Research paper

Flexural Properties of Structural Laminated Bamboo/Solid Wood Composite Box Hollow Beams[1)]

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【Summary】

Laminated Moso bamboo members were fabricated with different alignments and used as flanges with Japanese cedar lumber as web members to investigate the flexural performance of laminated bamboo/wood box hollow beams. The results showed that the efficiencies of finger joints in the bending tests were 64.3 and 53.2% for beams respectively laminated horizontally and vertically with bamboo laminae. The maximum bending capacities of the box hollow beams using laminated bamboo members either horizontally or vertically as flanges were 31.3 and 49.7%, respectively, higher than those of beams with Japanese cedar flanges. Furthermore, improved maximum bending capacities, of 69.1 and 74.2%, were respectively found for laminated bamboo/wood box hollow beams further reinforced with 10 d box nails and wood screws between the interface of the bamboo flange and solid wood web compared to that of solid wood box hollow beams. Based on the design deflection limitations, box hollow beams fabricated with laminated bamboo flanges can provide equivalent distributed loads of 1.85~2.09 KN m^{-1}, corresponding to loads 30.9 to 47.5% higher than those of solid beams.

Key words: composite beam, bamboo/wood box hollow beam, mechanical property, Moso bamboo.

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研究報告

結構用層積竹木複合箱型空心梁之抗彎性質[1)]

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摘 要

本研究利用不同之配置方式層積孟宗竹構材，並作為結構用層積竹木箱型空心複合梁之梁翼材，同時採用柳杉材作為梁腹材，進行木材箱型空心複合梁之抗彎性質評估。結果顯示竹集成元分別採用水平或垂直層積組合之梁構材，透過抗彎試驗其指接效率為64.3及53.2%。在箱型空心複合梁方面，梁翼之集成竹構材分別以水平或垂直配置時，其最大抗彎承載力較柳杉梁翼箱型空心梁高31.3及49.7%。同時竹木箱型空心複合梁分別以10 d箱用釘或木螺釘在梁翼及梁腹介面補強時，將能優於實木箱型空心梁69.1及74.2%。基於撓度限制之設計，以集成竹作為梁翼之箱型空心梁具有1.85~2.09 kN m^{-1}之等效均布載重性能，且優於實木梁30.9~47.5%。

關鍵詞：複合梁、竹木箱型空心梁、機械性質、孟宗竹。

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INTRODUCTION

Box beams are designed to efficiently use relatively small sizes of wood-based materials in structural applications. The outer surfaces of the top and bottom of a beam produce maximum compressive and tensile stresses when subjected to a flexural load. Consequently, the flexural performance of a box beam can be improved by using stronger flange members. Bamboo is a renewable natural resource that grows rapidly and is known for its lightness and excellent mechanical properties. For commercial purposes, the compressive and bending strengths of bamboo can generally reach a maximum in 3~5 yr (Li and Li 1983). The density and mechanical properties of bamboo are reduced towards the bottom of the bamboo culm with natural variations in characteristics (Tang 1989). Yeh (1984) reported that the bending strength of a bamboo culm tested with short specimens was only 20.8% of long bamboo culms due to early shear failure or splitting along the neutral axis. In addition, the modulus of rupture (MOR) of beams made from laminated bamboo strips is much higher than that of long bamboo culm specimens, i.e., 2.0-, 2.5-, and 3.3-times those of plain bamboo culms laminated with inner, middle, and outer layers of culm walls, respectively. It was suggested that using laminated bamboo as flange materials will improve the structural performance of box beams especially when combined with low-quality lumber from rapidly grown plantation trees. Liu et al. (1992) studied the effect of stacking patterns of bamboo strips during lamination on the bending strength of laminated bamboo. The modulus of rupture of beams containing bamboo strips with the surface of the epidermal layer facing down during glue application was 24.8% higher than that of beams with the epidermal layer facing up. Beams laminated either with the strips glued in pairs with the epidermal layers face to face or with the pith peripheral layers glued face to face in consecutive pairs had similar bending strengths and fell between those of stacking patterns mentioned above. Therefore, the stacking pattern of bamboo strips is an important consideration when developing laminated bamboo structural members. Furthermore, the presence of nodes in the bamboo culm can reduce the bending and tensile strengths of bamboo, as reported by Lin et al. (1976), which can affect the structural performance of full-size laminated bamboo members. In this study, bamboo strips were laminated in various orientations and used as flanges for making composite box hollow beams to investigate the flexural performance of beams and assess the possibility for their use in engineering applications.

