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The Measurement of the Local Slip in Bamboo-Reinforced Concrete Beams Using Moment-Curvature and Bond-Stress

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ABSTRACT

This paper presents a method of measuring local slip in bamboo-reinforced concrete beams. Local slips (s_o) are calculated by reducing the elongation of the bamboo reinforcement (e_{bo}) with the elongation of the concrete (e_{co}). The elongation of bamboo reinforcement (e_{bo}) is determined in two ways, namely, read directly through a strain-gauge mounted on the bamboo reinforcement and calculated based on the force analysis or curvature moment as a control. The elongation of the concrete (e_{co}) is calculated using force analysis or curvature moment. The process of calculating curvature moments and bond stress employs the Excel program. The steps in calculating the elongation of concrete (e_{co}) consist of calculating the curvature moment, calculating the bond-stress at the initial crack, and calculating the bond-stress at the second crack until the beam collapses. Further, the results of the calculation of the elongation of the concrete (e_{co}) and the elongation of the bamboo reinforcement (e_{bo}) resulting from the reading of the strain-gauge are substituted in the local slip calculation equation. The results of the calculation analysis show that the local slip is approaching the local slip resulting from the experiment. The relationship behavior of bond-stress vs. slip indicates conformity with the experimental results. The local slip calculation based on the moment-curvature can be considered as control of the experiment result.

KEYWORDS

Local slip; bamboo-reinforced concrete (BRC); moment-curvature; bond-stress

List of symbols

u :	Bond-stress (MPa)
u_{bo} :	The peak of bond-stress (MPa)
u_b :	Local bond-stress (MPa)
U_{bx} :	Total bond-force (N)
u_{bx} :	Bond stress at a distance x away from the zero-slip section (MPa)
V :	Shearing force of the beam (N)
\sum_o :	Circumference of the cross-section of bamboo reinforcement
d :	Distance from the maximum press fiber to the center of the bamboo tensile reinforcement area (mm)
a :	Height of concrete stress block equivalent (mm)
jd :	The internal lever arm = $d - \frac{1}{2} a$
ε_{bo} :	A strain of bamboo reinforcement
ε_{bc} :	Bamboo strain in cross-section Z



ε_{bx} :	Bamboo strain function
e_{bo} :	Elongation of bamboo reinforcement (mm)
e_{co} :	Elongation of concrete (mm)
$e_{c,co}$:	Elongation of concrete due to the compressive force (mm)
$e_{c,bo}$:	Elongation of concrete due to bond force (mm)
L :	Span length (at Fig. 3) (mm)
L_o :	$\frac{1}{2}$ crack distance the side left plus $\frac{1}{2}$ crack distance the side right of the observation point as shown in Fig. 5 and Eq. (3) for the local-slip (mm)
ϕ :	Bamboo reinforcement diameter (mm)
f_{bt1} :	Bamboo stress at an uncracked section, bamboo stress at zero-slip point (N/mm ²)
f_{bt2} :	Bamboo stresses at cracked sections (N/mm ²)
f_{bt1} :	The stress of bamboo reinforcement at slip length (at the zero-slip point as shown in Fig. 5) (N/mm ²)
f_{bt2} :	The stress of bamboo reinforcement at slip length (at the crack point as shown in Fig. 5) (N/mm ²)
BRC :	Bamboo Reinforced Concrete
SRC :	Steel Reinforced Concrete
S :	Crack spacing (mm)
S_x :	Distances from the cracked sections to zero slip point (mm)
S_o :	Slip length or 1/2 the distance between two adjacent cracks (mm)
s_o :	Local slips at the points where the peak bond stresses occur (mm)
s :	Slip (mm)
f_c' :	Characteristic strength of concrete (MPa)
f_{bx} :	Bamboo stress at a distance x from zero-slip section (MPa)
f_{btx} :	Bamboo stress function at slip length (MPa)
f_{bt1} :	Bamboo stress at zero-slip point (MPa)
f_{bt2} :	Bamboo stress at a crack point (MPa)
$\Phi'_{(s_o)}$:	Constitutive relationship
E_b :	Modulus of elasticity of bamboo (N/mm ²)
M_1 :	Bending moment at the supports in a continuous beam (N-mm)
M_2 :	Bending moment at mid-span in a continuous beam (N-mm)
ρ :	Tension reinforcement ratio
A_{bt} :	Area of tensile reinforcement (mm ²)
b :	Beamwidth (mm)

1 Introduction

Research on bamboo as reinforcing concrete has been done a lot and the majority of failures are the failure of adhesion between bamboo and concrete. The main factors causing adhesive failure are the lower elastic modulus of bamboo than concrete, hygroscopic properties, and the hydrolysis process. The difference in the modulus of elasticity of bamboo which is lower than concrete causes the concrete not to grip the bamboo reinforcement after the cement hydration process, which eventually occurs swelling [1]. This shows that bamboo reinforcement cannot bond with the concrete (no direct contact) post hardened concrete. To overcome the weaknesses of bamboo requires treatment such as soaking, drying [2] adding waterproof coatings such as Sikadur[®]-752 [3,4], and strengthening bond-stress. Therefore, bamboo as concrete reinforcement does not have a significant effect without treatment and waterproof layer adhesive. Treatment and application of waterproof layer adhesive is a must.

There are many ways to prevent the hygroscopic process between bamboo reinforcement and concrete during the hydration process. The use of adhesives and waterproof coatings such as Sikadur 32 Gel [5–7];

Sikadur 32 LP [8]; Sikadur[®]-752 [9,10]; asphalt and bitumen [11]; Concrevice 1315 [12]; paint [13]; Sikadur-31CFN [14]; Araldite Epoxy Resin Coal Tar [15]; synthetic resin and synthetic rubber [16]; lime water treated bamboo mat coated with epoxy and sand [8]; TrueGrip BP with coarse sand, water-based epoxy coating with fine sand, TrueGrip EP with coarse sand, Exaphen with coarse sand, and enamel, water-based epoxy coating with coarse sand, [1]. Meanwhile, to calculate water absorption in bamboo reinforcement can use method A from ASTM 4442-92 [17].

