Construction and Building Materials 188 (2018) 1092–1100

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental evaluation of bamboo reinforced concrete slab panels

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HIGHLIGHTS

- Enhancement of bond strength at bamboo concrete interface.
- Application of newly developed bamboo reinforcement in RC slab panels.
- Improvement in flexural performance of slab panels with proposed bamboo reinforcement.

ARTICLE INFO

Article history:
Received 10 May 2018
Received in revised form 11 August 2018
Accepted 25 August 2018

Keywords:
Bamboo reinforced concrete
Flexural test
Bamboo reinforcement
Bond strength
Semicircular groove
Mechanical strength

ABSTRACT

Reinforced concrete structural members are primarily subjected to static gravity loads. The conventional steel reinforcement is used to provide additional tensile strength and energy absorption capacity to concrete members. But conventional M.S. (Mild steel) or HYSD (High Yielding Strength Deformed) bars are heavy in weight, costly, nonrenewable and un-ecofriendly material. Aiming to mitigate this concern a sustainable, renewable, ecofriendly material like bamboo has been used as substitute to steel in the present work. Bamboo-concrete Bond behaviour was first studied through a series of pull-out tests. Bond strength investigation has resulted in a unique bamboo strip profile along with a surface treatment the combination of which exhibited maximum bond strength under uniaxial loading. This new bamboo strip is further used as main reinforcement in concrete slab panels. Feasibility and effectiveness of this unique bamboo profile used as reinforcement was investigated through experimental testing of concrete slab panels. A total 15 concrete slab panels were fabricated and tested as per Eurocode EN-1448-5 (2006). The effect of total replacement of main steel reinforcement by bamboo on the flexural behaviour of slabs in terms of load-deformation characteristics, energy absorption capacity, crack patterns and failure modes have been studied. Test results show that there is improvement in the load carrying and deformation capacity when proposed bamboo strip is used as reinforcement in concrete slab panels as compared to that of PCC (Plain Cement Concrete) and RCC (Reinforced Cement Concrete) slabs. Interestingly the structural behaviour of slabs using newly developed bamboo reinforcement has shown significant improvement in flexural performance and it was marginally better than the RC slabs having M.S. bars as main reinforcement.

1. Introduction

The reinforcing of concrete structures has been studied by using fibrous reinforcement materials. These fibrous reinforcements include synthetic and natural fiber. Besides synthetic fibers other materials such as steel, glass and carbon in fibrous form have been used as concrete reinforcement along with concrete. Although these conventional materials provide significant improvement in properties of concrete they are obtained from nonrenewable and unsustainable sources which makes them a costly building material. Considering the limitations of these synthetic fibers the focus has been to use renewable and sustainable material. These are natural fibers which contains lignocellulosic materials in their composition. There are many such materials exist in the nature which have the potential to be used in concrete and make concrete structures more sustainable and ecofriendly. One such fiber which belongs to Grass family is bamboo [1].

Conventional RC structures are made up of steel and concrete. This form of structures is built because of their ability to withstand high loads, ease in construction, durability, etc. Over the period of time especially, in last two decades, there is a tremendous increase in demand for housing and infrastructure and the majority of them is RC structures. To meet this requirement, the production rate of cement and steel are boosted and now reaching to the point of

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https://doi.org/10.1016/j.conbuildmat.2018.08.162
0950-0618/

saturation. The scenario in developing countries is not so favorable as the demand for this conventional material kept on increasing but the amount of material is limited. Moreover, the level of destruction caused to the atmosphere is enormous. The amount of CO_2 released in the atmosphere is about 50 times higher in steel and cement production compared to bamboo which consumes 1-tonne of CO_2 during its growth [2,3]. Being the fastest growing renewable, eco-friendly material, it could be a proper and a sustainable alternative to conventional steel reinforcement.

There are more than 1200 species of bamboo currently noted around the globe [3]. The availability of bamboo species depends upon the locality, type of soil, climatic condition, water, etc. Interestingly the availability of bamboo is very high in regions adjacent to developing countries. Also, in small villages of these countries bamboo is being used extensively as a building material from long past.

The traditional method of selecting engineering materials is no longer solely based on strength, efficiency and cost, but additional consideration must be given to the performance of the material, not only in terms of structural capacity but also in terms of the environment. Bamboo in its natural form is a highly efficient material. With these additional parameters under consideration, bamboo quickly becomes a potential reinforcing material for structural use [3].

From technical perspective bamboo is a fast-growing grass. It has high strength to weight ratio (about six times higher compared to steel) compared to reinforcing steel; it reaches its optimum strength in 3–4 years and attains complete maturity in 5 years. Like a steel bar it can support both tension and compression parallel to fibers, whereas many other materials cannot withstand against compression loading. However, being an organic material, durability of the material is a drawback for bamboo [4].

