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# Fracture Behavior and Mechanical Properties of Bamboo Reinforced Concrete Members

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**Abstract**

Recently, in the attention in response to global warming issues and sustainable society, the manufacturing using natural materials has become actively. Bamboo, low cost, fast growing, and broad distribution of growth, is expected to contribute significantly to earthquake-resistant construction and seismic retrofit technology for developing countries. This report has been prepared to assist the seismic retrofit of the masonry structures in the design and construction of bamboo reinforced concrete. A study of the feasibility of using bamboo and non-steel as the reinforcing material in concrete members was conducted in our laboratory. Six beam specimens were constructed and a total of 11 beam tests were performed to examine the flexural cracking and the shear cracking strength. Additionally, monotonic compression tests were carried out on 16 column specimens, which has 200mm in diameter and 500mm in height with confining steel bars or PP-band spirals, in order to study fracture behavior and mechanical property of bamboo confined concrete.


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*Keywors:* Bamboo ; Bamboo Reinforced Concrete ; Beam ; Column ; Shear Failure ; Flexural Failure

## 1. INTRODUCTION

In recent years, steel prices have soared. For developing countries, steel is difficult to obtain because of expensive prices, and for the construction industry, usage of steel is currently limited heavily. The production of steel has high consumption of fossil fuels; therefore, the steel discharge in the construction of structures has been presented, showing the possibility of drastic reduction by research institutes. Meanwhile, for developing countries, it is important to make the development of buildings construction; low cost, no requirement of sophisticated technologies and reliable construction methods. Recently, in the attention in response to global warming issues and sustainable society, the manufacturing using natural materials has become actively. Bamboo, low cost, fast growing, and broad distribution of growth, is expected to contribute significantly to earthquake-resistant construction and seismic retrofit technology in developing countries. The authors also have been studied for understanding the mechanical behavior of bamboo reinforced concrete member and

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Table 1. Properties of beam specimens

| | | Shear Span (mm) | Shear Span Ratio | Longitudinal Reinforcement | | Stirrup | | Concrete Strength (N/mm²) |
|---|---|---|---|---|---|---|---|---|
| | | | | Upper | Lower | Type | spacing | |
| RC | | 500 | 2.0 | Steel D10 | Steel D13 | ϕ4 (SR295) | 100 | 30 |
| BRC1 | | 500 | 2.0 | | Bamboo ϕ15*1 | | | |
| BRC2 | | 500 | 2.0 | Bamboo ϕ13*1 | | | | |
| BRC3 | -1 | 500 | 2.0 | Bamboo ϕ13*2 | Bamboo ϕ15*2 | PP-Band | 50 | |
| | -2 | 175 | 0.7 | | | | | |
| | -3 | 150 | 0.6 | | | | | |
| BRC4 | -1 | 250 | 1.0 | | | PP-Rope | | |
| | -2 | 200 | 0.8 | | | | | |
| | -3 | 150 | 0.6 | | | | | |
| BRC5 | | 150 | 0.6 | | | flax Rope | | |
| BRC6 | | 150 | 0.6 | | | None | None | |

*1:Black bamboo *2:Japanese Timber Bamboo

Fig. 2. Materials for Hoop (PP-Band, PP-Rope, Flax Rope)

