Table 5 that P_{EG} and P_{TG} are well in agreement with each other.

Table 6, specifically shows the comparison of only plain treated and plain untreated bamboo specimens along with their failure mode. It is seen that after application of surface treatment, there is a sharp increase in the bond strength value in each type of adhesive used. The linear stiffness indicates the linearity of the load-displacement curves in that category. All plain treated bamboo samples have exhibited a linear elastic behavior within a maximum average displacement of 10 mm. All the plain treated samples have failed because of loss of bond.

On the other side the effect of surface treatment on grooved bamboo samples is seen from Table 7. As compared to untreated grooved specimens (GP), the treated grooved specimens have shown larger bond strength confirming the effect of surface treatment and grooves. The participation of all the grooves embedded inside the concrete simultaneously, have resulted in maximum mechanical resistance. The treated grooved bamboo samples have sustained relatively higher load and deformations (up to 12 mm) before failure. This is possibly due to ribbed action of wrapped steel wire and groove concrete interlocking which is absent in treated plain bamboo samples. All treated groove samples have shown complete groove failure except GG samples where a complete bond failure with partial groove failure is observed.

Table 8, clearly shows that in untreated bamboo samples despite the fact that shrinkage is a critical issue. Yet, untreated grooved bamboo samples perform better (with average bond strength of 0.49 MPa) than the untreated plain bamboo samples (with average bond strength of 0.14 MPa). This indicates that even in the absence of adhesive (expensive) surface treatment, the proposed grooved

Table 5 Results of pull-out force for plain and grooved bamboo reinforcement

S.N.	Plain Bamboo	Experimental ultimate load P_{EP} (kN)	Grooved Bamboo	Experimental ultimate load P_{EG} (kN)	Theoretical ultimate load P_{TG} (kN)	P_{EG}/ P_{TG}
1	AP	1127	AG	5016	5334.30	0.94
2	BP	7797	BG	11310	12008.10	0.94
3	CP	4587	CG	7310	8312.32	0.88
4	DP	7217	DG	9150	10882.50	0.84
5	EP	1147	EG	4800	4836.20	0.99
6	FP	6503	FG	7683	9488.00	0.81
7	GP	700	GG	2357	2331.10	1.01

Table 6 Experimental results of bond strength for plain treated bamboo reinforcement

S.N.	Plain Bamboo	Bond Strength (MPa)	Increase in Bond Strength	Linear Stiffness (kN/m)	Mode of Failure
1	AP	0.21±0.034	1.50	146	Bond Failure
2	BP	1.4±0.035	10.50	784	Bond Failure
3	CP	0.84±0.067	6.00	645	Bond Failure
4	DP	1.37±0.130	9.80	806	Bond Failure
5	EP	0.22±0.021	1.60	157	Bond Failure
6	FP	1.20±0.065	8.60	705	Bond Failure
7	GP	0.14±0.010	1.00	92	Bond Failure

Table 7 Experimental results of bond strength for treated grooved bamboo reinforcement

S.N.	Plain Bamboo	Bond Strength (MPa)	Increase in Bond Strength	Linear Stiffness (kN/m)	Mode of Failure
1	AG	1.04±0.150	2.10	538	Groove Failure
2	BG	2.35±0.083	4.80	1138	Groove Failure
3	CG	1.44±0.021	2.90	744	Groove Failure
4	DG	1.88±0.124	3.80	1029	Groove Failure
5	EG	0.97±0.086	1.90	469	Groove Failure
6	FG	1.54±0.051	3.10	831	Groove Failure
7	GG	0.49±0.015	1.00	390	Bond and Partial Groove Failure

Table 8 Comparison of bond strength between plain and grooved bamboo reinforcement

S. N.	Plain Bamboo	Bond Strength (MPa)	Grooved Bamboo	Bond Strength (MPa)	% increase in Bond strength
1	AP	0.21±0.034	AG	1.04±0.150	379
2	BP	1.4±0.035	BG	2.35±0.083	60
3	CP	0.84±0.067	CG	1.44±0.021	71
4	DP	1.37±0.130	DG	1.88±0.124	37
5	EP	0.22±0.021	EG	0.97±0.086	353
6	FP	1.20±0.065	FG	1.54±0.051	28
7	GP	0.14±0.010	GG	0.49±0.015	259

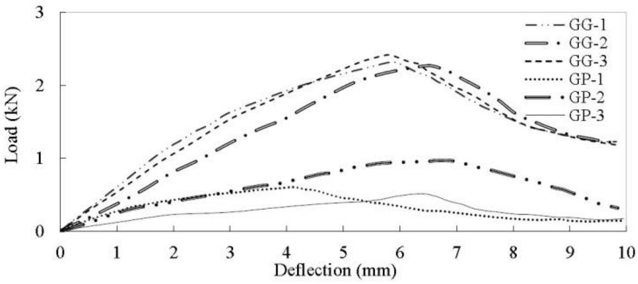


Fig. 12 Typical load-displacement curves for untreated plain and grooved bamboo samples

bamboo profile is able to enhance the bond strength. It is possible due to participation (partial) of grooves in mechanical interlock taking place between bamboo and concrete.

