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Investigation on Elastic Properties of Bamboo and Behavior of Bamboo Reinforced Concrete Beams

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Abstract: *Research is being undertaken to find an alternate material to steel in reinforced concrete elements. Bamboo has emerged as a possible material, which can be used as an alternative to steel. Present research work involves both experimental and analytical studies. In experimental study, various physical and mechanical properties of bamboo were evaluated. A comparative study was conducted on bamboo reinforced concrete beam and steel reinforced concrete beam, in terms of flexural strength, shear strength and bond strength. In analytical study, finite element modelling of PC, RC and BRC beams were performed using commercially available finite element software, ABAQUS. Results obtained from experiments were used as input for modelling.*

Keywords: *Modulus of elasticity, Poisson's ratio, Flexural strength, Shear strength, Bond strength, FEM, ABAQUS*

1. Introduction

Present day construction industry is heavily dependent on two materials, concrete and steel. The consumption of former has its bearing on cement which marked 4.3 billion metric tons of global consumption in 2014 [1], whereas 840 million metric tons of steel as rebar has been consumed globally in the same year [2].

Even though high rise buildings and other dominant structures in developed countries takes lion's share in global consumption of building materials, consumption cannot be ignored in low rise dwellings on which urban population in developing countries like India and other South Asian countries depend upon. Most of these low rise buildings are reinforced concrete structures. The scope of the present study is to investigate the feasibility of bamboo, as an alternative to steel rebar for beams in low rise structures.

Bamboo has a clear advantage over steel on cost comparison. Cost of steel used as rebar is as high as Rs.45000 per metric ton in Bengaluru, India [3], and bamboo costs approximately Rs.5000 per metric ton. There are research works carried out on bamboo, to understand its feasibility as a reinforcing material. But still the practical application of the same has not seen the light of day due to lack of information related to its practical applicability such as its design considerations, its ability to take loads, its durability, its cutting and bending etc. [4]

In the present study, physical and elastic properties of bamboo were investigated. Steel reinforced concrete elements and bamboo reinforced concrete elements were compared in terms of its flexure, shear and bond strength. Finite element analysis of RC and BRC beams were conducted and results were compared with experimental results.

2. Literature review

There are numerous research articles, discussing the possibility of bamboo as a reinforcing material. According to Ghavami (2004) [5], bamboo has the potential to be utilized as a reinforcing material, which possesses high tensile strength of 370 MPa. National Building Code of India (2005) Group 2 (Section 3B) [6] provides information about various physical and mechanical properties of bamboo available in India. According to which, average density of various species of bamboo available in India is 614 kg/m³. Compressive strength of bamboo culms is 42 MPa. Modulus of elasticity of bamboo is 7762 MPa. Lima et al (2008) [7] studied the durability aspects of bamboo, when it is used as reinforcement in concrete. Bamboo reinforced beams were subjected to various chemical attack repeatedly and bamboo splints were removed and tested for mechanical strength. It was observed that there was not much significant change in properties of bamboo, thus confirming its durability aspects. Vengala et al. (2010) [8] researched on compressive strength, flexure strength and shear strength of bamboo culms and obtained 47 MPa as maximum compressive strength, 11 MPa as maximum shear strength, 60 MPa as maximum flexural strength. Modulus of elasticity of bamboo was obtained in the range of 20000 MPa to 40000 MPa. Sen et al. (2011) [9] performed analytical study on plain concrete laminates with bamboo as retrofitting material and it was concluded that load carrying capacity of beams increased by 83.3% with the application of bamboo retrofitting. It has also been discussed by the author that 0.75% to 5% is

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practically applicable percentage of reinforcement for a bamboo reinforced beam.

Zhang et al. (2012) [10] determined elastic modulus of recombinant bamboo as 37 GPa, and compression strength of 129 MPa. Terai et al. (2012) [11] have reported the tensile strength of bamboo as 197 Mpa, and bond strength of bamboo with M10 concrete was found to be 1.2 MPa to 1.35MPa.

Sakaray et al. (2012) [12] evaluated the tensile strength of bamboo as 125MPa, compressive strength as 108Mpa and modulus of elasticity as 15000MPa. Sidhpura et al. (2013) [13] obtained the tensile strength of bamboo as 174 MPa and ultimate load taken by BRC beams was 41kN. According to Sabnani et al. (2013) [4], bamboo possesses enough strength to be used as replacement to steel. The authors have commented that design of bamboo reinforcement is similar to steel reinforcement.