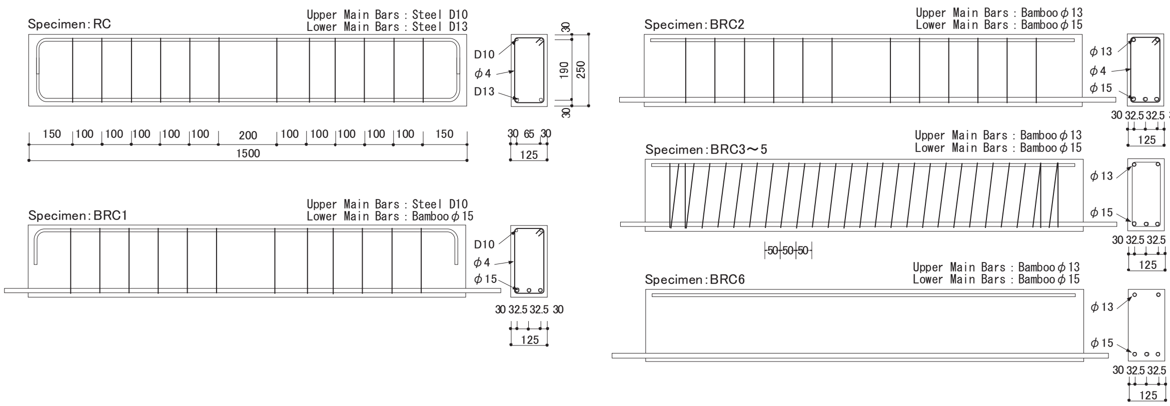



Fig. 1. Details of beam specimens

clarifying the differences of structural properties from steel reinforced concrete and bamboo reinforced concrete. In this paper, some tests of bamboo reinforced concrete beams and columns carried out in our laboratory are reported.

## 2. Test of Bamboo reinforced concrete beams

The characteristics of the test specimens are listed in Table 1. Four kinds of test variables were employed as shown in Table1. They are the longitudinal bar (D13 steel, φ15 bamboo (Black Bamboo), φ15 bamboo (Japanese Timber Bamboo)), the types of stirrup and spacing (φ4@100, pp-band@50, pp-rope@50, flax rope@50, unconfined) and shear span ratio (0.68, 0.80, 0.91, 1.14, 1.83, 2.28). The details of these specimens are shown in Figure 1. The longitudinal tension bar was D13 for reinforced concrete (RC), and φ15 bamboo for bamboo reinforced concrete (BRC). In order to investigate the shear and flexural behavior of bamboo-reinforced beam without steel stirrup, therefore the 7 specimens were cast, a total of 11 beams were tested under monotonic 3- or 4-point bending test. The stirrup and spacing were φ4 tie and 100mm for 3 specimens (RC, BRC1 and BRC2), PP-band and 50mm spiral for BRC3, PP-rope and 50mm spiral for BRC4, flax rope and 50mm spiral for BRC5 and unconfined for BRC6.

Beam specimens were loaded concentrically with a tensile/compression tester with 5MN capacity. During the loading test, the load (P) was measured by load cell. Displacements (δ) of the specimen were externally measured by displacement transducers instrumented at the bottom of the specimens.

Figure 3 shows failure crack patterns of beam tests. The bending crack initiation load $P_f$, the shear crack initiation load $P_s$, the longitudinal bond crack initiation load $P_b$ and the ultimate load $P_{max}$ were obtained after taking account of the condition of beams support and are given in Table2. Figure 4 shows the relationship between crack loads and shear span ratio. In this figure, the calculated load of the bending and the shear crack are the proposed formulations predicting the