Many researchers have carried out their experimentation on the feasibility of using bamboo as alternative reinforcement in structural concrete. The use of raw bamboo either full culm or in the form of splints (A strip of bamboo culm) has three major disadvantages. The first one is the durability of bamboo strips over a considerable period of time inside structural concrete leading to weakening and splitting of bamboo fibers due to water absorption. The second is chemical decomposition of bamboo due to alkaline nature of aqueous concrete. The third is the loss of bonding between bamboo and concrete due to inadequate chemical and mechanical action at the interface. The above issues have been addressed by many researchers. A few important works have been discussed below to study the structural behavior of bamboo reinforced concrete (BRC) members. In 2016, [5] have investigated impact behaviour of BRC simply supported one-way slabs (300 mm x 300 mm) under impact loading. The concrete used for casting slab panels consist of rice husk in 5% and 10% proportion (with respect to Ordinary Portland Cement complying to ASTM type I). The effect of bamboo diameter and slab thickness on impact strength of slab panels were studied during the experimentation. It is reported that there exists a linear relationship for first and ultimate crack strength with respect to bamboo diameter and slab thickness in both type of concrete mix. The impact strength of these BRC slabs compared to conventional RCC slabs (control specimens) needs further investigation. [6] in 2013 investigated the performance of BRC slab panels subjected to impact loading. In this work, they have used oil palm shells (OPS) as substitute to conventional aggregate inside concrete mix with OPS to cement ratio as 0.45 and 0.6. The impact strength for first crack was mainly influenced by bamboo diameter but it is even more sensitive to slab thickness.

Several researches had been carried out specifically on use of bamboo strip as main reinforcement in slab panels. For instance, [7] in 2017 have examined the flexural performance of BRC slabs with Styrofoam as infill panel which is a type of expanded polystyrene (EPS). EPS is a recyclable and ecofriendly material. It was reported that slabs casted with the combination of bamboo reinforcement and EPS infill panel becomes light in weight by 27%, with 6% decrease in load carrying capacity. The bond slip strength of the bamboo reinforcement could have been improved more by incorporating additional mechanical action at bamboo concrete interface. This might have helped in enhancing load-deformation behaviour of BRC slabs. [8] in 2016 has investigated the flexural behaviour of bamboo based ferrocement slab panels. They have used bamboo strip skeletal as reinforcement in one-way slabs along with chicken wire mesh. The effect of replacement of cement by fly ash and with variation in thickness of slab has been studied. The results of slabs tested under monotonically increasing uniformly distributed flexural load show that the first crack load and ultimate loads were similar in both type of slabs. The contribution of bamboo strips with respect to mortar and wire mesh of the theoretical ultimate capacity of slab was about three times higher corresponding to the experimental ultimate load capacity. [9] in 2001 used *babudua* bamboo bars (*Thalia Geniculata*) as main reinforcement in one-way slabs. There was significant improvement in both flexural and shear strength of slabs relative to the theoretically predicted results. These slabs have exhibited high ductile behaviour and produced large deflections prior to failure. [10] in 2003 also used *babudua T. Geniculata* bamboo bars as main reinforcement in two-way slabs which are supported on all four sides. This time this author has tested the slabs under monotonic as well as cyclic loading and it was observed that there was significant improvement in flexural strength and punching shear strength of these slabs than those of theoretically predicted values under both type of loading conditions. *Babudua* bamboo reinforcement in concrete slab has provided adequate stiffness against deflection. [11] in 2015 have investigated the effect of bamboo reinforcement on flexural behaviour of slab panels under centrally uniformly distributed load. They reported that the slabs have performed better when bamboo and steel reinforcement are used together, compared to steel reinforcement samples (control specimens) as well as bamboo reinforcement samples (bamboo alone). [12] in 2014 tested BRC slabs under concentrated uniformly distributed load. The design moment was found less than the experimental ultimate moment. It is reported that this behaviour of BRC slabs was very similar to the conventional RCC slabs and hence working stress method can be used to design BRC elements. [13] in 2013 have used bamboo splints as reinforcing material in bamboo reinforced concrete wall panels (BRCWP). The bamboo reinforcement cage was prepared as per the guidelines of NBC India (2016), part-6. The bamboo splints of width 20 mm and thickness around 8–15 mm have been used with simple varnish coating and sand blasting. The wall panels are then tested under uniformly distributed eccentric loading from top and bottom ends resembling a two action of load. The effect of aspect ratio (AR: 1.6–2) and thickness ratio (TR: 12.5–15) on ultimate load and deformations at predefined locations have been observed during the experimentation. While slenderness ratio and grade of concrete were kept constant. It was reported that ultimate load of BRCWP increases with increase in TR and it decreases with increase in AR. An equation was proposed based on the observation to predict the ultimate load of BRCWP. The previous research work shows that bamboo has the required potential to be used as main reinforcement in structural concrete. Such BRC members can be more durable if the bamboo concrete bond behaviour is taken care. The efficiency of the proposed bamboo strip profile along with the surface treatment has been explored experimentally in the present study.

In the present work, feasibility and performance of slab panels using bamboo strips as main reinforcement has been investigated experimentally. Fifteen slabs were tested which include three major categories i.e. PCC (Plain cement concrete), RCC (Reinforced cement concrete), and BRC (bamboo reinforced concrete). The experimentation included a series of flexure tests performed using Flexural testing machine (FTM). The flexural performance of each slab panel under concentrated loading was investigated experimentally.

2. Experimental programme

The experimentation has been carried out in the following steps:

- General Characteristics of Bamboo Reinforcement
- Bamboo Surface Treatment and procedure
- Casting and Curing Concrete slab panels
- Testing Methodology

2.1. General characteristics of bamboo reinforcement

Selection of bamboo from many available species was difficult. There is a huge variation in bamboo species from the site and culm position. There were many species of bamboo available in the local region. So, only one has to be shortlisted. This is done with the help of literature related to the cultivation and harvesting of bamboo along with field experts in the local bamboo industry. It was decided, to use *Bambusa arundinacea* (Katang) as it is found suitable than other species in terms of its mechanical and physical properties. National Building code of India (NBC) [14] have mentioned its use for construction purposes.