Patel et al. (2013) [14] researched on bamboo reinforced slab panels and obtained deflection of 10mm for singly reinforced and 6.85mm for doubly reinforced panels of size 900mm x 250mm x 75mm. Khan (2014) [15] conducted flexural strength test on BRC beams by varying the cross section shape of bamboo splints in beams and reported flexural strength of beams as 6.48MPa for triangular shaped splints. Sethiya et al. (2014) [16] have reported tensile strength of bamboo splints as 114MPa and compressive strength as 70.16 MPa.

Gupta et al. (2015) [17] performed a thorough study on bamboo for investigating its various physical and mechanical properties, and obtained results of 90.72MPa as compressive strength and 282MPa as tensile strength for bamboo splints. Adewuyi et al. (2015) [18] have reported that beams reinforced with bamboo can take flexural stresses of 6.22MPa.

From the literature collected and studied for the current research work, it was observed that, basic mechanical properties of bamboo such as its tensile strength, compressive strength and modulus of elasticity has been studied in many research works, but Poisson's ratio of bamboo has not been discussed in any of the available literature. Also values obtained for modulus of elasticity of bamboo are not consistent. Shear strength test of bamboo reinforced beams and analytical modeling and analysis of bamboo has not been performed in any of the collected research works.

3. Experimental study

Bamboo selected for the study was the one available locally in market from Bengaluru, India.

3.1. Physical properties

Physical properties of bamboo were tested based on the procedures given in IS: 8242 – 1976 [19] and IS: 6874 – 2008 [20]. Density test, moisture content test and shrinkage test on bamboo were performed.

3.1.1. Density test: It was conducted as per IS: 6874-2008 [20]. Volume and mass of 14 bamboo pieces of size 25mm with a wall thickness of 10mm, as shown in figure. 1 was measured.

Volume of bamboo pieces were measured by water displacement method. Bamboo specimens were oven dried for 24hrs at 103±2˚ C and weighed again to know their oven dried masses.

$$\text{Density in g/cm}^3 = \frac{\text{Oven dried mass in g}}{\text{Volume in cm}^3} \quad (1)$$

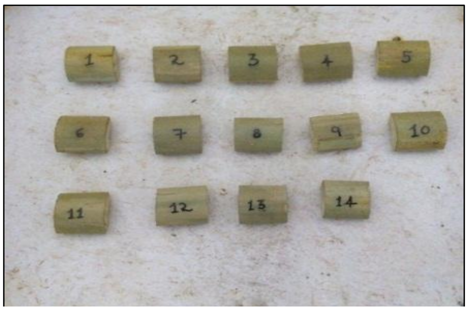

***Figure 1.** Bamboo specimen for density test*

3.1.2. Moisture content test: Moisture content of bamboo was determined based on the data obtained from density test. Green weight of bamboo pieces and their oven dried masses were used for evaluating the moisture content in bamboo specimen.

$$\text{Moisture content \%} = \frac{m_1 - m_2}{m_1} X100 \quad (2)$$

Where, m_1 = Green mass in g
m_2 = Oven dried mass in g

3.1.3. Shrinkage test: Shrinkage test of bamboo specimen provides information about the possible reduction in dimensions of bamboo when they are subjected to high temperature.

Shrinkage test was conducted on three bamboo culms, numbered as SH – 1, SH – 2 and SH – 3. Length, diameter and wall thickness of the entire three specimens were measured and locations of measurements were marked on the specimen to facilitate the measurement at the same locations after the shrinkage of bamboo.

All three specimens were kept in oven for 24hrs. at 103±2˚ C. After 24hrs, their dimensions were measured at the same locations. Difference in the dimensions gave the shrinkage of bamboo.

$$\text{Shrinkage in\%} = \frac{\text{Original size} - \text{New size}}{\text{Original size}} X100 \quad (3)$$

3.2. Mechanical properties

Bamboo was tested for mechanical properties as discussed below:

3.2.1. Compressive strength: Compressive strength test was conducted as per IS: 6874 – 2008 [20]. Two types of specimen were taken. First type was culms with intermediate node, numbered as 1A, 1B and 1C.

Second type was culms without node, numbered as 2A, 2B and 2C. Specimens used for testing are shown in figure 2 and figure 3. Dimensions of the entire specimen were measured before they were tested. Details of specimen are shown in table 1.

