Effect of Different Veneer-joint Forms and Allocations on Mechanical Properties of Bamboo-bundle Laminated Veneer Lumber

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Bamboo-bundle laminated veneer lumber (BLVL) was produced by veneer lengthening technology. The objective of this study was to evaluate the effect of different veneer-joint forms and allocations on the mechanical properties of BLVL. Four veneer-joint forms, *i.e.*, butt joint, lap joint, toe joint, and tape joint, and three lap-joint allocations, *i.e.*, invariable allocation (Type I), staggered allocation (Type II), and uniform allocation (Type III), were investigated in laminates. The results revealed that the mechanical properties of veneer-joint BLVL were reduced in comparison with that of un-jointed BLVL. It was found that the best veneer-joint form was the lap joint laminate, of which the tensile strength, modulus of elasticity, and modulus of rupture values were reduced by 38.41%, 0.66%, and 10.92%, respectively, when compared to the un-jointed control samples. Type III showed the lowest influence on bending and tensile properties, followed by Type II.

Keywords: Bamboo-bundle laminated veneer lumber; Joint forms; Mechanical properties; Joint allocations

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INTRODUCTION

As wood resource availability declines and its demand increases in today's modern industrialized world, it is important to explore new, sustainable building materials. In particular, bamboo has recently been recognized as a promising alternative raw material due to its abundance, fast growth rate, and high tensile strength (Jiang *et al.* 2013; Meadows *et al.* 1992; Nugroho and Ando 2000). The utilization of bamboo, however, is limited by its round and hollow shape, which makes it difficult to create connections with this tubular shape (Mahdavi and Clouston 2011; Sulastiningsih 2009).

Bamboo-bundle laminated veneer lumber (BLVL), lumber-like in dimensions, consists of several plies of bamboo bundle sheets bonded together with the grains in the parallel direction. As a potential bamboo-based composite, BLVL not only can overcome the limitations of its cylindrical macrostructure, but also preserve the natural microstructural properties of bamboo (Shin *et al.* 1989). Owing to its excellent mechanical properties and dimensional stability (Meng *et al.* 2011; Qiu *et al.* 2013), BLVL has been extensively applied in small-size structural components in China, such as stair boards and platform floors.

In recent years, the demand for long-span building materials has increased with increasing construction of environmentally sustainable buildings. On the other hand, the processing of small-diameter and large-taper bamboos generates many short and narrow pieces of bamboo bundles. Consequently, to manufacture large-scale BLVL used for such structures as beams, pillars, and roof trusses, the member length should be extended by joining the structural components with effective joining methods. Joining the structural laminates with an end-to-end joint is the most widely used approach. Özçifçi (2007) examined the scarf joint performance of laminated veneer lumber (LVL). The author indicated that the scarf joint was 23 to 82% lower in modulus of rupture (MOR) than the non-jointed samples, and that the properties of LVL increased with the decreasing of scarf angle. Yeh and Lin (2012) also showed that the bending strength of laminated Moso bamboo that was finger-jointed was about 36% lower than the non-jointed samples. This method can cause a sharp drop of the mechanical strength triggered by severe concentrations of local stress.

In the present work, a new approach, in which veneers were lengthened with effective joints at different cross sections, was developed to produce large span BLVL. The specific objectives were as follows: (1) to explore the technical manufacturing feasibility of BLVL with lengthening technology; (2) to compare the tensile and bending properties of BLVL with different veneer-joint forms; and (3) to evaluate different lap-joint allocations on the mechanical properties of BLVL.

MATERIALS AND METHODS

Preparation of Bamboo-bundle Sheet

The bamboo material used in this study was of the species *Dendrocalamus farinosus,* which is abundantly grown in Asia. Bamboo culms (120 cm in length) were initially split into four pieces and then manually fed into a bamboo untwining machine to produce bamboo bundles. The bamboo untwining machine was specially designed for rolling and brooming the bamboo strips into a loosely reticulate bamboo bundle (4 mm in thickness). Bamboo green was scraped to remove wax and silica by means of a steel brush installed on the untwining machine. Each bamboo bundle sheet was prepared using a sewing machine, which connected the bamboo bundles in the width direction. Finally, the bamboo bundle sheets were cut into pieces 300 mm in length and then air-dried until the moisture content (MC) reached 8 to 12%.