The bamboo samples chosen for study were between 4 and 5 years of age. At this age, this species shows the highest performance in terms of its mechanical and physical characteristics [2,15]. 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 fibers (the fiber concentration of bamboo culm was maximum at the outside region of the culm compared to the inside region). This exercise helped to select good samples representing good physical and mechanical properties [16].

The raw bamboo culm was first processed in the laboratory. After procuring bamboo samples they are first cleaned manually to remove any natural substances attached to its exterior surface, then these samples are kept in a 6% boric acid solution with normal water for 72 h. This exercise is done to protect bamboo from termites and insects to prevent borers attack before the application of bamboo as reinforcement. After 72 h bamboo culms are air dried in mild temperature for 5 days. Then these well processed samples are used for making splints (Size: 600 mm x 20 mm × 10 mm) used as reinforcement. These specimens were having moisture content of 25% with density of 1125 kg/m^3 [16–18].

To find out the physical and mechanical properties of the chosen bamboo species, guidelines provided by IS: 6874 [19] and ISO 22157 [20] have been followed. Table 1, shows results of various mechanical properties. Finally, these selected bamboo specimens are further subjected to surface treatment to eliminate shrinkage of bamboo inside concrete.

2.2. Bamboo surface treatment and procedure

In order to study and improve bamboo-concrete bond behaviour a series of pull-out tests were carried out. During these tests, the effect of chemical action due to surface treatment and effect of mechanical action due to grooves on bamboo profile was studied extensively. Many groove profile patterns for bamboo along with various surface coatings were studied together, to arrive at most effective surface treatment and groove pattern.

It is ensured that the conventional bamboo strip is plain along the length and possesses a rectangular cross section approximately as shown in Fig. 1 (20 mm × 10 mm). The newly developed bamboo profile consist of semicircular grooves along the thickness of same (plain) bamboo as shown in Fig. 2 The groove pattern is designed such that maximum pull-out strength is developed at the bamboo - concrete interface through the groove concrete interlocking. This is achieved

Table 1
Mechanical properties of *B. arundinacea.*

S.N.	Type of test	Parameter	*Bambusa arundinacea*
1	Tension	Young's Modulus (MPa)	7560
		Stress at peak (MPa)	200
		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

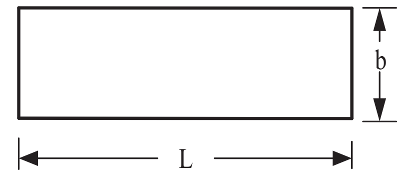

Fig. 1. Regular plain rectangular bamboo strip.

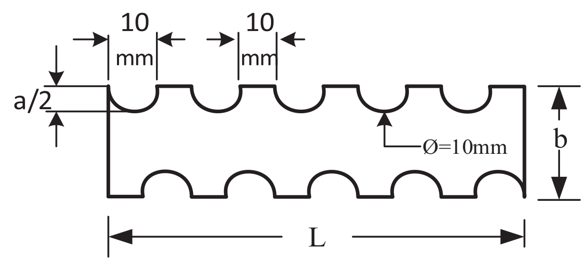

Fig. 2. Semicircular grooved rectangular bamboo strip.

when a 10 mm diameter semicircular groove created at a spacing of 20 mm c/c in a zigzag manner.

In the present work for bamboo surface treatment a total of six chemical coatings were explored. Among the treatments Bond tite chemical was found most effective in improving bond strength. The surface treatment was carried out in two-steps. In the first step, solution of Bond Tite chemical was prepared, this consist mixing of two parts, part A and part B as per the standard proportion mentioned by the manufacturer, i.e. 100:100 by volume or 100:80 by weight, it was then applied to the bamboo strips prepared for making slab panel specimens. This coating will ensure that the bamboo strips remains water repellent. Immediately after the coating of chemical mixture, the bamboo strips are helically wrapped with a single layer of plain steel wire with uniform diameter of 1 mm and yield strength of 400 MPa. Finally, the coated specimens are subjected to sand blasting process; sand particles used in the process were of size 1 mm to 2 mm. Both types of bamboo strip reinforcement (plain and grooved) develops initial friction with a combined effect of sand particles and wrapped steel wire at bamboo concrete interface. The grooved and plain bamboo reinforcement post surface treatment are shown in Figs. 3 and 4, respectively.

In the present work Bond Tite chemical adhesive was used to coat exterior surface of the bamboo strip. The quantity (weight based) of this mixture required to form a uniform thin coating on the plain bamboo strip is about 10 gm, which cost ₹8/-. Apart from this, on an average ₹1.5/- per meter was required to procure raw bamboo strip. The treatment also included fine sand particles (20 gm) and wrapped thin steel wire (2 m), which together cost around ₹2/- per meter length of the bamboo strip. Therefore, total cost of complete treatment for one-meter bamboo strip is ₹11.5/- nearly same amount is required for grooved bamboo strip also. Therefore, the ratio of the cost of steel reinforcement to the cost of treated bamboo strip per meter length is 1.3, 2.08, 3.2 for 6 mm; 8 mm and 10 mm diameter bar and this cost increases even more as the diameter of reinforcing bar increases. Hence cost wise treated bamboo strips are economical than that of the conventional steel reinforcement.

Unlike conventional steel, the manufacturing of bond tite chemical adhesive does not have any hazardous impact on the surrounding atmosphere in the form

Fig. 3. Preparation of grooved bamboo reinforcement.

Fig. 4. Preparation of plain bamboo reinforcement.

of harmful gas emissions as reported in technical and material safety data sheet. Being a versatile adhesive, it is easy to use and can function in any weather conditions. Also, this chemical possesses excellent thermal properties as well as extremely low water absorption.