Reinforced concrete bonds are formed by the mechanism of adhesion, friction, and mechanical interlock between reinforcement and concrete. The bond strength is strongly influenced by the fracture energy [18] as well as the complex interactions between local deformation, chemical adhesion, and other factors [19]. As for the interlock mechanism of bamboo reinforced concrete, the transfer of shear forces between bamboo reinforcement and concrete is the dominant factor after adhesive bonding. The application of adhesive, waterproof layer and modification of the surface roughness of bamboo reinforcement are efforts to increase bond-stress and prevent slippage. Several methods to increase adhesion strength and prevent slippage between bamboo reinforcement and concrete include modifying the roughness such as by notching [20,21], coir winding [22], adding hooks [23], or installing hose clamps [3].

Bamboo has high elastic properties due to the high tensile strength of bamboo fibers. Archila et al. [24] in their summary wrote that Bamboo is essentially an elastic brittle material. Bamboo has elastic properties that will be advantageous in the post-cracking behavior of reinforced concrete which requires sufficient bonding between bamboo and concrete. The elastic properties of bamboo is an opportunity to be investigated. Some of the advantages of BRC beams include: (1) BRC beam has high elastic properties which can absorb energy after the ultimate load of 33 kN [3]. After the ultimate load is released, the beam returns to flatness or deflection tends to return to zero as shown in the video on the following link: <https://goo.gl/6AVWmP> [3,4]; (2) BRC beams are one of the construction elements with low-cost, renewable materials, reduce environmental pollution, easy to get, and bamboo is very abundant in tropical and subtropical areas around the world [5].

The reference for calculating the bond stress and slip of bamboo reinforcement with concrete is based on the reference for calculating the bond stress and slip of steel reinforcement. Several references are used as a basis including Diab et al. [25], Siempu et al. [26], Tang et al. [27], Wang et al. [28], Wang et al. [29], Jacques et al. [30], Lin et al. [31], and Piyasena et al. [32].

Diab et al. [25] conducted a pull-out test of 16 mm diameter steel reinforcement embedded in concrete, and propose a bond-stress vs. slip relationship model with a limit point of “friction bond limit” of 50%, a limit point of “proof bond strength” of 60%, and a limit point of “bond-stress at pre-cracking” of 70%. The embedded length of steel reinforcement in concrete affects increasing the ultimate tensile bond strength and ultimate slip. The crack length affects decreasing the adhesive strength and increasing the slip. Cracked specimens lose about 30% of their bond strength. Cracks can reduce the stiffness of the concrete section, and make the distribution of bond stresses uneven along the length of the reinforcement bar.

Siempu et al. [26] conducted a study on the parameters influencing flexural bond stress in reinforced concrete and concluded that with increasing concrete strength, the bond-stress increases. The flexural bond-stress is lower than the bond-stress from the pull-out test. Tang et al. [27] predicts modeling relationships local bond stress vs. slip of reinforcing bars embedded in concrete with different strengths, and propose an empirical formula for the ultimate local bond stress is a function of the strength of the concrete, the thickness of the concrete cover, and the diameter of the reinforcement, which are following the experimental values. Wang et al. [28] examine the bond-slip performance and constitutive model of the interface between reinforcing steel bars and brick masonry. They concluded that the initial bond stiffness of the micro-slip segment increases with increasing vertical compressive stress, and the ultimate bond stress increases significantly. However, this model cannot be adopted due to different test methods and specimens.

Wang et al. [29] examines the crack propagation process of lightly reinforced concrete beams considering bond-slip behavior. The conclusion shows that the bond-slip behavior has a significant effect on the crack extension properties. Beam failure is usually due to the formation and growth of one central crack. When cracks penetrate through the reinforcing zone, slip between the reinforcement and concrete begins, and then the interface shear stress increases, which causes debonding of the reinforcing-concrete interface. Jacques et al. [30] investigated the effect of high strain rates on reinforcing bonds in concrete. High levels of strain were found to significantly increase the bond end bond strength of the beam, whereas they do not significantly affect the general shape of the curve of bond stress vs. slip. Lin et al. [31] examined the bond-slip behavior of FRP-reinforced concrete beams, and one of his conclusions wrote that bond-slip was proven to have a major effect on the flexural behavior of FRP reinforced concrete beams. BFRP reinforced concrete beams perform much better than other reinforced concrete beam specimens due to the strong bonding of BFRP reinforced concrete beams.

This study discusses the slip calculation method on bamboo reinforced concrete beams (BRC) based on moment-curvature and bond-stress. Some of the difficulties in obtaining slip data between reinforcement and concrete from the experimental results are obtaining concrete elongation (e_{co}) data and reinforcement elongation. The difficulty in finding concrete elongation (e_{co}) is usually due to the installation of the concrete strain-gauge is inaccurate or damage. Meanwhile, difficulties in obtaining reinforcement elongation usually occur after the initial crack due to the yielding and damaged reinforcement. The limitation of measurement and local slip analysis in this study was carried out at predetermined observation points, namely at the time of the initial crack, the second crack, the third crack, and until the crack at the ultimate load. It is suspected that the calculation method in this study can be a solution to get the length of the slip that occurs.

2 Materials and Methods

2.1 The Materials and Experiment

The specimens used in the study were eight pieces of bamboo reinforced concrete beam with single reinforcement. The size of the beams is 75 mm × 150 mm × 1100 mm. The geometry and reinforcement details of BRC beams are shown in Fig. 1. Installation of hose-clamp at both ends of the bamboo reinforcement functions as a hook-like such as steel reinforcement. Material properties of bamboo reinforcement and concrete are shown in Tab. 1. Beams are flexural tested using the four-point load method [33] as shown in Fig. 2.

