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Development of structural composite products made from bamboo II: fundamental properties of laminated bamboo lumber

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Abstract This experiment explored the technical feasibility of using bamboo zephyr mat with pre-hot-pressed treatment for the manufacture of laminated bamboo lumber (LBL), which is similar in construction to that of laminated veneer lumber (LVL). Six LBL boards (made from four-ply bamboo zephyr mats) with approximate dimensions of 2 × 42 × 42 cm were fabricated using resorcinol-based adhesive. The experimental design involved three combinations of layered structures (types I, II, and III) and two LBL loading positions (H-beam and V-beam) during the bending test. These materials were then compared to ordinary LVL. Results indicated that the bending properties (moduli of rupture and elasticity) of LBL were comparable to those of LVL, but there was no significant effect on the physical and mechanical properties among the three types of LBL beam. Interestingly, orienting the glue line to the vertical direction (V-beam) could maximize the ultimate strength of the LBL.

Key words Laminated bamboo lumber · Bamboo zephyr mat · Pre-hot-pressed · Bending properties

Introduction

Recently, the use of bamboo has been expanded to include its manufacture into various structural composite products.[1–4] Previous studies showed that moso bamboo's favorable stiffness and strength properties make it a promising material for the manufacture of various engineered composite products, such as bamboo zephyr board.[5]

Elements in the composite product, such as a sheet/mat, should be wide to facilitate handling during the manufacturing process; the elements should also be long along the grain to retain the strength of the fiber. Considering these two important conditions, it is concluded that the bamboo zephyr strand mat is suitable for constructing a new structural composite product. Zephyr is a sheet material of a fibrous net-like structure prepared similarly to scrimber, which was developed in Australia.[6,7] The process involves progressive crushing of materials through several sets of rollers until a continuous fibrous sheet is obtained.[8,9]

Composite products composed of these zephyr-type elements and processed by hot pressing have a large amount of thickness swelling caused by water. Additionally, there is a large degree of unevenness of the surface of the board, especially thin boards, and many spaces among the elements, causing a weakening of the bonding strength between them and a poor appearance of the products. Considering these facts, the bamboo zephyr elements were pretreated by a hot-press method to reduce these problems. This study explored the technical feasibility of bamboo zephyr mats with pre-hot-pressing treatment for the manufacture of laminated bamboo lumber (LBL).

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Materials and methods

Bamboo zephyr mat production with hot-pressed treatment

Mature moso bamboo culms (*Phyllostachys pubescens* Mazel), with an average base diameter of 13.7–18.4 cm and a thickness of 9.8–12.3 mm, were collected from Kagoshima Prefecture, Japan. The density of the bamboo was about 0.74 g/cm^3. Each culm was split into quarters and was passed

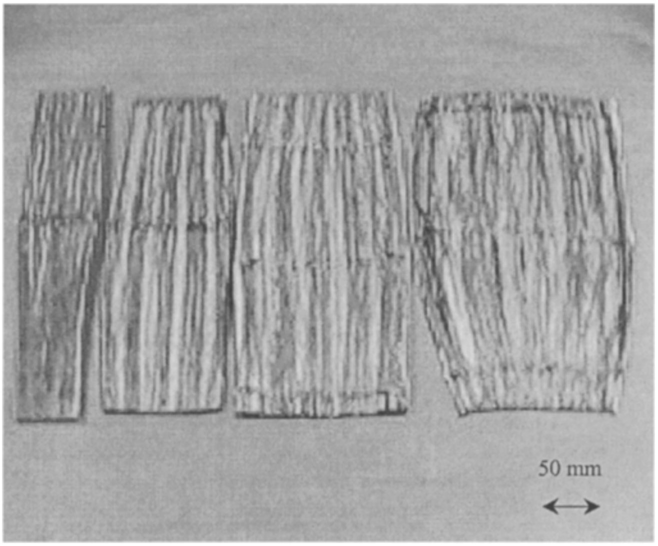

Fig. 1. Bamboo zephyr mat from moso bamboo after pre-hot-pressed treatment. From left to right: treatment at temperatures of 100°, 130°, 150°, and 180°C, respectively