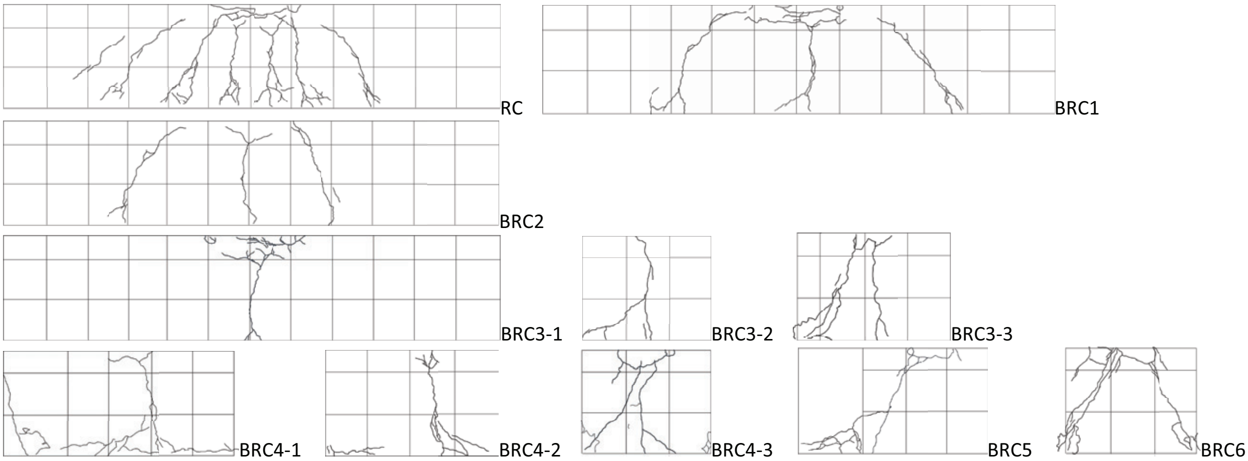



Fig. 3. Failure crack pattern of beam specimens

Table 2. Test results

| Specimen | Shear Span (mm) | Shear Span Ratio | $P_f$ (kN) | $P_s$ (kN) | $P_b$ (kN) | $P_{max}$ (kN) |
|---|---|---|---|---|---|---|
| RC | 500 | 2.0 | 5.6 | - | - | 76.3 |
| BRC1 | 500 | 2.0 | 12.4 | - | - | 40.1 |
| BRC2 | 500 | 2.0 | 12.2 | - | - | 40.5 |
| BRC3-1 | 500 | 2.0 | 15.3 | - | - | 40.2 |
| BRC3-2 | 175 | 0.7 | 54.0 | 90.7 | - | 90.7 |
| BRC3-3 | 150 | 0.6 | 80.6 | - | 109.8 | 113.1 |
| BRC4-1 | 250 | 1.0 | 34.8 | - | 76.8 | 76.8 |
| BRC4-2 | 200 | 0.8 | 60.5 | - | 85.0 | 96.5 |
| BRC4-3 | 150 | 0.6 | 82.5 | 82.5 | 73.2 | 82.5 |
| BRC5 | 150 | 0.6 | - | 76.0 | 65.0 | 76.0 |
| BRC6 | 150 | 0.6 | - | 71.6 | - | 113.1 |

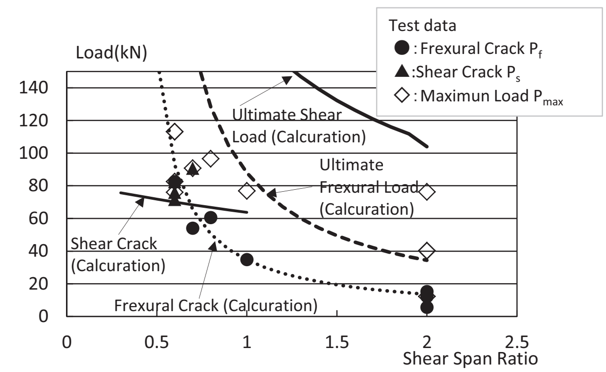



Fig. 4. Relationship between cracking load and shear span ratio

crack load of shear and bending. It is shown in Figure 4 that the formula of the shear and flexural crack load give a strong effect in comparison with the test data, and the deformation mode in bending crack and shear crack changes at 0.7 of shear span ratio.

## 3. Test of Bamboo reinforced concrete columns

A total of 16 prismatic specimens were prepared (Table 3). The specimens had 200mm*200mm cross section in area and 500mm in height (Figure 5). Each specimen has 100mm high rigidity blocks from the top and the bottom faces as a stub in order to measure the relative axial displacement between these two locations. In the production of bamboo confined concrete column specimens, longitudinal reinforcement of steel (D13, D16, φ16) and of bamboo (φ15, φ24) and confinement reinforcement of steel (3mm) and PP-band (15.5mm*0.49mm) were used. Some mechanical properties of these reinforcements and concretes are given in Figure 6.

Columns were loaded concentrically with a tensile/compression tester with 5MN capacity as shown in Figure 7. In this paper, the average relative displacement between two stubs was used to calculate the axial displacement. In addition, some 30mm long foil strain gages were also attached on the concrete surface parallel to the vertical axis.

Figure 8 shows photos of specimens after testing. The general behavior of confined specimens was comparatively ductile and complex unlike plain unconfined columns. The vertical longitudinal cracks were noticed invariably first of all for almost all the columns just before the cover spalling. These cracks thereafter eventually led to the spalling of cover concrete, and specimens failed in the central instrumented region.