2.3. Casting and curing of concrete samples

2.3.1. Selection of type of concrete

Only one grade of concrete (M20) was used as concrete is a common part in this work. The mix design and testing of concrete specimens (cube) was carried out as per the guidelines of IS 10262 and IS 456 [21,22]. Final mix proportion along with other important properties are shown in Table 2. In the mixed design, the coarse aggregate quantity was used as a combination of 20 mm and 10 mm size aggregate in the ratio of 70:30 in order to easily accommodate concrete mass with 10 mm size aggregate into the semicircular groove thereby establishing bamboo-concrete interlocking. The cement used is Ordinary Portland Cement (OPC) 53 grade complying to IS 12,269 [23]. After casting and 28 days curing of concrete specimens these were tested for determining important properties, as reported at Table 2.

The slab test specimens were divided into five categories; each category consisting of three specimens each. Amongst the five categories two were control category which were identified as PCC (Plain cement concrete) and RCC (Reinforced cement concrete). The remaining three categories were basically of BRC slab panels. These samples were given identification based on the type of bamboo reinforcement used. They were: UTBRC i.e. Untreated (plain) BRC slab panels, PTBRC i.e. Plain treated BRC slab panels, GTBRC i.e. Grooved treated BRC slab panels.

2.3.2. Casting of slab panel test specimens

As per the guidelines of European standard EN 14488-5 [24] the casting of all slab specimens was done. A square type PCC, RCC, and BRC slab panels were casted. Fig. 5 shows schematic representation of slab panel specimen and its test setup.

The main reinforcement cage prepared for BRC as well as RCC types of slabs are shown in Figs. 6 and 7, respectively. This reinforcement cage was placed inside the

Table 2
Properties of the concrete.

Mix Proportion C: S: A	Compression (MPa)			Tensile strength (MPa)	Flexural strength (MPa)	Specific weight (kg/m^3)	Slump (mm)
1:2.46:4.07 at water to cement ratio of 0.55	Strength 28	Elastic modulus 24,000	Design strength 20	2.35	4.7	2400	45

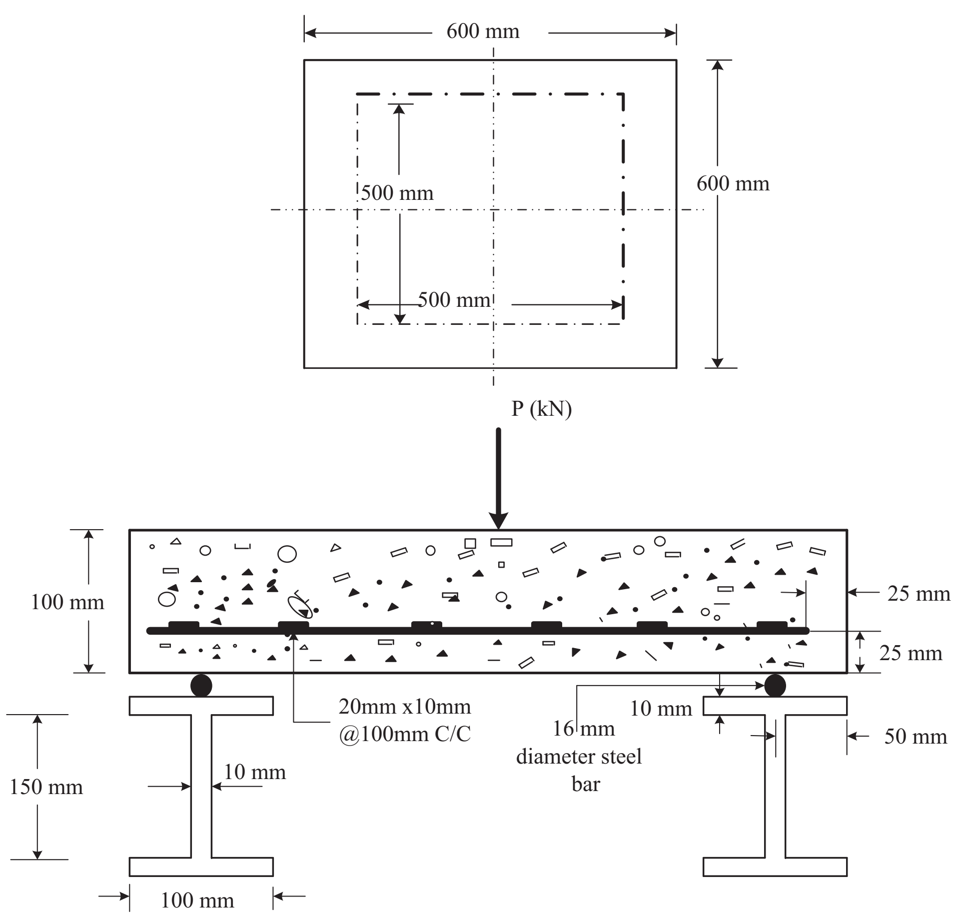

Fig. 5. Schematic representation of slab panels and supporting frame used during test.

Fig. 6. Casting of PTBRC and GTBRC slab panels.