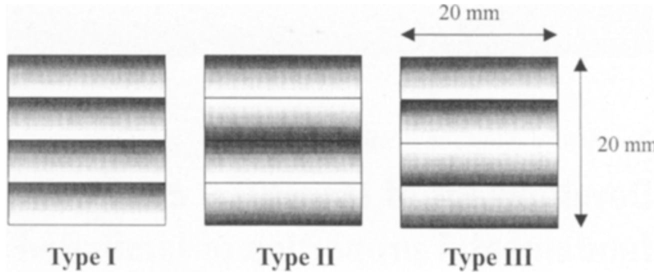

Fig. 2. Combination of layered structure on laminated bamboo lumber (LBL). *Light color*, inner layer; *dark color*, face layer

through a roller press crusher five times to make a bamboo zephyr strand mat.

Pretreatment by hot pressing the bamboo zephyr mat was done by changing the condition of the temperature of the hot platens and the pressing time. For this study, bamboo zephyr in green condition (with approximate 30% moisture content) was hot-pressed for 6 min at hot platen temperatures of 100°, 130°, 150°, and 180°C at a pressure of 60 kgf/cm^2. The average initial thickness of the bamboo zephyr before it was hot-pressed was 11 mm; five specimens were tested for each condition. Bamboo zephyr mat from moso bamboo after the pre-hot-pressed treatment is seen in Fig. 1.

Based on the above result, the mats were then placed between platens of a 45 × 45 cm electrically heated hydraulic laboratory hot-press and flattened using a pressure of 60 kg/cm^2 at 150°C for 6 min. A distance bar was used to control the bamboo zephyr mat thickness at 6 mm. All bamboo zephyr mats were passed through a planer to remove most of the inner and outer (epidermal) layers until a thickness of 5 mm was reached.

LBL production

Before this manufacturing process, a preliminary experiment was carried out on the glue bond made between the bamboo zephyr mats of LBL (two-ply) with varying application rates for the glue. This experiment involved two factors: three combinations of the layer structure (face-face, face-inner, and inner-inner layers) and three of glue spread rates (240, 300, and 360 g/m^2 single glue line). Five 5 × 5 cm specimens prepared from these products were then used for each treatment condition.

Six LBLs (four layers) with approximate dimensions of 2 × 42 × 42 cm were fabricated using resorcinol-based adhesive (D-33; Oshika Shinko Co.) The experimental design involved three combinations of the layered structure (types I, II, and III), as illustrated in Fig. 2. The adhesive with a glue spread rate of 300 g/m^2 was then applied to the bamboo zephyr mat by hand brushing. After glue spreading, four layers of bamboo zephyr mats were prepared and cold-pressed at a pressure setting of 20 kg/cm^2 at room temperature for 12 h.

Testing properties

The LBL specimens were conditioned at a controlled temperature of 25°C and 65% relative humidity (RH) for at least 2 weeks. All the boards were trimmed and cut into various test specimens as follows: 2 × 2 × 32 cm for static bending tests; 5 × 5 cm for internal bonding (IB) strength tests; 5 × 5 cm for thickness swelling (TS) and water absorption (WA) tests; and 5 × 10 cm for linear expansion (LE) determination.

The sample materials were tested for bending properties [modulus of rupture (MOR) and modulus of elasticity (MOE)], IB strength, and dimensional stability (WA, TS, and LE). Tests were performed on the specimens in accordance with JIS A-5908[10] and JIS Z-2113.[11]

For static bending the specimens were randomly separated into two groups with five replications for each treatment: one group for a load applied to the specimens with a horizontal glue-line (H-beam) and the other for load specimens with a vertical glue line (V-beam). Three test specimens were prepared by each treatment for the IB, TS, WA, and LE tests. For dimensional stability, the specimens were submerged horizontally under 25 mm of distilled water. After 2-h and 24-h submersions the specimens were suspended to drain for 10 min to remove the excess water, and the weight and thickness of each specimen were determined immediately.