Based on the comparison shown in Table 8, it is noted that samples treated with Bond Tite chemical adhesive have been the most effective chemical in increasing bond strength in both types of bamboo reinforcement.

The effect of Bond Tite chemical on fresh bamboo samples shows that the density of fresh bamboo has reached to 1200 kg/m^3 and moisture content to 10%. The average tensile strength and elastic modulus of bamboo composite remains unchanged. For un-grooved treated bamboo reinforcement increase in bond strength has been observed in the sequence of ‘AP’, ‘EP’, ‘CP’, ‘FP’, ‘DP’ and ‘BP’ however, in case of treated grooved bamboo reinforcement it alters in sequence of ‘EG’(minimum), ‘AG’, ‘CG’, ‘DG’, ‘FG’ and ‘BG’(maximum). Typical load displacement relationship for untreated plain as well as grooved bamboo samples (GP and GG) is shown in Fig. 12. In GP samples, the failure takes place because of failure of bond mechanism between raw plain bamboo and concrete. From Fig. 12 it is observed that the sample shows linear elastic behavior before the bamboo starts slipping from the concrete cylinder. The descending portion of the curve in the graph indicates the slippage of bamboo taking place without the increase in load.

Fig. 13 correlates load-displacement curve of GP samples shown in Fig. 12. It is observed that bamboo has simply come out of the concrete cylinder even with very small pullout load, confirming to the fact that untreated plain bamboo develops a very weak bond with the surrounding concrete when used as reinforcement. The curve in Fig. 12 shows that the grooved samples have

Fig. 13 Bond failure of untreated plain bamboo

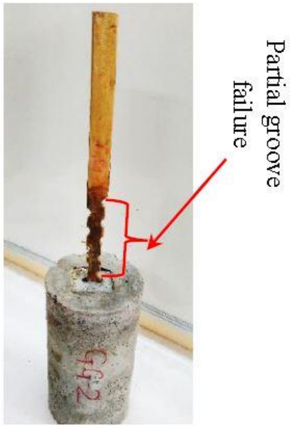


Fig. 14 Partial groove and bond failure of untreated grooved bamboo

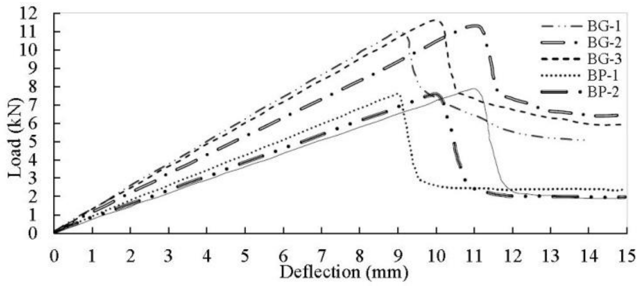


Fig. 15 Typical load-displacement curves for treated plain and grooved bamboo samples

shown behavior resembling linear elastic until ultimate load is reached; thereafter the slipping of bamboo starts and curves gradually moves downwards, owing to the complete bond failure. The contribution of groove mechanical interlock during pullout operation has resulted in sustaining higher pull-out load in GG samples compared to that of GP samples.

Fig. 14 shows the failure of untreated grooved bamboo pullout samples. The grooved bamboo strips comes out from concrete cylinder where only a few grooves (4 to 5) are sheared off completely. While few grooves on the reinforcement remaining undamaged indicating a partial groove failure mode. On the other side, amongst treated plain as well as treated grooved bamboo pull-out samples,

Fig. 16 Bond failure of treated plain bamboo

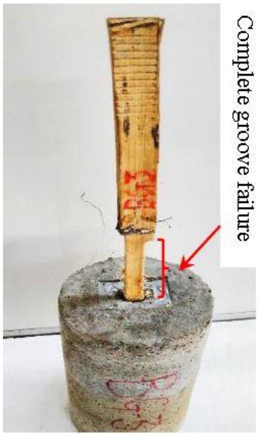


Fig. 17 Groove shear failure of treated grooved bamboo

Fig. 15 shows the comparison of the typical load-displacement curve for specimens treated with Bond Tite adhesive, sand blasting, and steel wire wrapping. The failure of plain treated bamboo samples (BP) is because of failure of bond mechanism.

