Selected properties of full-sized bamboo-reinforced composite beam
Nugroho, Naresworo¹, Ando, Naoto²

ABSTRACT
To increase the role of bamboo and to get maximal benefit, a study concerning the properties of bamboo reinforced composite beam in full-scale size for construction material was conducted. 10 pieces of sugi wood (*Cryptomeria japonica*) with dimension of 300 x 4.5 x 10.5 cm were used, whereas 3-m long of round moso bamboo (*Phyllostachys pubescens*) were split into quarter and made bamboo zephyr with roller press crusher. Bamboo zephyr then hot-pressed at 160°C with pressure of 50 kgf/cm² for period of 15 minutes to produce bamboo mat. All bamboo-mat were passed through a planner to remove inner and outer (epidermal) layer until the thickness of 7.5 mm reached and used as a flange of the composite beam. Resorcinol-based adhesive was manually applied at 300 g/m² in a single glue line. The bamboo reinforced composite beams were then loaded into the long-clamping system at 20 kgf/cm² for 12 hours of minimum pressing time at room temperature. Three kinds of non-destructive test to obtain modulus of elasticity (i.e. deflection measurement, ultrasonic wave propagation measurement and fundamental vibration frequency measurement) were carried out on each specimen. The beams were also tested destructively in a bending machine under four point loading system. The MOE of bamboo reinforced composite beam improved substantially by reinforcing with bamboo mat flanges. Improvements ranged from 49.5% to 76.7% greater than the MOE of sugi wood as a control. The average MOR values of composite beam also improved by 90.16, 92.57 and 108.64 % by reinforcement with 1, 2 and 3-layers, respectively. It can be said that the MOE and MOR values of bamboo composite beam increase with the increasing the number of bamboo mat layers.

1. INTRODUCTION
Interest has burgeoned in combining wood and other raw material, such as bamboo into composite products with unique properties and cost benefits. The main reason for developing such products was to produce composite products that exhibit specific properties that superior to those of the component materials alone, such as increased strength properties. With the continuously increasing demands for timber-based structural material, further research work is needed to develop new engineering products from available natural resources. The previous studies showed that moso bamboo's (*Pylllostachys pubescens* Mazel) favorable stiffness and strength property make it a promising material for the manufacture of various engineered composite products such as bamboo zephyr board, laminated bamboo lumber or bamboo composite beam (Lee et.al, 1997; 1998, Nugroho and Ando, 1999). Since bamboo possesses much higher tensile strength than common wood material along the longitudinal direction, this study attempts to analyze the characteristic of bamboo-reinforced sugi-wood as a structural beam member. To increase the role of bamboo and to get maximal benefit, in the form of bamboo reinforced composite lumber, a study concerning the properties of this product in full-scale size for construction material considerably needed. The reasons for reinforcing low quality wood with bamboo are to improve the strength and stiffness of the wood.

2. MATERIALS AND METHODS

2.1. Materials
In this study, 10 pieces of sugi wood (*Cryptomeria japonica*) with dimension of 300 x 4.5 x 10.5 cm is used and already kiln-dried. Whereas, 3-m long of round bamboo were split into quarter and made bamboo zephyr with roller press crusher. Bamboo zephyr then hot-pressed at 160°C with pressure of 50 kgf/cm² for period of 15 minutes to produce bamboo mat. All bamboo-mat were passed through a planner to remove inner and outer (epidermal) layer until the thickness of 7.5 mm reached.

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2.2. Specimens Production

Sugi wood and bamboo-mat are then graded by using non-destructive test (deflection method and Pundit apparatus) to obtain modulus of elasticity. 4 pieces with good quality of sugi wood are used as a control and another 6 pieces (low quality) were randomly divided and cut in three group size: A: 300 x 4.5 x 9 cm (2pcs); B: 300 x 4.5 x 7.5 cm (2pcs) and C: 300 x 4.5 x 6 cm.

