J Wood Sci (2012) 58:120–127
DOI 10.1007/s10086-011-1233-7

ORIGINAL ARTICLE

Finger joint performance of structural laminated bamboo member

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Received: 22 March 2011 / Accepted: 14 October 2011 / Published online: 28 December 2011

Abstract The structural performance of finger-jointed laminated bamboo was investigated for two bamboo species by considering the finger length, profile orientation, lamination direction, culm growth height, and mechanical properties of bamboo materials. Based on the growth height variation and bamboo species, the best finger-jointed laminated bamboo was found for the lamina processed from the middle growth height of a moso bamboo culm with the finger profile shown on the width face of the beam. It was 38.7% higher in bending strength than the lowest group, with the lamina from the lower ma bamboo culm showing the finger profile on the thickness face of the beam. When considering the finger length and lamination orientation, the strongest finger-jointed laminated bamboo joined with an 18-mm finger, showing the finger profile on the width face of a vertically laminated beam was 50.1% higher in bending strength than the lowest group having a 12-mm finger showing the finger profile on the thickness face of a vertically laminated beam. The laminated ma bamboo showed higher finger-joint efficiency, 11.6%, than moso bamboo, and the members showing the finger profile on the width surface was 12.3% better in joint efficiency than that showing on the thickness surface of the beam.

Keywords Finger joint · Bamboo · Bending strength

Introduction

Bamboo is one of the most important forest resources, 7.2% of the forest area in Taiwan. There are 75 bamboo species, including 17 indigenous species and 58 exotic species [1]. The six major commercial bamboo species including *Phyllostachys makinoi* (makino bamboo), *P. pubescens* (moso bamboo), *Dendrocalamus latiflorus* (ma bamboo), *Bambusa oldhamii* (green bamboo), *B. stenostachya* (thorny bamboo), and *B. dolichoclada* (long-shoot bamboo) are used in many applications in daily life, depending on their particular quality. Those bamboo species are also extensively used as building materials for the beam, post, roof truss, and wall elements of residential houses and farms. It is also known that the strength properties of a bamboo culm vary with the culm growth height, growing ages, and bamboo species [2, 3]. In recent years, the bamboo industry has gradually lost its competitive advantages due to the rise in labor cost and replacement by new materials such as steel and polymer. The bamboo industry faces challenges in upgrading production technology and developing innovative products against low-end products. As global warming becomes an issue, there are several considerations in developing innovative products for the forest product industries. The sustainability of materials, environmental friendliness, and capability of reuse, reduce, and recycle are important considerations. To be the green construction materials, however, the flexibility in the structural space is always limited by the diameter of the bamboo culm and the rigidity of the bamboo structures.

It is well known that glued laminated timber features dispensed natural defects and enhance dimensional stability, strength, and uniform quality. The manufacturing techniques can be applied in designing projects for large spaces, long spans, and curved structures [4]. It solves the limitation of the structure size and becomes an important building structural member for modern wood-based architecture. This inspires an alternative approach considering disassembling the bamboo culm into thin flat laminae and

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then laminating them together with adhesive to form a designated structural member with better rigidity and higher loading capacity. In that case, one of the advantages of laminated products for bamboo is that the member length can be extended to any desired size by joining the structural elements end to end with an effective joint. Liu and Lii [5] examined the joint performance of solid wood assembled with various adhesives. They indicated that the scarf joint was 20–47% lower in strength than that of finger joint, and the butt joint showed poor strength, being 70% lower than the finger joint. The finger joint method could be the most extensive approach for glulam manufacturing and might be applied to the laminating bamboo process. The structural performance of a finger joint for the different wood species has been verified to be influenced by the ratio of finger spacing to finger length and the ratio of the width of the finger tip to finger spacing [6, 7]. On the other hand, the wall of bamboo culm contains a high percentage of parenchyma cells and uneven vascular distribution, affecting the mechanical properties for each bamboo species [8, 9]. These might show the different joint characteristics from solid wood during the finger joint assembly in advance. Liu et al. [10] indicated that the gluing strength and bamboo failure percentage vary for the strips glued together with the surfaces having different vascular configurations. Therefore, by considering the effective culm thickness and diameter, the bamboo member laminated from different culm growth heights of two major species and finger-joined with various finger lengths in addition to the orientation of finger profile is developed in this study to clarify the flexural performance of the laminated bamboo member for potential structural application.

