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Enhancing bamboo reinforcement using a hose-clamp to increase bond-stress and slip resistance

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ABSTRACT

Bamboo can be used as reinforcement for concrete, especially in simple construction, because of its high tensile strength. Any collapse that occurs in a bamboo reinforced concrete beam is often caused by failure of the bond between bamboo and concrete. Many researchers have suggested using adhesive coatings or roughness modifications to bamboo reinforcement, but a slip failure pattern still appears. The aim of this research is to increase bond-stress and slip resistance by using a hose-clamp, and to obtain a relationship model of load vs. deflection and bond-stress vs. slip between bamboo reinforcement and concrete. The experiments use 75 mm × 150 mm x 1100 mm concrete beams. Concrete beam specimens comprise 24 bamboo-reinforced beams, one beam with 8 mm diameter steel reinforcement, and one without reinforcement. Hose-clamp spacing varies by 0 cm, 15 cm, 20 cm, and 25 cm. Beam testing uses a four-point loading method. Test results show an increase in bond-stress and flexural capacity, and reduced slip between bamboo reinforcement and concrete, when hose-clamps are used. There are differences in the relationship of load vs. deflection and bond-stress vs. slip between bamboo reinforced concrete beams and steel reinforced concrete beams.

1. Introduction

Exploiting industrial building materials with an indifference to using renewable building materials can cause permanent environmental pollution. Bamboo, as a renewable building material, can minimize energy consumption, protect non-renewable natural resources, reduce pollution and maintain a healthy environment. Bamboo is a material with an economic advantage because growth is relatively fast, allowing it to achieve maximum mechanical resistance within a few years. In addition, bamboo is very abundant in the tropics and subtropics throughout the world [1].

Bamboo can be used for concrete reinforcement for modest housing communities in areas where it is abundant, especially underdeveloped villages. However, bamboo is considered unprofitable because of the methods required to prepare it for such use. Researchers have tried to simplify bamboo treatment and eliminate operational problems in using it as the main structural component. Many of them focus on examining whether bamboo reinforcement is really cheaper than steel reinforcement, taking into account operational costs, depreciation losses, required skills, and on-the-job training needs for long-term use [2]. Other researchers discuss the feasibility of bamboo in technical, cost, durability, and other terms [3–10].

A frequent barrier to developing bamboo reinforced concrete is the failure of the bond between the bamboo reinforcement and the concrete. This occurs because of the slippery nature of the bamboo surface, and imperfect attempts to modify its roughness. Treatments to counteract the slipperiness have included soaking, drying, waterproof coating, and sprinkling with dry sand. Nevertheless, the collapse pattern is still dominated by slip failure between bamboo reinforcement and concrete. Tripura and Singh [11] recently proposed a column reinforcement technique to increase the strength and performance of bamboo reinforcement, but the user must pay attention to humidity, and bond properties need to be determined for better results.

The aim of this research is to increase bond-stress and slip resistance using a hose-clamp, and to obtain a relationship model of load deflection and bond-stress and slip between the bamboo reinforcement and the concrete. The concept of installing a hose-clamp on to bamboo reinforcement is similar to the concept of using deformed bar reinforcement in concrete [12] as shown in Fig. 1 and Fig. 2, where there are frictional force interaction and the bearing force between bamboo reinforcement and concrete. Installing hose-clamps in this way will increase slip resistance and bond-stress. The frictional force of the bamboo reinforcement surface will be distributed on the hose-clamp that functions as a shear connector. Strengthened bamboo

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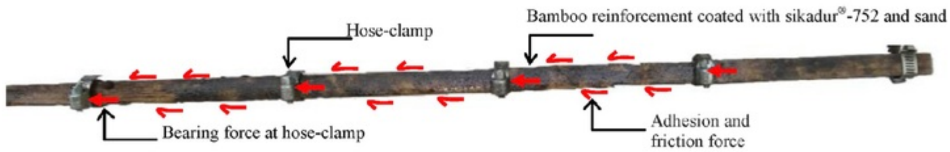

Fig. 1. Bamboo reinforcement with a hose-clamp.

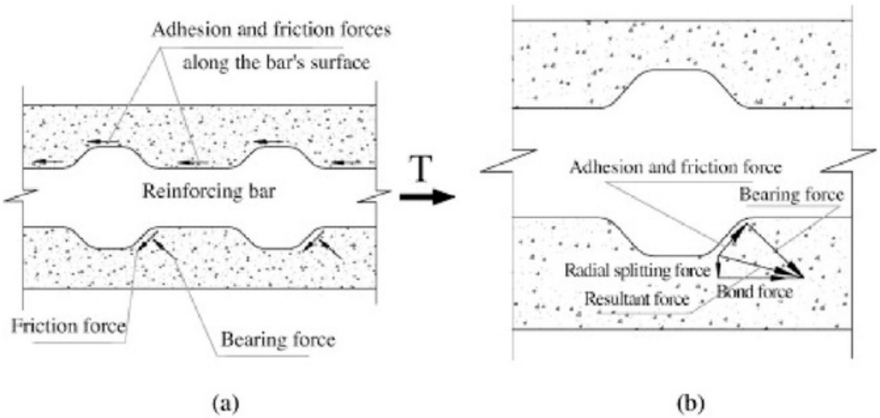

Fig. 2. The friction force and bearing force of a deformed bar [12].

reinforcement using a hose-clamp is then applied to concrete beams and evaluated by flexural testing.

2. Theory

The reinforced concrete bond is formed by the mechanism of adhesion, friction and mechanical interlock between the reinforcement and the concrete. Bond strength is strongly influenced by fracture energy [13] as well as complex interactions between local deformation, chemical adhesion, and other factors [14]. The shear forces transferred between the bamboo reinforcement and the concrete is the dominant factor after the adhesive bond. A good bond between concrete and reinforcing bamboo is essential so that the system can behave as planned, and also to fulfill the required performance of the structure in the long run. The bamboo reinforcement surface condition and the shearing surface area are important factors in the shear stress value.

Roughness modification of bamboo reinforcement is carried out by notching [15], wire and coir winding [16], the addition of hooks [17], or installation of hose-clamps [18–20]. These methods can increase the bearing capacity of a bamboo reinforcement concrete beam, but still have drawbacks, such as difficult implementation, and a notching process can weaken bamboo reinforcement. Agarwal et al. [21] conducted research on a bamboo reinforced concrete beam using waterproof coating Sikadur 32 Gel and sand. The capacity of the beam load increased by up to 29.41% for a 1.49% bamboo reinforcement area, but slip failure still occurred. Gisleiva C.S [22]. tested bamboo reinforced concrete beams using a two points load method, and showed that the beam crack occurs due to bond failure between bamboo reinforcement and concrete, followed by sliding failure and slip.

The bamboo reinforcement adhesive should also serve as an impermeable layer and sand sheathing binder to the bamboo reinforcement. Some types of adhesives that have been used include: Negrolin, Sikadur 32 Gel [1]; Sikadur-31CFN [23]; Araldite, Tepecrete P-151, Anti Corr RC, and Sikadur 32 Gel [21]; Araldite, epoxy resin, and coal tar [24]; paint and dry sand [25]; layer asphalt and sand on bamboo reinforcement [26]; asphalt layer and coir rope coiled [27]; Concresive Master Inject 1315 [28]; synthetic resin and synthetic rubber [29]; water-based epoxy coating with fine sand, water based epoxy coating with coarse sand, TrueGrip EP with coarse sand, TrueGrip BP with coarse sand, Exaphen with coarse sand, and enamel [30]; and lime water treated bamboo mat coated with epoxy and sand [31].