MATERIALS AND METHODS

For lamination, bamboo culms should have a thick wall and large diameter. A commercial bamboo species mainly used for the structural construction in bamboo culm was used as the lamination materials. A rapidly grown wood species constituting one of the major plantation species was chosen to develop the composite members in the study.

Materials

Japanese cedar (*Cryptomeria japonica*) planted in the Alishan area of Taiwan about 25 yr ago was harvested. Sawn lumber was then planed to 40×90×3600 mm in dimensions after being kiln-dried to a 11.7±0.3% moisture content. Moso bamboo (*Phyllostachys pubescens* var. *pubescens*) grown in Chiayi County, Taiwan, was harvested at the age of 4~5 yr with on average diameter of 124 mm at the lower end of the culm. Bamboo strips were obtained by splitting a culm into 6 pieces and then planning them into a rectangular cross-section by removing both the outer (epidermal) and inner layers (pith peripheral). The dimensions of the bamboo strips were 6×33×1850 mm after being treated with a 1% boiling boron solution and being kiln-dried. A commercial resorcinol phenol formaldehyde adhesive (RPF, type AD500, Sports Leader, Tainan, Taiwan) with a 52~58% solids content and hardener (type: H501) of paraformaldehyde in a 69~73% solution were used for laminating the bamboo strips. Laminated bamboo members of 30×120×1850 mm were assembled with vertical or horizontal layers by stacking bamboo strips sequentially with the surface of the epidermal layer facing the same direction. Glue was applied at 250 g m^{-2}, and pressure application was 1.47 MPa. The bamboo members were then finger-jointed longitudinally to a length of 3650 mm with RPF adhesives using a longitudinal finger jointer (model: KMFJ-400S, Chuan Chier Industrial, Kaohsiung, Taiwan). The finger length was 12 mm, the finger spacing was 4 mm, and the tip width was 0.65 mm; it was processed using a finger shaper (model KMFJ-400, Chuan Chier Industrial). The laminated bamboo members were used as flange material and Japanese cedar solid wood as web material to fabricate box beams of 120 mm wide and 150 mm deep. Four types of laminated bamboo/wood composite box hollow beams with bamboo strips oriented horizontally (WB-H) or vertically (WB-V) were fabricated with RPF adhesives, as shown in Fig. 1. Two box hollow beams were further reinforced with either box nails (WB-VN) or wood screws (WB-VS). The box nails were 3.4 mm in diameter and 75 mm long, while the wood screws were 5.8 mm in diameter and 63.5 mm long. Both fasteners were driven from upper and bottom flanges to the web at a 300-mm spacing during box hollow