Table 3. Properties of column specimens

| UNIT | Specimen designation | Concrete | Longitudinal Reinforcement | | | Transverse Reinforcement | | | Load Type |
|---|---|---|---|---|---|---|---|---|---|
| | | $f_c$(MPa) | Type | Number-Diameter | $p_g$(%) | Type | s(mm) | $p_w$(%) | |
| 1 | LR-16PP@50 | 10.0 | Steel | 4-ϕ16 | 2.01 | PP-Band | @50 | 0.151 | monotonic |
| 2 | LB-15PP@100 | | Bamboo | 4-ϕ15 | 1.13 | PP-Band | @100 | 0.078 | monotonic |
| 3 | LB-24PP@100 | | Bamboo | 4-ϕ24 | 2.35 | PP-Band | @100 | 0.078 | monotonic |
| 4 | MR-16PP@50 | 20.0 | Steel | 4-ϕ16 | 2.01 | PP-Band | @50 | 0.151 | monotonic |
| 5 | MB-15PP@100 | | Bamboo | 4-ϕ15 | 1.13 | PP-Band | @100 | 0.078 | monotonic |
| 6 | MB-24PP@100 | | Bamboo | 4-ϕ24 | 2.35 | PP-Band | @100 | 0.078 | monotonic |
| 7 | HB-15ϕ@50 | 30.0 | Bamboo | 4-ϕ15 | 1.13 | ϕ3 bar | @50 | 0.141 | monotonic |
| 8 | HB-15PP@50-C | | Bamboo | 4-ϕ15 | 1.13 | PP-Band | @50 | 0.151 | Cyclic |
| 9 | HB-15PP@50 | | Bamboo | 4-ϕ15 | 1.13 | PP-Band | @50 | 0.151 | monotonic |
| 10 | HB-24PP@50 | | Bamboo | 4-ϕ24 | 2.35 | PP-Band | @50 | 0.151 | monotonic |
| 11 | HB-24ϕ@100 | | Bamboo | 4-ϕ24 | 2.35 | ϕ3 bar | @100 | 0.071 | monotonic |
| 12 | HB-24PP@50 | | Bamboo | 4-ϕ24 | 2.35 | PP-Band | @100 | 0.078 | monotonic |
| 13 | HR-D13ϕ@50 | | Steel | 4-D13 | 1.27 | ϕ3 bar | @50 | 0.141 | monotonic |
| 14 | HR-D13PP@50 | | Steel | 4-D13 | 1.27 | PP-Band | @50 | 0.151 | monotonic |
| 15 | HR-D16ϕ@100 | | Steel | 4-D16 | 1.99 | ϕ3 bar | @100 | 0.071 | monotonic |
| 16 | HR-D16PP@100 | | Steel | 4-D16 | 1.99 | PP-Band | @100 | 0.078 | monotonic |

