The Effect of Joint Form and Parameter Values on Mechanical Properties of Bamboo-Bundle Laminated Veneer Lumber (BLVL)

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Bamboo-bundle laminated veneer lumber (BLVL) was produced by joint lengthening technology. The objective of this study was to evaluate the effect of joint form and the values of key parameters on mechanical properties of BLVL. Two joint forms, *i.e.*, finger joint and scarf joint, and two corresponding joint parameters, *i.e.*, finger length and scarf angle, were investigated in laminates. The results indicated that the mechanical properties of jointed BLVL were reduced in comparison to those of BLVL without joints. For finger-joint form, the BLVL member with 14 mm fingers achieved better compressive strength, bending modulus of rupture (MOR), and tensile strength than 19 and 25 mm ones. For scarf-joint form, the 30° scarf-jointed member exhibited the highest bending modulus and tensile modulus of rupture (MOR) in this study, then followed the 45° and 60° ones. The 60° scarf-jointed BLVLs were better than 30° and 45° groups in compression strength. Synthesis of the testing results revealed that finger-jointed BLVLs achieved better bending modulus of rupture than scarf-jointed ones.

Keywords: Bamboo-bundle laminated veneer lumber; Joint; Finger length; Scarf angle; Bending properties; Tensile properties; Compression properties

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INTRODUCTION

In recent years, laminated bamboo fibrillated-veneer lumber (LBL) has been extensively promoted and applied as non-structural and structural components in China for its high strength, modulus, and bamboo material utilization rate (Yu *et al.* 2011; Qiu *et al*. 2013). However, some characteristics of LBL, including high density (above 1.2 g·cm^{-3}), poor uniformity, performance, and dimensional stability, have a deleterious effect on its application as structural and engineering material. Inspired by the manufacture of laminated veneer lumber (LVL) (Kurt *et al*. 2012), the bamboo bundles were arranged and tied together so that separated and loose bundles were linked to a uniform bamboo bundle sheet. Layers of bamboo bundle sheets were laid in parallel and hot-pressed to manufacture Bamboo-bundle Laminated veneer Lumber (BLVL), which exhibited favorable density uniformity, dimensional stability, and stability of mechanical performance in comparison to LBL (Chen *et al*. 2014; Deng *et al*. 2014).

With an increasing demand for long-span structural components and a decreasing supply for large-size wood products, much attention has been paid to using large-span bamboo-based composites as engineering material (Wang *et al*. 2014). However, there is much difficulty for domestic bamboo-based panel products to achieve a size larger than 1220 mm by 2440 mm, which is caused by restrictions related to domestic hot pressing plates, such that demands for the production of large-span bamboo-based engineering components is far from being adequately met. Consequently, to manufacture large-span BLVL, some effective joining means should be adopted so that the length and width of board will be extended. Some veneer-joint forms and allocations have been investigated in laminates by Zhang *et al*. (2014), and the lap joint emerged as the best veneer-joint form in the experiments.

Connection plays an important role in structural components, and end-to-end jointing has been the most common approach (Fig. 1). The butt joint form (Fig. 1a) has the advantage of convenient operation but leads to products with poor bonding strength (Liu and Lii 1989), thus making it an unsuitable joining means for the manufacture of structural material.

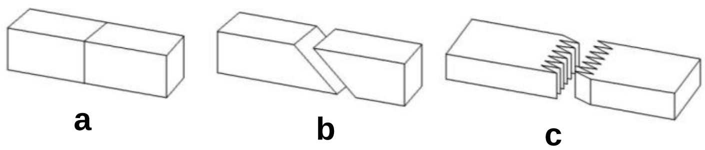

Fig. 1. End-to-end grain joints for wood. (a) Butt joint, (b) scarf joint, and (c) finger joint

The scarf joint (Fig.1b) is an end joint formed by joining the ends of two pieces that have been tapered or beveled to form sloping plane surfaces with adhesive. Such joints have been found to give better bonding strength, but they result in relatively larger amounts of material waste in comparison with butt joint form (Liu 2005). Özçifçi (2007) investigated the role of geometry on the mechanical performance of scarf joints in LVL bonded with two types of adhesives. The results indicated that the bending strength and modulus of elasticity (MOE) of LVL increased as the scarf angle was varied from 60° to 30°, along with increasing waste material. Huang (2008) applied the scarf jointing method to the manufacture of wind turbine blades materials, and found that the bending MOE decreased as the scarf angle was varied from 3.81° to 45°, while the longitudinal compression strength showed the rise-fall trend.