Materials and methods

Material preparation

Two major commercial bamboo species, i.e., moso bamboo (*Phyllostachys pubescens* var. *pubescens*, P) from Chyia-i county and ma bamboo (*Dendrocalamus latiflorus*, D) from Nan-tou county, were harvested at the age of 4–5 years. There were 65 ma bamboo culms and 80 moso bamboo culms used in the study. Bamboo strips from lower, middle, and upper growth heights, respectively, of a 6-m culm were selected with a spacing of 1.5 m. The 1-m culms cut from assigned growth portions were then split into 30-mm wide strips, and the outer skin (epidermal) and inner cavity layer (pith peripheral) were removed by a planer to obtain thicknesses of 3, 4, and 6 mm for the flat strips from the upper (U), middle (M), and lower (L) growth portions, respectively. The strips or laminae were then kiln-dried down to 11.4% before the laminating process. Resorcinol phenol formaldehyde adhesive (RPF, type: AD500, Sport Leader, Tainan, Taiwan) with a solids content of 55% was applied with paraformaldehyde (Hardener 501) in a 72% solution during the bamboo strip lamination. The laminated bamboo members of 30 × 30 × 1000 mm were assembled with a vertical (V) or horizontal (H) layout by stacking the bamboo strips sequentially with the surface of the epidermal layer facing the same direction to ensure optimum adhesive performance [10]. Glue was then applied at a rate of 250 g/cm^2, and the pressure application was 1.47 MPa for 4 h. Following assembly, the laminated bamboo members were cut in half and finger-jointed longitudinally with RPF adhesives using a longitudinal finger jointer (model: KMFJ-400S, Chuan Chier Industrial, Kaoshiung, Taiwan). The feather-type finger formation was done by a finger shaper (model: KMFJ-400, Chuan Chier Industrial). The orientation of the finger profile during the cutting process considered the fingers formed parallel or perpendicular to the glue lines, showing the fingers on the width (W) or thickness (T) surface of the laminated beam member. The finger lengths were 12, 15, and 18 mm, respectively, with a finger spacing of 4 mm and tip width of 0.65 mm (Fig. 1), and the experimental codes of 2, 5 and 8 were designated to each testing condition of finger lengths in the study.

Mechanical property evaluation

The basic mechanical properties of the bamboo for each species were evaluated in both the static bending test and tensile test using the bamboo strips selected from U, M, and L growth portions. The strips were further divided into specimens with or without node groups to examine the effect of the bamboo node on the strength properties.

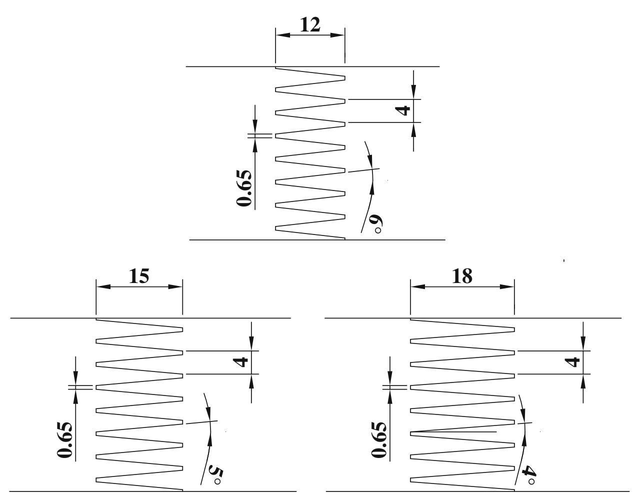

Fig. 1 Profiles of the feather-type finger joint formation processed using 3 cutter specifications (units, mm)

The size of bamboo strip specimens was 20 mm wide and 100 mm long for concentrated loading test with a loading span of 84 mm. The size of tensile testing specimens was 15 mm wide, 390 mm long, and with double curved necking down to 3 mm wide in the center. There were 12 replicates for each testing condition and total of 288 specimens. The specimen density was calculated based on the weight and volume of the kiln-dried bamboo strips. The compressive test, shearing test, bonding test and bending test were performed using 30 × 30-mm laminated bamboo specimens assembled with different bamboo species and growth portions. The standard test CNS 453 was referred for longitudinal compressive test, CNS 455 for shearing test, CNS 11031 for bonding test, and CNS 454 for static bending test with a consideration of lamination orientation. There were 12 replicates for each testing condition and total of 360 specimens. Further, the bending properties of the laminated bamboo members under investigation in terms of the parameters of the bamboo species (P, D), growth height (U, M, L), layout direction of lamination (V, H), finger length (12, 15, 18 mm or coded with 2, 5, 8), and orientation of finger profile (W, T). The combination of parameters for the lamination direction and finger profile orientation is shown in Fig. 2 and Table 1. The 30 × 30 × 960-mm laminated bamboo specimens were flexurally tested with a four-point loading followed by CNS 11031 standard. The laminated bamboo not receiving the finger joint process was first tested to examine the effects of the parameters among bamboo species, growth height, and lamination direction on the bending properties. Then, the bamboo members laminated horizontally and joined with 12-mm finger formation were tested to examine the effects of parameters among the bamboo species, growth height, and finger profile orientation on the bending