In the pull-out testing of concrete, the bond strength decreases as the steel reinforcement diameter increases; the deeper the embedded reinforcement steel, the higher the bond-stress value [32,33]. Javadian et al. [30] investigated bamboo pull-out, using a type of epoxy coating, to determine the bonding behavior between bamboo reinforcement and concrete. The results showed that bamboo-composite reinforcement without layers has sufficient ties with the concrete matrix, but with the epoxy base layer and sand particles provides extra protection without loss of bond strength. Where failure occurs, it is at the bond between reinforcing steel with concrete, and slippage. The pull-out testing results by Muhtar et al. [19] on bamboo reinforced concrete with Sikadur®-752 coating and hose-clamps embedded in concrete cylinders indicated an increase of tensile stress of up to 240% compared to untreated bamboo reinforced concrete. The pattern of collapse indicates the collapse pattern of bond and concrete cone failure and Bamboo failure of a node. This shows that using a hose-clamp on bamboo reinforcement works well, with the concrete remaining attached to the bamboo reinforcement.

Installation of hose-clamps increases slip resistance along the bamboo reinforcement. The frictional force of the bamboo reinforcement surface is distributed on the hose-clamp that serves as a shear connector. The bonding stress parameter between bamboo reinforcement and concrete can be shown in flexural capacity, crack pattern, and beam failure pattern.

Hose-clamp installation on bamboo reinforcement serves as anchoring friction between bamboo reinforcement with concrete. The friction strength, τ_b of the bamboo pullout test can be calculated using Eq. (1) [30]:

$$\tau_b = \frac{P}{(2a + 2b)L_a} \tag{1}$$

where P is the pullout force, (2a + 2 b) is the dimension of the bamboo cross-section, and L_a is the length of bamboo surface attachment.

The bond-stress (u) of the BRC beam can be calculated by Eq. (2) and Eq. (3) [25,34]:

$$u = \frac{V}{jd.\ \Sigma o} \tag{2}$$

$$jd = \left(d - \tfrac{1}{2}a\right) \tag{3}$$

where V is the shearing force of the beam, Σo is the circumference of the nominal surface area of the bamboo reinforcement in length units, d is the distance from the maximum press fiber to the center of the bamboo tensile reinforcement area, and a is the height of concrete stress block equivalent.

3. Materials and methods

3.1. Preparation of bamboo reinforcement

This research uses bamboo petung (Dendrocalamus asper) between three and five years old [21], 6 m long from its base. Bamboo is cut and separated according to the planned size, then soaked in water to remove the starch content for approximately 30 days. After soaking, bamboo is dried in free air for about 30 days [21,35]. The dried bamboo is cleaned on the inner side and trimmed with a grinding machine to the required shape for bamboo reinforcement measuring 7 × 10 mm^2, 10 × 10 mm^2 and 15 × 15 mm^2. The number of bamboo reinforcement nodes used varies between two and three pieces.

3.2. The waterproof coating Sikadur®-752 and installation of hose-clamp

After the bamboo reinforcement preparation process is complete, the next step is the waterproof coating and installation of hose-clamps. The waterproof coating used was Sikadur®-752, and the coating was carried out twice. Sikadur®-752 is applied to the bamboo reinforcement to prevent water absorption; the effectiveness and durability of Sikadur®-752 adhesive require further research. The specification of Sikadur®-752 is shown in Table 1. Hose-clamps installation is carried out after the first stage Sikadur®-752 waterproof coating is dry. The second layer of waterproofing is applied with the aim of making the first stage impermeable, and of strengthening the bond between hose-clamps and bamboo reinforcement. The hose-clamp used is a ¾" diameter stainless steel unit made in Taiwan specifications are not available. The distance variation of the hose-clamp setting is 0 cm, 15 cm, 20 cm, and 25 cm. To overcome bamboo node disturbance, hose-clamps are installed in one of two ways, either by stretching the hose-clamp bolt and inserting directly from the tip of the bamboo reinforcement, or by opening the hose-clamp bolt first and installing the unit using a screwdriver. Nearly one-third of the surface of bamboo reinforcement is slippery. To increase its roughness, sand is sprinkled on [30] after the Sikadur®-752 waterproof coating is half-dry. The sand used is fine volcanic dust sand from Raung Mountain, Jember, Indonesia, which contains particles of iron. The process of preparing bamboo, including waterproof coating and sprinkling sand, up to hose-clamp installation, is shown in Fig. 3 and Fig. 4.

Table 1
The specification of Sikadur®-752.

Components	Properties
Aspect	Yellowish
Mix density	Approx. 1.08 kg/l
Mix ratio, by weight/ volume	2 : 1
Pot life 30 °C	35 min
Compressive strength	620 kg/cm^2 at 7 days 640 kg/cm^2 at 28 days
Tensile strength	270 kg/cm^2 at 28 days
Bond strength, to concrete	> 20 kg/cm^2 (concrete failure, over mechanically prepared concrete surface)
Flexural strength	400 kg/cm^2 at 28 days
Modulus of elasticity	10,600 kg/cm^2

Fig. 3. Tidying a bamboo bar with a grinding machine.

Fig. 4. Processing a waterproof coating, a sand coating, and a hose-clamp installation.

3.3. Pull-out tests

The dimensions of bamboo reinforcement used in the pull-out tests are 15 mm × 15 mm x 400 mm, while the size of the concrete cylinder is a diameter of 150 mm and a length of 300 mm. A bamboo reinforcement is inserted into the middle of a concrete cylinder with a depth of 200 mm. Specimens are tested after 28 days; 15 test pieces were made, with five treatments, namely (a) normal, (b) hose-clamp with span 10 cm, (c) Sikadur®-752, (d) Sikadur®-752 and hose-clamp with span 15 cm, and (e) Sikadur®-752 and hose-clamp with span 20 cm. The purpose of the treatment on the specimen is to increase the bond-strength between bamboo and concrete. Specimen details from the pull-out test are shown in Fig. 5, while the manufacture of specimens and pull-out test settings are shown in Fig. 6.

3.4. Testing methods

The mix design of normal concrete for this research comprised Portland Pozzolana Cement (PPC), sand, coarse aggregate, and water with a proportion of 1:1.8, 1:2.8, 2:0.52. Sand and gravel are from the Malang area. The cylinder specimen measured 150 mm diameter and 300 mm height. A universal testing machine (UTM) with 2000 kN capacity was used for a compression test. The values of the concrete compressive strength test and the bamboo tensile strength test were used as the basis for the theoretical calculation of the beam.

The beam test specimen comprised 26 pieces with a size of 75 mm × 150 mm x 1100 mm, as shown in Fig. 7, consisting of 24

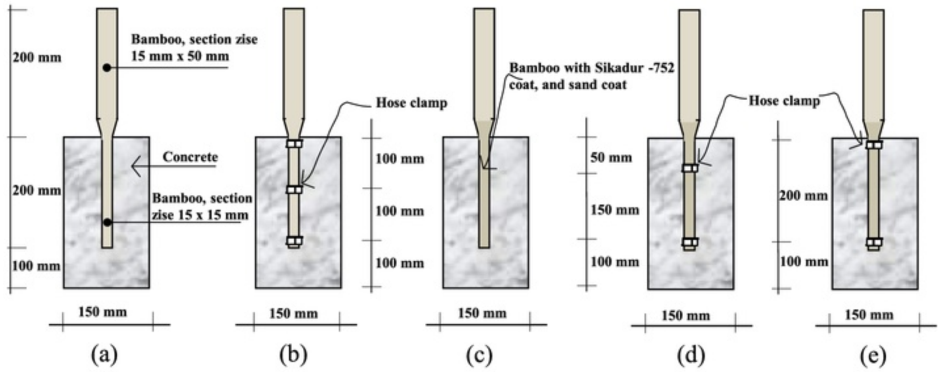

Fig. 5. Specimen details of the pull-out test.

pieces of the bamboo reinforced concrete beam (BRC), one steel reinforced concrete beam (SRC), and one concrete beam without reinforcement (PC). Bamboo reinforcement is installed as tensile reinforcement with a variation of reinforcement area of 140 mm^2, 200 mm^2, and 450 mm^2. The steel bars used are 8 mm in diameter with an A_s = 100.48 mm^2 reinforcement area. The use of 2 bars of 8 mm diameter is not equivalent to the bamboo reinforcement area used; if equalized it must be made in non-dimensional conditions, but this is not fully suitable because its behavior will not be the same if it has reached post-crack. This requires further research.