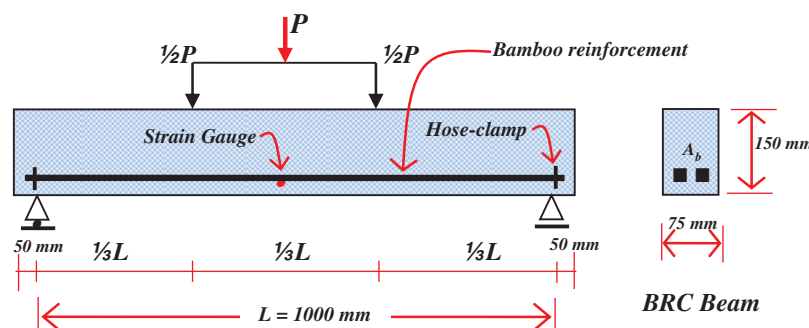


Figure 1: Detail and geometry of the bamboo reinforced concrete beam

There are 16 specimens of BRC beams, consisting of 4 variations of the area of bamboo reinforcement, namely 100 mm², 140 mm², 200 mm², and 450 mm². The BRC beam specimen has 2 strain gauges installed on the bamboo reinforcement to detect the elongation of the bamboo reinforcement as shown in Figs. 1 and 2.

2 pieces of strain gauge are installed on the bamboo reinforcement in the middle of the span as shown in Fig. 2. The purpose of the installation of strain gauge is to obtain the elongation of bamboo reinforcement in the calculation of the local slip (slip in the middle of the measured span), and this is also to control the extension of the calculated reinforcement through curvature moment and bond stress. Elongation of bamboo reinforcement is obtained in two ways, namely through the experiment of the BRC beam and through calculation curvature moment and bond-stress based on experimental data such as loading history data and crack patterns. Because the installation of strain-gauge at the observation point is limited, then the lengthening of the bamboo reinforcement from the experiment needs to be controlled by the results of the lengthening of the bamboo reinforcement with the results of moment-curvature analysis and the bond stress.

Table 1: Material properties of bamboo reinforcement and concrete

Bar type and concrete	Reinforcement size, (mm)	Modulus of elasticity (E), (MPa)	Tensile strength, (MPa)	Compressive strength, f_c' (MPa)	Poisson's ratio (ν)
Petung Bamboo (<i>Dendrocalamus asper</i>)	15 × 15	17235.74	126.68	–	0.25
Concrete	–	26324.79	–	31.31	0.20

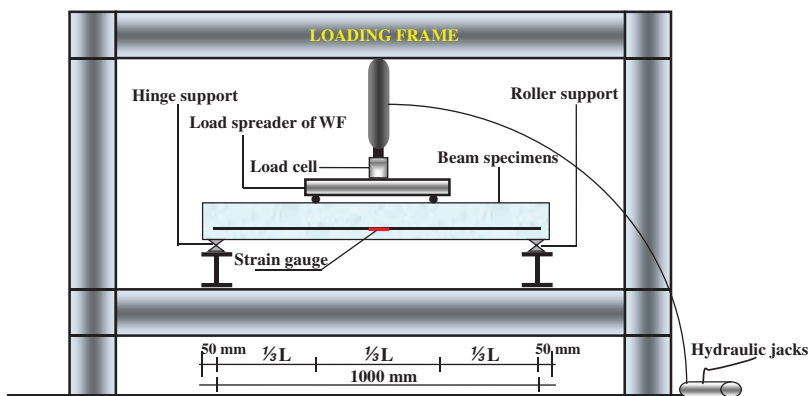


Figure 2: Flexural test settings for the four-point flexural test method [33]

The elongation of bamboo reinforcement from the experimental results is obtained from the formula $\varepsilon = e_{bo}/L_o$, with L_o is $\frac{1}{2}$ crack distance the side left plus $\frac{1}{2}$ crack distance the side right of the observation point. The strain-gauge is mounted by attaching it to the bamboo reinforcement with sufficiently elastic insulation to prevent damage after the initial crack occurs. But in reality, strain-gauge readings on the BRC beam can continue to be carried out until the ultimate load and even the BRC beam collapse. This proves that the strain-gauge and bamboo reinforcement are not damaged, as shown in the video on the following link: <https://goo.gl/6AVWmP> [3]. The video shows that the BRC beam has good elastic properties. The maximum deflection that occurs tends to return to zero after the load is released landed, or the BRC beam returns flat [34].

The load is applied at a distance of $\frac{1}{3}L$ from the beam support, using the WF load spreader. The strain gauge is attached to the bamboo reinforcement with a distance of $\frac{1}{2}L$ from the span of the beam. The strain gauge is connected to a digital strain-meter. Hydraulic jacks are used for beam loading with a 200 kN load cell connected to the data logger. Crack patterns and failure patterns were observed and identified from the

first crack to the collapse of the beam. Crack pattern data and loading history are used as input data for calculating slip through moment-curvature and bond stress. The test equipment setup and load scheme are shown in Fig. 2.

2.2 The Basis of the Method

Crack patterns and flexural behavior in steel-reinforced concrete beams are used as the basis for this method. How crack and bond-slip patterns occur is shown in Figs. 3 and 4 [32]. When there is an initial flexural crack on the BRC beam under load, the stress of the bamboo reinforcement on the cross-section of the crack increases because the tensile stress on the concrete is transferred to the bamboo reinforcement. This increase in bamboo stress is held up by bond-forces that occur along with the reinforcement on both sides of the crack. This bond force is associate with a bond-slip, and the length of the bond-slip is dependent on the increase in the bamboo reinforcement stress as the bond-stress relationship, bond-slip, and reinforcement dimensions.

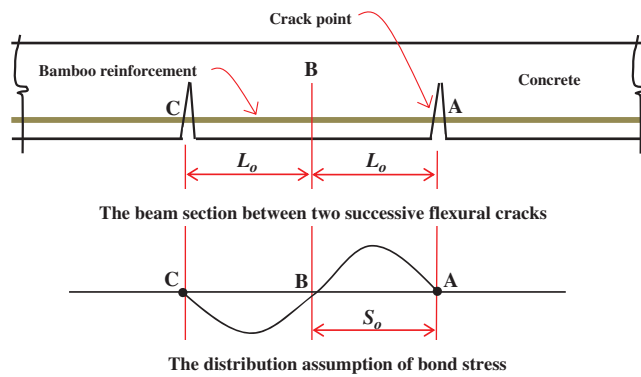


Figure 3: The flexural cracks and the distribution assumption of bond stress on the beam section [32]