Manufacturing Veneer-jointed BLVL

A commercial phenol formaldehyde (PF) resin with a solids content of 15% was used in the test. The bamboo bundle sheets were immersed into this adhesive for 5 min and dried to 8 to 12% MC. Samples with different veneer-joint forms were manufactured as follows. BLVLs were produced by assembling three layers of bamboo bundle sheets with the grains oriented in the parallel direction. Each layer was 300 mm in length except for the core layer, which was joined by two shorter sheets. Four different veneer-jointed forms, *i.e.*, butt joint, lap joint, toe joint, and tape joint, were used (Fig. 1). The toe joint formation was made by a laser cutting machine (CMA-6040, Yueming Laser, China). Among them, the lap length was 10 mm, and the toe length was 30 mm with the toe spacing of 20 mm, and the width of the gummed paper was 16 mm. The assemblies were hot-pressed by a Carver 3895 thermocompressor (Carver, Inc, Wabash, IN USA), with a hot-pressing temperature of 150 °C for 10 min, and the pressing pressure was 4.5 MPa. The final dimensions of BLVL were 300 mm (length) × 140 mm (width) × 8.0 mm (thickness).

Samples with different lap-joint allocations were produced as follows. BLVLs were manufactured by assembling five layers of lap-joint bamboo bundle sheets. Each layer was also 300 mm in length. The assemblies were hot-pressed for 15 min at 150 °C. The dimensions of the BLVL were 300 mm × 140 mm × 12.5 mm. Three lap-joint allocations, *i.e.*, the invariable allocation (Type I), staggered allocation (Type II), and uniform allocation (Type III), were used and are shown in Fig. 2.

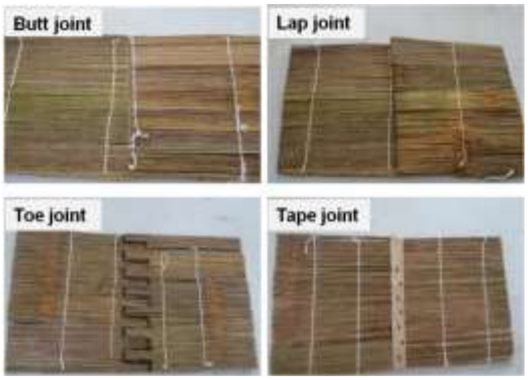

Fig. 1. Veneer-joint forms

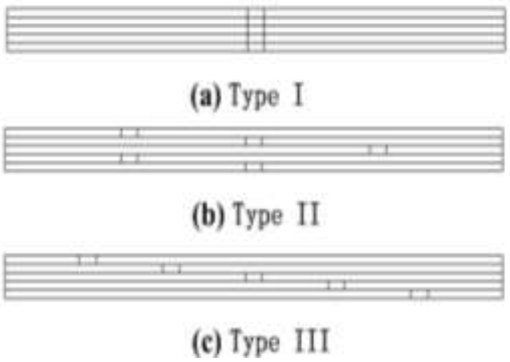

Fig. 2. Joint allocations

Testing

After cutting the BLVLs into desired specimen dimensions, the modulus of rupture (MOR), modulus of elasticity (MOE), and tensile strength (TS) were measured. The specimens for the three-point bending tests had dimensions of 300 mm (length)×20 mm (width)×12.5 mm (thickness) with the joint located in the middle of the specimens. The national standard of The People’s Republic of China GB/T 17657-1999 was followed for the tests. The bending tests were performed displacement-controlled with a velocity of about 6 mm/min and the MOE was evaluated in the range between 20 and 40% of failure load. The size of tensile testing specimens was 10 mm wide, 280 mm long, and with double curved necking down to 2 mm wide in the center. Tensile tests in accordance with GB/T 15780-1995 were performed using an INSTRON 5582 mechanical testing machine (Instron, Norwood, MA USA). The specimens were tested with a rate of about 2 mm/min, reaching failure after approximately 1 to 2 min. Eight replicates were carried out for each test. A one-way analysis of variance (ANOVA) using SPSS software was performed for the statistical data analysis.