The flexural beam test is carried out using a four-point technique [36]. There are two points loads with spacing ⅓L from the beam support, using a WF load spreader. The strain gauge is mounted on bamboo reinforcement ½L from the beam support. The strain gauge is connected to the digital strain meter. The deflection that occurs in the beam is detected using LVDT (linear variable displacement transducers) ½L from the beam support. A hydraulic jack is used for beam loading and 200 kN load cell connected to the load indicator. Load indicator readings are used as hydraulic jack controllers, deflection readings, and strain readings, according to load control methods. After the test beam reaches its ultimate load, readings are taken according to the deflection control method. The pattern of collapse is observed and identified through cracks that occur, starting from the first crack until the beam collapses. The test equipment settings and load scheme are shown in Fig. 8.

4. Results and discussion

4.1. Material test and pull-out test

The bamboo tensile test returned an average tensile stress of 126.68 N/mm^2 and an average strain of 0.0074. The average of the modulus of bamboo elasticity is calculated based on formula $E = \sigma/\varepsilon$, and 17,235.74 MPa was obtained. Modulus of steel elasticity was 207,735.92 MPa. In bamboo tensile testing, the majority of failures of bamboo reinforcement occur at the point of the bamboo node as shown in Fig. 9, so that the modulus of elasticity is taken as an average test result of bamboo reinforcement with nodes and without nodes. Fig. 10 and Fig. 11 show a graph of the stress-strain relationship of bamboo and steel, a graph of the stress-strain relationship of bamboo tends to be linear until fracture stress occurs, so there are difficulties in determining the yielding point, especially if bamboo has been used as concrete reinforcement. So in this study, the method for determining the yield point of bamboo reinforcement in the concrete beam was based on ASTM E2126-09 [37] scope 1.2, which is for specimens constructed from wood or metal framing, braced with solid sheathing. Compression tests were carried out in accordance with ASTM C 39 [38] after 28 days of concrete age. The compressive strength of the average cylinder is 31.31 MPa and the average weight of the cylinder is 125.21 N.

The data from the pull-out test results of bamboo reinforcement, treated with waterproof coating Sikadur®-752, sand and hose-clamp rings embedded in concrete cylinders, showed an increase in bond-stress of 214% and 200% compared to bamboo without treatment, with

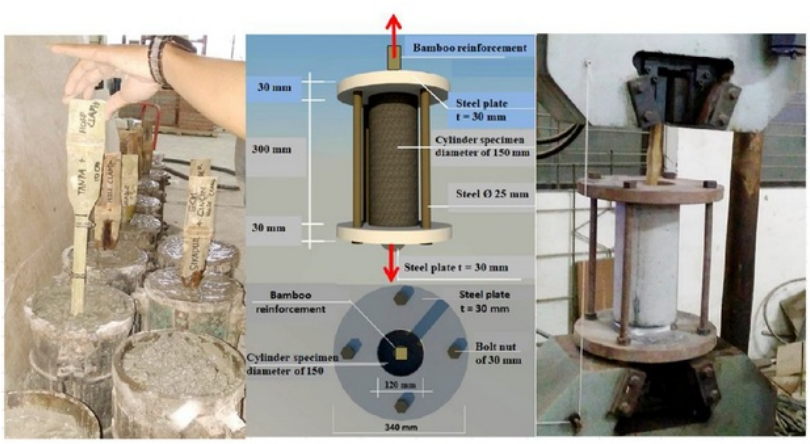

Fig. 6. Manufacture of specimens and pull-out test settings.

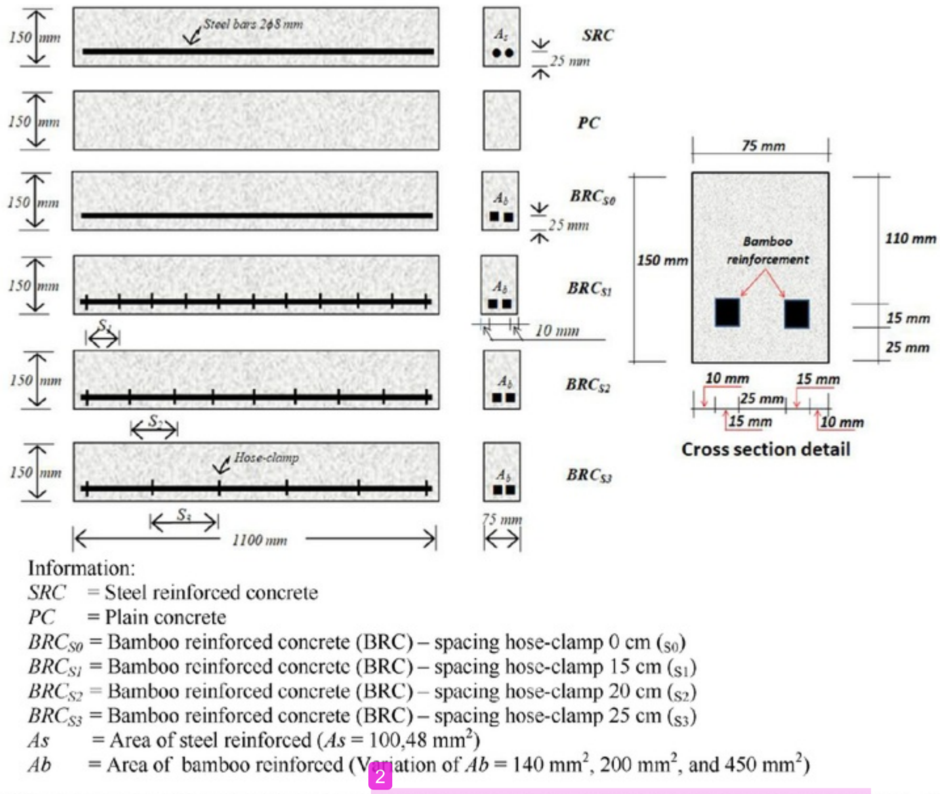

Fig. 7. Geometry and distance variations of beams with hose-clamp. Information: *SRC* = Steel reinforced concrete *PC* = Plain concrete BRC_{S0} = Bamboo reinforced concrete (BRC) – spacing hose-clamp 0 cm ($_{S0}$) BRC_{S1} = Bamboo reinforced concrete (BRC) – spacing hose-clamp 15 cm ($_{S1}$) BRC_{S2} = Bamboo reinforced concrete (BRC) – spacing hose-clamp 20 cm ($_{S2}$) BRC_{S3} = Bamboo reinforced concrete (BRC) – spacing hose-clamp 25 cm ($_{S3}$) *As* = Area of steel reinforced (*As* = 100,48 mm^2). *Ab* = Area of bamboo reinforced (Variation of *Ab* = 140 mm^2, 200 mm^2, and 450 mm^2).

a distance of hose-clamps of 15 cm and 20 cm, respectively; with the loading rate, respectively 39.5 kN and 37.5 kN. For bamboo reinforcement without waterproof coating Sikadur®-752 and sand, but using hose-clamps with a distance of 10 cm, this increased by 8%, whereas bamboo reinforcement with waterproof coating Sikadur®-752 and sand without hose-clamps increased by 125% compared to untreated bamboo, as shown in Fig. 12.