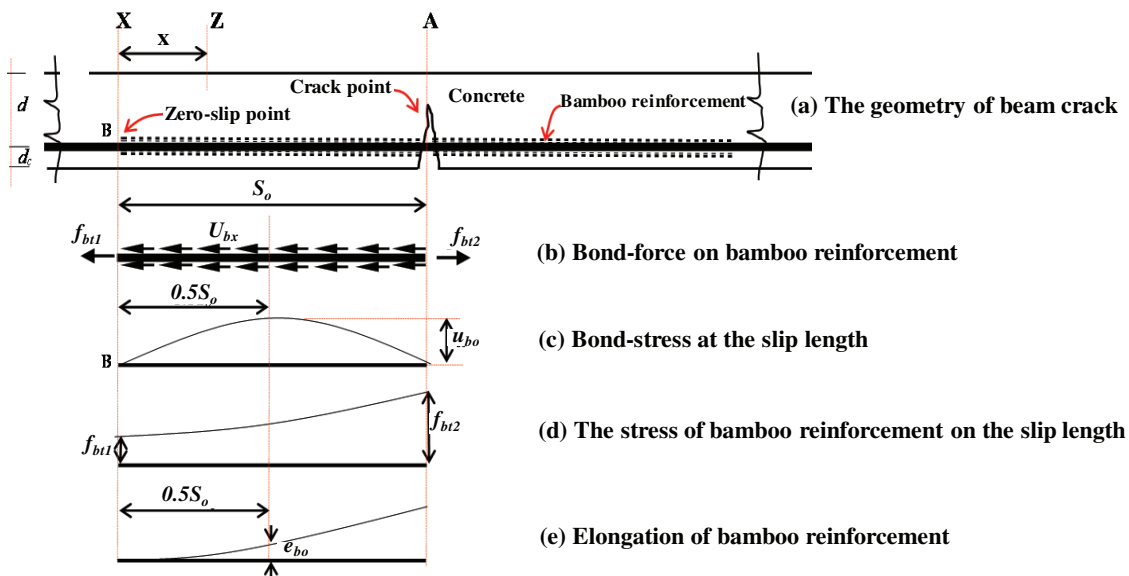


Figure 4: The initial flexural cracks on the BRC beam; (a) the geometry of BRC beam crack; (b) bond-force on bamboo reinforcement; (c) bond-stress at slip length; (d) the stress of bamboo reinforcement at slip length; (e) elongation of bamboo reinforcement [32]

The basic formula for calculating the bond-stress (u) is based on the formula Park et al. [35] in Chapter 9 sub-chapter 9.1.3 Flexural Bond. The local slip (s_o) calculation as shown in Eq. (9) is based on the Piyasena formula [32] through the moment-curvature of the beam section, the bond-stress of the first crack, and the bond-stress of the second crack until collapses beam. Piyasena formulas [32] starting from Eqs. (4)–(19) were translated or counted by an excel program. Figs. 3 and 4 shows the beam section after the initial bending crack occurred in cross-section A. Increased bamboo reinforcement stress due to cracking that occurs in the form of a slip S_o . Distance S_o is referred to as slip length. The bamboo reinforcement stress f_{bt} at both ends of the bamboo reinforcement and bond force U_{bx} along S_o is shown in Fig. 4a. The variation of bond stress u_{bo} and bamboo reinforcement stress f_{bt} on the slip length is shown in Figs. 4b and 4c. While elongation of bamboo reinforcement e_{bo} is shown in Fig. 4d. The elongation of bamboo reinforcement is zero at the $x = 0$ position due to the bond stress equal to zero, while the tensile stress of bamboo reinforcement at the $x = 0$ position is not equal to zero as shown in Figs. 3 and 4.

2.3 Calculation Process

Preparation for the calculation process is to carry out the flexural test to the BRC beam. A strain gauge is attached to the bamboo reinforcement. The data from the strain gauge readings were analyzed according to the loading stage and the cracking process. The calculation of elongation of bamboo reinforcement (e_{bo}) is obtained from the strain formula as shown in Eq. (3). Elongation of concrete (e_{co}) is calculated through the curvature moment by entering material data, geometry data, load data, crack behavior, and other experimental data, and these data are used to calculate curvature-moment, the calculation of bond-stress, and slip when the initial crack, and the calculation of bond-stress and slip when the second crack until the beam collapses. The details of the calculation process are shown in Fig. 5.