There is a linear relation between pull-out load and corresponding displacement for plain (BP) samples. Once the pull-out force exceeds the bond resistance bamboo slips out of cylinder shown by the sudden drop in the curve in Fig. 15. The failure mode of the treated plain bamboo sample is shown by Fig. 16. Here it can be noticed that the surface treatment has been completely taken off including wrapped steel wire during the pull-out operation. From the post failure samples, it is clearly visible that only fresh part of the embedded bamboo has come out of cylinder leaving behind adhesive coating, steel wire and sand particles. This shows that with adequate surface treatment the bamboo is able to develop an efficient bonding with the surrounding concrete. The load-displacement curve of grooved bamboo samples (BG) in Fig. 15 also shows that BG specimens have sustained higher pullout load with higher linear stiffness than that of plain treated bamboo samples confirming the additional effect of mechanical resistance because of groove-concrete interlocking at the bamboo concrete interface. The failure of BG samples can be seen from Fig. 17. Here the failure is attributed to mainly two factors, first, is a loss of adhesion and friction developed because of surface treatment. The second factor is due to shearing of individual grooves. The grooves sheared off because longitudinal shear strength of bamboo (along fibres) is overcome by the concrete shear strength (Azadeh and Kazemi 2014, Khatib and Nounu 2017). The failure of grooves also indicates that adequate bonding is established at the bamboo-concrete interface. Removal of grooves indicate their participation in resisting the pull-out load. After the failure of pull out samples, treated grooved bamboo does not have any grooves or any part of the treatment. As a result, the portion of the embedded bamboo sample in Fig. 17 came out, which is without any groove or surface treatment.

Amongst all pull out samples considered in the present study, BG samples have shown highest bond strength. This clearly indicates that, Bond Tite surface treatment along with proposed bamboo surface treatment can improve the bamboo concrete composite action in resisting load. This newly obtained bond strength is comparable to conventional design bond strength given by IS-456 (2000). The comparison between actual bond strength obtained from present study to that of conventional plain steel and ribbed steel reinforcement is shown in Table 9.

Table 9 Comparison of design bond stress for plain bars in tension and the proposed bamboo reinforcement

Grade of Concrete (MPa) & Reinforcement Type	M 20 & Plain steel reinforcement (IS-456)	M 20 & Ribbed steel reinforcement (IS-456)	M 20 & Proposed bamboo reinforcement (Present Study)
Design bond stress (MPa)	1.20	1.92	2.35

4. Observations and conclusions

In this study, bamboo-concrete interface action is investigated to understand the effect on bond strength. The experimental investigation has been carried out on pull-out samples, prepared using chemical and/or mechanical treatments. Following conclusions are made based on the experimental and analytical investigations. The pullout strength of un-grooved (i.e., plain) untreated bamboo reinforcement increases in the range of 1.5 to 10.5 times after treating with aforementioned (six) chemical coating and amongst them, 'Bond Tite (B)' treatment enhances the bamboo concrete bond behaviour utmost (i.e., 10.5 times more). The proposed grooved bamboo reinforcement (un-treated) also shows enhancement in bond behavior compared to un-grooved untreated bamboo reinforcement and resist approximately three times more pull-out force. Further, the resistance offered by grooved bamboo reinforcement without chemical treatment is more than un-grooved bamboo reinforcement treated using 'Triflor PAUL lacquer (A)' and 'Bitumen VG-30 (E)'. However, a combination of grooved bamboo reinforcement with chemical coating has yielded in maximum pull-out strength which is about 6 times (for 'Bitumen (E)' coating) & 16 times (for 'Bond Tite (B)' coating) more than un-grooved untreated bamboo reinforcement. The average experimental bond stress results for treated grooved bamboo samples are comparable with design bond stress values suggested by IS 456:2000 for plain as well as ribbed steel bar with M20 grade of concrete. This study specifically focuses on bond performance improvement between bamboo and concrete. The present research also explores the potential of a new type of coating (Bond Tite), which has not been used before for enhancing bamboo concrete bond strength. Still, effectiveness of the proposed Bond Tite surface treatment and grooved bamboo profile needs further investigation to assess its structural performance and durability aspect. However, this research has shown that the proposed grooved design of a bamboo strip with Bond Tite chemical treatment has improved the bond performance significantly.

Acknowledgement

This research is financially supported by Technical Education Quality improvement Programme -II (TEQIP-II) An initiative of Ministry of Human Resource and Development (MHRD), Government of India.

References

Agarwal, A., Nanda, B. and Maity, D. (2014), “Experimental investigation on chemically treated bamboo reinforced concrete beams and columns”, *Constr. Build. Mater.*, **71**, 610-617.

Azadeh, A. and Kazemi, H.H. (2014), “New approaches to bond between bamboo and concrete”, *Key Eng. Mater.*, **600**, 69-77.