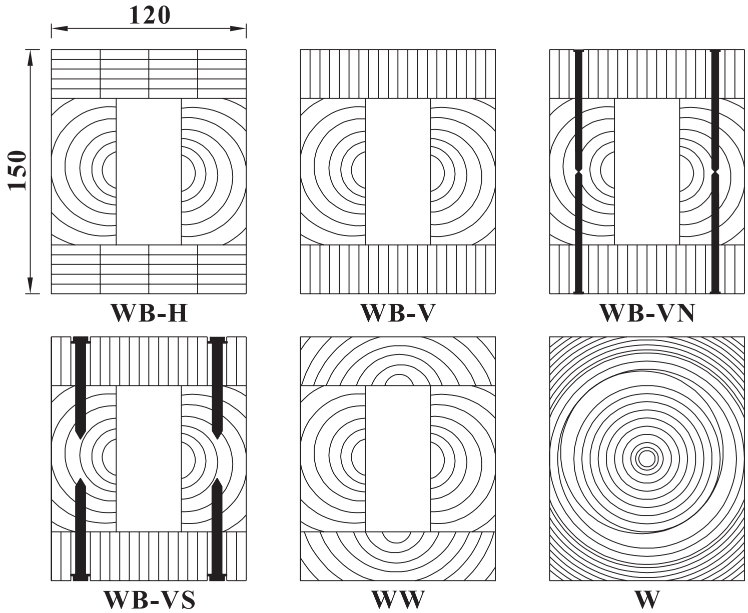

Fig. 1. Types of laminated bamboo/wood box hollow beams. units: mm (W, Japanese cedar; B, laminated bamboo; V, vertical; H, horizontal; N, box nail; S, wood screw).

beam fabrication. In addition, box hollow beams fabricated with Japanese cedar solid wood flanges (WW) and solid beams (W) with the same dimension in cross-section as the box hollow beam were included as control groups.

Test method

A nondestructive bending test was performed to obtain the static bending modulus of elasticity (MOE) of the Japanese cedar solid wood members, which were used for the web material. The MOE was evaluated by applying an initial load of 116 N and a second load of 233 N on the center of the beam. It was calculated by:

$$MOE = \frac{\Delta P \times L^3}{4\Delta y \times b \times h^3}\ ; \qquad (1)$$

where ΔP is the difference between loads at the 2 levels within the proportional limit; L is the total span; Δy is the flexural displacement difference corresponding to loads of ΔP; b is the beam width; and h is the depth. The static bending tests with 2-point loading were used for the laminated bamboo specimens. Specimens were divided into groups of beams with or without finger-joints, i.e., the B-F and B groups. The B-F group was further divided into the B-FH and B-FV groups, and the B group was likewise further divided into the B-H and B-V groups based on the horizontal or vertical laminations of the bamboo strips. Specimens were 30×30×1000 mm, and the tested span was 900 mm. The static bending modulus of rupture can be estimated as:

$$MOR = \frac{P_b \times L}{b \times h^2}\ ; \qquad (2)$$

where P_b is the maximum load. The MOE can be estimated as:

$$MOE = \frac{(L^3 - 3 \times L \times l^2 + 2 \times l^3) \times \Delta P}{4 \times b \times h^3 \times \Delta y}\ ; \qquad (3)$$

where l is the loading span. Each laminated bamboo group had 10 replicates. Box hollow beams and solid beams were tested with 2-point loading using a bending test machine with a span of 3510 mm. The MOR and MOE can be estimated as:

$$MOR = \frac{M \times y}{I_t}\ ; \qquad (4)$$

$$MOE = \frac{\Delta P \times (3 \times L^2 - 4 \times a^2)}{48 \times \Delta y \times I_t}\ . \qquad (5)$$

where M is the bending moment; y is the distance from the neutral axis to the utmost surface of the flanges; I_t is the transformed moment of inertia; and a is the distance from the loading point to the supports. Each beam type had 4 replicates.

RESULTS AND DISCUSSION

The static bending tests were performed on the laminated bamboo with or without finger joint processing, and the flexural properties of the laminated bamboo/wood composite box hollow beams were investigated.

Flexural properties of laminated bamboo beams

The MOR of bamboo beams with strips laminated vertically was 19.1% higher than that laminated horizontally as shown in Table 1. Both MOR values of laminated bamboo beams were much higher than those of Moso bamboo in the original round shape, i.e., 51.1 MPa, as reported by Yeh (1984). Similar results were found for the specific strength if the variation in the material density parameter was considered. In the case of laminated bamboo beams with finger joints, the MOR values were significantly reduced due to failure at the critical joints. The efficiencies of the finger joints in the bending tests were 64.3 and 53.2% for beams laminated horizontally and vertically, respectively. In addition, MOE values of finger-jointed bamboo beams were also reduced by 15.8 and 18.1% for beams laminated horizontally and vertically, respectively. Janoviak et al. (1993) found good joint efficiencies of 65.5~79.9% in bending strength for 3 hardwood species finger-jointed horizontally with RF resin, although the finger-joint geometry of the specimens fabricated on the commercial glulam production line was not described. Sakuma and Boh (1998) also obtained a joint efficiency of 65% for Acacia lumber jointed with RPF resin in 16-mm-long fingers and 0.48-mm-wide tips. This suggested a similar finger joint performance for bamboo materials compared to hardwood materials.