As reinforced material, bamboo mat after graded were then grouped into three categories, E values of less than $6 \times 10^4$ kgf/cm² were grouped into category III, 6 to $7 \times 10^4$ kgf/cm² were grouped into category II and E value that are more than $7 \times 10^4$ were grouped into category I. Three types of beam were construct with pre-arrange into required quality zoned such as shown in Fig 1. The resorcinol-based adhesive (D-33 from Oshika Sinko Co.) was manually applied at 300 g/m² in a single glue line. The bamboo reinforced composite beams were then loaded into the long-clamping system at 20 kgf/cm². Minimum pressing time at room temperature was 12 hours, but all the beam produced were let to set overnight, thus adequate time were allowed for the curing of the adhesive. The beams were then planned down and the finished dimension was approximately 4.5 cm widths, 10.5 cm depths and 300 cm lengths.

2.3. Testing Methods

Three kinds of non-destructive test to obtain modulus of elasticity were carried out on each specimen.

Deflection measurement; applying concentrated loading system, five 1 kg dead weight were put manually and the deflection at mid-span was measured by a digital dial gauge with 0.01 mm reading unit. The span was 200 cm. The modulus elasticity calculated by this method (Ed) was static one and regarded as a control value.

Ultrasonic wave propagation time measurement; specimen was put on soft-formed polyurethane pillows for not being disturbed the specimen’s free vibration during test. With a 200 kHz transmit transducer, the propagation time of transverse wave from one end of specimen to the other end was measured. An ultrasonic wave modulus of elasticity (Euw) was calculated by the equation:

$$\frac{1}{t_{uw}} = \sqrt{\frac{E_{uw} g}{\rho}}$$

where:
- $t_{uw}$: propagation time per unit length of specimen
- $E_{uw}$: ultrasonic wave modulus of elasticity
- $g$: gravitational acceleration constant
- $\rho$: average density of specimen at test

Fundamental vibration frequency measurement; a specimen was hung at the center of its length or was put on soft-formed polyurethane pillows as the same as above case. When standard hammer hit the one end of specimen, the sound another end of a microphone caught specimen. Then this signal was put into a Fast Fourier Transformation (FFT) spectrum analyzer and the fundamental vibration frequency was detected. A frequency modulus of elasticity (Efr) was calculated by:

$$f = \frac{1}{2} \sqrt{\frac{E_{fr} g}{\rho}}$$

where:
- $f$: fundamental vibration frequency
- $L$: length of specimen
- $E_{fr}$: frequency modulus of elasticity
- $g$: gravitational acceleration constant
- $\rho$: average density of specimen at test.

The beams were tested destructively in a bending machine under a four point loading system shown in Fig.1. Specimens were tested in a 10-ton universal testing machine under four-point loading. The total span was 270 cm. Deflection at mid-span was measured by a digital dial gauge. The specimens were supported and loaded through steel plates to minimize stress concentration in test specimens and to obtain a relatively uniform load level under the loading plates. The vertical movement of the loading head was controlled at low speed, which resulted in a rate of cross head movement of approximately 5-mm/min and specimen failure within 30 minutes. The applied loads and the crosshead movements were continuously monitored and recorded during testing using a personal computer based data acquisition system. Failure characteristics of each specimen were also recorded schematically. The apparent MOE and MOR were computed from the following standard equation (ASTM, 1994):
\[ MOE = \frac{P_{pl}L^3}{4.7bh^3\delta_{pl}} \]  

\[ MOR = \frac{P_{\text{max}}L}{bh^2} \]

where:

\( P_{pl} \) = load at proportional limit (kgf)  
\( L \) = beam span (cm)  
\( b \) = beam width (cm)  
\( h \) = beam height (cm)  
\( \delta_{pl} \) = mid span deflection (cm)  
\( P_{\text{max}} \) = maximum breaking load (kgf)

Fig. 1. Testing arrangement of bamboo reinforced composite beam; S=sugi wood as control; A,B,C= composite beam with 1,2,3 layers of bamboo mat as a flange, respectively.

3. RESULTS AND DISCUSSIONS

3.1. Non-destructive testing
The non-destructive evaluation methods were feasible for assessing the mechanical quality of material in the manufacture of composite lumber. The measurement of MOE is a good way to characterize the damage that possible occurred during mechanical test. Bamboo reinforced composite lumber were constructed from bamboo mat flange and low quality of sugi wood as web. According to the results obtained in this study, ultrasonic wave and fundamental vibrations frequency method for measuring the MOE gave similar values (Table 1), whereas deflection method tend to under estimate the MOE value, as also shown in Fig 2. For practical applications, however, a non-contact measuring method, i.e. \( E_{fr} \) obtained by measuring the fundamental vibrations frequency and density, is regarded as the most suitable. It is also pointed out that \( E_{fr} \) can be used quite effectively for grading or sorting beam or log before sawing. Contact methods such as measuring ultrasonic wave propagation time required close contact between the sensor/probe and surface of the timber cross-section, which is not easy to maintain. When using ultrasonic wave, a large volume of timber may cause too much delay of wave for its arrival to be detected (Nakai et.al., 1990).
3.2. Bending Testing