Chaallal, O. and Benmokrane, B. (1993), “Pullout and bond of glass-fibre rods embedded in concrete and cement grout”, *Mater. Struct.*, **26**(3), 167-175.

Fang, H.Y. and Mehta, H.C. (1978), “Sulfur-sand treated bamboo rod for reinforcing structural concrete”, *Adv. Chem.*, **165**, 241-254.

Ganesan, N., Indira, P.V. and Himasree, P.R. (2018), “Strength and behaviour of bamboo reinforced concrete wall panels under two way in-plane action”, *Adv. Concrete Constr.*, **6**(1), 1-13.

Ghavami, K. (1995), “Ultimate load behaviour of bamboo-reinforced lightweight concrete beams”, *Cement Concrete Compos.*, **17**(4), 281-288.

Ghavami, K. (2005), “Bamboo as reinforcement in structural concrete elements”, *Cement Concrete Compos.*, **27**(6), 637-649.

Imadi, S.R., Mahmood, I. and Kazi, A.G. (2014), *Biomass and Bioenergy*, Springer International Publishing, 27-46.

IS 10262 (2009), Specifications for Concrete Mix Proportioning Guidelines, Bureau of Indian Standards, New Delhi, India.

IS 456 (2000), Specifications for Code of Practice for Plain and Reinforced Concrete, Bureau of Indian Standards, New Delhi, India.

IS 6874 (2008), Indian Standard Specifications for Method of Tests for Bamboo, Bureau of Indian Standards, New Delhi, India.

ISO 22157-1 (2004), International Organization for Standardization, International Standard Bamboo-determination of Physical and Mechanical Properties-Part I: Requirements, Geneva, Switzerland.

Javadian, A., Wielopolski, M., Smith, I.F.C. and Hebel, D.E. (2016), “Bond-behavior study of newly developed bamboo-composite reinforcement in concrete”, *Constr. Build. Mater.*, **122**, 110-117.

Khatib, A. and Nounu, G. (2017), “Corrugated bamboo as reinforcement in concrete”, *Proc. ICE-Struct. Build.*, **170**(4), 311-318.

Lima, H.C., Willrich, F.L, Barbosa, N.P., Rosa, M.A. and Cunha, B.S. (2008), “Durability analysis of bamboo as concrete reinforcement”, *Mater. Struct.*, **41**(5), 981-989.

Mathur, V.K. (2006), “Composite materials from local resources”, *Constr. Build. Mater.*, **20**(7), 470-477.

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

Pacheco-Torgal, F. and Jalali, S. (2011), “Cementitious building materials reinforced with vegetable fibres: A review”, *Constr. Build. Mater.*, **25**(2), 575-581.

Reis, J.M.L. (2006), “Fracture and flexural characterization of natural fiber-reinforced polymer concrete”, *Constr. Build. Mater.*, **20**(9), 673-678.

Saikia, P., Dutta, D., Kalita, D., Bora, J.J. and Goswami, T. (2015), “Improvement of mechano-chemical properties of bamboo by bio-chemical treatment”, *Constr. Build. Mater.*, **101**, 1031-1036.

Sakaray, H., Togati, N.V.V.K. and Reddy, I.V.R. (2012), “Investigation on properties of bamboo as reinforcing material in concrete”, *Int. J. Eng. Res. Appl.*, **2**, 77083.

Schneider, N., Pang, W. and Gu, M. (2014), “Application of bamboo for flexural and shear reinforcement in concrete beams”, *Structures Congress*, 1025-1035.

Sharma, B., Gatóo, A., Bock, M. and Ramage, M. (2015), “Engineered bamboo for structural applications”, *Constr. Build. Mater.*, **81**, 66-73.

Sharma, B., Gatoo, A., Bock, M., Mulligan, H. and Ramage, M. (2014), “Engineered bamboo: state of the art”, *Proc. Inst. Civil Eng., Constr. Mater.*, **168**(2), 57-67.

Terai, M. and Minami, K. (2012), “Research and development on bamboo reinforced concrete structure”, *Proceedings of 15th World Conference on Earthquake Engineering*, Lisbon Portugal.

Tripura, D.D. and Sharma, R.P. (2014), “Bond behaviour of bamboo splints in cement-stabilised rammed earth blocks”, *Int. J. Sustain. Eng.*, **79**(1), 24-33.

Xiao, Y., Yang, R.Z. and Shan, B. (2013), “Production, environmental impact and mechanical properties of glubam”, *Constr. Build. Mater.*, **44**, 765-773.

Zhang, Y.M., Yu, Y.L. and Yu, W.J. (2013), “Effect of thermal treatment on the physical and mechanical properties of phyllostachys pubescen bamboo”, *Eur. J. Wood Wood Prod.*, **71**(1), 61-67.

JK