Figure 2. *Bamboo culms with node for compressive test*

Compressive strength was tested in UTM, by subjecting the culms with axial load, till the failure of specimen. Ultimate load taken by the specimen and their mode of failure was noted.

$$\text{Compressive strength} = \frac{\text{Ultimate failure load in N}}{\text{Area of application of load in mm}^2} \quad (4)$$

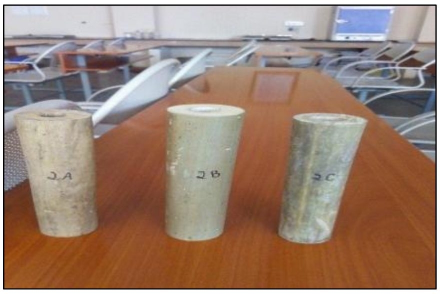

Figure 3. *Bamboo culms without node for compressive test*

Table 1: *Details of bamboo culms for compressive test*

Specimen	Length (mm)	Diameter (mm)	Wall thk. (mm)	Area of cross section (mm²)
1A	154	35	11	829.38
1B	154	35	10	785.39
1C	153	35	10	785.39
2A	145	35	11	829.38
2B	155	35	10	785.39
2C	150	34	10	753.98

3.2.2. Tensile strength: Tensile strength of bamboo was evaluated by applying a tensile load on bamboo splints as performed by Sevalia et al. [21]. Bamboo splints selected for tensile testing were of length 650mm, 20mm wide and 10mm wall thickness. Bamboo splints were subjected to tensile load in UTM. During tensile testing, it was difficult to hold the splint between two jaws of UTM, since bamboo is a soft material and tend to slip from the grip. Hence two small metal pieces having threads on their surfaces were kept between the jaws and bamboo splint to provide a better grip, while conducting the test. Load was applied continuously till failure. Arrangement for tensile testing is shown in figure 4.

$$\text{Ultimate tensile strength} = \frac{\text{Ultimate tensile load in N}}{\text{Area of cross section in mm}^2} \quad (5)$$

Figure 4. *Tensile testing of bamboo*

3.2.3. Modulus of rupture & modulus of elasticity: Static bending test was performed on bamboo splints to evaluate the modulus of rupture and modulus of elasticity.

Procedure for the test was adapted from IS: 8242-1976 [19]. Bamboo splint of length 200mm, 20mm wide with 10mm wall thickness was placed horizontally on roller supports of UTM. Load was applied continuously at the center of the splint. Deflection of bamboo splint was measured using a dial gauge. Modulus of rupture and modulus of elasticity of bamboo were determined based on ultimate load and maximum deflection of bamboo splint.

$$\text{Modulus of rupture} = \frac{1.5\,P_1\,l}{bd^2} \quad (6)$$

$$\text{Modulus of elasticity} = \frac{P_2 l^3}{4bh^3 d} \quad (7)$$

Where, P_1 = Failure load in N
P_2 = Load at proportional limit in N
l = Span in mm
b = Width of specimen in mm
h = Depth of specimen in mm

3.2.4. Poisson's ratio: Three bamboo culms were selected for the test. Their dimensions were measured before they were tested. Diameter was measured at 3 different locations and the locations were marked. Dimensions measured are given in Table 2.

Specimens were kept loaded in UTM. Using calipers, diameters were measured at the same locations. Length of the specimen before and after loading was also noted down. Strain in lateral direction and corresponding strain in longitudinal direction were measured. Test setup is shown in figure 5.

$$\text{Poisson's ratio} = \frac{\text{Lateral strain}}{\text{Longitudinal strain}} \quad (8)$$

Figure 5. *Poisson's ratio test*

Table 2: *Details of specimen for Poisson's ratio*

Specimen	1	2	3
Length, L (mm)	155	152	151
Top diameter, D1 (mm)	74.5	72.5	76.5
Middle diameter, D2 (mm)	73.5	72.5	76.0
Bottom diameter, D3 (mm)	74.0	73.5	74.5
Average diameter, D (mm)	74.0	72.83	75.67

3.3 Casting of beams

15 beams of size 150mm x 150mm x 700mm were cast for the testing of flexural and shear strength. Among 15 beams, 6 were plain concrete (PC) beams, 3 steel reinforced concrete beams (RC) and remaining 6 were bamboo reinforced concrete beams (BRC).