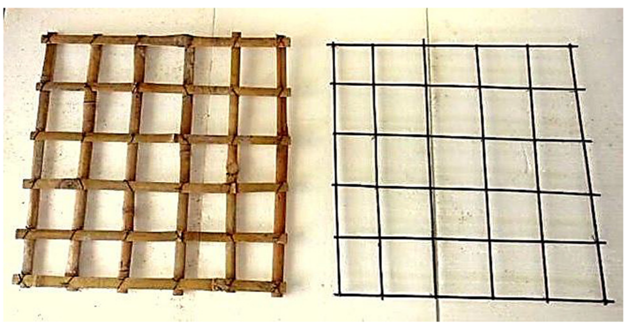

Fig. 7. Casting of UTBRC and RCC slab panels.

mould uniformly at an effective cover of 25 mm from bottom and all four side edges.

In RCC slabs the steel rebars used were of 6 mm diameter and a yield strength of 250 MPa (IS Fe-250 grade) placed at 110 mm c/c (0.3%). The casting of all 15 slabs was carried out in batches. Each batch consists of three slab samples and three cube specimens to ascertain concrete compressive strength. The average cube strength of each batch at the age of 7 days and 28 days was 19 MPa and 28 MPa, respectively. The slab panels after casting kept for initial setting of fresh concrete remained at room temperature of 28$_{0}$c and humidity of 50% in laboratory. These specimens were demoulded after 24 h. and kept inside curing tank under normal temperature for 28 days. Overall size of each slab was 600 mm × 600 mm × 100 mm; the cross section of bamboo strip used was 20 mm × 10 mm, approximately. The spacing of bamboo reinforcement was 100 mm c/c (2%) with a total length of 550 mm in each principal direction. The slab specimen was resting on a solid circular rod of 16 mm diameter which was attached to a square shape supporting frame made of hard steel material using I-section as shown in cross section of Fig. 5. The solid circular cross section rod acts like a continuous roller support along all the four sides. The span of slab was considered as c/c distance between two opposite rods -500 mm.

Fig. 8. FTM used during slab testing.

Fig. 9. Slab panel subjected to central concentrated load.

2.4. Testing Methodology

The experimental setup consisted of a FTM confirming to 4.2 and 4.3 of EN 12390-4 (2000) of 100 kN capacity [25]. The load cell was used to apply concentrated loading as shown in Fig. 8. Digital LVDT (Linear Variable Displacement Transducer) was used to measure the deformation placed at the centre of slab, as shown in Fig. 9.

Specimen was placed inside the set up prepared for flexure test as shown in Fig. 8. It was ensured that loading head, central cross section of specimen and fixed bottom support lies in one vertical plane. The load was gradually applied at the interval of 100 N/S. The readings of load and deformation were recorded by a calibrated electronic control system attached with a host PC. The specimens were loaded till the failure. The results of slab panels obtained from FTM are summarized in Table 3. The load and deflections at instant of first crack and at ultimate stage were recorded.

3. Test results and discussions

The calculation of ductility and energy absorption capacity parameters for slab samples was carried out with the help of these results. The PCC slabs have showed linear elastic behaviour up to first crack load of 35 kN at an average displacement of 2.2 mm as shown in Fig. 10.

After the first crack, the slabs failed suddenly showing a brittle mode of failure as seen by the crack pattern in Fig. 11. The maximum load supported by PCC slabs was 37 kN at an average displacement of 2.35 mm. The brittle mode of failure is mainly because of absence of any reinforcing material in concrete. Results in Table 3, shows that PCC slabs have least ductility and energy absorption capacity.

Table 3 shows that conventional RCC slabs having 6 mm diameter steel bars in both principal directions have supported higher average ultimate load of 70.9 kN at an average displacement of 7.8 mm. RCC slabs showed linear elastic behaviour as observed in Fig. 12 till the point where load nearly reaches to a constant value at the occurrence of first crack. The failure of RCC slabs was because of diagonal tension cracks as can be seen from the crack patterns at tension face (bottom side) of the slab panel shown in Fig. 13. The deformation ductility and energy absorption capacity were found to be maximum in this category among all of the slabs considered.

From Table 3, it was observed that UTBRC slabs have sustained ultimate load of 60.6 kN at average displacement of 5.48 mm before failure. This ultimate load was 51% higher than ultimate load of PCC slabs. Similarly, there was improvement in the ductility and energy absorption capacity of UTBRC slabs compared to PCC slabs. This confirms the effect of bamboo strip reinforcement, even though it was untreated, it increased the slab strength compared to PCC.

Fig. 14 shows that initially slabs behave in a linear elastic manner till the ultimate load was reached, then the curve starts dropping rapidly from the point of failure. In the crack pattern observed

Table 3
Experimental Results of Loads and Deflections.