RESULTS AND DISCUSSION

The Effect of Different Joint Forms on Tensile Properties

The mean tensile strength values of the BLVLs are presented in Fig. 3. The effect of jointing methods on the tensile strength (TS) was significant. The highest value of TS (209.77 MPa) was found for the non-jointed samples (Control; Fig. 3). Jointed veneer had a negative effect on the TS of the samples. Compared with the control samples, the TS value was reduced by 50.46%, 48.88%, 48.16%, and 38.41% for the butt joint sample (Butt), tape joint sample (Tape), toe joint sample (Toe), and lap joint sample (Lap), respectively. Failure in the veneer-jointed laminations was observed to be initiated at the tips of the joints, propagating along the weak grain direction, which in effect reduced the effective cross section to produce a brittle failure. The result of Duncan’s multiple range test analyses (Fig. 3) showed significant differences in the TS of the various BLVLs with different joint forms ($p < 0.05$). The lap jointed sample had the highest TS value of all the veneer-jointed forms. For the tensile tests, the lap joint veneer can bear a certain amount of tensile load because of the bonding interface, while the veneers of the other three joint forms barely have load-carrying capacity. During the process of a tensile test, the effect of stress transfer on bonding interface can increase the value of tensile loading of specimens at a certain degree compared to the other three joint forms. Therefore, those without the loading bridge effect exhibited a smaller TS value.

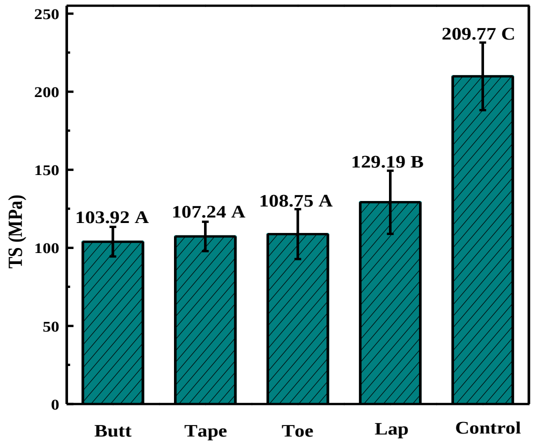

Fig. 3. TS of BLVLs with different joint forms; Different letters indicate a significant difference at the 0.05 level

The Effect of Different Joint Forms on Bending Properties

Bending tests were performed on 210-mm BLVL samples with different veneer-joint forms. The results indicated that jointed samples caused a reduction in the MOR and MOE values (Fig. 4) when compared to the control samples. The joint caused a concentration of local stress at the glue line of the jointed pieces, which decreased the operative cross section. The decrease in the operative cross section reduced the moment of inertia, which resulted in decreased bending strength (Bayatkashkoli *et al.* 2012).