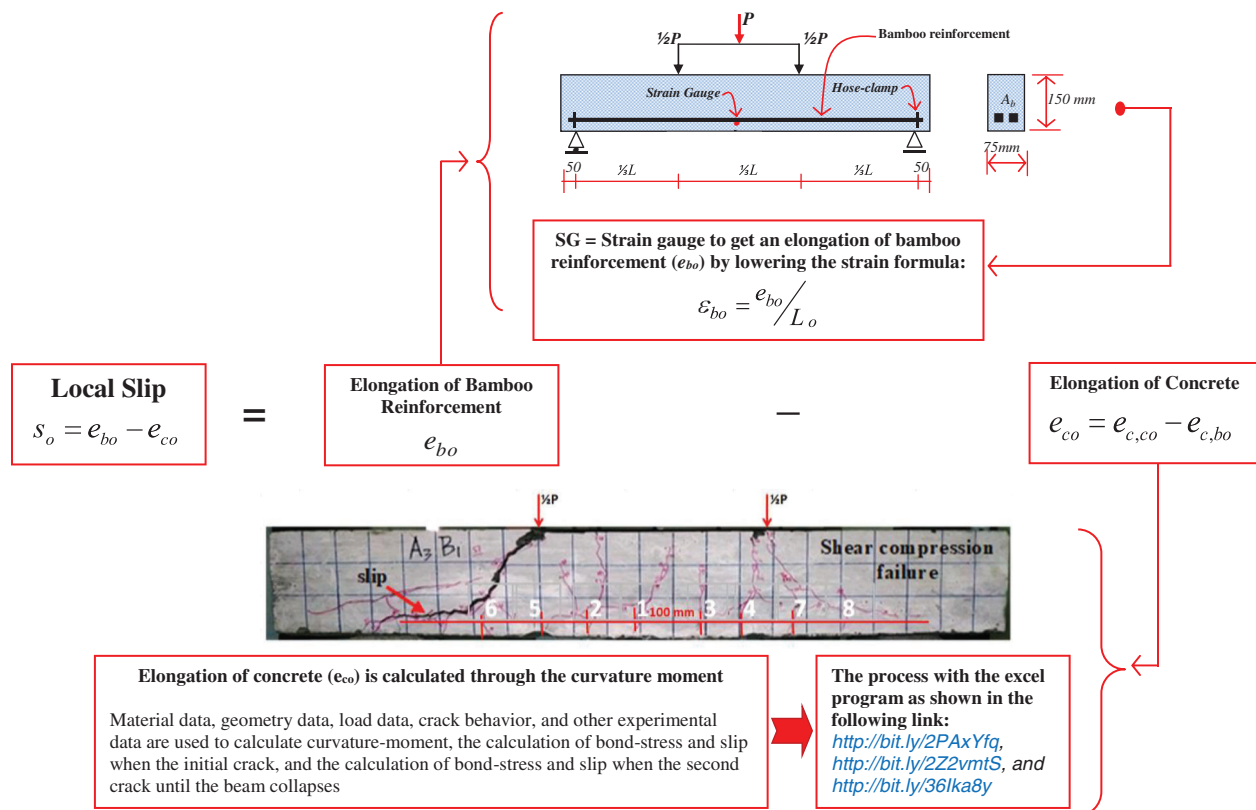


Figure 5: The slip calculation process of the BRC beam

The local slip (s_o) calculation method is based on experimental results data and analysis of curvature moments in cross-sections of bamboo-reinforced concrete beams. The geometry of the beam test specimen for the experiment is shown in Fig. 1 and the beam specimen test settings are shown in Fig. 2. The calculations of bond-stress are carried out in two ways, namely using the approach formula as shown in Eqs. (1) and (2) and through curvature-moment analysis as control. Local slip (s_o) calculation is carried out in two ways, namely through the reading of the strain-gauge for elongation of bamboo reinforcement (e_{bo}) using Eq. (3) and through the curvature-moment for elongation of concrete (e_{co}). The elongation of bamboo reinforcement (e_{bo}) from the curvature-moment analysis is used as a control for the elongation of bamboo reinforcement (e_{bo}) from the strain-gauge reading. Bond-stress and local slip calculations through the curvature-moment are performed using an Excel program based on Eqs. (4)–(19). Bond-stress data from the curvature-moment analysis is used as bond-stress control from calculations using Eqs. (1) and (2). The steps for calculating bond-stress and local slip are as follows:

Step 1: The bond-stress (u) calculation of the BRC beam, based on experimental data using Eqs. (1) and (2) [3,13,35].

$$u = \frac{V}{jd \cdot \Sigma o} \quad (1)$$

$$jd = (d - 1/2a) \quad (2)$$

where,

V is the shearing force of the beam.

Σo is the circumference of the cross-section of bamboo reinforcement.

d is the distance from the maximum press fiber to the center of the bamboo tensile reinforcement area.

a is the height of the concrete stress block equivalent.

Step 2: Calculation of the elongation of bamboo reinforcement (e_{bo}) through the reading of the strain gauge when the flexural test of a beam using the approach formula as shown in Eq. (3).

$$\varepsilon_{bo} = e_{bo}/L_o \text{ or } e_{bo} = \varepsilon_{bo} \cdot L_o \quad (3)$$

Step 3: Calculation of bond-stress (u) and local slip (s_o) through the curvature-moment using the Excel program.

The calculation of bond-stress and local slip through the curvature-moment using the Excel program based on Eqs. (4)–(19) [32] with the following steps:

- A) The calculation of curvature-moment using the Excel program as shown in the following link: <https://bit.ly/3ltwPEb>. In the program, there is a calculation of the internal forces before cracking, when cracks occur (M_{cr}), after the initial cracking until the bamboo reaches yield point or the bamboo stress value is reached f_b , and after bamboo reaches the yield point until the concrete stress reaches f_c' .
- B) The calculation of bond-stress and the local slip of the first crack as shown in the following link: <https://bit.ly/2UpCQFQ>.
- C) The calculation of bond-stress and the local slip of the second crack until rupture is shown in the following link: <https://bit.ly/2Ukj2Uo>.

The equations used in the calculation of bond-stress and local slip (Point B and Point C) based on the curvature-moment are as follows: Eq. (4) is an equation of force balance working on bamboo reinforcement

between the crack section and the zero-slip point. Determining bond-stress u_{bo} and slip length S_o is carried out through trial and error because of the nature of the non-linear constitutive relationship of Eq. (5).

$$\frac{\pi\phi^2}{4}(f_{b2} - f_{b1}) = \frac{2}{3}\pi\phi \cdot u_{bo}S_o \quad (4)$$

The peak bond-stress u_{bo} and local slip s_o must meet the constitutive relationship Eq. (5).

$$u_{bo} = \Phi'(s_o) \quad (5)$$

where $\Phi'(s_o)$ is the constitutive relationship given in Eqs. (6)–(8).

$$\frac{u_b}{\sqrt{f'_c}} = 150s \rightarrow \text{if} \Rightarrow s \leq 0,004 \quad (6)$$

$$\frac{u_b}{\sqrt{f'_c}} = 0,47 + 33s \rightarrow \text{if} \Rightarrow 0,004 < s < 0,010 \quad (7)$$

$$\frac{u_b}{\sqrt{f'_c}} = 0,71 + 9s \rightarrow \text{if} \Rightarrow s > 0,010 \quad (8)$$

Local slip s_o at the point where the bond-stress u_{bo} occurs (at a distance of $0.5S_o$ from the zero-slip point as shown in Fig. 3 is calculated by Eq. (9) as follows:

$$s_o = e_{bo} - e_{co} \quad (9)$$

Elongation of bamboo reinforcement e_{bo} in Eq. (9) is the result of the strain-gauge reading, as shown in Eq. (3). Elongation of bamboo reinforcement e_{bo} in Eq. (16) results from the derivation and solving of Eqs. (10)–(15), used as control data for calculating the results of elongation of bamboo reinforcement from the outcomes of experiments in Eq. (3).