Slab series	Load at First Crack (kN)	Deflection at First Crack load (mm)	Ultimate Load (kN)	Deflection at Ultimate load (mm)	Ratio of Ultimate load to first crack load	Ratio of Deflection at Ultimate load to first crack load	Energy Absorption (Joules)
PCC-1	35	2.1	41.0	2.5	1.2	1.171	61.0
PCC-2	34	2.3	38.9	2.4	1.1	1.040	53.4
PCC-3	37	2.3	40.0	2.4	1.0	1.045	57.2
Average	**35 ± 1.5**	**2.26 ± 0.1**	**40.03 ± 1**	**2.45 ± 0.06**	**1.134**	**1.085**	**57.19 ± 3**
RCC-1	55	3.0	71.6	8.4	1.3	2.789	535.5
RCC-2	53	2.9	70.5	7.6	1.3	2.545	466.0
RCC-3	50	2.8	70.6	7.7	1.4	2.745	407.8
Average	**53 ± 2.5**	**2.92 ± 0.1**	**70.92 ± 0.6**	**7.87 ± 0.42**	**1.349**	**2.693**	**469.83 ± 63**
UTBRC-1	40	2.8	58.3	6.1	1.4	2.183	289.2
UTBRC-2	41	2.9	62.7	5.9	1.5	2.024	281.5
UTBRC-3	42	3.2	60.9	5.5	1.4	1.706	211.5
Average	**41 ± 1**	**2.98 ± 0.2**	**60.61 ± 2**	**5.84 ± 0.34**	**1.478**	**1.971**	**260.79 ± 42**
PTBRC-1	45	3.0	71.3	6.7	1.6	2.299	289.1
PTBRC-2	44	2.7	69.4	7.3	1.6	2.692	338.3
PTBRC-3	48	2.4	69.4	7.0	1.4	2.922	337.8
Average	**46 ± 2**	**2.70 ± 0.3**	**70.11 ± 1**	**7.05 ± 0.19**	**1.538**	**2.637**	**321.74 ± 28**
GTBRC-1	58	2.6	79.4	9.6	1.4	3.678	411.6
GTBRC-2	55	2.3	75.5	9.2	1.4	3.980	506.6
GTBRC-3	60	2.4	76.3	9.1	1.3	3.794	379.6
Average	**58 ± 5.5**	**2.43 ± 0.1**	**77.09 ± 2**	**9.27 ± 0.25**	**1.338**	**3.817**	**432.63 ± 66**

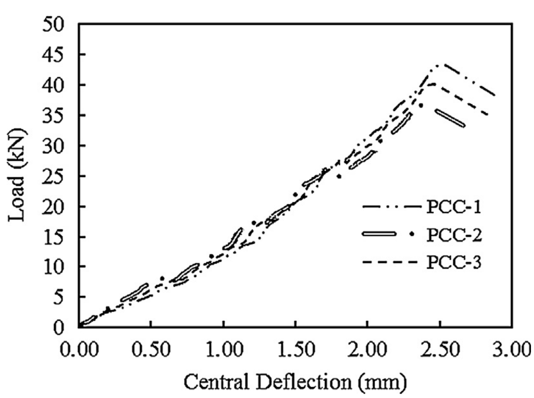

Fig. 10. Load-deflection response of PCC slab.

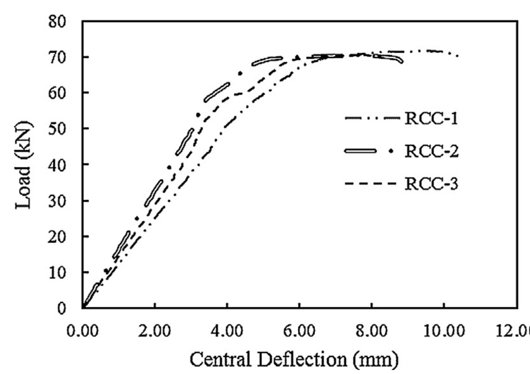

Fig. 12. Load-deflection response of RCC slab.

Fig. 11. Crack pattern in PCC slab.

Fig. 13. Crack pattern in RCC slab.

at Fig. 15 reported diagonal tension crack except few which moves normal towards the four sides of the slab.

Fig. 16 shows linear elastic behaviour of PTBRC slabs till the ultimate load was reached and then the curve drops suddenly. The results of PTBRC slabs have showed an increase in ultimate load by 75% and 51% compared to PCC and UTBRC slabs, respectively. The ultimate load of PTBRC slab has reached very close to that of RCC slabs. The average maximum deformation of PTBRC slabs was relatively less than those of RCC slabs. It can be seen that the crack on the bottom face has initiated from centre of slab and

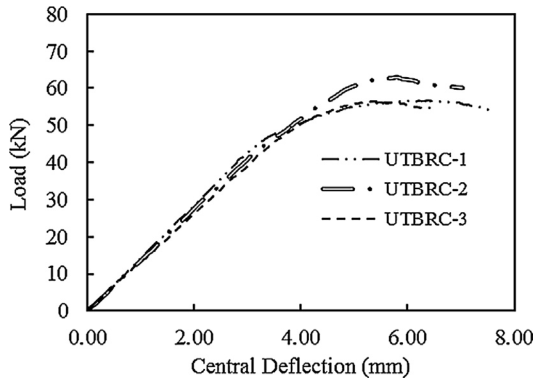

Fig. 14. Load-deflection response of UTBRC slab.

Fig. 15. Crack pattern in UTBRC slab.

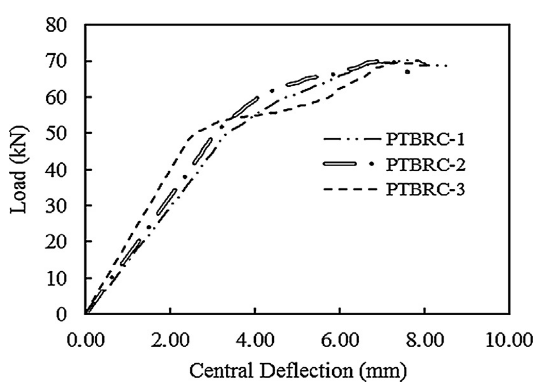

Fig. 16. Load-deflection response of PTBRC slab.

propagated towards four sides of slabs as shown in Fig. 17. Energy absorbed by PTBRC slabs is 23% more than UTBRC slabs

This indicates that the proposed surface treatment improved the bamboo concrete composite action, by enhancing bond strength at the bamboo-concrete interface. Further these treated plain bamboos are grooved and used in slab panels (GTBRC).