Test specimens with waterproof coating Sikadur®-752, sand, and hose-clamps showed a collapse pattern of "bond and concrete cone failure" as shown in Fig. 13a. This shows that the waterproof coating Sikadur®-752 and the hose-clamps on the bamboo reinforcement have worked well, as indicated by the concrete attached to the bamboo reinforcement. Test specimens with waterproof coating Sikadur®-752 and sand, but without hose-clamps, show a collapse pattern of "bond-slip failure", but have a fairly high bond strength, as shown in Fig. 13b. Whereas the specimen with hose-clamps without waterproof coating Sikadur®-752 or sand show a collapse pattern of the "bond-slip failure" with bond-stress similar to that of untreated bamboo reinforcement. This shows that there is an action of absorbing water between bamboo reinforcement and concrete. When the concrete is wet, the bamboo

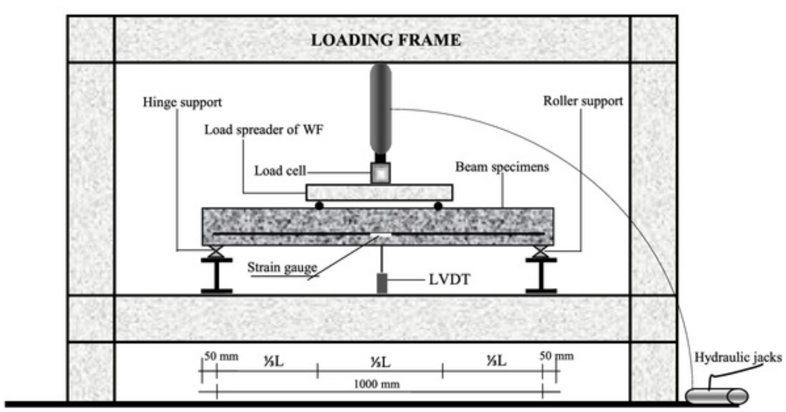

Fig. 8. The setting of the flexural beam test.

Fig. 9. The pattern of failure in bamboo reinforcement.

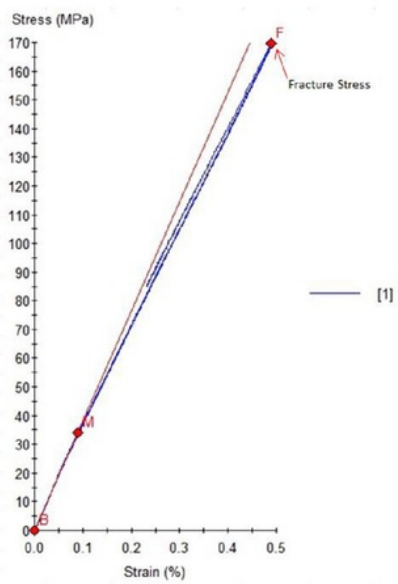

Fig. 10. The stress-strain relationship of normal bamboo reinforcement.

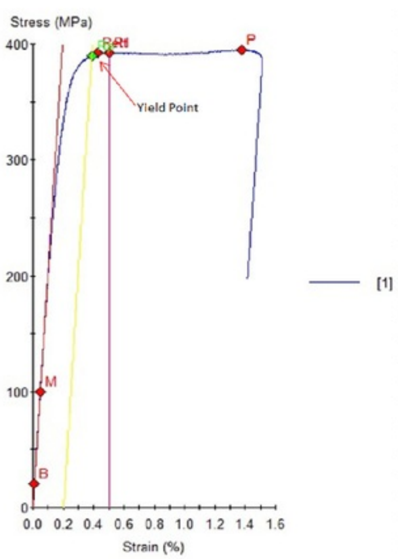

Fig. 11. The stress-strain relationship of steel reinforcement.

reinforcement absorbs water so that the bamboo reinforcement swells. When the concrete is dry, the water in the bamboo reinforcement is absorbed by the concrete, so that the bamboo reinforcement shrinks and the hose-clamp becomes loose. This causes a slip to occur and the hose-clamp has no effect on bond-stress. The pattern of the collapse is shown in Fig. 13b.

The analysis of the test results and the pattern of collapse shows that the use of waterproof coating is absolutely necessary; the installation of hose-clamps on bamboo reinforced concrete without waterproof coating has no significant effect.

4.2. *The flexural capacity of the bamboo reinforced concrete beam*

Theoretical analysis of beam flexural capacity is based on Ghavami (2005) [1]. From the analysis of stress and strain distribution of flexural beam elements, the balance between the concrete compressive force (C) and the tensile force (T) must be fulfilled. The tensile strength of bamboo reinforcement (T) was obtained by multiplying bond-stress from the pull-out test results by the shear area of bamboo reinforcement; this is because, based on the results of the study, the collapse of bamboo reinforced concrete was caused by the loss of bond between bamboo reinforcement and concrete. Data from theoretical calculations and BRC beam experimental results are shown in Table 2.

The initial crack of BRC beams from theoretical calculations occurred at a load of 6.87 kN, while ultimate loads occurred at 29.62 kN, 33.73 kN, and 45.27 kN, respectively on BRC beams with bamboo reinforcement areas of 140 mm^2, 200 mm^2, and 450 mm^2. The average load of the initial crack of the experimental results occurs at a load of 7.35 kN. Fig. 14 shows the average initial crack load and the average ultimate load of a BRC beam from theoretical calculations and experimental results. The average ultimate load of the experimental results is 90% of the ultimate load resulting from the theoretical calculations. This is one solution to the problem of the low capacity of bamboo reinforced concrete beams, as reported by several previous researchers. They concluded that the flexural capacity of bamboo reinforced concrete beams reached only 56% of its capacity if the tensile strength of bamboo was full [17], only 29%–39% of the capacity of steel reinforced concrete beams with the same reinforcement dimensions and width [39], and only 35% of steel reinforced concrete beams at the same strength level [40].

Fig. 15 shows a comparison of the ultimate load of BRC beams and SRC beams, based on reinforcement area variation and hose-clamp distance. BRC beams with a reinforcement area of 450 mm^2 have the highest ultimate load for all variations in the distance of the hose-clamps. Whereas when viewed from the variation in the distance of the hose-clamps, BRC beams with a distance of 20 cm hose-clamps have the highest ultimate load, 33.25 kN. BRC beams with a ratio of 4% bamboo reinforcement area exceed the ultimate load of steel reinforced SRC beams by up to 38.54% with a steel reinforcement area ratio of 0.89%.

The results of the analysis of variance on all data from the flexural test show the non-significant effect of hose-clamps on the beam capacity, whereas from the pull-out test results, as shown in Fig. 12, the effect of hose-clamps is significant. This indicates that: (1) the distance of the installation of the hose-clamps has not been optimum or is still too tight for flexural tensile reinforcement. Installation of tight hose-clamps will reduce the elastic properties of bamboo and bamboo reinforcement becomes more rigid. Bamboo has high tensile strength in the direction of the fiber (longitudinal direction), but is weak in the transverse direction, so that when receiving a flexural tensile force, there will be a concentration of stress, and bamboo reinforcement ruptures, especially at the point of the bamboo node and the position of the hose-clamp; (2) installation of effective hose-clamps if used on pure tensile elements, such as truss elements or as the length of distribution (L_d) for bamboo reinforcement; (3) waterproof coating Sikadur®-752 and sand have a significant effect on bond-stress. This is indicated by the ultimate load of BRC-s0 beam approaching the ultimate load of

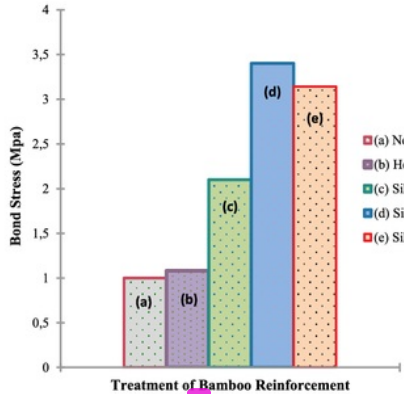

Fig. 12. Variation of the bamboo bond-stress.

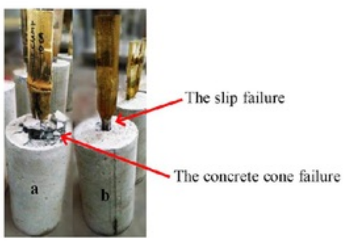

Fig. 13. The failure mode of the pull-out test.

BRC-s1, BRC-s2, and BRC-s3 beams. The installation of hose-clamps without waterproof coating treatment does not have an effect on the bond-stress or beam capacity. The installation of hose-clamps as flexural tensile reinforcement needs further research, with the hose-clamps distance larger and more effective.