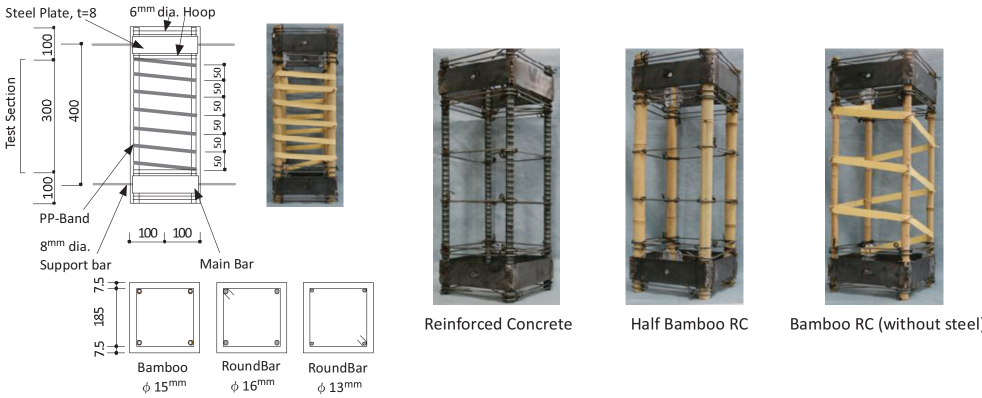



Fig. 5. Details of column specimens

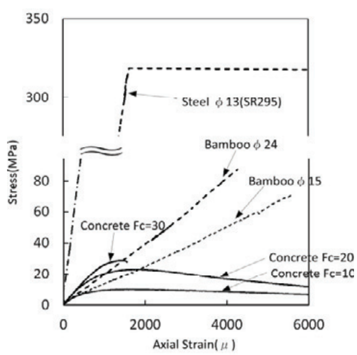



Fig. 6. Mechanical Characteristics of materials for column specimens

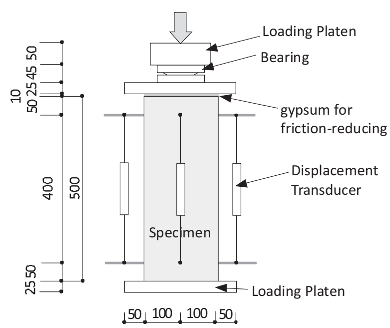



Fig. 7. Test setup

In Figure 9, dark line shows the behavior of confined concrete. In this figures, the columns were analyzed to obtain the load-displacement curves of confined concrete, as suggested by Sakino & Sun (1994) and Araki (2008).

Figure 10 shows the ratio of $P_{max}$ to $P_u$ of all specimens, where

$$P_u = 0.85 f_c' \times (A_g - A_{steel\ or\ bamboo}) + f_y \times A_{steel\ or\ bamboo} \quad (1)$$

The ratio $P_{max}$ / $P_u$ ranges from 0.81 to 1.27 for RC and 0.79 to 1.20 for Bamboo RC.