GTBRC slabs showed increase in ultimate load by 92.5%, 8.7%, 27.2% and 10% as compared to PCC, RCC, UTBRC and PTBRC slab panels, respectively, as showed in Table 3.

Fig. 18 shows that these slabs had linear elastic behaviour before failure takes place. Energy absorption capacity of these slabs

Fig. 17. Crack pattern in PTBRC slab.

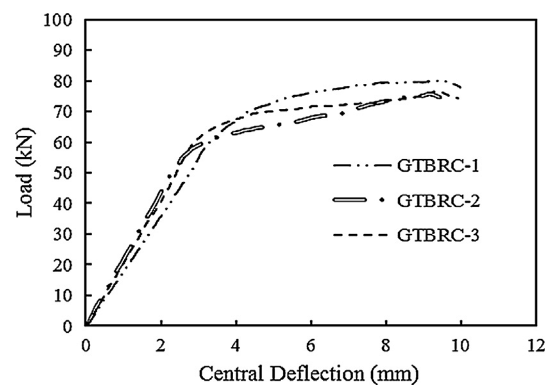

Fig. 18. Load-deflection response of GTBRC slab.

was higher than other BRC slabs and it was very close (8.6% less) to RCC slabs. The additional increase in load carrying capacity was primarily because of adequate bonding between bamboo and concrete.

The enhancement in bamboo-concrete bond has significantly improved the bamboo concrete composite action. The chemical action of surface treatment and mechanical action of groove-concrete interlocking simultaneously were responsible for providing the additional bond strength. This resulted in increased flexural strength of slab panels having bamboo reinforcement which were

Fig. 19. Crack pattern in GTBRC slab.

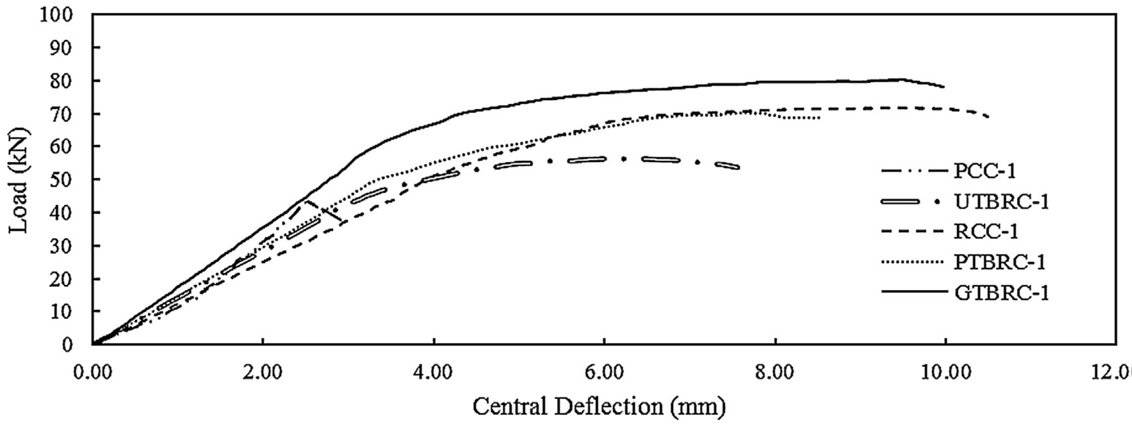

Fig. 20. Comparison of Load-deflection response of all slabs.

treated and grooved as per the proposed procedure. The failure of GTBRC slab specimen was assessed by the crack pattern shown in Fig. 19. In this case, the cracks have originated on the tension side, at the periphery of rectangular loading plunger and radiated diagonally towards each corner indicating ductile mode of failure.

Fig. 20 compares the behaviour of all of the 5 types of slab panels under concentrated flexural loading. The effect of reinforcing material on flexural strength of slabs can be observed from the curves shown in Fig. 20. Flexural strength increases from PCC to GTBRC slab panels. This is because of the contribution of tensile strength and energy absorption capacity of bamboo strip reinforcement used in untreated, treated and grooved treated forms.

4. Observations and conclusions

The present research investigated the flexural performance of BRC slab panels under concentrated loading. The contribution of bamboo strips of *B. arundinacea* which are used as main reinforcement in concrete slab panels was investigated experimentally. The experimental investigation showed that the first crack load of slabs increases in the order of 'PCC', 'UTBRC', 'PTBRC', 'RCC'; 'GTBRC'. In the other hand the increase in ultimate load carrying capacity alters in the sequence of 'PCC'(minimum), 'UTBRC', 'RCC' 'PTBRC', 'GTBRC'. The contribution of bamboo strips with respect to PCC in each of the BRC slab was around 1.5–2 times higher in increasing flexural strength at limited deflections and it was similar to those of conventional RCC slabs. The energy absorption capacity of GTBRC slabs under the same deflections was relatively higher by 48%, 21% and 9% than PCC, UTBRC and PTBRC slabs respectively. The overall research showed that instead of using treated plain bamboo strip, the proposed grooved bamboo strip (2%) used in concrete slab panels, improved flexural strength, energy absorption capacity, ductility and mode of failure (ductile) compared to that of PTBRC and RCC (0.3%) slab panels. However, the durability of such BRC members against the extreme atmospheric conditions needs further investigation. Finally, it can be concluded that bamboo strips of B. *arundinacea* if treated with this proposed technique can be used as reinforcing material in concrete slab panels. And such type of BRC structural members can be used in low cost housing as roofing member under a limited gravity loading situation. This type of BRC slabs may prove to be very economical and eco-friendly solution, compared to conventional RCC slabs.