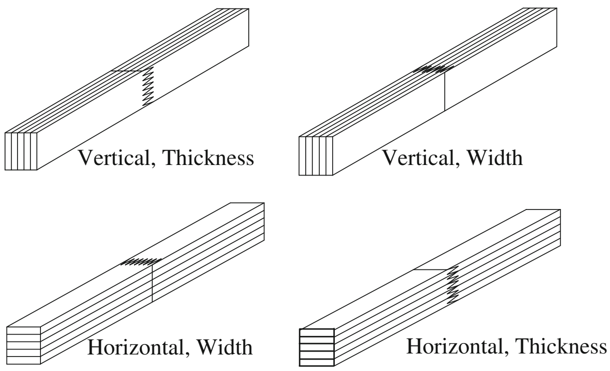

Fig. 2 Configuration of the lamination direction and finger profile orientation of the laminated bamboo members for bending tests. *V-T* Laminated vertically, finger profile shown on thickness surface, *V-W* laminated vertically, finger profile shown on width surface, *H-W* laminated horizontally, finger profile shown on width surface, *H-T* laminated horizontally, finger profile shown on thickness surface

Table 1 Experimental design of each finger joint combination of the laminated bamboo members

Treatment	Bamboo species	Growth height	Lamination direction	Orientation of finger profile	Finger length (mm)
D-L-H-T-2	Ma b.	Lower	Horizontal	Thickness	12
D-L-H-W-2	Ma b.	Lower	Horizontal	Width	12
D-M-H-T-2	Ma b.	Middle	Horizontal	Thickness	12
D-M-H-W-2	Ma b.	Middle	Horizontal	Width	12
D-U-H-T-2	Ma b.	Upper	Horizontal	Thickness	12
D-U-H-W-2	Ma b.	Upper	Horizontal	Width	12
P-L-H-T-2	Moso b.	Lower	Horizontal	Thickness	12
P-L-H-W-2	Moso b.	Lower	Horizontal	Width	12
P-M-H-T-2	Moso b.	Middle	Horizontal	Thickness	12
P-M-H-W-2	Moso b.	Middle	Horizontal	Width	12
P-U-H-T-2	Moso b.	Upper	Horizontal	Thickness	12
P-U-H-W-2	Moso b.	Upper	Horizontal	Width	12
P-L-V-T-2	Moso b.	Lower	Vertical	Thickness	12
P-L-V-W-2	Moso b.	Lower	Vertical	Width	12
P-L-V-T-5	Moso b.	Lower	Vertical	Thickness	15
P-L-V-W-5	Moso b.	Lower	Vertical	Width	15
P-L-H-T-5	Moso b.	Lower	Horizontal	Thickness	15
P-L-H-W-5	Moso b.	Lower	Horizontal	Width	15
P-L-V-T-8	Moso b.	Lower	Vertical	Thickness	18
P-L-V-W-8	Moso b.	Lower	Vertical	Width	18
P-L-H-T-8	Moso b.	Lower	Horizontal	Thickness	18
P-L-H-W-8	Moso b.	Lower	Horizontal	Width	18

properties. Further, laminated moso bamboo members assembled with the laminae from the lower portion of the bamboo culm were tested to examine the effects of the parameters among the lamination direction, finger length, and finger profile orientation on the bending properties. There were 8 replicates for each testing condition and total of 176 specimens.

Results and discussion

Mechanical properties of the bamboo strips

Table 2 shows the modulus of rupture (MOR) of moso bamboo strips were 48.7% higher than that of ma bamboo strips when combining the results for three different growth heights. Bamboo density may be an important parameter influencing the mechanical properties [3, 10], while moso bamboo material is 21% higher in density than ma bamboo, as indicated in Table 3. In addition, the clear ma bamboo strip specimens were 56.5% higher in MOR than the specimens containing nodes. A similar trend was noted for the moso bamboo strips without nodes, being 17.3% higher compared to the moso bamboo strips with nodes. Similar results were reported by Hamdan et al. [11]. They noticed anatomically the failure at the node further progressed laterally in shear which occurred along the weak fiber matrices.

Table 2 Bending and tensile properties of the bamboo strips

Treatment	MOR (MPa)	MOE (GPa)	Tensile strength (MPa)
P-L-clear	126.6 (8.3)^{B}	8.78 (0.78)^{B}	147.9 (18.4)^{BC}
P-L-node	102.2 (14.1)^{C}	8.50 (0.82)^{B}	105.4 (12.7)^{D}
P-M-clear	153.4 (10.5)^{A}	8.13 (0.78)^{BCD}	160.2 (9.7)^{B}
P-M-node	133.8 (9.9)^{AB}	6.87 (0.60)^{BC}	116.2 (9.7)^{D}
P-U-clear	146.7 (6.8)^{AB}	3.99 (0.44)^{FG}	165.1 (8.9)^{B}
P-U-node	127.8 (11.7)^{B}	3.67 (0.42)^{G}	72.0 (9.2)^{E}
Mean	131.8	6.66	127.8
D-L-clear	81.2 (4.9)^{D}	5.15 (1.18)^{DEFG}	133.6 (26.2)^{C}
D-L-node	70.2 (4.9)^{D}	4.52 (2.03)^{EFG}	38.8 (7.1)^{F}
D-M-clear	139.6 (17.1)^{AB}	11.25 (1.20)^{A}	194.6 (19.4)^{A}
D-M-node	60.6 (19.61)^{D}	5.72 (2.25)^{DEF}	69.0 (10.9)^{E}
D-U-clear	103.9 (22.8)^{C}	8.63 (2.20)^{B}	164.5 (18.3)^{B}
D-U-node	76.2 (9.5)^{D}	6.29 (0.78)^{CDE}	25.7 (5.3)^{F}
Mean	88.6	6.93	104.4