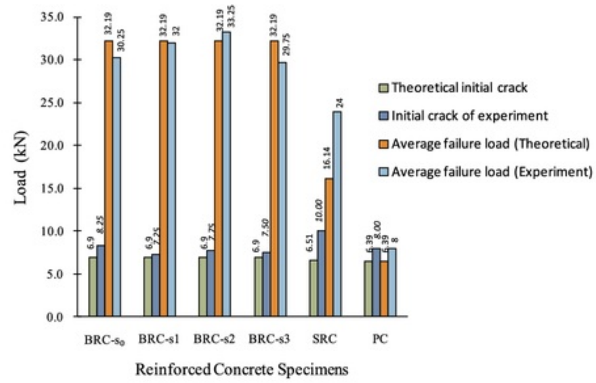

Fig. 14. The ultimate load of theoretical and experimental results of the BRC beam.

4.3. The load-deflection relationship model of the bamboo reinforced concrete beam

The pattern of the load-deflection relationship between BRC and SRC beams is strongly influenced by the mechanical properties of bamboo and steel reinforcement materials. The different characteristics of stress and strain in bamboo and steel are the dominant factors in determining the characteristics of load-deflection relationships. On the stress-strain characteristics of bamboo, it does not have a long initial melting point. This means the service load range point or the proof bond strength point cannot be directly determined. The relationship between load and deflection was carried out on BRC beams with a

Table 2
Flexural beam test results.

No	Specimens	code	Theoretical calculations			Flexural test results					
			First crack load (kN)	Ultimate load base on the tensile strength of bamboo (kN)	Ultimate load base on the shear area of bamboo reinforcement (kN)	First crack load (kN)	Average first crack load (kN)	Failure load (kN)	Average failure load (kN)	Deflection at failure (mm)	Average deflection at failure (mm)
1	BRC - s0	A1B1	6.87	11.39	29.61	8.50	8.25	22.00	21.75	12.10	12.40
2	As = 140 mm^2	A1B1				8.00		21.50		12.69	
3	BRC - s1	A1B2	6.87	11.39	29.61	7.00	6.75	21.00	18.50	6.08	6.40
4	As = 140 mm^2	A1B2				6.50		16.00		6.72	
5	BRC - s2	A1B3	6.87	11.39	29.61	6.00	6.25	22.00	22.25	9.09	9.20
6	As = 140 mm^2	A1B3				6.50		22.50		9.31	
7	BRC - s3	A1B4	6.87	11.39	29.61	8.00	7.75	19.50	20.75	10.21	11.57
8	As = 140 mm^2	A1B4				7.50		22.00		12.92	
9	BRC - s0	A2B1	6.87	15.86	33.73	6.50	6.75	26.50	27.75	10.21	11.17
10	As = 200 mm^2	A2B1				7.00		29.00		12.12	
11	BRC - s1	A2B2	6.87	15.86	33.73	6.50	7.00	33.00	30.75	14.84	13.39
12	As = 200 mm^2	A2B2				7.50		28.50		11.94	
13	BRC - s2	A2B3	6.87	15.86	33.73	6.50	6.75	31.00	31.50	13.25	13.50
14	As = 200 mm^2	A2B3				7.00		32.00		13.74	
15	BRC - s3	A2B4	6.87	15.86	33.73	8.50	8.00	29.50	29.00	9.66	10.80
16	As = 200 mm^2	A2B4				7.50		28.50		11.94	
17	BRC - s0	A3B1	6.87	32.19	45.27	8.50	8.25	31.50	30.25	10.92	11.41
18	As = 450 mm^2	A3B1				8.00		29.00		11.90	
19	BRC - s1	A3B2	6.87	32.19	45.27	7.00	7.25	31.00	32.00	12.18	12.60
20	As = 450 mm^2	A3B2				7.50		33.00		13.02	
21	BRC - s2	A3B3	6.87	32.19	45.27	8.00	7.75	33.50	33.25	14.69	12.01
22	As = 450 mm^2	A3B3				7.50		33.00		9.32	
23	BRC - s3	A3B4	6.87	32.19	45.27	7.50	7.50	29.50	29.75	7.61	9.15
24	Ab = 450 mm^2	A3B4				7.50		30.00		10.69	
25	SRC	SRC	6.51	16.63		10.00	10.00	24.00	24.00	6.33	6.33
	As = 100,48 mm^2										
26	PC	PC	6.39	9.42		8.00		8.00		1.29	

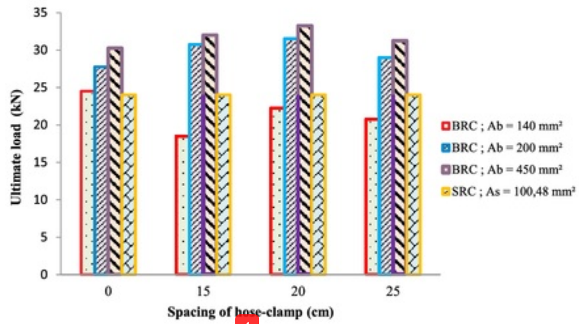

Fig. 15. The comparison of the ultimate load of BRC beams and SRC beams, based on reinforcement area and hose-clamp distance.

bamboo reinforcement area of 450 mm^2 with a hose-clamp distance of 0 cm, 15 cm, 20 cm, and 25 cm. This is because it has the highest ultimate load and good data consistency.

Fig. 16 and Fig. 17 show the differences in the behavior of load-deflection and load-strain relationships of BRC and SRC beams. The BRC beam has a much higher deflection. This shows higher energy absorption, but lower stiffness. The SRC beams can directly determine the initial yield point of reinforcement. A graph of the load-deflection relationship of the SRC beam shows the elastic area or friction bond limit (I), elasto-plastic (II), and plastic (III), while the BRC beam does not clearly show plastic areas – the BRC beam load-deflection graph tends to be linear. However, the crack moment (M_{cr}), which is the point of friction bond limit, can be known directly through the initial crack that occurs.

The service load range is determined based on ASTM E 2126-09 [37], that is by drawing a vertical line through the $0.4P_{ultimate}$ line meeting with a $0.2P_{ultimate}$ horizontal line. From the analysis results, the average value of $P_{service}$ load is 18.79 kN or about 60% of $P_{ultimate}$. While the elastic range or friction bond limit points using Eq. (4) [33]:

$$\frac{P_{cr}}{P_{ultimate}} = \overline{R}u - 2.3(\sigma) = 20.08\% \approx 20\% \tag{4}$$

Table 3 shows that the lowest elastic value, 22.58%, occurred in the BRC-s1 beam, the highest, 27.59%, in the BRC-s0 beam. The average value of the elastic range is 24.61% of the ultimate load. From the calculation using Eq. (4), the value of the elastic limit is obtained by 20% of the ultimate load. The elastic limit on the SRC beam is 41.67% of the ultimate load. It can be concluded that the point of the elastic limit is 20% of the ultimate load, and the service load range is 60% of the ultimate load. The idealization of the BRC beam load-deflection relationship model is shown in Fig. 18.

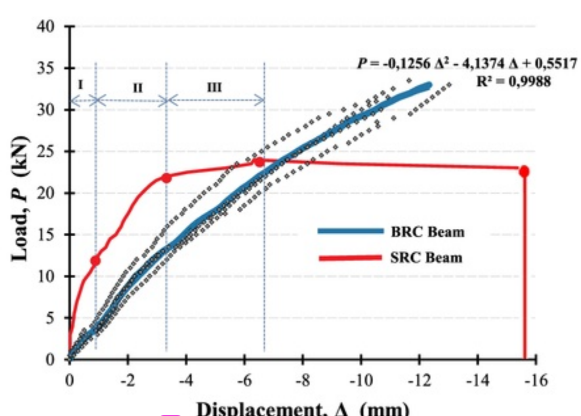

Fig. 16. Load-deflection relationship of BRC beams.

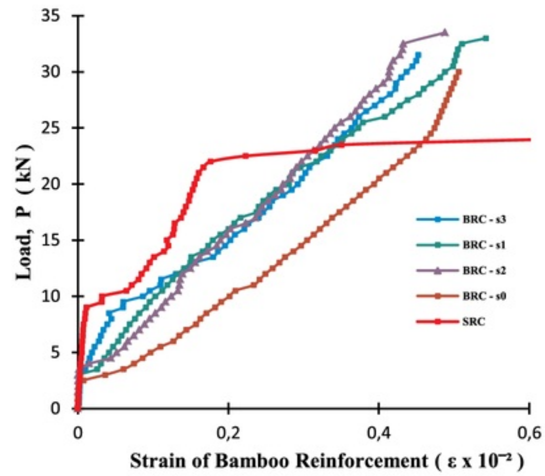

Fig. 17. Load-strain relationship of BRC beams.