5. Conflict of interest

The authors declared that there are no conflict of interest.

Acknowledgement

This research was 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

[1] A. Anandamurthy, V. Guna, M. Ilangovan, N. Reddy, A review of fibrous reinforcements of concrete, J. Reinf. Plast. Compos. 36 (7) (2017) 519–552.
[2] Y. Xiao, R.Z. Yang, B. Shan, Production, environmental impact and mechanical properties of glubam, Constr. Build. Mater. 1 (44) (2013) 765–773.
[3] B. Sharma, A. Gatoo, M. Bock, H. Mulligan, M. Ramage, Engineered bamboo: state of the art, Proc. Inst. Civ. Eng,-Constr. Mater. 168 (2) (2014) 57–67.
[4] S.R. Imadi, I. Mahmood, A.G. Kazi, Bamboo fiber processing, properties, and applications, in: Biomass and Bioenergy, Springer, Cham, 2014, pp. 27–46.
[5] Z.C. Muda, S. Beddu, A. Syamsir, J.S. Ating, N.L. Kamal, K.N. Mustapha, S. Thiruchelvam, F. Usman, M.A. Alam, A.H. Birima, O.S. Zaroog, Impact resistance behaviour of light weight rice husk concrete with bamboo reinforcement, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2016. 1, 012020.
[6] Z.C. Muda, F. Usman, S. Beddu, M.A. Alam, S. Thiruchelvam, L.M. Sidek, H. Basri, S. Saadi, Impact resistance performance of green construction material using light weight oil palm shells reinforced bamboo concrete slab, IOP Conference Series: Earth and Environmental Science, IOP Publishing, 2013. 1, 012063.
[7] A. Wibowo, I. Wijatmiko, C.R. Nainggola, Structural behavior of lightweight bamboo reinforced concrete slab with EPS infill panel, AIP Conf. Proc., AIP Publishing, 2017. 1, 020024.
[8] S.J. Chithambaram, S. Kumar, Flexural behaviour of bamboo based ferrocement slab panels with flyash, Constr. Build. Mater. 134 (2017) 641–648.
[9] C.K. Kankam, B. Odum-Ewuakye, Flexural behaviour of babadua reinforced one-way slabs subjected to third-point loading, Constr. Build. Mater. 15 (1) (2001) 27–33.
[10] C.K. Kankam, B. Odum-Ewuakye, Babadua reinforced concrete two-way slabs subjected to concentrated loading, Constr. Build. Mater. 20 (5) (2006) 279–285.
[11] P.M. Perera and C.S. Lewangamage. Experimental investigation on flexural behaviour of bamboo reinforced concrete slab panels. <https://www.researchgate.net/profile/Jude_Perera/publication/.pdf>.
[12] D. Bhonde, P.B. Nagarnaik, D.K. Parbat, U.P. Waghe, Experimental investigation of bamboo reinforced concrete slab, Am. J. Eng. Res. 3 (1) (2014) 128–131.
[13] N. Ganesan, P.V. Indira, P.R. Himasree, Strength and behaviour of bamboo reinforced concrete wall panels under two way in-plane action, Adv. Concr. Constr. 6 (1) (2018) 1–13.
[14] National Building Code of India, Group-2, Part 6 Section 3B, Bureau of Indian Standards, New Delhi, 2005.
[15] H.C. Lima, F.L. Willrich, N.P. Barbosa, M.A. Rosa, B.S. Cunha, Durability analysis of bamboo as concrete reinforcement, Mater. Struct. 41 (5) (2008) 981–989.
[16] B. Sharma, A. Gatóo, M.H. Ramage, Effect of processing methods on the mechanical properties of engineered bamboo, Constr. Build. Mater. 15 (83) (2015) 95–101.
[17] Y.M. Zhang, Y.L. Yu, W.J. Yu, Effect of thermal treatment on the physical and mechanical properties of Phyllostachys pubescens bamboo, Eur. J. Wood Wood Prod. 71 (1) (2013) 61–67.
[18] T. Tan, N. Rahbar, S.M. Allameh, S. Kwofie, D. Dissmore, K. Ghavami, W.O. Soboyejo, Mechanical properties of functionally graded hierarchical bamboo structures, Acta Biomater. 7 (10) (2011) 3796–3803.

[19] Indian Standard Specifications for Method of Tests for Bamboo, I.S. 6874:2008, Bureau of Indian Standards, New Delhi, 2008.
[20] ISO (International Organization for Standardization). International standard ISO 22157–1:2004 (E), bamboo – determination of physical and mechanical properties – part I: requirements. Geneva (Switzerland): ISO, 2004.
[21] Indian Standard Specifications for Concrete Mix Proportioning Guidelines, I. S. 10262: 2009, Bureau of Indian Standards, New Delhi, 2009.
[22] Indian Standard Specifications for Code of Practice for Plain and Reinforced Concrete, IS 456-2000, Bureau of Indian Standards, New Delhi, 1987.
[23] Indian Standard Specifications for Ordinary Portland Cement, 53 Grade, IS 12269-2013, Bureau of Indian Standards, New Delhi, India, 2013.
[24] Testing of sprayed concrete - Part 5: Determination of energy absorption capacity of fiber reinforced slab specimens. British Standard. 2006. BS EN 14488-5, 2006.
[25] Testing of hardened concrete - Part 4: Compressive strength – Specification for testing machines. British Standard. 2000. BS EN 12390-4, 2000.