The static bending and related physical properties of the sample beam are shown in Table 7.2.3. Flexural properties for sugi wood dimension lumber were included as a reference (control). The MOE of bamboo reinforced composite beam loaded edgewise in four-point loading improved substantially by reinforcing with bamboo mat flanges. Improvements ranged from 49.5% to 76.7% greater than the MOE of unreinforced sugi wood.

### Table 1. Comparison between tested MOE versus predicted MOE (non destructive method)

<table>
<thead>
<tr>
<th>Code of Beam</th>
<th>Predicted MOE (x10³ kgf/cm²)</th>
<th>Tested MOE (x10³ kgf/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_{d-flat}$</td>
<td>$E_{uw}$</td>
</tr>
<tr>
<td>A1</td>
<td>79.28</td>
<td>110.44</td>
</tr>
<tr>
<td>A2</td>
<td>49.83</td>
<td>68.49</td>
</tr>
<tr>
<td>B1</td>
<td>68.40</td>
<td>98.16</td>
</tr>
<tr>
<td>B2</td>
<td>47.89</td>
<td>68.38</td>
</tr>
<tr>
<td>C1</td>
<td>66.99</td>
<td>115.07</td>
</tr>
<tr>
<td>C2</td>
<td>76.28</td>
<td>106.97</td>
</tr>
<tr>
<td>S1</td>
<td>57.10</td>
<td>72.14</td>
</tr>
<tr>
<td>S2</td>
<td>57.23</td>
<td>64.20</td>
</tr>
<tr>
<td>S3</td>
<td>53.85</td>
<td>56.80</td>
</tr>
<tr>
<td>S4</td>
<td>47.10</td>
<td>55.99</td>
</tr>
</tbody>
</table>

Note: $E_{d-flat}$: deflection measurement with concentrated loading system, $E_{uw}$: ultrasonic wave propagation time measurement, and $E_{fr}$: fundamental vibration frequency measurement.

![Predicted MOE vs tested MOE of bamboo reinforced composite beam.](image)

**Tested MOE ($10^3$ kgf/cm²)**

Fig. 2. Predicted MOE vs tested MOE of bamboo reinforced composite beam.
Table 2. Bending properties of bamboo reinforced composite beam and sugi wood as a control

<table>
<thead>
<tr>
<th>Beam Code</th>
<th>Beam Type</th>
<th>Density (g/cm³)</th>
<th>MOE (10^3 kgf/cm²)</th>
<th>Pmax (kgf)</th>
<th>MOR (kgf/cm²)</th>
<th>Failure Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>1-Layer bamboo reinforcement</td>
<td>0.458</td>
<td>101.49</td>
<td>1905</td>
<td>1135</td>
<td>BF</td>
</tr>
<tr>
<td>A2</td>
<td></td>
<td>0.430</td>
<td>76.26</td>
<td>1815</td>
<td>1068</td>
<td>BF</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.444</td>
<td>88.87</td>
<td>1860</td>
<td>1101</td>
<td>BF</td>
</tr>
<tr>
<td>B1</td>
<td>2-layers bamboo reinforcement</td>
<td>0.492</td>
<td>100.80</td>
<td>2035</td>
<td>1204</td>
<td>* (SF)</td>
</tr>
<tr>
<td>B2</td>
<td></td>
<td>0.482</td>
<td>84.31</td>
<td>1750</td>
<td>1025</td>
<td>BF</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.487</td>
<td>92.56</td>
<td>1910</td>
<td>1115</td>
<td>BF</td>
</tr>
<tr>
<td>C1</td>
<td>3-layers bamboo reinforcement</td>
<td>0.555</td>
<td>107.76</td>
<td>1985</td>
<td>1162</td>
<td>SF</td>
</tr>
<tr>
<td>C2</td>
<td></td>
<td>0.540</td>
<td>102.32</td>
<td>2105</td>
<td>1253</td>
<td>SF+BF</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.547</td>
<td>105.04</td>
<td>2045</td>
<td>1208</td>
<td></td>
</tr>
<tr>
<td>S1</td>
<td>Control (Sugi wood)</td>
<td>0.389</td>
<td>58.75</td>
<td>920</td>
<td>504</td>
<td>BF</td>
</tr>
<tr>
<td>S2</td>
<td></td>
<td>0.396</td>
<td>64.10</td>
<td>1120</td>
<td>612</td>
<td>BF</td>
</tr>
<tr>
<td>S3</td>
<td></td>
<td>0.375</td>
<td>58.95</td>
<td>1030</td>
<td>637</td>
<td>BF</td>
</tr>
<tr>
<td>S4</td>
<td></td>
<td>0.381</td>
<td>56.01</td>
<td>1165</td>
<td>562</td>
<td>BF</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>0.385</td>
<td>59.45</td>
<td>1059</td>
<td>579</td>
<td></td>
</tr>
</tbody>
</table>