The total bond-force U_{bx} acting on the surface of the bamboo reinforcement is calculated by integrating Eq. (10) as follows:

$$U_{bx} = \int \pi\phi \cdot u_{bx} dx = \frac{4u_{bx}\pi\phi}{s_o} \left(\frac{x^2}{2} - \frac{x^3}{3s_o} \right) \Rightarrow (x \leq S_o) \quad (10)$$

The bamboo stress f_{btx} is calculated using Eq. (11).

$$\frac{\pi\phi^2}{4}(f_{btx} - f_{bt1}) = U_{bx} \quad (11)$$

Substituting Eq. (11) into Eq. (10) produces Eq. (12).

$$f_{btx} = f_{bt1} + \frac{16u_{bo}}{s_o\phi} \left(\frac{x^2}{2} - \frac{x^3}{3s_o} \right) \Rightarrow (x \leq S_o) \quad (12)$$

Bamboo strain ε_{bx} is calculated by the formula $\varepsilon_{bx} = f_{btx}/E_b$. The elongation of the bamboo reinforcement e_{bo} at a distance of $0.5S_o$ from the slip-zero is calculated by integrating Eq. (13).

$$e_{bo} = \int_{x=0}^{x=0,5S_o} \varepsilon_{bx} dx \quad e_{bo} = \int_{x=0}^{x=0,5S_o} \left\{ \frac{f_{bt1}}{E_b} + \frac{16u_{bo}}{s_o\phi E_b} \left(\frac{x^2}{2} - \frac{x^3}{3s_o} \right) \right\} dx \quad (13)$$

Results of integrating Eq. (13) are shown in Eq. (14).

$$e_{bo} = \frac{f_{bt1}s_o}{2E_b} + \frac{u_{bo}s_o^2}{4E_b\phi} \quad (14)$$

In the calculation of e_{bo} , the use of bamboo stress f_{bt2} at the crack point is more appropriate than the use of bamboo stress f_{bt1} at the zero-slip point as shown in Fig. 4, because the crack width is expressed as a function, so f_{bt1} at Eq. (14) replaces f_{bt2} and resetting of Eq. (4) becomes Eq. (15).

$$f_{bt1} = f_{bt2} - \frac{8u_{bo}s_o}{3\phi} \quad (15)$$

Substituting Eq. (15) into Eq. (14) produces Eq. (16).

$$e_{bo} = \frac{f_{bt2}s_o}{2E_b} - \frac{13u_{bo}s_o^2}{12E_b\phi} \quad (16)$$

Elongation of concrete e_{co} on Eq. (9) is determined using Eq. (19). The value of elongation of concrete $e_{c,co}$ due to the compressive force in Eq. (19) is calculated using Eq. (17) [32], and the value of elongation of concrete $e_{c,bo}$ due to bond force is calculated using Eq. (18) [32].

$$1000e_{c,co} = \left(2,5 \frac{s_o}{d} + 0,5\right) \frac{d}{100} \geq 0 \quad (17)$$

$$1000e_{c,bo} = \left(1,3 \frac{s_o}{d} - 0,5\right) \left(\frac{s_o}{100}\right) u_{bo} \left(\frac{4\rho d}{\phi}\right) \geq 0 \quad \text{where } \Rightarrow \rho = \frac{A_{bt}}{bd} \quad (18)$$

$$e_{co} = e_{c,co} - e_{c,bo} \quad (19)$$

Step 4: The validate data against calculation data of bond-stress and local slip uses the approach of Eqs. (1)–(3) and curvature-moment with Excel program.

Step 5: The calculation data validation with graphical diagram drawings as shown in Fig. 8.

3 Results and Discussion

3.1 Experimental Results

The results of photographic data of crack and slip patterns from the BRC beam experiment from the initial crack until collapse is shown in Fig. 6. The raw data of bond-stress and slip from the BRC beam experiment using the approach formula is provided in the following link: <http://bit.ly/2S74E1S> and the graphic image data is shown in Fig. 7. The graphic image data of the relationship of bond-stress and local slip from the BRC beam experiment with regression analysis is shown in Fig. 7.

Fig. 6 shows the collapse pattern of BRC beams, namely the failure pattern of “shear compression failure”, meaning that the majority of crack patterns occur due to slippage between bamboo reinforcement and concrete. The initial crack shows a flexural crack that propagates from the lower fiber of the beam and continues upward through the concrete cover. When the cracks reach the point of bamboo reinforcement, they start to branch, some continue to go upwards and some go sideways in the direction of the bamboo reinforcement. The cracks that occur mostly propagate sideways in the direction of the bamboo reinforcement because at the interface bamboo reinforcement and concrete is the lowest bond-stress point. From the observations of the experimental results, the BRC beam has the advantage that the surface returns to flat after load shedding, even though it has experienced shear failure. This shows that bamboo reinforcement has high tensile strength and elastic properties as shown in the research of Muhtar et al. [3] via the video at the following link: <https://goo.gl/6AVWmP> As the load increases, the cracks

continue to occur and the slip gets bigger until the shear failure occurs in the beam. BRC beams have low stiffness, but BRC beams have high elastic properties [34].