Mean within a column marked by different letters from A to G in superscript form showing a value-ranking from large to small. Values marked with the same letter are insignificantly different at the level of $P < 0.05$ by Duncan's multiple-range test, and may be overlapped with the next letters. Value between parentheses is standard deviation

P Moso bamboo, *D* ma bamboo, *L*, *M*, *U* lower, middle, and upper growth heights of a culm

While for the clear strips, no spontaneous fracture occurred as the crack became deflected in the direction of the weak matrix of the fiber bundle. The bamboo strips sampled from the middle and upper growth heights of a culm displayed 28.1 and 19.6% higher MOR, respectively, than that from the lower portion of two bamboo species. For tensile strength, both ma bamboo and moso bamboo showed similar strength when testing the clear specimens, i.e., strips without nodes. However, as compared to the clear specimen results, only 27.0% left in tensile strength for the ma bamboo strip groups containing nodes, and 62.4% left for the moso bamboo strip specimens containing nodes. The tensile strength of the ma bamboo strip containing node also displayed only 45.1% of the moso bamboo specimens containing node. Higher reduction indicated the tensile strength of the bamboo strips is more sensitive to the existence of nodes than MOR and depends on the bamboo species.

The bamboo strips were laminated for shearing, compressive, and bonding tests. The laminated bamboo from the middle and upper growth heights of culms displayed higher compressive strength, of 26.7 and 32.4%, respectively, than that from the lower growth portion of a culm for two bamboo species (Table 3). Generally, the compressive strength of the laminated moso bamboo was 20.8% higher than that of ma bamboo when combining the results for three different growth heights. In addition, moso bamboo showed 66.0% greater shearing strength than ma bamboo. Although a significant difference in shearing strength of the laminated bamboo was found, among different growth heights of ma bamboo, moso bamboo from lower, middle, and upper growth heights showed similar values. Note that the bonding strength of the laminated

Table 3 Shearing and compressive strength of the laminated bamboo

Treatment	Density (g/cm^3)	Shear strength (MPa)	Compressive strength (MPa)	Bonding strength (MPa)
P-L	0.73 (0.01)^{B}	16.8 (0.5)^{A}	54.2 (2.9)^{B}	12.2 (0.7)^{A}
P-M	0.72 (0.01)^{B}	17.4 (0.7)^{A}	66.1 (1.9)^{A}	10.1 (0.4)^{B}
P-U	0.76 (0.01)^{A}	17.1 (0.7)^{A}	69.6 (2.7)^{A}	7.1 (0.1)^{C}
Mean	0.74	17.1	63.3	9.8
D-L	0.55 (0.03)^{E}	9.2 (0.7)^{D}	42.5 (2.9)^{C}	6.2 (0.8)^{D}
D-M	0.61 (0.03)^{D}	10.3 (0.3)^{C}	56.4 (5.4)^{B}	4.2 (0.7)^{E}
D-U	0.68 (0.02)^{C}	11.4 (0.6)^{B}	58.4 (4.7)^{B}	2.5 (0.6)^{F}
Mean	0.61	10.3	52.4	4.3

Mean within a column marked by different letters from A to F in superscript form showing a value-ranking from large to small. Values marked with the same letter are insignificantly different at the level of $P < 0.05$ by Duncan's multiple-range test and value between parentheses is standard deviation

P Moso bamboo, *D* ma bamboo, *L*, *M*, *U* lower, middle, and upper growth heights of a culm bamboo was only 57.3 and 43.5%, respectively, with the shearing strength of both moso bamboo and ma bamboo showing the critical strength properties for making laminated bamboo products. Thus, the bonding strength of moso bamboo can meet the minimum requirement for making a wood glulam member of southern pine and Douglas fir, while a better gluing process may be needed for improving the bonding performance of ma bamboo based on the standard criterion [12].