Note: BF: bending failure; SF: shearing failure; and *: buckling was occurred during test

With the increasing the number of layers, the average MOE values of composite beam showed substantially increased, because the three beam types differed in terms of total thickness of bamboo mat flanges. According to a four-point loading test, the maximum displacement of the beam is expected to occur at the mid-span of the composite beam. It is found that, from this study, adding the number of layers could result in higher values of beam strength and stiffness and therefore reduce the deflection of the composite beam, as shown in Fig. 3.
The average MOR values of composite beam also improved by 90.16, 92.57 and 108.64 % by reinforcement with 1, 2 and 3-layers, respectively. Additionally, it can be seen that the MOR values for the composite beam also increase with the increasing the number of bamboo mat layers. These facts show that adding bamboo reinforcement to sugi wood in this manner improves strength more than stiffness. Longitudinal shear failures can be readily detected when the lines were broken in shearing mode. Other possible combination failure modes on bending failures were noted. In some cases failures in the shearing mode especially in three layers reinforcement (C-1 and C-2 beam) were readily apparent as presented in Fig 4. At the first time, bending failures were happened on the A-1 and A-2 beam, and continued by longitudinal shear failures that typically occurred close to the mid depth at the beam. The longitudinal shear failures were located between one of the loading heads and shear cracks propagated from the initial failure location through to the end of the beam. The same trend was resulted on B-2 beam that had combinations between bending and shear failures. Interestingly, B-1 beam did not have any specific failure; because buckling phenomenon was occurred during bending test and lateral stability seemed poor.

Careful consideration must be given to potential problems that can arise in bamboo reinforced wood products. These include shear performance between the reinforcement layers and the wood and between the reinforcement layers themselves and dimensional stability of the wood in relation to that of the bamboo reinforcement. Increasing the number of bamboo layers for reinforcement resulted in changing all strain distributions and magnitudes within the composite beam. When using one layer for reinforcement, the maximum strain distribution near the top and lower beam surface (strain gauge s-1, s-5, s-6 and s-10) is significantly lower compare to 2 or 3-layers reinforcement. The failures process on beam during testing could monitor at strain distribution curves. It was interested that the outside bamboo layers contribute more toward the MOE value in bending, and bamboo layer that had high stiffness were more efficient when placed near the upper and lower surfaces of the beam.

The bamboo flanges of bamboo reinforced composite beam carry most of the bending stress (tension and compression) and the sugi wood as a web carries the bulk of the shear stresses. The flange-web glue-line transmits the stresses between adjacent components in the cross section of the beam. Because the web possesses a somewhat lower MOE, tension and compression stresses are amplified in the flanges, as a result, the properties of flange material are especially important, such as bamboo that have its properties.
4. CONCLUSIONS

Based on the results of bamboo reinforced composite beam under four point loading test, the following conclusions can be drawn as follows:

a. Ultrasonic wave and fundamental vibrations frequency method gave similar values for measuring the MOE, whereas deflection method tends to under estimate the MOE value.
b. By reinforcing sugi wood as web with bamboo mat as flange, strength and stiffness of the bamboo reinforced composite beam increase significantly

c. In some cases failures in the shearing mode were readily apparent, especially with the beam that consist bamboo flange more than one layer.

5. REFERENCES