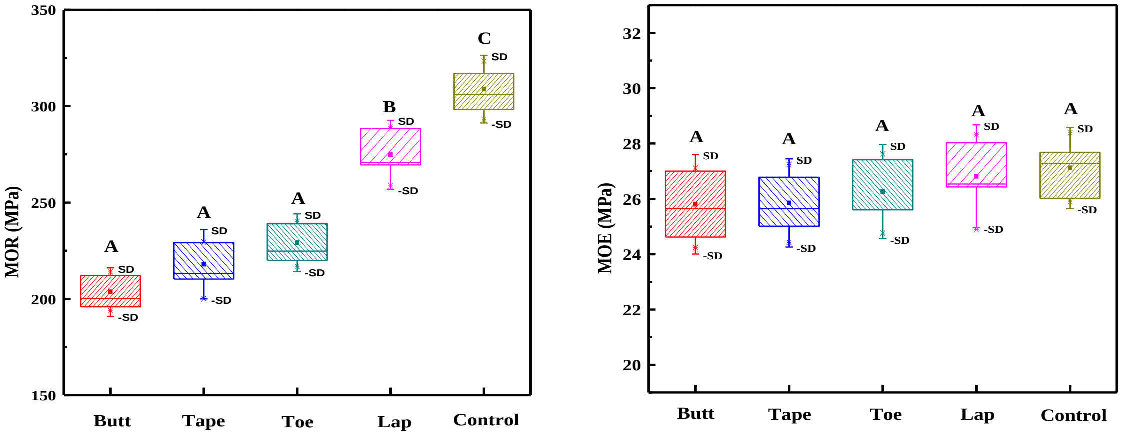

Fig. 4. Bending properties of samples with different joint forms; SD, standard deviation Different letters indicate a significant difference at the 0.05 level

The values of MOR were reduced by 34.08%, 29.41%, 25.80%, and 11.03%, and of MOE were reduced by 4.83%, 4.67%, 3.15%, and 1.36% for Butt, Tape, Toe, and Lap specimens, respectively. Thus, the lap joint form had the lowest reduction on the bending strength of BLVLs when compared to the other three joint forms. BLVL density may be an important parameter influencing the mechanical properties (Liu *et al*. 1992; Tang 1989), where the Lap had the highest density. Figure 4 shows the result of multiple Duncan's test analyses. A significant difference was found on the MOR among different joint forms, whereas the MOE differences among the joint forms were not significant ($p>0.05$). The ultimate stiffness of a laminate is generally controlled by the stiffness of the outer tension lamination, and the joint in the core lamination does not have a significant effect on the stiffness of the laminate (Spaun 1981).

Mechanical Properties of BLVLs with Different Lap-joint Allocations

The bending and tensile properties of BLVL with lap-joint were better than those with the other three joint forms. So on the research of joint allocations, bamboo-bundle veneer on each layer was lengthened using the lap-joint approach. Table 1 shows the MOR, MOE, and TS values of BLVLs with different lap-joint allocations. As can be seen from Table 1, the lap-jointed groups exhibited a considerable reduction in MOR, MOE, and TS when compared to the control. Among the three types, Type III samples showed the highest MOR (220.88 MPa), MOE (23.91 GPa), and TS (92.09 MPa), which was 11.64%, 8.67%, and 54.52% lower than the control samples, respectively. Type I samples showed the largest negative influence on the mechanical properties of BLVL. When the loading was applied to the BLVL, internal stresses were developed at the lap joints, which resulted in stress concentration at the tips of the joints that introduced failure points (Dansoh *et al.* 2003). In addition, stress in joints of all layers of Type I converged on the same cross section, which lead to lower strength when compared with Type II and Type III where the joints were scattered.

Table 1. Mechanical Properties of Samples with Different Joint Allocations

	Control	Type I	Type II	Type III
MOR (MPa)	249.98 A （8.75）	70.00 B （11.64）	121.35 C （12.92）	220.88 D （10.80）
MOE (Gpa)	26.18 A （1.78）	18.96 B （5.01）	22.40 C （5.59）	23.91 C （5.57）
TS (MPa)	202.47 A （6.72）	40.28 B （9.28）	82.84 C （15.12）	92.09 C （6.29）

Values between parentheses are coefficient of variation
Different letters in a given row indicate a significant difference at the 0.05 level by Duncan's multiple-range test

CONCLUSIONS

1. Bamboo-bundle laminated veneer lumber (BLVL) using veneer lengthening technology was successfully fabricated, and the structural performance of BLVL with respect to joint forms and joint allocations was investigated.
2. Compared with non-jointed samples, the veneer-joint specimens showed a significant reduction in tensile strength (TS) and modulus of rupture (MOR), while an

insignificant reduction was observed in the modulus of elasticity (MOE). For the veneer-joint BLVL, the best mechanical properties was found for lap-joint samples, followed by toe-joint samples, tape-joint samples, and butt-joint samples.

3. In the examination of the mechanical properties of BLVL with different lap-joint allocations, uniform allocation (Type III) exhibited the greatest bending and tensile properties among the three allocation types. The mechanical properties of veneer-jointed BLVL might be improved by utilizing a lap joint form and uniform lap-joint allocation.

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