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Flexural Performance of Bamboo-Reinforced-Concrete Beams using Bamboo as Main Rebars and Stirrups

Makoto Yamaguchi[1], Kiyoshi Murakami[2], and Koji Takeda[3]

[1]*Assistant Prof., Graduate School of Science and Technology, Kumamoto University, Japan*
2-39-1, Kurokami, Chuo-ku, Kumamoto-shi, 860-8555 Kumamoto, Japan
yamaguchi@arch.kumamoto-u.ac.jp
[2]*Prof., Graduate School of Science and Technology, Kumamoto University, Japan*
2-39-1, Kurokami, Chuo-ku, Kumamoto-shi, 860-8555 Kumamoto, Japan
murakami@arch.kumamoto-u.ac.jp
[3]*Associate Prof., Graduate School of Science and Technology, Kumamoto University, Japan*
2-39-1, Kurokami, Chuo-ku, Kumamoto-shi, 860-8555 Kumamoto, Japan
takeda@arch.kumamoto-u.ac.jp

ABSTRACT

The use of bamboo as a structural element may contribute to the reduction of material-based energy use of a structure. To investigate the feasibility of using bamboo as a reinforcing material in reinforced-concrete members, flexural loading tests were carried out on reinforced-concrete beams in which all rebars, including the main rebar and the stirrups, were replaced with bamboo. The main results obtained are as follows: (1) good load-carrying capacity, which was by determined when the main bamboo rebar ruptured, can be obtained if the number of bamboo stirrups is enough to prevent the shear failure of the beam; (2) the load-carrying capacity of the beams can be calculated using section analysis based on the Bernoulli–Euler assumptions; and (3) the bending moment–curvature relationships of the beams can be estimated by accounting for the bond slip of the main bamboo rebars using a reduced Young's modulus of the main rebars.

Keywords. Bamboo-reinforced-concrete beams, Flexural performance, Section analysis, Main rebar, Stirrup

INTRODUCTION

Bamboo is as a natural fibre-reinforced plastic in which vascular bundle sheaths, called ‘bamboo fibre’, are formed between parenchymal cells to protect phloems and conducting vessels. Further, because the water absorption and shrinkage deformation of well-dried bamboo are relatively low, it can potentially be used as a reinforcement in reinforced-concrete (RC) members. Moreover, the use of bamboo as a structural element may contribute to the reduction of the material-based energy use of RC structures.

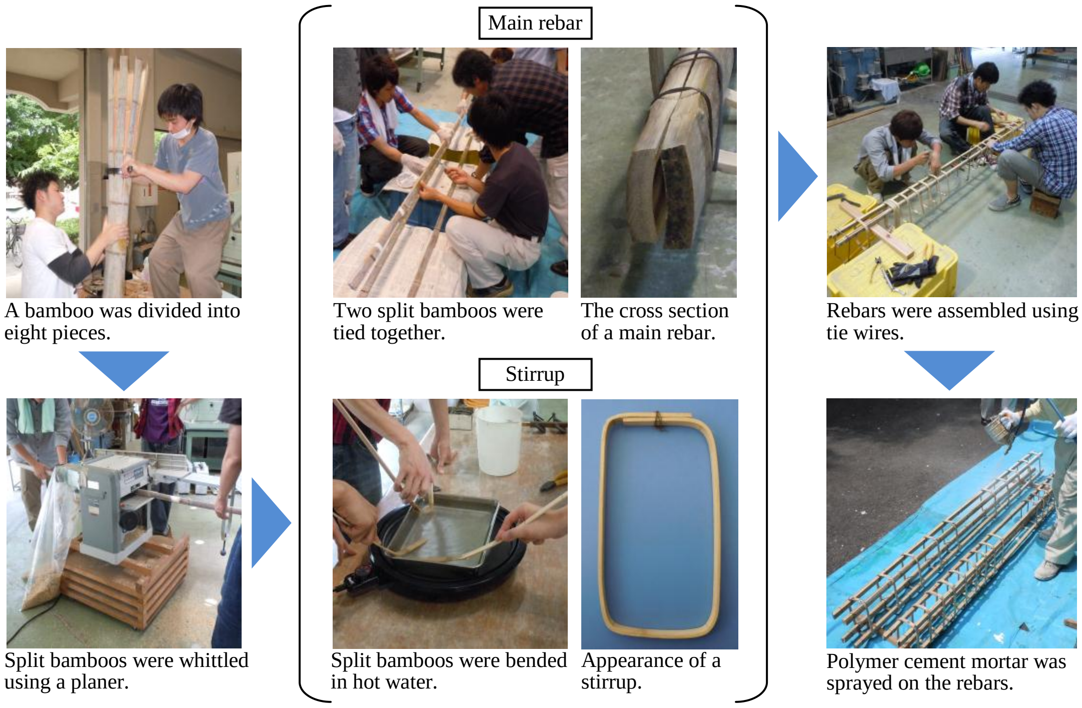
In the 1930s, many concrete structures reinforced by bamboo rebars were constructed in Japan because of a lack of steel materials in the war-time economy (Tamai et al., 2009). Today, experimental studies of the mechanical properties of bamboo-RC members are being conducted by several researchers (Ghavami, 1995, 2005; Terai et al., 2011). The authors have also studied the flexural performance of RC members that have bamboo rebars rather than steel rebars (Nakayama et al., 2009; Shimoda et al., 2010). In this study, to expand on our previous studies, experimental investigations were conducted on the flexural performance of bamboo-RC beams in which all rebars, including the main rebar and stirrups, were replaced with bamboo rebars.