Percentage of reinforcement in RC beams and BRC beams were kept constant at 3.5%. RC beams were reinforced with 4 numbers of 16mm diameter bars, and BRC beams were reinforced with 4 numbers of splints with each having a cross section of 20mm x 10mm. Beams were cast only with flexural reinforcement and shear reinforcement was not provided. A clear cover of 25mm was provided for all the nine beams.

Concrete used for the beams was prepared with OPC 53 grade cement, slag sand and coarse aggregates of size 20mm down. All the necessary tests on concrete ingredients were conducted to know the properties of materials and mix design was prepared. Slump test was conducted to test the workability and the slump obtained was 75mm. Proportions of materials is shown in table 3.

Table 3: *Mix proportions for concrete*

Materials	Weight in kg for 1m³ of concrete
Cement	400
Fine aggregates	713
Coarse aggregates	1075
Water	205

28 days compressive strength was tested for cubes of side 150mm. Beams were cast in suitable molds and vibrated in mechanical vibrator. Before casting BRC beams, bamboo splints were coated with epoxy resin to avoid water absorption.

3.4. Testing of beams

Beams were tested for flexural strength and shear strength in UTM.

3.4.1. Flexural strength of beams: 3 PC beams, 3 RC beams and 3 BRC beams were tested for flexural strength in UTM according to IS: 516 – 1959 [22]. Effective span of the beams was 600mm. A dial gauge was placed at the center of beams on their base to measure deflection.

PC beams were numbered as PC – 1, PC – 2 and PC – 3, RC beams as RC – 1, RC – 2 and RC – 3. BRC beams as BRC – 1, BRC – 2 and BRC – 3. Behavior of PC, RC and BRC beams under load and their mode of failure was observed.

$$\text{Flexural strength} = \frac{P\,l}{bd^2} \quad \text{if } a > 200\text{mm} \tag{9}$$

$$\text{Flexural strength} = \frac{3Pa}{bd^2};\ \text{if } 170\text{mm}<a<200\text{mm} \tag{10}$$

Where, P = Maximum load applied on beam in N
l = Effective span of beam in mm
b = Width of beam in mm
d = Depth of beam in mm
a = Distance of the crack from nearest support.

3.4.2. Shear strength of beams: 3 PC beams and 3 BRC beams were tested for shear strength. Testing was performed in UTM. In shear testing, load was applied at a distance of 100mm from one of the supports. PC beams were numbered as PC – 4, PC – 5 and PC – 6 and BRC beams as BRC – 4, BRC – 5 and BRC – 6. Ultimate load taken by beams and their mode of failure was observed.

$$\text{Shear strength} = \frac{V}{bd} \tag{11}$$

Where, V = Ultimate shear force in N
b = Width of beam in mm
d = Effective depth of beam in mm

3.5 Bond strength

Bond strength of bamboo with M20 concrete was compared with that of steel, by conducting pull out test on cubes, having steel bar and bamboo splints as reinforcement according to the guidelines of IS: 2770 (Part – 1) – 1967 [23].

6 cubes of side, 150mm were cast, 3 cubes were provided with a 16mm diameter bar each and 3 cubes with a bamboo splint each of size 20mm x 10mm as cross section and projecting outward by 510mm from face of the cube. Pull out test was conducted in UTM, by fixing reinforcement to top grip of the machine and passing rod or splint through the middle portion of the machine. Method adapted for fixing bamboo splint to UTM top jaw was same as the setup used for tensile testing of splints. Test setup is shown in figure 6.

$$\text{Bond strength} = \frac{P}{\pi dl} \quad \text{for steel bars} \tag{12}$$

$$\text{Bond strength} = \frac{P}{2[bl+wl]} \text{ for bamboo splints} \quad (13)$$

Where, P = Maximum applied load at slip in N
d = Diameter of steel bar
l = Embedded length of reinforcement
b = Width of bamboo splint
w = Wall thickness of bamboo splints

Figure 6. *Pull out test setup*

Slip of reinforcement was measured using a scale mounted on the machine. Bond strength of bamboo and steel were determined based on the ultimate load taken by the cubes. Ultimate load was considered as the load at which concrete failed or a maximum slip of 2.5mm was observed.

4. Analytical study

Numerical modelling and analysis of beams was performed in ABAQUS 6.10, which uses finite element technique for analysis. Parameters selected for modelling are described in table 4. Analytical modelling for PC, RC and BRC beams was performed in the same manner, as experimental program. Reinforcement was embedded in concrete. Load applied on PC, RC and BRC beams were the ultimate load taken by respective beams in experimental study.