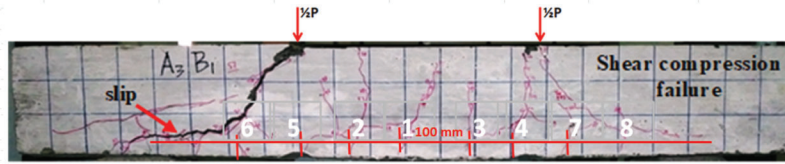


Figure 6: The photographic data of crack and slip patterns from the BRC beam

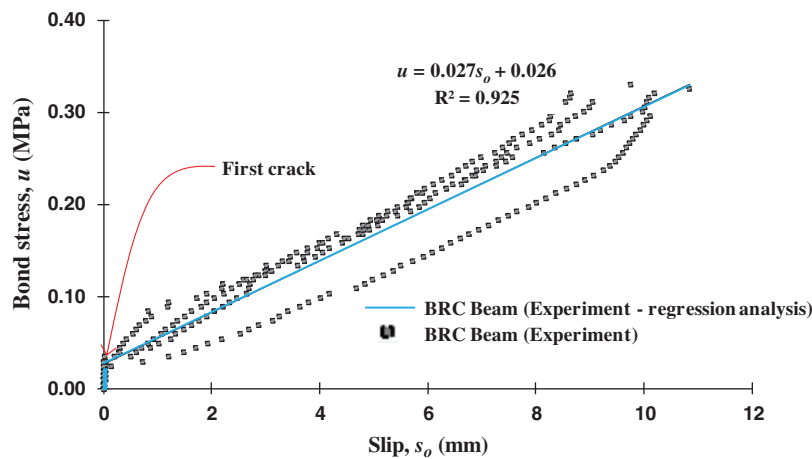


Figure 7: The relationship of bond stress vs. slip of experimental results

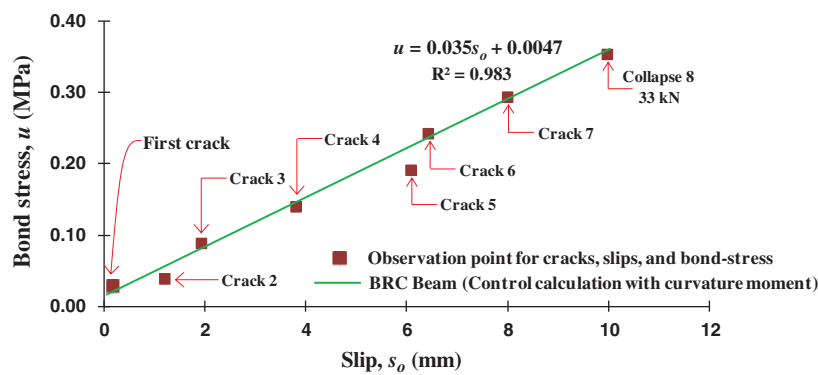


Figure 8: The relationship of bond stress vs. slip from the calculation results of the curvature moment

3.2 The Validation Local-Slip Using Moment-Curvature and Bond-Stress

The calculation results of bond-stress and local slip uses curvature-moment are shown in Tab. 2, while the Excel program data from the calculation process of curvature-moment, the calculation of bond-stress and local slip at the initial crack, and the calculation of bond-stress and local slip from the second crack until the beam collapses, are each shown on the following links: <https://bit.ly/3ltwPEb>, <https://bit.ly/2UpCQFQ>, and <https://bit.ly/2Ukj2Uo>.

Table 2: The data of bond-stress and the local slip of BRC beam from the calculation of the curvature-moment

Control calculation of bond-stress and local slip with curvature-moment						
Crack	M_1	M_2	S	S_x	Bond-stress, u (MPa)	Local slip, s_o (mm)
(1)	(2)	(3)	(4)	(5)	(6)	(7)
First crack	–	–	0	0	0.034	0
Crack 2	1.250	1.430	0.100	0.035	0.037	1.214
Crack 3	1.868	2.100	0.075	0.047	0.088	1.930
Crack 4	2.486	2.620	0.060	0.029	0.139	3.808
Crack 5	3.104	3.880	0.075	0.033	0.191	6.092
Crack 6	3.722	4.650	0.090	0.044	0.242	6.430
Crack 7	4.340	4.420	0.080	0.040	0.294	8.004
COLLAPSE 8	4.958	4.650	0.080	0.041	0.354	9.992

The Excel program can be used directly by inputting material data, cross-sectional geometry data, initial cracking moments until the beam collapses, and the beam cracking process. The use of the Excel program on the links: <https://bit.ly/3ltwPEb>, <https://bit.ly/2UpCQFQ>, and <https://bit.ly/2Ukj2Uo> is carried out by still paying attention to Eqs. (4) to (19) as a control. The second concern is the trial and error calculation process to meet the equilibrium requirements, for example when the first crack occurs, the correction of a neutral line is done based on the known crack moment. Each calculation process in the Excel program is equipped with basic equations and complete information.

Fig. 8 shows a graph of the relationship of bond-stress vs. local slip of calculation results base on curvature-moment and bond-stress at observation points of cracks and slips. The crack observation of the BRC beam was carried out at eight crack points as shown in Fig. 6 and Tab. 2. The observation points of bond-stress vs. local slip from the initial crack until the collapses beam were analyzed by regression analysis. The coefficient of determination (R^2) in the relationship of bond-stress vs. local slip is 0.983, which means that after the initial crack there is an increase in bond-stress by 98% running linearly with an increase in a local slip on the BRC beam.

3.3 Discussion

Fig. 9 shows the relationship of bond-stress vs. local slip of the BRC beam experimental results and the calculation results based on the curvature moment and bond-stress. The two graphs show similarity or coincide. When viewed from the results of the regression analysis with the coefficient of determination parameter, R^2 is 0.925 for the experimental results and 0.983 for the analysis results of the curvature-moment and bond-stress. The relationship graph of bond-stress vs. local slip base on curvature-moment shows a difference of approximately 6% from the experimental results. This shows that the amount of observational data such as crack patterns or loading history greatly affects the accuracy of the calculation. While the calculation process is a definite thing in the analysis. However, the experimental results are not fully accurate because the human error factor at the time of testing greatly determines the accuracy of the test data. Calibration of test equipment is also very important to increase the accuracy of the experimental data. Errors caused by human errors usually occur when setting tools and test objects.

Fig. 10 shows the relationship model of bond-stress vs. local slip from the BRC beam of the experimental results, the calculation results based on curvature-moment and bond-stress, the SRC beam

of the experimental results [3], and the results of the pull-out test of steel reinforcement [25]. Diab et al. [25] tested the pull-out of steel reinforcement embedded in concrete. The test results show that the relationship of bond-stress vs. slip shows: (a) Friction bond limit of 50%, (b) Proof bond strength of 60%, and (c) Bond-stress at pre-cracking by 70%.