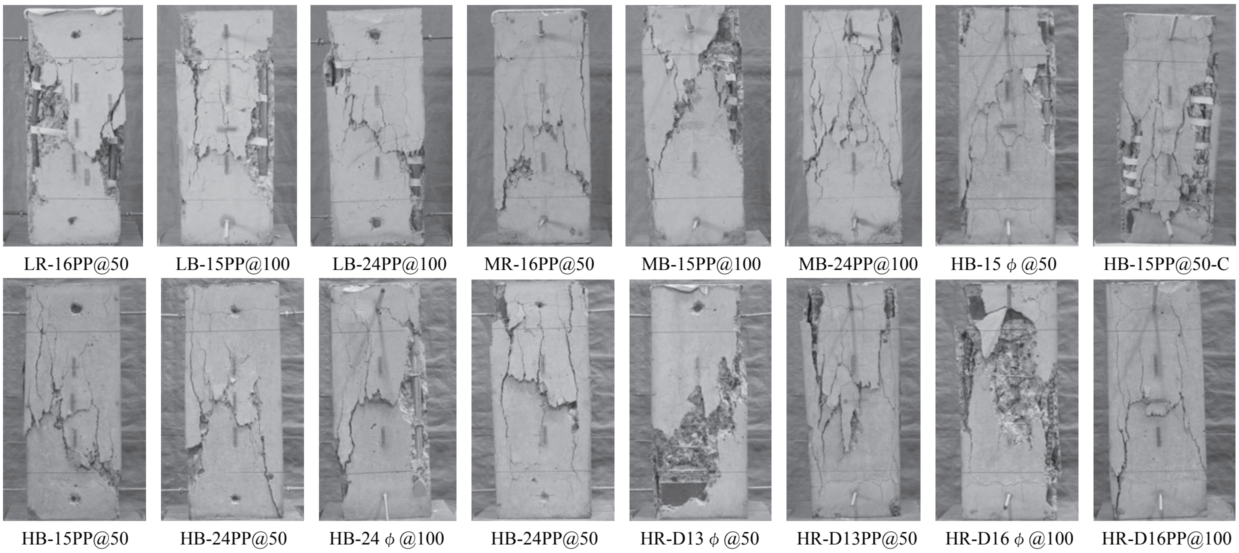



Fig. 8. Failure patterns of column specimens

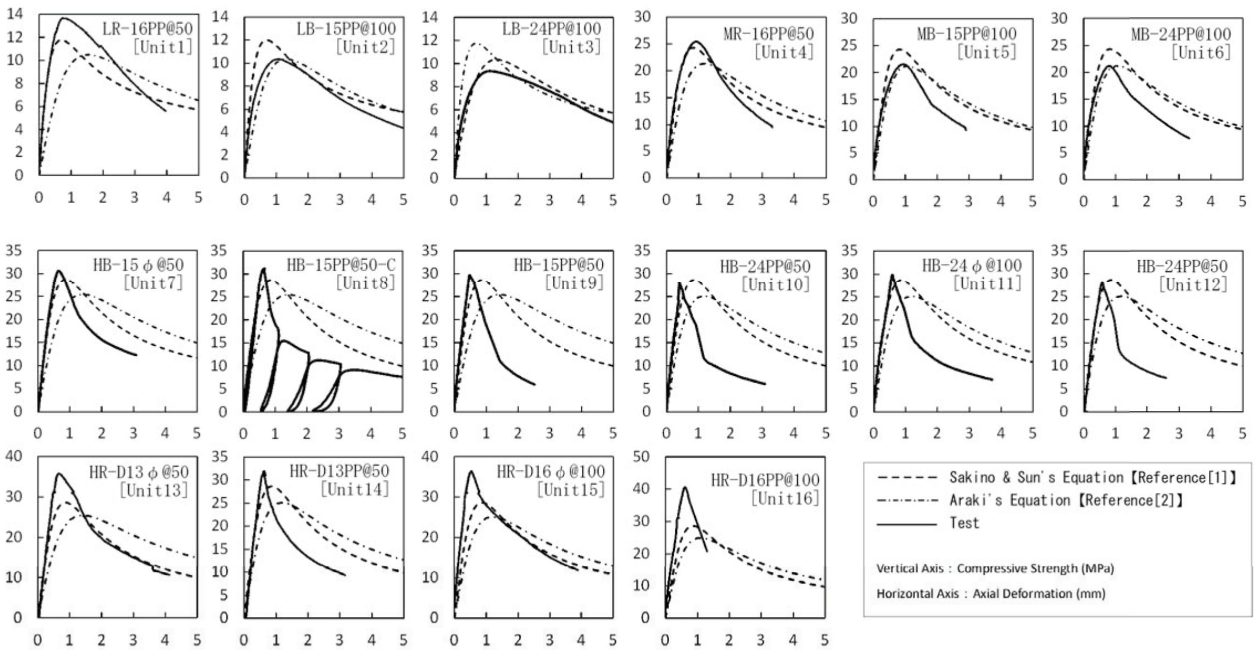



Fig. 9. Compressive stress and axial deformation curves

Figure 11 shows effect of test variables. Figure 11(a) shows comparisons of columns with different strength concretes. The post peak curves of the higher strength concrete mix columns are steeper indicating faster rate of strength decay as compared to the lower strength concrete specimens.

The effect of PP-band was investigated by comparing results of two sets each of RC and BRC columns. The compared specimens of each sets had the same kind of longitudinal reinforcement (Figure 11(b)). The results show that the effect of using PP-band has not very significant difference of the fracture behavior in case of 30MPa strength concrete columns.

Figure 11(c) shows the three sets of specimens with different strength of concretes to investigate the effect of longitudinal bars. For each matched set with concrete strength, the stress-displacement curves were similar to each other.