Table 4: *Parameters for modelling*

Property	**Value**
Density of concrete	2400 kg/m³
MoE of concrete	26925 MPa [5000√fck [24], fck = 29 MPa from exp. results]
Poisson's ratio of concrete	0.15
Density of steel	7850 kg/m³
MoE of steel	200000 MPa
Poisson's ratio of steel	0.3
Density of bamboo	731 kg/m³ [Exp. result]
MoE of bamboo	45475 MPa [Exp. result]
Poisson's ratio of bamboo	0.46 [Exp. result]
Boundary conditions	Restrained in global Y direction and free to rotate in any direction, located at 50mm from beam ends
Loading	Pressure load applied on a strip of 10mm x 150mm
Method of analysis	Linear static
Element types	C3D8R, an 8 - node linear brick element for concrete, T3D2, a 2 – node linear 3D truss element for reinforcement [25]

5. Results and discussion

5.1. Experimental results

Results of the various experimental tests carried out are explained.

5.1.1 Density test: Density of bamboo indicates that bamboo is a very light material when compared with other building materials such as steel (7850 kg/m³) and concrete (2400 kg/m³). Results of density test are shown in table 5. Range of density obtained (684 kg/m³ to 777 kg/m³) indicates that bamboo used for the study is homogeneous throughout its length and it was also observed that there are no internal defects in bamboo.

Table 5: *Results of density test*

Sample no.	**Green weight (g)**	**Volume (cm³)**	**Oven dry mass (g)**	**Density (g/cm³)**
1	3.189	3.7	2.727	0.737
2	3.167	3.5	2.721	0.777
3	3.266	3.8	2.802	0.737
4	3.236	3.8	2.781	0.731
5	3.14	3.8	2.692	0.708
6	3.196	3.7	2.758	0.745
7	3.242	4.0	2.795	0.698
8	2.951	3.4	2.548	0.749
9	2.87	3.4	2.471	0.726
10	3.31	3.8	2.826	0.743
11	3.385	4.0	2.926	0.731
12	3.265	3.8	2.821	0.742
13	3.438	4.0	2.950	0.737
14	2.95	3.7	2.533	0.684
Average				0.731 g/cm³

5.1.2. Moisture content: Results of moisture content test are shown in table 6.

Table 6: *Results of moisture content test*

Sample no.	**Green weight (g)**	**Oven dry mass (g)**	**Moisture content (%)**
1	3.189	2.727	16.9
2	3.167	2.721	16.4
3	3.266	2.802	16.6
4	3.236	2.781	16.4
5	3.14	2.692	16.6

6	3.196	2.758	15.9
7	3.242	2.795	16.0
8	2.951	2.548	15.8
9	2.87	2.471	16.1
10	3.31	2.826	17.1
11	3.385	2.926	15.7
12	3.265	2.821	15.7
13	3.438	2.950	16.5
14	2.95	2.533	16.5
	Average		16.3

Moisture content indicates the green nature of bamboo. In the present study, moisture content was found to be 16.3%, which is below 20% as suggested by IS: 6874 – 2008 [13].

5.1.3. Shrinkage test: Bamboo was tested for shrinkage along length, diameter and wall thickness. In the present study, shrinkage observed was 0.44% along length, 9.05% along wall thickness and 3.62% along diameter.

5.1.4. Compressive strength test: From the test results, it was observed that the culms with intermediate node take up more compressive loads, than those without node. This could be because of presence of more fibers near the node. Compressive strength for culms with and without intermediate node was obtained as 97.48MPa and 83.28MPa respectively.

5.1.5. Tensile strength test: Tensile strength of bamboo obtained was 203 MPa, which is about 80% of that of mild steel (250MPa). This is an indication that bamboo possesses enough tensile strength to be used as tensile reinforcement. Splints failed in tension are shown in figure 7.

Figure 7. *Failure of splints in tension*

5.1.6. Modulus of rupture & modulus of elasticity: Modulus of rupture of bamboo provides vital information about flexural strength of bamboo, since bamboo is to be used as reinforcement in concrete elements.

Based on the deflection of bamboo on the applied load, modulus of elasticity was calculated. Modulus of elasticity for the splints was found to be 45,475MPa. Bending test on bamboo splint is shown in figure 8 and test results are shown in table 7.