Table 3
Load-displacement relationship calculation data.

Specimens/ Code	No	Theoretical calculations		Flexural test results			
		First crack load (kN)	Ultimate load (kN)	First crack load, P_{cr}(kN)	Failure load, $P_{ultimate}$ (kN)	Deflection at failure (mm)	P_{cr}/ $P_{ultimate}$ (%)
(a) BRC-s0/ A3B1	1	6.87	32.19	8.50	31.50	10.92	26.98
	2			8.00	29.00	11.90	27.59
(b) BRC-s1/ A3B2	1	6.87	32.19	7.00	31.00	13.02	22.58
	2			7.50	33.00	12.18	22.73
(c) BRC-s2/ A3B3	1	6.87	32.19	8.00	33.25	14.69	23.88
	2			7.50	33.00	9.32	22.73
(d) BRC-s3/ A3B4	1	6.87	32.19	7.50	29.50	7.61	25.42
	2			7.50	30.00	10.69	25.00
Mean values (*Ru*)				7.69	31.31	11.29	24.61
Standard deviation (σ)				0.46	1.73		1.97

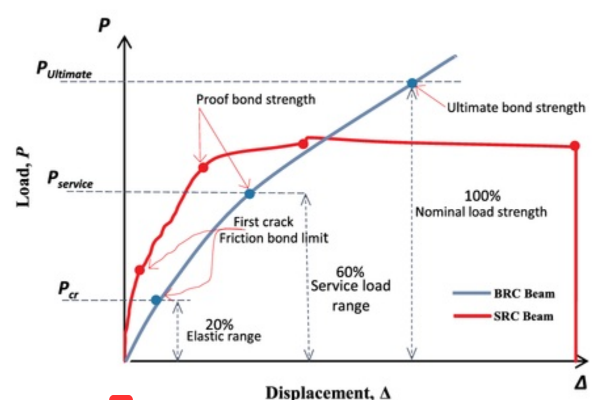

Fig. 18. The idealization of the load-deflection relationship model of BRC beam.

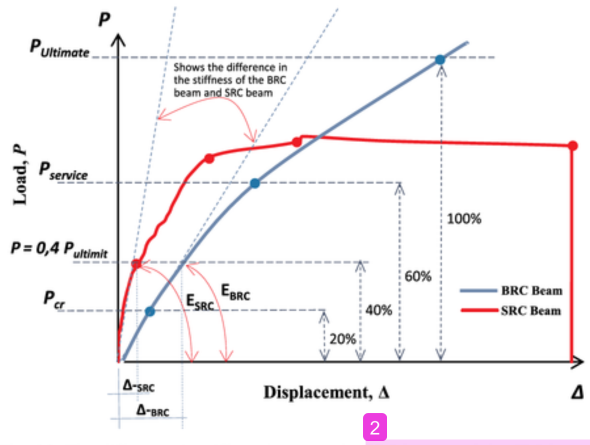

Fig. 19. The difference in stiffness between the BRC beam and the SRC beam.

In Fig. 19, if horizontal lines are drawn at service limits $P_{service}$, and linear lines are parallel to the SRC beam load-deflection diagram, it will be seen that the BRC beam stiffness is much lower than SRC beam stiffness. The average value of the BRC beam stiffness was lower – 43.92% – compared to the SRC beam. Whereas if we take when the initial crack load of the SRC beam, or $0.4P_{ultimit}$, is obtained, the BRC beam stiffness is lower than 75% of the SRC beam stiffness, as shown in Fig. 19. This is a weakness of the BRC beam that needs to be considered in future studies. The principle of the theory of confined concrete and shear reinforcement can be a solution to overcome the low rigidity of the BRC beam.

4.4. The bond-stress of flexural beam

Measurements and observations of slip (s) are carried out from when the initial crack occurs until the beam has collapsed. The measurement of slip (s) is taken in two ways, namely direct measurement through a strain gauge attached to a bamboo reinforcement for elongation of bamboo reinforcement (e_{bo}), and measurement through force analysis or curvature moment for elongation of the concrete (e_{co}). The readings from the strain gauge installed on bamboo reinforcement can still be carried out even though the concrete has been cracked, because when the concrete cracked, the bamboo reinforcement was still not yielding or was still in an elastic condition. Direct measurement through strain gauge and measurement through force analysis is carried out as control and comparison. Slip (s_o) at the point where the bond-stress occurs is calculated based on Eq. (5) [41].

$$s_o = e_{bo} - e_{co} \tag{5}$$

where e_{bo} = elongation of bamboo reinforcement, and e_{co} = elongation of concrete. The elongation of concrete (e_{co}) is calculated using Eq. (6) [41].

$$e_{co} = e_{c,co} + e_{c,bo} \tag{6}$$

where $e_{c,co}$ = elongation of concrete due to the compressive force, and $e_{c,bo}$ = elongation of concrete due to bond force.

The purpose of installing hose-clamps on bamboo reinforcement is to increase slip resistance between bamboo and concrete reinforcement. The test results and the calculations of bond-stress and slip can be seen in Table 4 and Table 5. Fig. 20 shows the relationship between bond-stress and slip in the BRC beam, divided into two stages. The first is the linear elastic stage, where the linear line curve shows the full elastic behavior of the BRC beam. The shear force that occurs on the reinforcement surface of bamboo is transferred to concrete. The maximum tensile stress on the beam is smaller than the flexural tensile strength, or smaller than the concrete collapse modulus. The second stage is a combination of elasto-plastic and plastic stages; this is consistent with the characteristics of the stress-strain of bamboo reinforcement which does not have a long yielding point, as shown in Fig. 10. This stage is the beginning of the micro slip of bamboo reinforcement and concrete.

The bond-stress of bamboo reinforcement starting to work up to ultimate bond-stress. The tensile stress that occurs is completely retained by bamboo reinforcement with its friction strength. Bond-stress increases with increasing slip resistance force. Likewise, the cracks increase and widen as the slip increases. The ultimate tension occurs when the maximum slip occurs on the bamboo reinforcement. The ultimate bond-stress occurs when the maximum slip occurs on the bamboo reinforcement.

From Table 5, the ratio between the friction bond limit and ultimate bond strength (u_f/u_u) ranges from 21% to 27%. While the bond-stress (u) from the friction bond limit up to ultimate bond strength can be approximated by Eq. (7), with the limit of $s_y < s_o \le s_u$, where s_y is slip on the initial crack of the beam, and s_u is the slip at the ultimate load as shown in Fig. 21.

$$u = 0.027s_o + 0.026 \tag{7}$$

4.5. The relationship model of bond-stress and slip in the bamboo reinforced concrete beam

Fig. 22 shows the bond-stress and slip relationship of BRC beam with a hose-clamp on bamboo reinforcement, where point a is the friction bond limit (u_f), and d is the ultimate bond strength (u_u). The ratio average of the friction bond limit (u_f) with the ultimate bond strength (u_u) of the BRC beam is 24%, and a minimum ratio of 21% occurs on the BRC-s1 beam, while a maximum ratio of 27% occurs on the BRC-s3 beam. The proposed u_f/u_u ratio is taken with Eq. (8) [33].

$$\frac{u_f}{u_u} = \overline{R}u - 2.3(\sigma) = 18.43\% \approx 20\% \tag{8}$$

The bamboo reinforced concrete beam (BRC) in Figs. 17 and 20 does not show elasto-plastic or plastic boundaries, so the boundaries point of proof bond strength (u_{pr}) and bond-stress at pre-cracking become nothing. This is in accordance with the stress-strain characteristic of bamboo reinforcement, that no length yield region occurs as it does in steel reinforcement. Thus, the region of post-friction bond limit (u_f) is a linear line until reaching ultimate bond strength (u_u). The value of the friction bond limit (u_f) point up to the ultimate bond strength (u_u) point is estimated at about 80%. If based on ASTM E 2126-09 [37], which sets out how to determine the yielding point of a wooden structure, then u_u is taken at $0.8u_{peak}$, and the ultimate bond strength (u_u) point is estimated at about 60%. Diab et al. [33], with a steel pull-out test, proposed the u_f/u_u ratio for the point (a) friction bond limit (u_f) of 50%, (b) proof bond strength (u_{pr}) of 60%, and (c) bond-stress at pre-cracking by 70%.