EXPERIMENTAL METHOD

Materials. The materials used in this experiment are listed in Table 1. A ready-mixed concrete with a nominal strength of 27 N/mm^2 and a specified slump of 18 cm was used. A main bamboo rebar was manufactured by tying two split moso bamboos (botanical name: *Phyllostachys pubescens*) with a section size of 30 × 10 mm so that their inner sides faced each other. Sliced moso bamboo with a section size of 15 × 3.8 mm was used as a stirrup. The bamboo stirrup was bent in hot water after its epidermis was removed using a planer. To prevent the bamboo from absorbing water and to strengthen the bond between the bamboo rebar and the concrete, polymer cement mortar was sprayed on the surface of the bamboo rebars after they were assembled using tie wires. Figure 1 shows the bamboo rebars being

Table 1. Materials Used

Concrete	Ready-mixed concrete Nominal strength: 27 N/mm^2 Specified slump: 18 cm Measured slump: 18.5 cm Measured air content: 4.1%		Main rebar	Moso bamboo Cross-sectional area: 600 mm^2 * A rebar is composed of two split bamboos with a section size of 30 × 10 mm.
Sprayed-on material	Polymer cement mortar		Stirrup	Moso bamboo Section size: 15 × 3.8 mm * Each Stirrup was bent in hot water.
	Emulsion; *E*	Poly-acrylic ester		
	Compound; *C*	Cement, Silica sand		
	Mix ratio	*E* : *C* = 1.0 : 3.5		



A bamboo was divided into eight pieces.

Split bamboos were whittled using a planer.

Two split bamboos were tied together.

The cross section of a main rebar.

Split bamboos were bended in hot water.

Appearance of a stirrup.

Rebars were assembled using tie wires.

Polymer cement mortar was sprayed on the rebars.

Figure 1. Bamboo Rebars Being Processed

processed.

Material Tests. Three cylindrical concrete specimens, 100 mm in diameter and 200 mm in height, were prepared for compressive and splitting tensile tests, and both tests were carried out in accordance with the Japan Industrial Standard. The tensile strength and Young's modulus of the main bamboo rebar were measured using six dumbbell-shaped specimens (see Figure 2), three of which included a node in their straight part, and the other three did not include the node.

Flexural Loading Tests on Bamboo-RC Beams. Figure 3 shows the configuration and rebar arrangement of the bamboo-RC beam specimens as well as their loading and supporting points. Each bamboo-RC beam has two bamboo rebars as compressive and tensile rebars. Stirrups were placed 200 mm apart in specimen A and 100 mm apart in specimen B. The flexural loading tests involved four-point bending over a span length of 2,000 mm and an interval of 500 mm between the loading points. Displacement at mid-span was measured using a displacement transducer with a capacity of 100 mm. To measure the curvature at mid-span, pi-shaped displacement transducers with a gauge length of 300 mm were installed at the positions of the compressive and tensile rebars at mid-span.