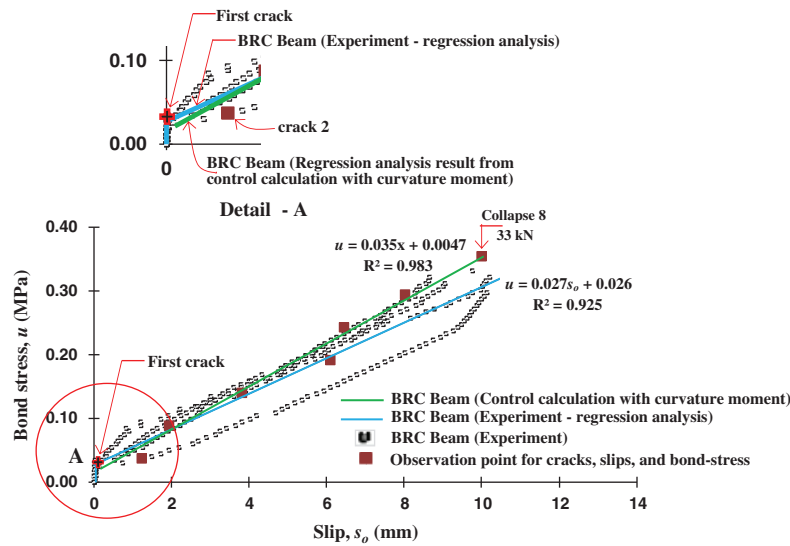


Figure 9: The relationship comparison of bond stress vs. slip from the calculation results of the curvature moment and experiment

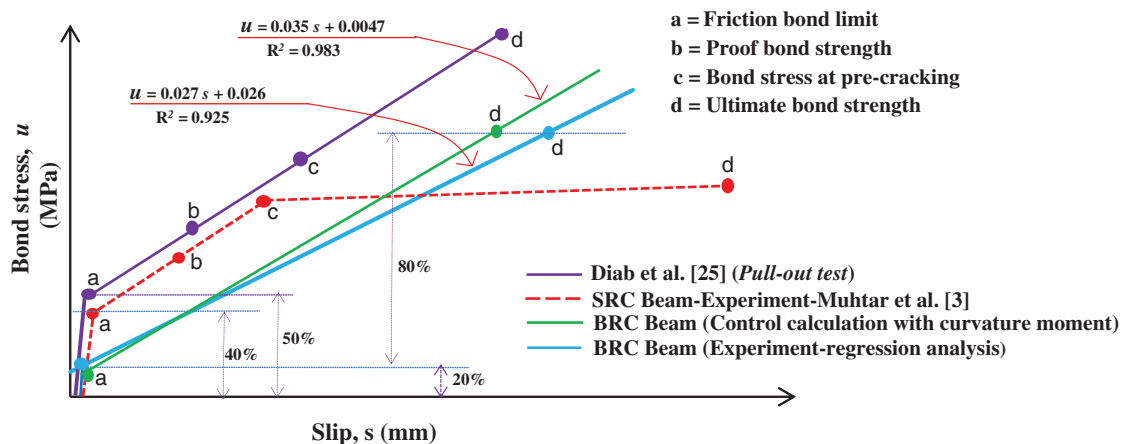


Figure 10: The idealization of the relationship model of bond stress vs. slip of BRC beam

Meanwhile, the BRC beams as shown in Figs. 8 and 9 do not show elastic or plastic limits, so the point of “proof bond strength” and “bond-stress at pre-cracking” become nothing. This is consistent with the stress-strain characteristics of bamboo reinforcement which does not show a clear melting point like steel reinforcement. Thus, from the limit point the “friction bond limit” becomes linear to the limit point “ultimate bond strength”. The value from the initial loading to the “friction bond limit” point is 20% and the value from the “friction bond limit” limit to the “ultimate bond strength” point is estimated to be around 80%.

The relationship of bond-stress vs. local slip for SRC beams shows the limit point of “friction bond limit”, “proof bond strength” and “bond-stress at pre-cracking” [3]. However, at the relationship of bond-stress vs. slip of SRC beam, there is a difference, namely from the limit point of “bond-stress at pre-cracking” to the limit point of “ultimate bond strength” show a horizontal line, as shown in Fig. 10.

In principle, this calculation method can be used only to control and validate models from experimental data. This method cannot be used for test methods whose purpose is to obtain the data needed for the model, because input data is highly dependent on experimental data. Calculation of the elongation of the concrete to be obtained still requires data from experimental results, such as crack pattern data. However, this method is a solution to establishing the elongation of the concrete and offers an alternative to using a concrete strain-gauge, which is mostly less accurate. And do not rule out the possibility of further research development; this method can predict a model—and evaluate the performance—of structural elements.

4 Conclusions

Based on the analysis and validation of experimental data using the slip calculation method based on the moment-curvature and bond-stress, several conclusions were obtained including: (1) The relationship of the bond-stress vs. local slip of the experimental results of the BRC beam and the calculation results based on the moment of curvature and bond-stress show similarities or coincide. The difference occurs in approximately 6% of the experimental results. The amount of observational data such as crack patterns, loading history, calibration of test equipment, and readiness of setting tools and specimens greatly affects the value of the accuracy of the calculation; (2) There are differences in the relationship of the bond-stress vs. local slip on the BRC Beams and SRC Beams, the difference is BRC beams do not show elastic or plastic boundaries, so the point of “proof bond strength” and “bond-stress at pre-cracking” become nothing; (3) In a BRC beam, the limit point “friction bond limit” to the limit point “ultimate bond strength” is a linear line. This shows the similarity with the stress-strain relationship behavior of bamboo reinforcement which does not show the melting point clearly; (4) Reading of the elongation of bamboo reinforcement (e_{bo}) through the strain gauge attached to the bamboo reinforcement can still be done even though the concrete has cracked, because when the concrete cracks the bamboo reinforcement does not yield and is still inelastic condition.

This calculation method is useful for controlling, validating, and sensitivity analysis of the relationship model of bond-stress vs. slip from the experimental results, especially the local slip value at certain observation points consisting of concrete elongation (e_{co}) and reinforcement elongation (e_{bo}).

This method is a solution for calculating concrete elongation (e_{co}) and is an alternative to a strain-gauge of concrete, which is largely inaccurate. It does not rule out the possibility for further research development, this method can predict the model and evaluate the performance of structural elements.

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