Figure 8. *Static bending test on bamboo splint*

Table 7: *Results of modulus of rupture and modulus of elasticity*

Specimen	1	2	3
Load, P (kN)	5.2	5.1	4.8
Length, l (mm)	150	150	150
Width, b (mm)	20	20	20
Depth, d (mm)	10	10	10
Deflection, h (mm)	5	4.7	4.6
Modulus of rupture (MPa)	337.5	360	315
Modulus of elasticity (MPa)	43875	45777	46773

Average modulus of rupture = 337.5 MPa
Average modulus of elasticity = 45475 MPa

5.1.7. Poisson's ratio:

Average Poisson's ratio of bamboo was obtained as 0.463

5.1.8. Flexural strength of beams: Flexural strength test was performed on PC, BRC and RC beams of 3 numbers each in UTM. 3 PC beams were subjected to flexural loading. Average ultimate load taken by PC beams was 28kN. PC beam, which failed in brittle manner is shown in figure 9.

BRC beams were reinforced with 4 numbers of bamboo splints with cross section area of 200mm². Average load taken by BRC beams was 32.31kN. All the three BRC beams failed in flexure, with the crack appearing near the center of the beam. It was observed that bamboo was in contact with concrete and gap was not observed between bamboo splints and concrete. Average flexural strengths of BRC beams were found to be 5.74 MPa, which is an increase of 15% compared with PC beams. Failure of BRC beam is shown in figure 10.

In flexural testing of RC beams, diagonal cracks started appearing on the surface. These cracks started from the point of application of load, i.e., loading roller and propagated towards the support roller diagonally. RC beams were provided with 4 bars of 16mm diameter (3.5% reinforcement), which lead to failure of beams in shear before their failure in flexure. Same pattern of cracks were observed in all the three beams. Cracks on RC beam are shown in figure 11. Since RC beams failed in shear, exact flexural strength of the beams could not be determined.

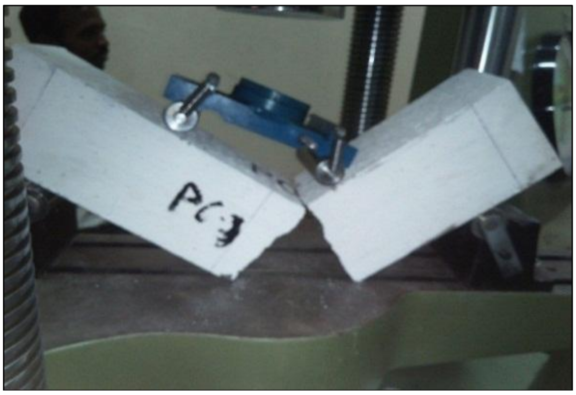

Figure 9. *Failure of PC beam in flexure*

Figure 10. *Failure of BRC beam in flexure*

Figure 11. *Crack formation in RC beam*

5.1.9. Shear strength of beams: 3 PC beams and 3 BRC beams were tested for shear strength in UTM. It was observed that beams failed near the supports. Cracks originated at the point of loading and propagated vertically downwards. All the PC beams failed with brittle fracture. Shear strengths calculated for the beams were used for comparison with that of BRC beams. Average shear strength of PC beams was found to be 0.896 MPa. Cracks developed in PC and BRC beams are shown in figure 12 and figure 13 respectively.

Figure 12. *Crack formation in RC beam*

Figure 13. *Cracks in BRC beam*

In shear testing of BRC beams, time taken by the beams for failure from their yielding point was higher when compared to PC beams. BRC beams showed ductile behavior, due to the presence of reinforcement. Formation of cracks was at the point of loading and propagated downwards. Average shear stresses developed in BRC beams was 1.57MPa.

5.1.10 Bond strength: For RC cubes tested for pull out strength, failure was by splitting of concrete cubes. This indicates that bond strength of concrete with steel was very high. Steel bars were slipped to an average distance of 1.3mm, considering all the three samples.

Bond strength of steel bars with concrete could not be determined, since the failure was observed in concrete cube, rather than bond between steel and concrete. In case of BRC cubes, bamboo splints were successfully pulled out by 10mm. Average bond strength of bamboo was obtained as 1.7MPa. Results obtained were compared with the maximum bond stress prescribed by IS 456 – 2000 [24] for M20 concrete. Bond between bamboo and concrete was also closely observed in flexure testing of BRC beams after failure, where no gap was observed between bamboo and concrete. RC and BRC cubes after pull out test are shown in figure 14 and figure 15 respectively.