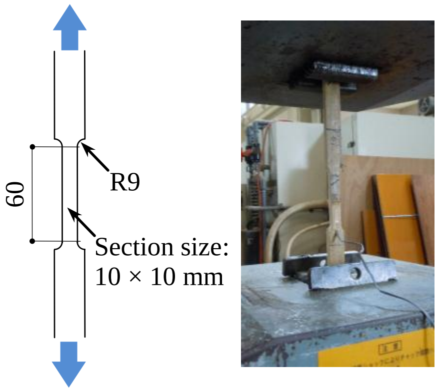


Figure 2. Tensile Test of Main Bamboo Rebar

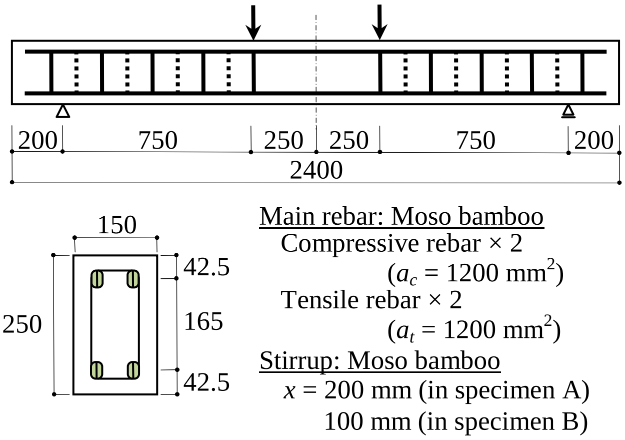


Figure 3. Configuration and Rebar Arrangement of Bamboo-RC Beam

RESULTS AND DISCUSSION

Material Test Results. Table 2 presents the material test results. The symbol representing the main bamboo rebar shown in Table 2 matches the symbol used for the bamboo-RC beam which includes that rebar. The measurements of the tensile strength of main rebar B were 15–20% smaller than those of main rebar A. Further, the tensile strength of main rebars A and B decreased by almost 25 and 18% respectively, when a node was included in their straight parts.

Fracture Behaviour of Bamboo-RC Beams. Figure 4 shows the ultimate fracture behaviour of the bamboo-RC beam specimens. The fracture process of specimen A is as follows: firstly, flexural-tensile cracks were dispersed inside the pure bending region; secondly, a flexural-shear crack occurred in the shear span; finally, a bamboo stirrup ruptured at the location of the flexural-shear crack. In contrast, in specimen B, one of the flexural-tensile cracks progressed, and then the ultimate fracture was caused by the rupture of a tensile bamboo rebar bridging the flexural-tensile crack. Therefore, the fracture behaviour of the bamboo-RC beams varied according to the spacing of the stirrups.

Load-Carrying Capacity and Deformation. Figure 5 shows the relationship between load and displacement at mid-span and between the bending moment and curvature. In specimen B, the latter part of the bending moment–curvature relationship could not be measured because of exfoliation of the pi-shaped displacement transducer at the location of the flexural cracking. The load increased linearly after the initial flexural crack appeared in both specimens, because the bamboo behaves linear-elastically until its tensile rupture. Although the maximum loads of specimens A and B were determined by the rupture of a stirrup and a main rebar respectively, these values were almost equivalent. This may be because the tensile strength of the main bamboo rebar used for specimen B was smaller than that for specimen A (see Table 2).

ANALYTICAL INVESTIGATION

To determine the practical use of a bamboo-RC member, it is necessary to establish a

Table 2. Material Test Results

a-1) Concrete (standard curing of 28 days)

γ (kN/m^3)	F_c (N/mm^2)	E_c (kN/mm^2)
23.3	26.0	1.83

a-2) Concrete (Field wet curing of 28 days)

γ (kN/m^3)	F_c (N/mm^2)	E_c (kN/mm^2)	ε_{co} (μ)	F_t (N/mm^2)
22.4	29.8	24.2	2537	2.21

Notes; γ: unit weight, F_c: compressive strength, E_c: Young's modulus, ε_{co}: strain at compressive strength, and F_t: splitting tensile strength.

b-1) Main bamboo rebar

	σ_b (N/mm^2)	E_b (N/mm^2)	ε_{ub} (μ)
A	177 [136]	11957 [9760]	15933 [15667]
B	140 [116]	10273 [10463]	16533 [11833]

b-2) Bamboo stirrup

σ_b (N/mm^2)	E_b (N/mm^2)	ε_{ub} (μ)
149	10152	14640

Notes; σ_b: tensile strength, E_b: Young's modulus, and ε_{ub}: fracture strain. The values in [ ] are data of main rebars including a node in their straight part.