Results and discussion

Effect of the pre-hot-pressed treatment

Okuma and Dong[12] have done research on the effect of hot-pressing chopstick material. They found that a pressing

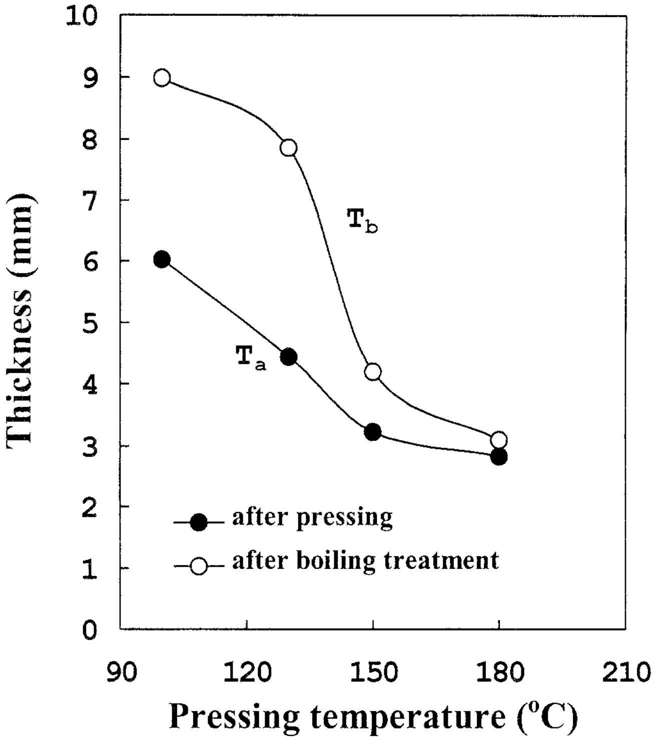

Fig. 3. Comparison of hot-pressed bamboo zephyr mat thickness before and after boiling at various pressing temperatures. *Filled circles* (T_a), bamboo zephyr mat thickness immediately after hot-pressing; *open circles* (T_b), thickness of the hot-pressed bamboo zephyr mat after boiling. Each point is the average of five measurements

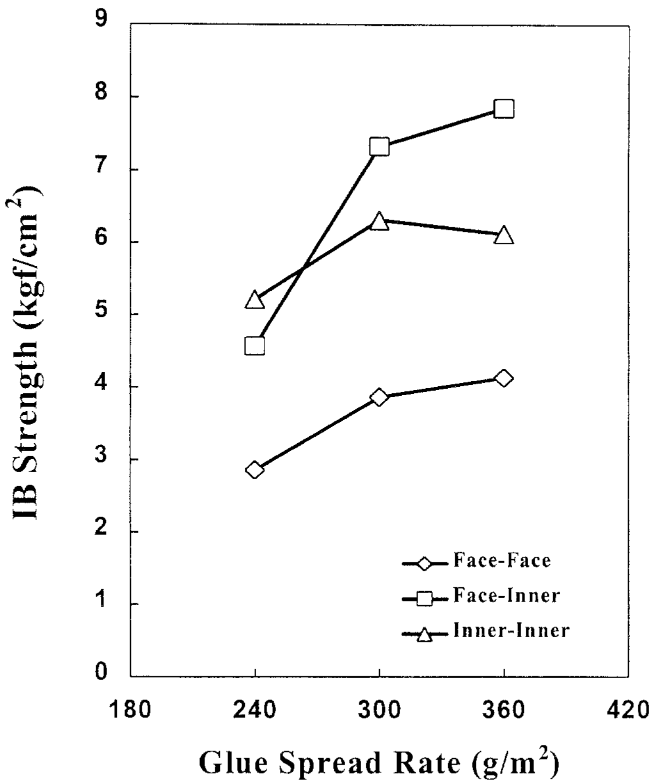

Fig. 4. Internal bond strength (*IB*) of two-ply LBL at different glue spread rates. *Diamonds*, glue spread rate on face-to-face layer; *squares*, glue spread rate on face to inner layer; *triangles*, glue spread rate on inner to inner layer

temperature of 180°C for 3 min with a chopstick moisture content of more than 18% was enough to change the compressed chopstick form into a stable size. At a temperature of 180°C, the main chemical component of wood chopstick (cellulose and lignin) partially disintegrated and plasticized. These conditions led to release of the internal stress caused by hot-pressing; therefore, the compressive deformation did not exhibit spring-back and was fixed in a stable condition.[12]

Bamboo requires a longer time than wood for hot-pressing because it contains a waxy component, with heavier and harder outer bark. The density of the compressed bamboo zephyr mat was increased to around 0.9 g/cm^3. This mat deforms not only in the thickness direction but also along its width; it becomes wider by hot-pressing under a high temperature. Notably, the bamboo zephyr mat became brown in color when compressed at a temperature of 180°C, and the mat seemed to be separated and degraded.