Flexural properties of laminated bamboo/wood box hollow beams

The maximum bending capacities of box hollow beams using laminated bamboo members either horizontally or vertically as flanges were 31.3 and 49.7%, respectively, higher than those of beams with Japanese cedar flanges, as shown in Table 2. The bending MOR of small Japanese cedar clear wood is about 55.9~71.2% MPa (Yeh et al. 2000, 2006), which results in 47.3~75.4% higher magnitudes for laminated bamboo beams. This explains the advantage of using laminated bamboo beams instead of low-quality plantation lumber for the flanges. The major cause of failure in box hollow beams using solid wood flanges was large knots or shakes

Table 1. Flexural properties of laminated bamboo beams with and without finger joints

	B-H[1)]	B-V	B-FH	B-FV
Modulus of rupture (MPa)	104.9±14.7	124.9±7.2	67.4±8.7	66.4±4.4
Specific strength (MPa)	143.7	171.0	92.4	90.9
Modulus of elasticity (GPa)	10.74±1.15	11.25±0.72	9.04±0.39	9.21±0.38

[1)] B, laminated bamboo; H, horizontal; V, vertical; F, finger-jointed.

Table 2. Flexural properties of laminated bamboo/wood box hollow beams

Composite beam type	Max. load (kN)	Bending moment (kN-m)	Modulus of rupture (MPa)	Apparent modulus of elasticity (GPa)
WB-H[1)]	37.06±1.74[bc2)]	21.68±1.02[bc]	49.21±2.24[b]	9.72±0.31[a]
WB-V	42.28±1.66[ab]	24.73±0.97[ab]	53.81±3.12[ab]	9.91±0.43[a]
WB-VN	47.74±3.96[a]	27.93±2.32[a]	61.69±5.19[a]	10.40±0.10[a]
WB-VS	49.18±4.86[a]	28.77±2.94[a]	62.70±6.01[a]	10.24±0.24[a]
WW	28.23±7.12[d]	16.52±4.17[d]	33.59±8.40[c]	7.59±0.01[b]
W	30.59±0.51[cd]	17.89±0.30[cd]	36.89±0.53[c]	6.65±0.63[c]

[1)] W, Japanese cedar; B, laminated bamboo; H, horizontal; V, vertical; N, box nail; S, wood screw.
[2)] Means (superscripts a, b, c, and d) within a given column with the same letter do not significantly ($\alpha \geqq 0.05$) differ as determined by Duncan's multiple-range test.

at the tension flanges. The major cause of horizontal shear failure was knots or shakes of solid wood webs for beams with laminated bamboo flanges, which developed better loading capacities. Improved maximum bending capacities, i.e., 69.1 and 74.2%, were found for laminated bamboo/wood box hollow beams further respectively reinforced with 10 d box nails and wood screws on the flanges. Most failures occurred at the center of the tension flange length where the laminated bamboo members are finger-jointed. This indicates that stronger finger joints should produce higher flexural properties of box hollow beams. Although the flexural performance can be improved by reducing the nail/screw spacing on the flanges, Chang and Yeh (2001) found no significant differences in maximum bending loads among spacings of 80, 100, and 120 mm for I-beam cases due to critical split failures along the nailing locations on the flange during the bending test. Furthermore, the maximum bending capacities of the WW box hollow beams were only slightly less than those of Japanese cedar solid wood beams (W), i.e., 7.7%, and laminated bamboo/wood composite box hollow beams also showed better flexural performance than solid wood beams.