The finger jointing method (Fig. 1c) has been one of the most extensively used approaches for extending glulam length and may be applied to the laminating bamboo process (Lin and Fu 2007). The behavior of finger-jointed black spruce was studied for three joint configurations: feather, male-female, and reverse (Bustos *et al*. 2003). The analysis indicated that the feather configuration performed better than male-female and reverse profiles, especially for horizontal structural joints. Ayarkwa (2000) discussed the influence of finger-joint geometry and end pressure on tensile properties of three finger-jointed tropical African hardwoods. Finger profile geometry was found to significantly affect ultimate tensile strength, but not tension MOE of finger-joints from the three species. The finger profile geometry having 18 mm finger length exhibited significantly the strongest and the most efficient finger-joint compared with those having 10 mm and 20 mm finger lengths. Research has also been conducted with jointed bamboo-based structural components. Yeh and Lin (2012) found that the finger-jointed laminated moso bamboo members showed a higher modulus of rupture (MOR) than ma bamboo members. It was also concluded that the flexural performance could be improved as the finger length was increased from 12 mm to 15 and 18 mm for the laminated bamboo members.

End-to-end jointing methods have been extensively used in the wood processing industry; however, there is not much information available concerning the influence of joint configuration on the structural performance of bamboo-based composites, especially finger and scarf joints. In the present work, scarf joints and finger joints were arranged and used for the manufacture of jointed BLVL, and the effect of scarf joint angle and finger joint length on mechanical properties (bending, tensile, and compression properties) of BLVL was investigated.

EXPERIMENTAL

Materials

Preparation of bamboo bundle sheet

Three-year-old bamboo (*Dendrocalamus farinosus*) was obtained from Yibin, Sichuan Province, China. The bamboo tubes were first split into four pieces of approximately the same size with the bamboo nodes removed, then rolled and broomed into loose reticulate bamboo bundle sheets with a certain uniformity of thickness by an untwining machine; the green wax and silica on the bamboo pieces were removed by means of steel brush installed on the machine. Bamboo bundle sheets were cross-linked in the width direction with no fracture along the length direction, maintaining the original bamboo fiber arrangement. The bamboo bundle sheets were finally cut into pieces of 300 mm in length and air-dried to a moisture content (MC) between 8 and 12%.

Preparation of BLVL

Phenol formaldehyde (PF) resin used in the experiment was obtained from Beijing Dynea Chemical Industry Co., Ltd. (China). The PF resin (initial solid content 45.53%) was diluted with water to a solid content of 17%. The bamboo bundles were immersed in the adhesive for 5 min and then dried to a MC between 8% and 12%. Five layers of bamboo bundle sheet were laid in parallel, and BLVL was shaped in a CARVER Auto M-3895 hot press (Carver Inc, USA) at a platen temperature of 155 °C and a 15 min hot-press time. The target dimensions of the BLVL were 300 mm (length) × 150 mm (width) × 12.5 mm (thickness), with a target density 1.0 $g \cdot cm^{-3}$.

Preparation of finger-jointed BLVL

The gear milling machine (Fig. 2a) and milling cutter used in the study were produced by Taiwan Jieming Machinery Co., Ltd. (China) and Shijiazhuang Vanguard Cutter Co. (China), respectively. Resorcinol phenol formaldehyde (R/PF) resin with a solids content of 66% used for jointing was obtained from Beijing Dynea Chemical Industry Co., Ltd. (China).

The BLVLs were gear milled into finger lengths of 14, 19, and 25 mm, respectively (Fig. 2b). Through adjusting the device, the embedment was 0.1 mm, with a feather configuration. Eight pairs of specimens were prepared for each mechanical test. The specimens were coated uniformly with R/PF resin on the inner side of the fingers, with double spread of 160 to 170 $g \cdot m^{-2}$ (Fig. 2c). Finally, two BLVL units were connected through end compression by mechanical loading equipment (Fig. 2d).