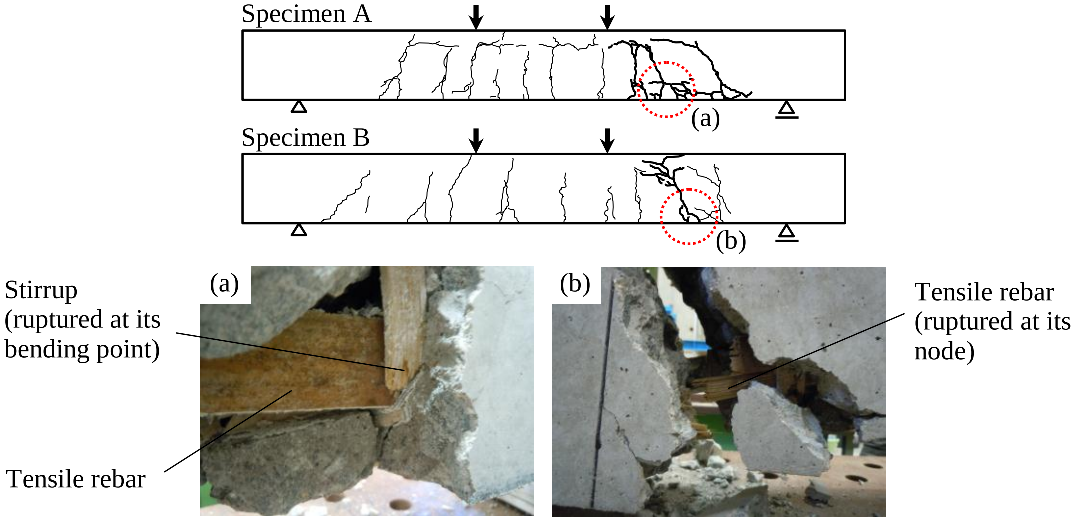


Figure 4. Fracture Behaviour of Bamboo-RC Beam Specimens

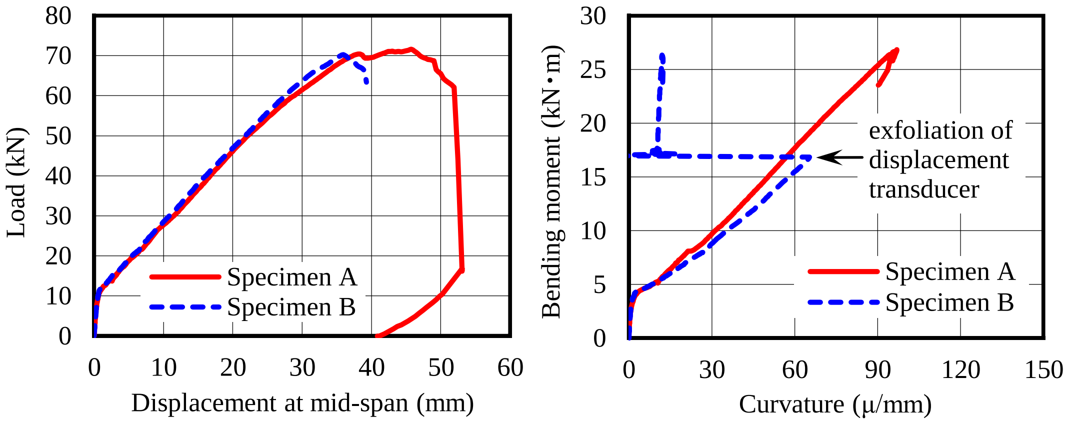


Figure 5. Load–Displacement and Bending Moment–Curvature Relationships

structural calculation method. Therefore, the applicability of section analysis using the Bernoulli–Euler assumptions to the bamboo-RC beams was investigated.

Assumptions for Analysis.

(1) The Bernoulli–Euler assumptions are adopted.

(2) The compressive stress–strain relationship of the concrete is expressed by the following equation:

$$\sigma = 6.75F_c\left(e^{-0.812\varepsilon/\varepsilon_{co}} - e^{-1.218\varepsilon/\varepsilon_{co}}\right) \tag{1}$$

where σ is the stress (N/mm^2), F_c is the compressive strength of the concrete (N/mm^2), ε is the strain, and ε_{co} is the strain at the compressive strength of the concrete.

(3) The stress–strain relationship of a main bamboo rebar is linear-elastic:

$$\sigma = E_b\varepsilon \;\; (\sigma \leq \sigma_b) \tag{2}$$

where E_b and σ_b are the Young's modulus and the tensile strength, respectively, of a main bamboo rebar (N/mm^2).

Analytical Method.

(1) The equilibrium of the internal forces is expressed as follows:

$$C_c + C_b = T, \quad C_c = \frac{b}{\phi}\int_0^{{}_c\varepsilon_c} \sigma d\varepsilon, \quad C_b = a_{c\,b}\sigma_c, \quad T = a_{t\,b}\sigma_t \tag{3}$$

where C_c is the resultant compressive force in the concrete (N); C_c and T are the resultant forces in the compressive and tensile rebars (N), respectively; b is the beam width (mm); ϕ is the curvature [1/mm]; ${}_c\varepsilon_c$ is the strain in the extreme compression fibre of the concrete; a_c and a_t are the cross-sectional areas of the compressive and tensile rebars (mm^2), respectively; and ${}_b\sigma_c$ and ${}_b\sigma_t$ are the stresses in the compressive and tensile rebars (N/mm^2), respectively.