The moduli of rupture of box hollow beams WB-V, WB-VN, and WB-VS using vertically laminated bamboo members as flanges were 60.2, 83.6, and 86.6% higher than those of WW beams, respectively. No significant difference was found between box hollow beams reinforced with nails and wood screws due to early failure at the finger joints on the bamboo flanges instead of at the interface between the flange and web, which has critical shearing stress in many other composite box hollow beam applications (Hoyle 1986, Gere and Timoshenko 1997). Although the MOR of the WB-H beam was close to that of the WB-V beam, it was also 46.5% higher than that of the WW beam. It was noted that both MOR values of box hollow beams fabricated with laminated bamboo flanges (WB-H and WB-V) in Table 2 were 73.0 and 81.0% of the bending results of laminated bamboo beams (BF-H and BF-V), as shown in Table 1. This means that using better-quality solid wood as the web materials can further enhance the flexural properties of laminated bamboo/wood box hollow beams. All laminated bamboo/wood composite box hollow beams showed apparent MOE values 28.1~37.0% higher than those of solid wood box hollow beams. Furthermore, the apparent MOE of the WW beam was 14.1% higher than that of solid beams.

Design considerations

According to the design criteria for wood-framed residential construction, the allowable bending deflection limitation of a beam member should be less than both 1/300 of the span and a value of 20 mm (Ministry of the Interior 2003). In this case, it would be < 11.7 mm based on the loading span in the bending test. The loading capacities of the bamboo/wood composite box beams under the limitation of the design deflection are shown in Table 3, which indicates about 11.0~15.4% of the maximum bending loads. The equivalent uniformly distributed loads of the WB-H and WB-V box beams were 30.9 and 34.9%, respectively, higher than that of the Japanese cedar solid beam. Improvements in the loading capacities of 40.9 and 47.5% were found for laminated bamboo/wood box hollow beams further reinforced with nails and wood screws on the flanges compared to solid beams. This verifies the improved structural performance of laminated bamboo/wood composite box hollow beams.

Strain distribution

To better understand the strain developed across the box hollow beam section, strain gages were mounted at the center of the beam length. According to the strain measurements across the box hollow beam depth, the neutral axis of the laminated bamboo/wood composite box hollow beams exhibited only a minor shift downward during the flexural testing, as shown in Fig. 2. The strain distributed across the depth for box hollow beams with bamboo flanges reinforced by mechanical fasteners, i.e., WB-VN, and WB-VS, showed a linear tendency; whereas WB-V beams and solid wood box hollow beams (WW) showed small differences in compressive strains near the interface of the flange and web members. This may have been due to slips between the interface of the flange and web materials during the flexural loading process. The strains on the utmost compression flanges of WB-H and WB-V beams at 40% of maximum flexural load level were 9.0 and 10.3%, respectively, higher than those on the utmost tension flanges. On the contrary, the utmost tension strain of the solid wood beam was 28.2% higher than that measured at the utmost compressive strain.

CONCLUSIONS

Box hollow beams fabricated with laminated bamboo flanges demonstrated better structural performance than beams with solid wood flanges and solid wood beams from rapidly grown plantation timber. Further improvement was found for flanges reinforced with box nails and wood screws. There was no difference in bending properties between beams reinforced with these 2 mechanical fasteners due to critical failure at the finger joints on the flanges. It is expected that better

Table 3. Loading capacities of laminated bamboo/wood composite box hollow beams under the limitation of the design flexural deflection

Beam type[2)]	WB-H	WB-V	WB-VN	WB-VS	WW	W
Load (kN)	4.87±0.09 (12.7%)[1)]	5.02±0.14 (11.9%)	5.25±0.07 (11.0%)	5.49±0.07 (11.2%)	4.34±0.08 (15.4%)	3.72±0.10 (12.2%)
Equivalent uniformly distributed load (kN m^{-1})	1.85±0.03	1.91±0.05	1.99±0.03	2.09±0.03	1.65±0.03	1.41±0.04

1) Calculated based on the ultimate bending load.
2) Beam types are described in the footnotes to Table 2.