Flexural properties of laminated bamboo members without finger joints

The bending tests of 960-mm laminated bamboo members were performed for two species sampled from various growth heights with two laying directions during the lamination. The results indicated that the failure always occurred at the bamboo nodes in each layer starting from the lower tension side of a beam member. The MOR of the moso bamboo laminated members were 21.0% higher than the ma bamboo laminated members when combining the results of both growth height and lamination orientation parameters (Table 4). This was mostly due to the higher density of the moso bamboo members [10]. Therefore, it showed a similar specific strength between two bamboo species as the density parameter was considered. Further, bamboo members laminated vertically were 16.5% higher in MOR than those laminated horizontally when combining the results of both bamboo species and growth height parameters. This was because there were smaller node defects exposed on the tension side of a beam for the members laminated vertically compared to those of laminated horizontally, in which the bamboo node was across the width of a beam. Overall, the beam members fabricated with the lamina from middle and upper heights of a bamboo culm showed 10.2 and 19.6% better MOR, respectively, than that from the lower portion of the bamboo culm. Note that the strongest laminated bamboo member was found in the case of the lamina from the upper portion of the moso bamboo culm and laminated vertically (P-U-V), being 67.0% higher in MOR than the lowest group which was fabricated with the lamina from lower portion of the ma bamboo culm and laminated horizontally (D-L-H).

Effect of growth height variation and bamboo species

The bending tests of the laminated bamboo members laminated horizontally and joined with a 12-mm long finger formation were performed. The MOR of the finger-jointed ma bamboo glulam members fabricated with lamina from the lower portions of a bamboo culm were 20.5% lower than those from the middle and upper growth heights of the bamboo culms (Table 5). Similar results were obtained in the cases of moso bamboo, which was 9.6%

Table 4 Bending properties of laminated bamboo containing nodes made from different bamboo species and growth height of culm

Treatment	MOR (MPa)	Specific strength	MOE (GPa)
P-L-V	124.9 (7.2)^{BC}	171.0 (9.8)	11.25 (0.72)^{CD}
P-L-H	104.9 (14.7)^{CDE}	143.7 (20.1)	10.74 (1.15)^{CD}
P-M-V	132.3 (9.9)^{AB}	183.8 (13.7)	11.47 (1.64)^{CD}
P-M-H	115.8 (4.9)^{C}	160.9 (6.8)	11.52 (1.52)^{CD}
P-U-V	144.1 (6.3)^{A}	189.5 (8.2)	11.02 (0.47)^{CD}
P-U-H	131.2 (10.4)^{AB}	172.7 (13.6)	12.46 (2.41)^{BCD}
Mean	125.5	170.3	11.41
D-L-V	101.0 (20.8)^{C}	183.8 (37.7)	13.72 (1.38)^{AB}
D-L-H	86.2 (8.4)^{EF}	156.8 (15.3)	13.11 (1.35)^{BC}
D-M-V	115.8 (11.6)^{C}	189.9 (18.9)	15.06 (2.02)^{A}
D-M-H	95.7 (5.2)^{E}	156.9 (8.5)	12.80 (1.39)^{BCD}
D-U-V	122.1 (3.5)^{BC}	179.5 (5.2)	12.34 (1.15)^{BC}
D-U-H	101.3 (2.0)^{CD}	149.1 (2.8)	10.92 (1.04)^{CD}
Mean	103.7	169.3	129.9

Mean within a column marked by different letters from A to F in superscript form showing a value-ranking from large to small. Values marked with the same letter are insignificantly different at the level of $P < 0.05$ by Duncan's multiple-range test, and may be overlapped with the next letters. Value between parentheses is standard deviation

P Moso bamboo, *D* ma bamboo, *L*, *M*, *U* lower, middle, and upper growth heights of a culm, *V*, *H* laminated vertically and horizontally

Table 5 Bending properties of the finger-jointed laminated bamboo member made from different bamboo species and growth height of a culm

Treatment	MOR (MPa)	Specific strength	MOE (GPa)
P-L-H-T-2	67.4 (8.7)^{CD}	92.4 (11.0)	9.04 (0.39)^{F}
P-L-H-W-2	73.0 (5.8)^{ABC}	100.1 (8.0)	9.61 (0.37)^{EF}
P-M-H-T-2	71.3 (10.2)^{BC}	99.1 (14.2)	13.17 (1.38)^{A}
P-M-H-W-2	81.1 (9.8)^{A}	112.7 (13.5)	11.28 (1.59)^{CD}
P-U-H-T-2	75.8 (9.5)^{ABC}	99.8 (12.5)	10.52 (0.97)^{DE}
P-U-H-W-2	79.6 (11.4)^{AB}	104.8 (15.0)	11.70 (1.29)^{BCD}
Mean	74.7	101.5	10.89
D-L-H-T-2	58.5 (9.1)^{E}	106.2 (16.6)	10.01 (0.49)^{EF}
D-L-H-W-2	60.3 (4.7)^{DE}	109.7 (8.6)	8.86 (0.56)^{F}
D-M-H-T-2	69.0 (4.6)^{C}	113.2 (7.4)	12.40 (1.06)^{ABC}
D-M-H-W-2	74.2 (5.4)^{ABC}	121.6 (8.8)	13.62 (0.61)^{A}
D-U-H-T-2	70.6 (6.7)^{BC}	103.8 (9.8)	12.77 (1.57)^{AB}
D-U-H-W-2	72.2 (5.9)^{ABC}	106.3 (8.7)	11.43 (1.46)^{CD}
Mean	67.5	110.1	11.51