The relation between the temperature of the hot platens and the average thickness of the compressed bamboo (T_a and T_b) are shown in Fig. 3. It can be seen that the average thickness of the compressed bamboo (T_a) is more than 6 mm at 100°C. It becomes less than 3 mm when the temperature is increased to more than 150°C. The thickness of the bamboo had a spring-back to T_b when the compressed specimen was dipped in boiling water for 1 min. The T_b is about 8 mm at a temperature of 130°C or less. The difference between T_b and T_a is rather large in the range of these platen temperatures, and the compressed deformation caused by hot-pressing was released more easily in this range of temperatures. However, T_b coincides with T_a when the platen temperature exceeds 150°C. These results mean that the compressed deformation of the bamboo cannot be released by soaking in boiling water, and it becomes stable when the pressing temperature is increased to over 150°C.

Based on these findings, the hot-pressing conditions for the bamboo zephyr mat should be adjusted at 150°C for 6 min, with the results shown in Fig. 1. To understand the interaction mechanism and the effect of temperature, pressure, pressing time, and initial moisture content on the bamboo zephyr mat, further studies are needed.

Internal bond strength on two-ply LBL

As shown in Fig. 4, the results indicated that the IB strength tends to decrease on the face-face layer compared to the other structured layers. Although bamboo zephyr mats were already planned, the residue of the outer layer and compressed crack or check remained on the bamboo mat surface. This means that the face layer was still expected to contain chemicals such as wax and silica, which can seriously affect the bonding strength of the glue line. Additionally, bamboo contains fiber-like structural features known as bundle sheaths and parenchyma, and the volume fraction of bundle sheaths increases from the inner to the outer surface of the wall. As a result, the face layer becomes harder than the inner layer, which can seriously affect the penetration of resin.

The highest IB strength occurred on the face-inner layer. The glue spread rate tends to increase the IB strength, but the differences between 300 and 360 g/m^2 were not significant. Based on this preliminary experiment, it was determined that the optimum amount of glue application for resorcinol-based adhesives was 300 g/m^2.

Properties of four-ply LBL

Three types of layered structures of LBL products (types I, II, and III) are shown in Fig. 5. The density of the LBL produced varies from 0.87 to 1.01 g/cm^3 (average 0.94 g/cm^3). The density of the LBL is higher than the original density of the moso bamboo due to the hot-press treatment applied during LBL manufacture, which results in denser products. The static bending properties of LBL are shown in Table 1. LBL exhibits superior strength, as indicated by its higher MOE and MOR values. Lee et al.[13] said that the MOR of moso bamboo in the air-dried condition was 1043 kg/cm^2, whereas the MOE was 108 290 kg/cm^2. Sulastiningsih et al.[14] reported the same result: that the MOR value of LBL is lower than the MOR value of the original bamboo. The reason for this finding lies in the fact that many splits occur in the bamboo zephyr mat, which reduces its strength. It also can be seen that the MOE of LBL is the same as the MOE of the original bamboo, based on the results of Lee et al.[13]

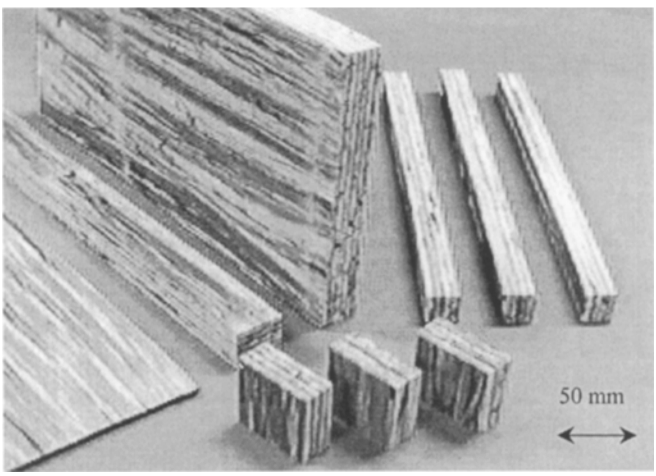

Fig. 5. Samples of laminated bamboo lumber (LBL). In the front are specimens of IB strength. In the background are, from left to right: bamboo zephyr mat, LBL board, and bending testing specimens