The difference between the relationship diagram of bond-stress and slip and the friction bond limit value (u_f) is far enough between the BRC and the SRC beam. This is due to a faster initial crack in the BRC beam. Initial cracks occur faster due to several reasons, including (1) the presence of microcracks around hose-clamps caused by air bubbles during the cement hydration process, (2) shrinkage occurring in bamboo reinforcement because the defects are not coated with a waterproof coating, especially during execution, and (3) the modulus of elasticity of bamboo is lower than concrete. Points (1) and (2) above are possible if work is not carried out under strict supervision.

4.6. Verification with the finite element method

Numerical verification is carried out in order to control the compatibility of the crack pattern of the BRC beam with the stress contour that occurs. The numerical method employed is the finite element

Table 4
Bond-stress and slip of the flexural beam test.

Specimens/ Code	Sample no	Theoretical calculations		Flexural test results						Flexural beam bond-stress (MPa)	Slip, s_o (mm)
		First crack load (kN)	Ultimate load (kN)	First crack load (kN)	Average first crack load (kN)	Failure load (kN)	Average failure load (kN)	Deflection at failure (mm)	Average deflection at failure (mm)		
(a) BRC-s0/ A3B1	1	6.87	32.19	8.50	8.25	31.50	30.25	10.92	11.41	0.31	9.05
	2			8.00		29.00		11.90			
(b) BRC-s1/ A3B2	1	6.87	32.19	7.00	7.25	31.00	32.00	13.02	12.60	0.33	10.85
	2			7.50		33.00		12.18			
(c) BRC-s2/ A3B3	1	6.87	32.19	8.00	8.00	33.50	33.25	14.69	12.01	0.33	9.76
	2			7.50		33.00		9.32			
(d) BRC-s3/ A3B4	1	6.87	32.19	7.50	7.50	29.50	29.75	7.61	9.15	0.30	10.12
	2			7.50		30.00		10.69			
(e) SRC	1	6.51	16.63	10.00	10.00	24.00	24.00	6.33	6.33	0.24	12.53

method, using the Fortran PowerStation 4.0 program. Theoretical analysis to calculate the load that causes the initial crack uses elastic theory (linear analysis) with a transformation section. For linear analysis, the material data included is the elastic modulus (E) and the Poisson ratio (ν). The non-linear phase is approached by giving a decrease in the strength of concrete 0.25–0.5 for the calculation of effective stiffness in the plastic area [42]. FEM analysis has not modeled the bond between bamboo reinforcement and concrete, where bamboo and concrete are considered to have the same displacement, with a different modulus of elasticity (E), so that they experience different stress. FEM analysis in this study has not been explained in detail and needs further analysis. In the constitutive relationship of finite element analysis, the problem-solving method has used the theory of plane-stress. Triangle elements are used to model plane-stress elements with two-way primary displacement at each point, so that the element has six degrees of freedom. The discretization of the beam plane was carried out using the triangle element shown in Fig. 23.

The modulus of elasticity (E), for each layer was calculated according to the conditions of the material. The layers consisting of the concrete and the bamboo reinforcement are calculated using the following Eq. (9) [43].

$$E_e = E_b.\ V_b + E_c.\ V_c \tag{9}$$

with E_e = equivalent elasticity modulus of BRC beam, E_b = modulus of elasticity of bamboo reinforcement, E_c = modulus of elasticity of concrete, V_b = relative volume of bamboo reinforcement in the calculated layer, and V_c = relative volume of concrete in the calculated layer. The stress-strain relationship for plane-stress problems has the form of an equation like Eq. (10).

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{E}{(1+\nu^2)} \begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \frac{1-\nu}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \tag{10}$$

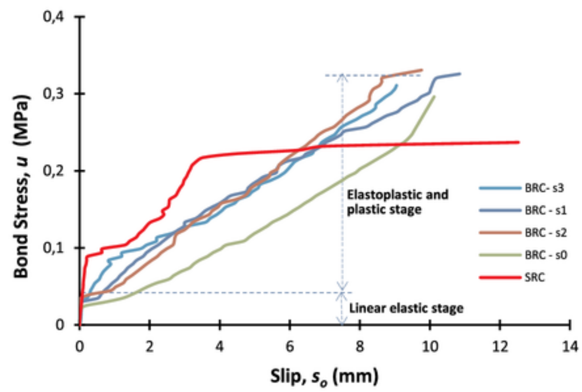

Fig. 20. Relocation bond-stress and slip on a BRC beam.

where E is the modulus of elasticity of the BRC beam and ν is Poisson's ratio. And the principal stress in two dimensions is be calculated with Eq. (11).

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}{}^2} = \sigma_{\max} \tag{11}$$

Fig. 24 shows that stiffness decreases after the initial crack, according to the loading stage of each mesh layer, and this is very influential on the results of the analysis. The average stiffness of the BRC beam was reduced from 26,324.76 MPa before cracking to 6581.20 MPa after the collapse [42], while the average value of the stiffness of the SRC beam was reduced from 30,334.11 MPa before cracking to 16,873.35 MPa after the collapse. Fig. 24 shows that the results of the load-deflection relationship model from the analysis are

Table 5
Bond-stress calculation.

Specimens/Code	Theoretical calculations		Flexural test results				
	First crack load (kN)	Ultimate load (kN)	First crack load (kN)	Failure load (kN)	Flexural beam bond-stress, u_u (MPa)	u_f (MPa)	u_f/u_u (%)
(a) BRC-s0/A3B1	6.87	32.19	8.50	31.50	0.311	0.079	25
	6.87	32.19	8.00	29.00	0.306	0.074	24
(b) BRC-s1/A3B2	6.87	32.19	7.00	31.00	0.326	0.069	21
	6.87	32.19	7.50	33.00	0.321	0.064	20
(c) BRC-s2/A3B3	6.87	32.19	8.00	33.50	0.331	0.079	24
	6.87	32.19	7.50	33.00	0.321	0.084	26
(d) BRC-s3/A3B4	6.87	32.19	7.50	29.50	0.296	0.074	25
	6.87	32.19	7.50	30.00	0.291	0.079	27
Mean values ($\bar{R}u$)					0.313		24
Standard deviation (σ)					0.01		2.42
(e) SRC	6.51	16.63	10.00	24.00	0.24		

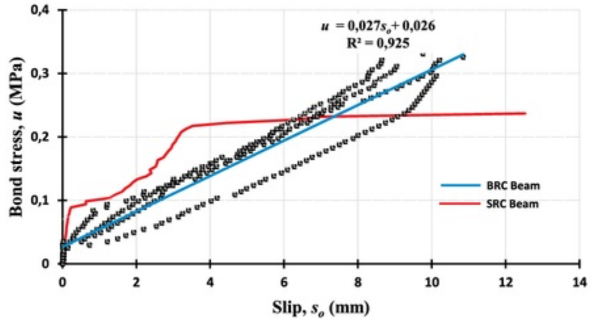

Fig. 21. The relationship of bond-stress and slip on a BRC beam.

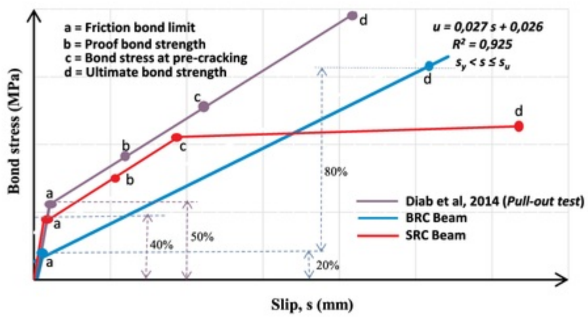

Fig. 22. The idealization of the bond-stress and slip relationship of the BRC beam.

quite close to the experimental results.