Mean within a column marked by different letters from A to F in superscript form showing a value-ranking from large to small. Values marked with the same letter are insignificantly different at the level of $P < 0.05$ by Duncan's multiple-range test, and may be overlapped with the next letters. Value between parentheses is standard deviation

P Moso bamboo, *D* ma bamboo, *L*, *M*, *U* lower, middle, and upper growth heights of a culm, *H* laminated horizontally, *T*, *W* finger profile shown on thickness and width surface lower in MOR for the member fabricated with lamina from the lower portion of the bamboo culms. Overall, the finger-jointed bamboo members made from the middle and upper growth heights of the culms were 14.1 and 15.1%, respectively, higher in MOR than that from the lower portions of the culms when combining the results of two bamboo species. These bending strength changes for the tested laminated bamboo are similar to that of the bamboo strip results and previous research works [2, 3]. Note that the strongest finger-jointed bamboo member was found in the case of the lamina processed from the middle growth height of a moso bamboo culm with the finger profile shown on the width face of the beam (P-M-H-W-2). It was 38.7% higher than the lowest group, which was fabricated with the lamina processed from the lower portion of a ma bamboo culm with the finger profile shown on the thickness face of the beam (D-L-H-T-2). In general, the finger-jointed moso bamboo member was 10.7% higher in MOR than the laminated ma bamboo member. However, the effect of the bamboo species parameters seems to be influenced by the finger joint processing compared to the specimens without joints. Further, the strength of the jointed moso bamboo members with a finger profile shown on the beam width face was 9.0% higher than those shown on the thickness face, but significant differences were not found in the case of ma bamboo. It has been suggested that joint stiffness and strength would be better and the effect of gluing performance could be improved if the finger profile was orientated vertically instead of horizontally for the solid wood and LVL cases [13–15]. The laminated bamboo member demonstrated more homogenous characteristics in the sense of cleavage strength difference in the radial and tangential direction compared to the solid wood [10].

On the other hand, the finger-jointed ma bamboo members fabricated with lamina from the middle growth height of a bamboo culm showed better bending modulus of elasticity (MOE), being 37.9% higher than those from the lower growth height. Moreover, a 31.1% higher bending MOE was obtained for the laminated moso bamboo groups. However, there was no significant difference in MOE between the finger-jointed members made from two bamboo species and joined by two finger profile orientations.

Effects of finger length and lamination orientation

Bending tests of the bamboo members laminated with lamina from the lower portions of a moso bamboo culm were performed. The MOR of the 15- and 18-mm long finger-jointed bamboo members laminated vertically were 19.8 and 17.6%, respectively, higher than those of the 12-mm long finger-jointed group when combining the results of two finger profile orientations (Table 6). In the cases of members laminated horizontally, both the 15- and 18-mm finger-jointed bamboo members had MOR 13.5% higher than the 12-mm finger-jointed group. Although Cheng [7] reported a 68–131% improvement in bending strength for three softwood species joined with 12-mm finger instead of 6-mm finger, Ayarkwa et al. [6] showed the bending strength of three hardwood species joined with 18-mm finger was higher than those joined with either 10- or 20-mm fingers. This indicated the finger length parameter might need to incorporate other geometric parameters during the finger formation, such as finger slope [16] and tip width [17]. Hernández et al. [18] also indicated that the combined action of the cutting speed and chip load had a significant effect on the strength of the finger joints. They pointed out that the effect of the cutting speed on the strength became more pronounced when an adequate chip load selected. The chip loads would be different for cutting 12-, 15-, and 18-mm fingers in same cutting speed with the same shaper machine. It might explain few differences in strength between 15- and 18-mm finger joints. Note that the strongest finger-jointed laminated bamboo member was found for the 18-mm finger with the finger profile shown on the width face of the vertically laminated beam (P-L-V-W-8), being 50.1% higher than the lowest group which had a 12-mm finger with the finger profile shown on the thickness face of the vertically laminated beam (P-L-V-T-2). Overall, the finger-jointed bamboo members laminated vertically showed a

Table 6 Comparison of static bending properties for the finger-jointed bamboo members laminated in vertical and horizontal direction and jointed with various finger length

Treatment	MOR (MPa)	MOE (GPa)
P-L-V-W-2	80.3 (7.4)^{CDE}	9.38 (0.38)^{DE}
P-L-V-W-5	93.1 (2.6)^{AB}	10.62 (0.86)^{ABC}
P-L-V-W-8	99.6 (12.0)^{A}	10.50 (1.14)^{BCD}
P-L-V-T-2	66.3 (4.3)^{G}	9.49 (0.56)^{E}
P-L-V-T-5	82.5 (7.7)^{CD}	10.69 (1.43)^{ABC}
P-L-V-T-8	72.9 (5.8)^{DEF}	11.74 (0.93)^{A}
Mean	82.5	10.40
P-L-H-W-2	73.0 (5.8)^{EFG}	9.61 (0.37)^{CDE}
P-L-H-W-5	85.8 (7.3)^{BC}	10.97 (1.19)^{AB}
P-L-H-W-8	83.9 (12.5)^{CD}	10.56 (1.82)^{BC}
P-L-H-T-2	67.4 (8.7)^{FG}	9.04 (0.39)^{E}
P-L-H-T-5	73.3 (14.0)^{EFG}	9.55 (0.31)^{CDE}
P-L-H-T-8	75.8 (7.7)^{EFG}	9.87 (0.75)^{BCDE}
Mean	76.5	9.93