(2) The equilibrium of the bending moment about the neutral axis is expressed as follows:

$$M = \frac{b}{\phi^2}\int_0^{{}_c\varepsilon_c} \sigma\varepsilon d\varepsilon + C_b\left(x_n - d_c\right) + T\left(d - x_n\right) \tag{4}$$

where M is the bending moment (N・mm), x_n is the neutral axis height (mm), d_c is the distance between the extreme compression fibre and the centre of gravity in the compressive rebar (mm), and d is the effective beam depth (mm).

Comparison of Measurement and Calculation Results. Figure 6 shows the comparison of the measurement and calculation results of the bending moment–curvature relationship. The bond slip at the interface between the main bamboo rebar and the concrete was accounted for by reducing the Young's modulus of the main bamboo rebar (Shimoda et al., 2010), and the calculation results were in good agreement with the measurement results when the Young's modulus was reduced by 0.6 times. The ultimate fracture in specimen B was caused by the node rupture in the tensile rebar, and the calculation result of the load-carrying capacity using the tensile strength of the main rebar including a node showed fairly good agreement with the measurement result. Further, for specimen A, the measurement result of the load-carrying capacity was lower than its calculation result, and this result corresponded to the fact that the rupture of the stirrup preceded the rupture of the main rebar.

These results clearly indicate that the load-carrying capacity of the bamboo-RC beams can be estimated using section analysis based on the Bernoulli–Euler assumptions. Furthermore, the bending moment–curvature relationship can be calculated by accounting for the bond slip between the main rebar and the concrete by using a reduced Young's modulus of the rebar. However, more investigations are needed to estimate the shear load-carrying capacity of the bamboo-RC beams with bamboo stirrups.

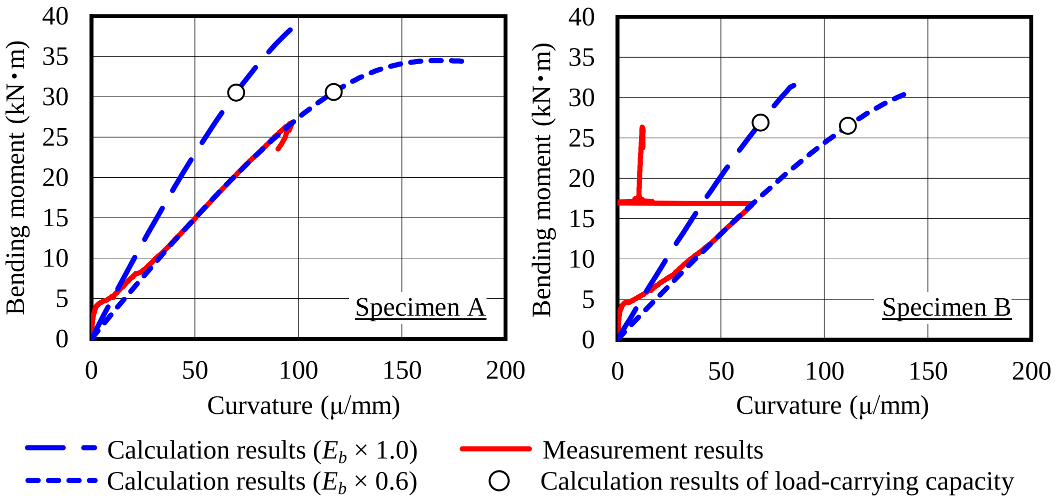


Figure 6. Comparison of Measurement and Calculation Results of Bending Moment–Curvature Relationship

CONCLUSIONS

In this study, experimental investigations of the flexural performance of bamboo-RC beams with bamboo main rebars and stirrups were conducted. Based on these investigation, we made the following conclusions:

(1) Good load-carrying capacity, determined by when the main bamboo rebar ruptured, can be obtained if the number of bamboo stirrups is sufficient to prevent the shear failure of the beam.

(2) The load-carrying capacity of the bamboo-RC beams can be calculated using section analysis based on the Bernoulli–Euler assumptions.

(3) The bending moment–curvature relationship can also be estimated by accounting for the bond slip between the main rebar and the concrete using a reduced Young's modulus of the main bamboo rebar.

However, further investigations are needed to estimate the shear load-carrying capacity of the bamboo-RC beams with bamboo stirrups. Moreover, it is necessary to evaluate economical and environmental values of replacing steel with a polymer-coated bamboo rebar in our future works.

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