Table 4. Test results and peak load

| UNIT | Concrete Strength | Main Bar | Hoop | | Test $P_{exp}$ | $P_u$(Eq.1) | $P_{exp}/P_u$ |
|---|---|---|---|---|---|---|---|
| 1 | Fc10 | ϕ16 | PP | @50 | 548.0 | 675.9 | 0.81 |
| 2 | | 15 | PP | @100 | 415.0 | 442.3 | 0.94 |
| 3 | | 24 | PP | @100 | 375.5 | 476.0 | 0.79 |
| 4 | Fc20 | ϕ16 | PP | @50 | 1020.0 | 1042.4 | 0.98 |
| 5 | | 15 | PP | @100 | 865.0 | 809.4 | 1.07 |
| 6 | | 24 | PP | @100 | 846.0 | 832.5 | 1.02 |
| 7 | Fc30 | 15 | ϕ3 | @50 | 1225.0 | 1043.0 | 1.17 |
| 8 | | 15 | PP | @50 | 1252.0 | 1043.0 | 1.20 |
| 9 | | 15 | PP | @50 | 1190.0 | 1043.0 | 1.14 |
| 10 | | 24 | PP | @50 | 1115.0 | 1059.4 | 1.05 |
| 11 | | 24 | ϕ3 | @100 | 1196.0 | 1059.4 | 1.13 |
| 12 | | 24 | PP | @100 | 1122.0 | 1059.4 | 1.06 |
| 13 | | D13 | ϕ3 | @50 | 1431.0 | 1197.0 | 1.20 |
| 14 | | D13 | PP | @50 | 1280.0 | 1197.0 | 1.07 |
| 15 | | D16 | ϕ3 | @100 | 1455.0 | 1280.1 | 1.14 |
| 16 | | D16 | PP | @100 | 1627.0 | 1280.1 | 1.27 |

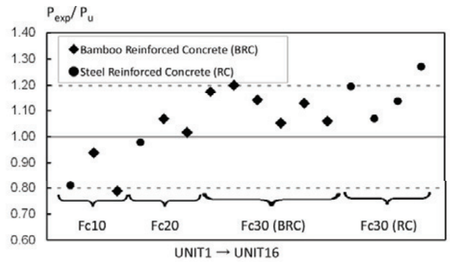
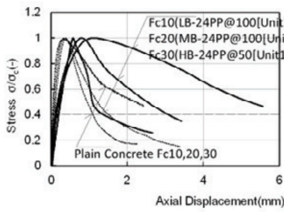
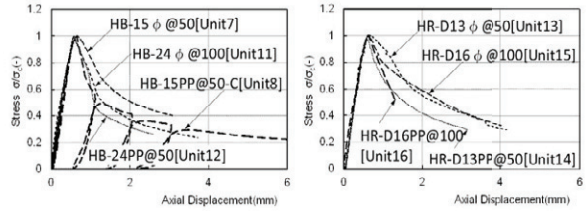


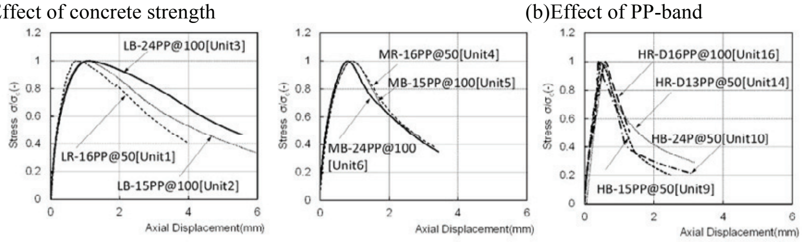

Fig. 10. Relation of the ratio Pexp/Pu




(a)Effect of concrete strength




(b)Effect of PP-band




(c)Effect of longitudinal reinforcement

Fig. 11. Stress and displacement relations with same combination of test variables

## 4. Conclusions

This paper presents the feasibility of using bamboo and non-steel as the reinforcing material in concrete members. In order to investigate the fracture behavior and the mechanical properties of Bamboo Reinforced Concrete members, six beam and 16 column specimens were constructed and both the uniaxial compression tests and the 3 point bending test were carried out. By analyzing the test results, the following conclusions were drawn in this study:

(1)Bamboo reinforced concrete beam: The test results of both RC and Bamboo RC beams are discussed. It is shown that the cracking patterns in Bamboo RC beams can becomes similar to the RC beams, and the predicted crack load of BRC beam give a strong effect in comparison with the test data. As a result, the fracture behavior of BRC beam can be evaluated by the existing formula of RC beam.

(2)Bamboo reinforced concrete column: It is clear confirmed the validity of the bamboo for the longitudinal bar and PP-Band for Hoop. The ductility of BRC columns is shown to be dependent on concrete strength.

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