Mean within a column marked by different letters from A to G in superscript form showing a value-ranking from large to small. Values marked with the same letter are insignificantly different at the level of $P < 0.05$ by Duncan's multiple-range test, and may be overlapped with the next letters. Value between parentheses is standard deviation

P Moso bamboo, *L* lower growth heights of a culm, *V*, *H* laminated vertically and horizontally, *T*, *W* finger profile shown on thickness and width surface, *2*, *5*, *8* finger length of 12, 15, and 18 mm

Table 7 Finger joint efficiency of the laminated bamboo members

Treatment	Efficiency (%)	Treatment	Efficiency (%)	Treatment	Efficiency (%)
D-L-H-T-2	67.8	D-M-H-T-2	72.1	D-U-H-T-2	69.6
D-L-H-W-2	69.9	D-M-H-W-2	77.5	D-U-H-W-2	71.3
P-L-H-T-2	64.3	P-M-H-T-2	61.5	P-U-H-T-2	57.8
P-L-H-W-2	69.6	P-M-H-W-2	70.1	P-U-H-W-2	60.7
P-L-V-T-8	58.4	P-L-V-T-5	66.0	P-L-V-T-2	53.1
P-L-V-W-8	79.7	P-L-V-W-5	74.6	P-L-V-W-2	64.3
P-L-H-T-8	72.2	P-L-H-T-5	69.9		
P-L-H-W-8	80.0	P-L-H-W-5	81.8		

P Moso bamboo, *D* ma bamboo, *L*, *M*, *U* lower, middle, and upper growth heights of a culm, *V*, *H* laminated vertically and horizontally, *T*, *W* finger profile shown on thickness and width surface, *2*, *5*, *8* finger length of 12, 15, and 18 mm

7.8% higher MOR than those laminated horizontally when combining the results of both orientation of lamination and finger length parameters. This might suggest a greater influence of the finger interface on joint strength than the influence of a node on the flexural strength of the laminated bamboo beam. Further, the laminated bamboo members jointed with the finger profile shown on the width face had better MOR, being 17.6% higher than the members with the finger profile shown on the thickness face of the beam. Thus, the results indicated the MOR of 12-, 15-, and 18-mm finger-jointed bamboo members laminated vertically and finger profile shown on the width face were 21.0, 12.8, and 36.6%, respectively, higher than those members with the finger profile shown on the thickness face of the beam. A similar tendency was also found for the bamboo members laminated horizontally. While the maximum tensile stress is developed on the convex side of the beam and the bending strength is controlled by the ultimate fiber stress on the tensile side. Bustos et al. [19] also pointed out that the outside finger in flatwise bending would receive the most load and initiates the failure.

For the MOE properties, the 15- and 18-mm finger-jointed laminated bamboo members were 11.5 and 13.7%, respectively, higher than that of the 12-mm finger-jointed groups when combining the results of finger profile orientation and lamination direction parameters. On the other hand, there was no significant difference in MOE between the finger-jointed members laminated in both the vertical and horizontal directions and two finger profile orientations.

Efficiency of finger joint

Finger-joint efficiency was determined for each species and members laminated with the lamina from different growth heights of a culm. The results are summarized in Table 7. The joint efficiency is based on averaged data of laminated bamboo members without joints and expressed as a percentage ratio of corresponding mean clear laminated bamboo strength. The bending strength results of the laminated bamboo indicate ma bamboo displayed 11.6% higher efficiency compared to the moso bamboo when combining the results of growth height, finger length, finger profile orientation, and lamination direction parameters. A similar trend is observed for the laminated bamboo members showing the finger profile on the width surface, being 12.3% better in joint efficiency than that showing the finger profile on the thickness surface of the beam when combining the results of species, growth height, finger length, and lamination direction parameters. Selbo [20] suggested a typical finger-jointed connection would have about 70% of the efficiency of clear wood. Efficiencies of 73.1 and 72.6% of the laminated bamboo member jointed with the 15- and 18-mm finger profile, respectively, were observed, possibly showing the adequacy of the finger geometry, while the 12-mm finger-jointed group showed efficiency of 62.8%. On the other hand, a similar finger-joint efficiency was found between the bamboo member laminated both vertically and horizontally. Overall, the highest joint efficiency was achieved with the longer finger profile showing on the width surface of a bamboo member laminated horizontally, and the lowest efficiency was found for the short finger profile showing on the thickness surface of the ma bamboo member laminated vertically.