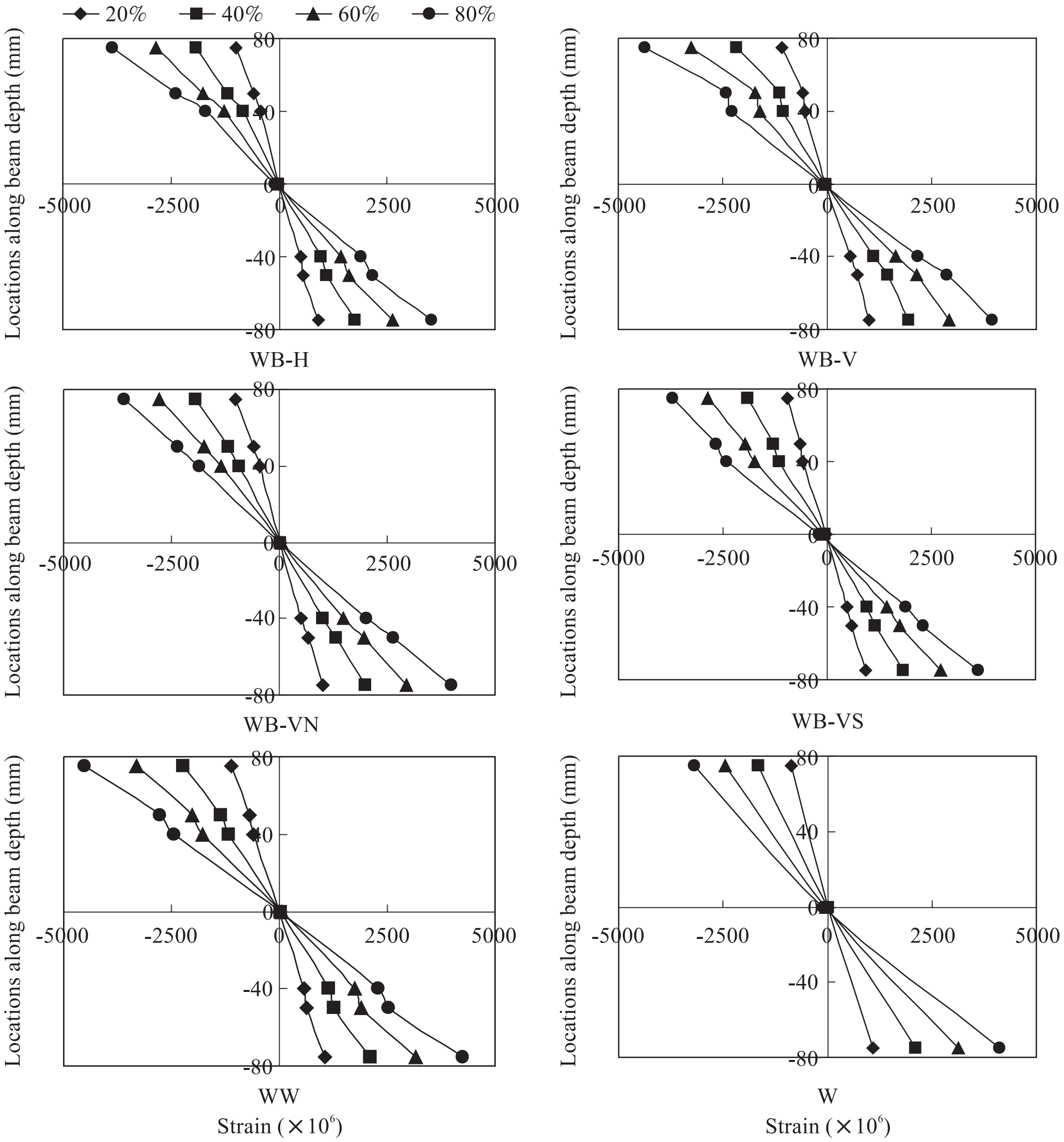

Fig. 2. Strain distribution on the cross-section of box hollow beams at different loading levels. (Beam types are described in the legend to Fig. 1.)

structural performance of box hollow beams can be achieved through improved joints for laminated bamboo members. Under structural design limitations, laminated bamboo/wood composite box hollow beams had 30.9~47.5% higher loading capacities than solid wood beams, illustrating their adequacy for structural applications.

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