Along with increasing load, deflection and moments will continue to increase. When the crack moment (M_{cr}) is exceeded, the initial crack will occur, especially at the maximum moment. After the initial crack occurs, bond-stress will occur on bamboo reinforcement and concrete. Bond-stress and cracks will continue to propagate at the weak point of the beam section.

Fig. 25 and Fig. 26 show the crack pattern of the experimental result BRC beam and the contour stress result from the Surfer 9.8 program simulation. The position of the crack line and crack propagation are in accordance with the tensile stress contours of the simulation results, ie at coordinates 15 to 95. The red represents the maximum tensile stress, and the grayish blue represents maximum compressive stress. After initial cracking in the middle of the span, branching cracks occur in the position of the bamboo reinforcement. New cracks arise and branch upwards, right, and left. However, most additional cracks propagate to

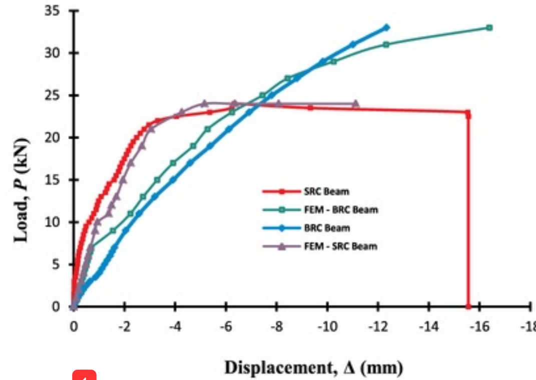

Fig. 24. The behavior of the load-deflection relationship of the BRC beam and the SRC beam using the finite element method.

the right and left, following the direction of bamboo reinforcement, in accordance with the maximum tensile stress contour resulting from the simulation. At this stage of branching cracks, the hose-clamp serves as a slip barrier and transfers the force to the concrete, as is evidenced by the many upward cracks that occur at the hose-clamp position, and the increasing spread of cracks spread. Documentation of the crack process can be seen by clicking the following link: https://goo.gl/6AVWmP.

The contribution of the hose-clamp to the bond-stress can be seen in the difference between the crack pattern in the results of this study and that of Agarwal's [21] study, as shown in Figs. 25 and 29. The crack line in the direction of the bamboo reinforcement proves the slip between bamboo reinforcement and concrete. The occurrence of slip proves that the elasticity modulus of bamboo is lower than that of concrete, causing low bond-stress. Therefore, the calculation of the BRC beam cross-sectional capacity must be based on the bamboo reinforcement shear area, not on the tensile strength of the bamboo reinforcement; this is in accordance with Ghavami's [1] research on the stress-strain distribution analysis of bamboo reinforced concrete beams.

Figs. 27 and 28 show the stress contours of the SRC beam resulting from the simulation in the Surfer 9.8 program and the crack pattern of the experimental result for the SRC beam. The coordinates of the crack pattern and the maximum tensile stress coordinates of the simulation results show suitability, which occurs at coordinates 35 to 75. Patterns of cracks and collapse are flexural cracks and flexural collapse. This proves that the bond strength of steel reinforcement is higher than the bond strength of bamboo reinforcement. After the initial crack occurs, along with increasing load, cracks continue to propagate upwards until collapse occurs.

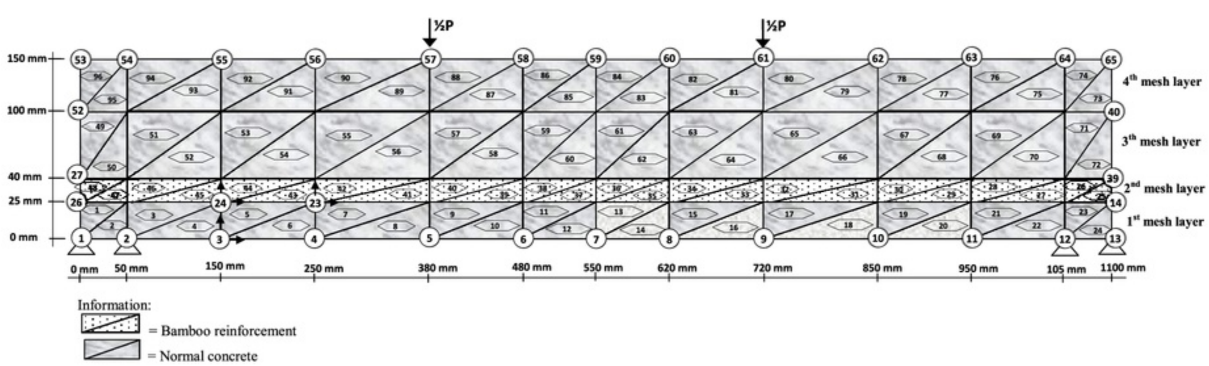

Fig. 23. Finite Element idealization of BRC beam.

Fig. 25. The crack pattern of the BRC beam.

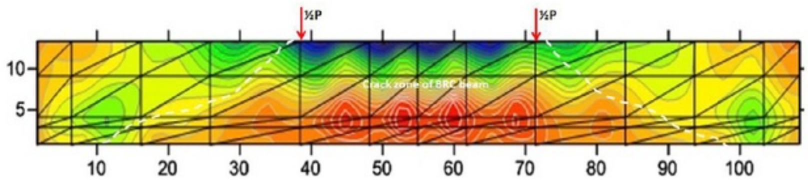

Fig. 26. The stress contour of the BRC beam.

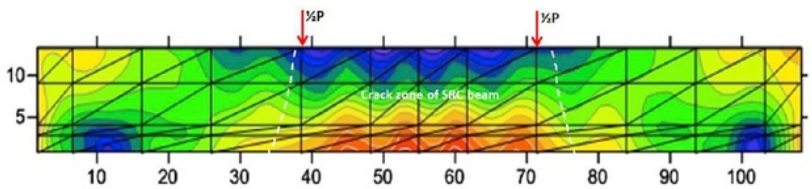

Fig. 27. The stress contour of the SRC beam.

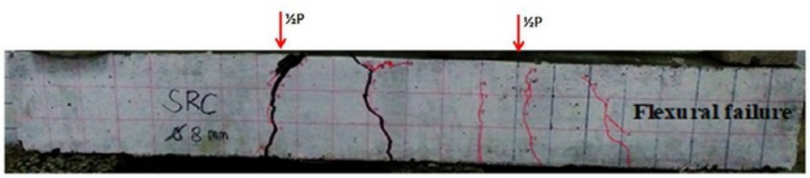

Fig. 28. The crack pattern of the SRC beam.

Fig. 29. Failure of bond-slip of the BRC beam [21].

5. Conclusions

Based on experiment, verification using the finite element method, and evaluation results on bamboo reinforced concrete beams with reinforcement using a hose-clamp, the following conclusions can be drawn:

(1) Installation of hose-clamps on bamboo reinforcement serves as a shear connector, can increase bond-stress, and reduce the slip between bamboo reinforcement and concrete.
(2) The BRC beam load-deflection relationship model has a gap that is far enough with the SRC beam load-deflection diagram. The stiffness of the BRC beam is lower than the stiffness of the SRC beam. The principle of the theory of confined concrete and shear reinforcement can be a solution to overcome the low rigidity of the BRC beam.
(3) The relationship model of bond-stress and slip in a BRC beam is different from the bond-stress and slip relationship model in an SRC beam. The friction bond limit of the BRC beam occurs at $0.2P_{ultimate}$ and the friction bond limit of the SRC beam occurs at $0.4P_{ultimate}$. This difference is due to the stress-strain characteristics and the elastic modulus of the materials from the two different test objects.
(4) The stress-strain characteristics of the materials, the modulus of elasticity of the materials, and the test method of the specimens are very influential to the relationship model of the bond-stress and slip.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2019.100896.

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