Although there was no significant effect among the three types of beam, the type II beam had better bending properties than the other types, although the IB strength was lower than that of other types. This may be due to the structure in the center of the beam, which has the weakest layer (face-face layer). As mentioned above, the resin had insufficient infiltration due to the high density of the face layer, which also contained wax and silica, influencing the bonding quality. The type of beam had no significant effect on physical properties, such as WA, TS, and LE.

A comparison of MOE and MOR values for the LBL beam and the laboratory-made LVL from lauan veneer (*Shorea* sp.)[15] is shown in Table 2. The average MOE and MOR values for LBL were comparable to those for the laboratory-made LVL. All of the V-beams had higher average MOE and MOR values than did the H-beams (Figs. 6, 7). This result is in agreement with those of Lee et al.,[16] who also studied LBL. The H/V ratios for MOE and MOR of LBL dropped to 0.87 and 0.82, respectively. These ratios indicate that vertically laminated specimens were stronger than horizontally laminated ones. However, for the MOR of laboratory-made LVL, the H/V ratio is 1.02. The ratios appeared to be close to unity, indicating no significant differences between the two beam loading orientations.

Regarding the MOR value in Table 2, the V-beam was at least 22% stronger than the H-beam. It might be due to the nature of the bamboo itself, which has a high tensile strength. As a result, the V-beam can support higher stress and transverse tension during bending. In contrast, the MOR of H-beams is poorer because of the glue line weakness effect. Notably, when the H-beam was subjected to a load during the bending test, a delaminating fracture occurred owing to the insufficient resin penetration due to the hard surface of the bamboo. This finding indicates that orienting the glue lines to the vertical direction can maximize the ultimate strength of these engineered lumber composites.

Table 1. Mean physical and mechanical properties of four-ply laminated bamboo lumber

Type of beam	MOE (×10^3 kgf/cm^2)		MOR (kgf/cm^2)		IB (kgf/cm^2)	WA (%)		TS (%)		LE (%)	
	H-beam	V-beam	H-beam	V-beam		2 h	24 h	2 h	24 h	2 h	24 h
I	96.2	121.0	639.0	851.0	8.60	12.70	24.10	5.90	12.10	0.19	0.48
	(9.4)	(15.9)	(101)	(87.5)	(2.96)	(3.68)	(7.00)	(1.95)	(3.70)	(0.09)	(0.12)
II	105.0	123.0	707.0	877.0	5.79	13.50	26.10	5.70	12.40	0.18	0.48
	(10.0)	(11.9)	(127.0)	(88.5)	(1.19)	(2.02)	(2.61)	(1.97)	(0.83)	(0.08)	(0.18)
III	107.0	111.0	689.0	755.0	9.10	12.70	24.30	5.60	11.90	0.18	0.48
	(10.7)	(10.0)	(56.9)	(42.9)	(2.98)	(3.64)	(7.03)	(1.77)	(3.71)	(0.08)	(0.17)

Numbers in parentheses are standard deviations from the sample mean
MOE, modulus of elasticity; MOR, modulus of rupture; IB, internal bond strength; WA, water absorption; TS, thickness swelling; LE, linear expansion

Table 2. Comparison of LBL mechanical properties with experimental LVL data[a]

Material	Specimen size (cm)	MOE (10^3 kgf/cm^2)	MOR (kgf/cm^2)
LBL: bamboo, four-ply	2 × 2 × 40		
Horizontal (H-beam)		103	678
Vertical (V-beam)		118	828
H/V ratio		0.87	0.82
LVL: lauan (*Shorea* sp.), eight-ply	4 × 4 × 80		
Horizontal (H-beam)		117	779
Vertical (V-beam)		104	762
H/V ratio		1.13	1.02

LBL, laminated bamboo lumber; LVL, laminated veneer lumber
[a] Data are from Ebihara[15]