Figure 14. *Failure of RC cube*

Figure 15. *Slip in BRC cube*

5.2. Analytical results

PC, RC and BRC beams were analyzed for linear static load to evaluate flexural stresses and their locations on the beam.

From analytical results, it can be observed that in PC and BRC beams, location of maximum stresses is at the bottom central part of the beam. Maximum flexural stress developed is of the magnitude 4.85MPa in case of PC beam, comparable to the experimentally obtained stress of 4.973MPa. Flexural stresses of BRC beams in analytical study were 5.72MPa. Flexural stresses obtained in BRC beam and the location of maximum stresses is comparable with experimental results.

In case of RC beam, maximum shear stresses were observed to be propagating from loading region to support region. Experimentally obtained crack pattern and analytical results shown in figure 16, figure 17 and figure 18 are of similar nature.

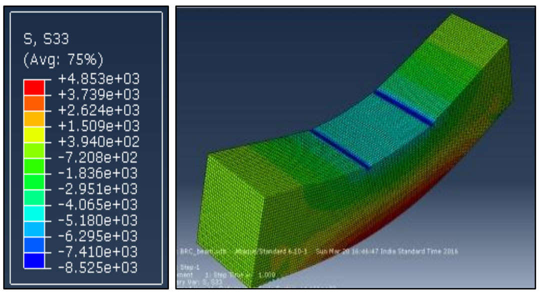

Figure 16. *Flexural stresses in PC beam*

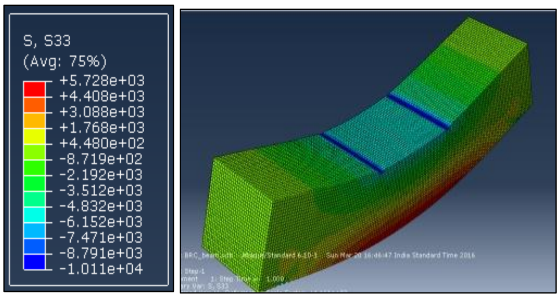

Figure 17. *Flexural stresses in BRC beam*

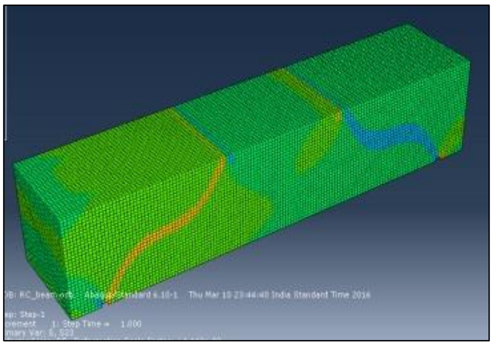

Figure 18. *Shear stresses in RC beam*

6. Conclusions

Following conclusions are drawn from the current study:

- Bamboo tested was found to be possessing density 731kg/m³, which makes it a light material and thus reduces the dead load of structure.
- Moisture content was obtained as 16.3%, which confirms the seasoning of bamboo.
- Shrinkage of 0.44% along length, 9.05% along wall thickness and 3.62% along diameter was obtained, which indicates the necessity of coating bamboo with a water proofing material before using it as a reinforcing material.
- Compressive strength of bamboo was found to be 97.48 MPa for culms with node and 83.28 MPa for culms without node.
- Tensile strength of bamboo splints was obtained as 203 MPa, which is 80% of that of steel. This makes it a good reinforcing material for low rise structures.
- Bamboo used in this project was found to be having modulus of elasticity, 45475MPa and Poisson's ratio of 0.46.
- Bamboo reinforced concrete beams are stronger than plain concrete beams in terms of flexural strength and shows ductile behavior. Flexural strength of beams were 15% higher than PC beams.
- BRC beams exhibits ductile behavior and PC beams were observed exhibiting brittle failure.
- Shear strength of BRC beams was found to be 1.51MPa which is 68% higher than that of PC beams (0.896 MPa).
- Bond strength of bamboo with M20 concrete was obtained as 1.7MPa. BRC, despite having lesser

strength than RC beams, can be used for low rise structures.

- Results and behavior of PC, RC and BRC beams obtained from analytical modeling and analysis were found to be close to the experimental results.

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