Conclusion

The structural finger-joint performance of the laminated bamboo members as related to finger geometry, profile formation, lamination orientation, and bamboo species was investigated, and the basic mechanical properties of bamboo materials were examined. The mechanical properties of bamboo material changes along the growth heights of a culm and the tensile strength is more sensitive to the existence of nodes than bending strength. Note that the bonding strength is more critical among the strength properties for making laminated bamboo products. The finger-jointed laminated bamboo members made from the middle and upper growth heights of culms are higher in both MOR and MOE than those from the lower portions of the culms. In addition, the finger-jointed moso bamboo members showed higher MOR than the laminated ma bamboo members. The flexural performance can be improved as the finger length increases from 12 mm to 15 and 18 mm for the laminated bamboo members. The finger-jointed bamboo members laminated vertically showed a slightly higher MOR than the laminated horizontally, suggesting greater influence of the finger interface on the joint strength than the influence of a node on the flexural strength of the laminated bamboo beam. The MOR of the bamboo members joining a finger profile shown on the width face is higher than the members with the finger profile shown on the thickness face of the beam for all the finger lengths and lamination directions. Based on finger-joint efficiency, moso bamboo is superior to ma bamboo, and the laminated bamboo members showing a finger profile on the width surface is better than those showing a finger profile on the thickness surface of the beam. Superior joint efficiency of the laminated bamboo member joined with the 15- and 18-mm finger profile was also found compared to the other 12-mm finger-jointed bamboo members.

References

1. Lu MC (1994) Resources and utilization of bamboos in Taiwan. In: Proceedings of problem analysis on bamboo research in south East Asia. Chi-Tou, Taiwan, pp 97–114
2. Li Y, Li Y (1983) Physico-mechanical properties of culm-wood of *Phyllostachys pubescens* produced in Guizhou. Bamboo Res 1:62–74
3. Tang JL (1989) Strength properties of bamboo material. For Prod Ind 8(3):65–78
4. USDA (1987) Wood handbook: wood as an engineering material. USDA forest service, agriculture handbook, vol 72. USA, 10-1–10-19
5. Liu CT, Lii WJ (1989) Effect of physcochemical properties and gluing methods on the qualities laminated wood made from fast-growing species (9). Studies on the fabrication of end-to-end grain joint laminated wood from Taiwan acacia, Formosan sweet gum and Taiwania. For Prod Ind 8(4):75–84
6. Ayarkwa J, Hirashima Y, Sasaki Y (2000) Effect of finger geometry and end pressure on the flexural properties of finger-jointed tropical African hardwoods. For Prod J 50(11/12):53–63
7. Cheng XX (1986) The study on mini-finger joint of wood. Thesis, National Taiwan University, pp 1–29
8. Yeh MC (1994) Evaluation on the mechanical properties of moso bamboo. Q J Chin For 27(1):107–118
9. Yeh MC (1995) Evaluation on the tensile strength of vascular bundle of moso bamboo. Q J Chin For 28(1):129–137
10. Liu CT, Lii WJ, Wang YH (1992) Laminated bamboo and wood for high value-added products and construction materials (I): the physical–mechanical properties and gluability of bamboo. For Prod Ind 11(1):19–29
11. Hamdan H, Anwar UMK, Zaidon A, Tamizi MM (2009) Mechanical properties and failure behaviour of *Gigantochloa scortechinii*. J Trop For Sci 21(4):336–344
12. Bureau of Standard, Metrology, and Inspection (2006) Structural glulam. CNS 11031. Taipei, Taiwan, pp 1–34
13. Janowiak JJ, Labosky P, Blankenhorn PR, Manbeck HB (1993) Finger-joint strength evaluation of three northeastern hardwoods. For Prod J 43(9):23–28
14. Biblis EJ, Carino HF (1993) Factors influencing the flexural properties of finger-jointed southern pine LVL. For Prod J 43(1):41–46
15. Yeh MC, Lin YL, Huang YC (2009) Evaluation on the bending properties of structural finger-jointed lumber. For Prod Ind 28(1):27–40
16. Strickler MD (1980) Finger-jointed dimensioned lumber: past, present and future. For Prod J 30(9):51–56
17. Hernández RE (1998) Analysis of strain in finger-jointed lumber. In: Proceedings of 5th world conference on timber engineering (WETC'98) Montreux, Switzerland, vol 1, pp 145–151
18. Hernández R, Coman R, Beauregard R (2011) Influence of machining parameters on the tensile strength of finger-jointed high-density black spruce lumber. Wood Fiber Sci 43(1):2–10
19. Bustos C, Beauregard R, Mohammad M, Hernndez RE (2003) Structural performance of finger-jointed black spruce lumber with different joint configurations. For Prod J 53(9):72–76
20. Selbo ML (1975) Adhesive bonding of wood. Washington, DC, USDA Technical Bulletin no. 1512, p 124