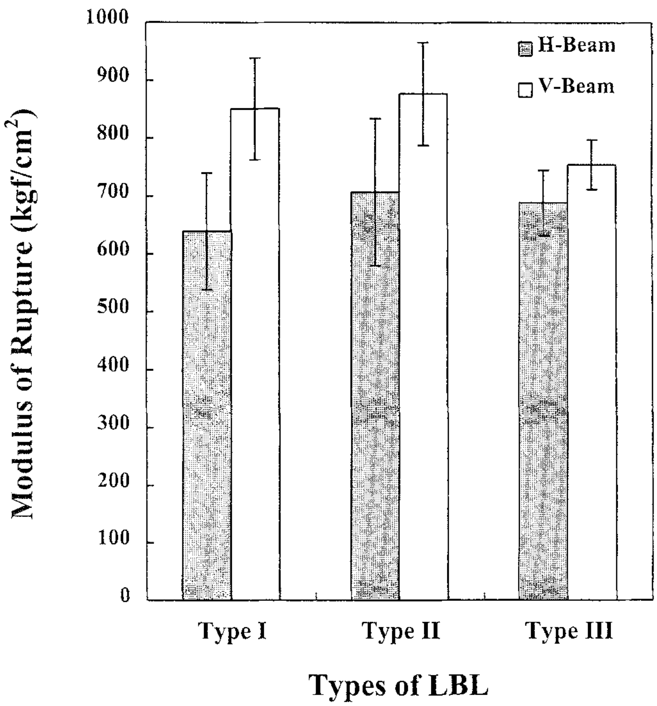

Fig. 6. Modulus of rupture of LBL according to the bending test position. *Shaded bars* (H-beam), load applied to the specimens with horizontal glue line; *open bars* (V-beam), load applied to the specimens with vertical glue line. Each vertical bar indicates the standard deviation

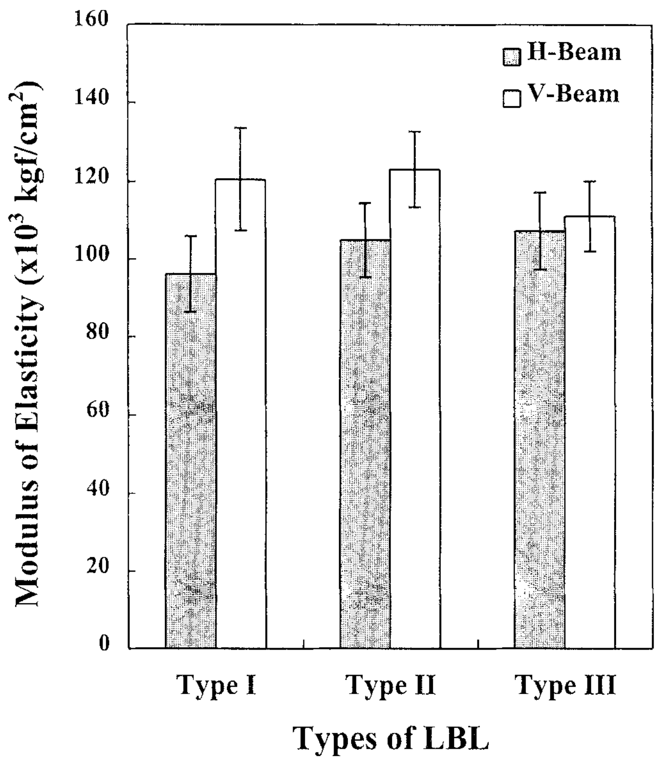

Fig. 7. Modulus of elasticity of LBL according to the bending test position. Symbols are the same as those in Fig. 6

Conclusions

Based on our study, the following conclusions can be reached.

1. The glue spread rate appears to be a significant variable for the internal bond strength on two-ply LBL.
2. There was no significant effect for three types of beam in terms of MOE and MOR values. The bending properties (MOR and MOE) of LBL produced with pre-hot-pressed bamboo zephyr mat were comparable to those of LVL produced with lauan veneer. Orienting the glue line in the vertical direction can maximize the ultimate strength of LBL.
3. It was demonstrated that manufacture of this product appears technically feasible. It is also recommended that further research should be done to investigate its other properties, such as biological resistance, fastener holding capacity, and a connection system for this product.

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