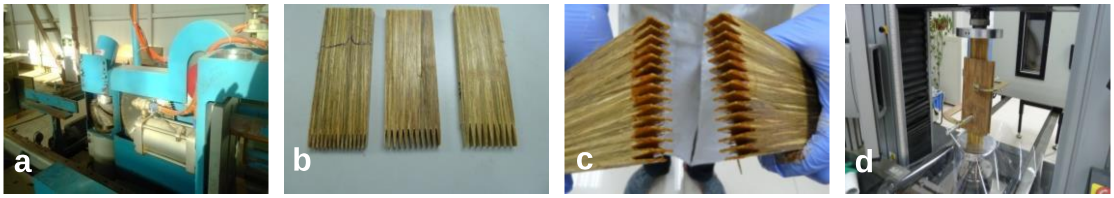

Fig. 2. Process of manufacturing finger-jointed BLVL. (a) Gear milling machine, (b) gear milled finger joints, (c) painting adhesive on finger joints, (d) gluing and meshing finger joints

Preparation of scarf-jointed BLVL

The BLVL unit was processed on the table saw, and 30°, 45°, and 60° cants were formed. Eight pairs of specimens were prepared for each mechanical test. The specimens were coated uniformly with R/PF resin on the surface of the cants, with double spread of 160 to 170 g·m^{-2}. Two BLVL units were then connected into one by hot pressing at 50 °C and 1.0 MPa for 1 h, followed by a 1 d indoor preservation. The prepared test samples are shown in Fig. 3.

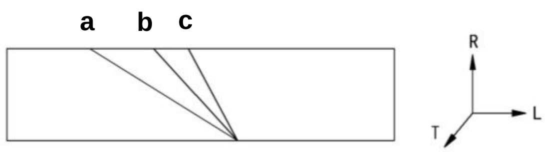

Fig. 3. Test samples with different angles of the scarf joint. (a) 30°, (b) 45°, and (c) 60°

Methods

Mechanical properties tests

The three-point bending test was conducted in accordance with Chinese national standard GB/T 17657 (1999) on specimens with dimensions of 300 mm (length) × 20 mm (width) × 12.5 mm (thick), with the joint located in the middle. The specimens for the parallel-to-grain tensile test were 10 mm wide and 280 mm long, with double curved necking down to 2 mm wide in the center.

The test was performed according to Chinese national standard GB/T 15780 (1995), using a mechanical testing machine (Instron 5582; Norwood, MA USA). For the longitudinal compression test, the specimens had a dimension of 7*H* (length) × 25 mm (width) × *H* (thickness) in accordance with Chinese national standard "*Bamboo Scrimber*", and the value of *H* was 12.5 mm in this study. Longitudinal compressive strength was determined by the following equation,

$$\sigma_c = \frac{P_{\max}}{bh} \tag{1}$$

where σ_c is the ultimate compressive strength, in MPa; P_{max} is the maximum load at which the specimen fails, in N; *b* is specimen width, in mm; and *h* is specimen thickness, in mm. For all the tests, BLVLs without joints act as the control samples. (The standard *Bamboo Scrimber* was primarily drafted by Research Institute of Wood Industry for Chinese Academy of Forestry, and proposed by State Forestry Administration, and it is being examined for approval.)

Statistics

Data were analyzed by a one-way analysis of variance (ANOVA) with the Duncan test using SPSS 18 software (SPSS, Inc., Chicago, IL, USA), and probability values of less than 5% were considered to be significant ($p < 0.05$). Graphs were drawn using Origin 8.0 software (OriginLab Corp.; Northampton, MA, USA).

RESULTS AND DISCUSSION

The Effect of Finger Length on Mechanical Properties of Jointed BLVL

Longitudinal compression properties with different finger lengths

The compression properties of jointed BLVL are shown in Fig. 4. It can be noticed that the maximum compression load was 29.47, 27.82, and 26.98 kN for specimens with finger length of 14, 19, and 25 mm, respectively, while the compression strength was 91.96, 86.45, and 84.01 MPa. For compression strength, the mean values of the 19 and 25 mm finger-jointed BLVL members were 5.99% and 8.65% smaller, respectively, than that of the 14 mm finger-jointed groups. As a result, it may be accepted that the larger finger length led to poorer longitudinal compression properties of BLVL members. A similar trend was also observed by Zhang (2013), who pointed out that the compression strength of vertical gearing milling finger jointed lumber with 13 mm finger length was higher than that with 30 mm finger length. The possible reason for this was that finger joints were such a discontinuous region for the whole jointed component that larger finger joint length contributed to a higher proportion of discontinuous region, and in turn poorer compression properties.

The compression stress-strain curves of BLVLs with different finger lengths are presented in Fig. 5. The progression of all the curves were basically the same, which could be divided into three stages. During the initial stage, the finger joints were closely compressed as loading increased slowly until the mergence was complete. The approximate elastic compression stage is next, in which a linear relationship was present between the compression stress and strain. Finally, the joints failed due to high compression, and caused plastic deformation of the BLVL.

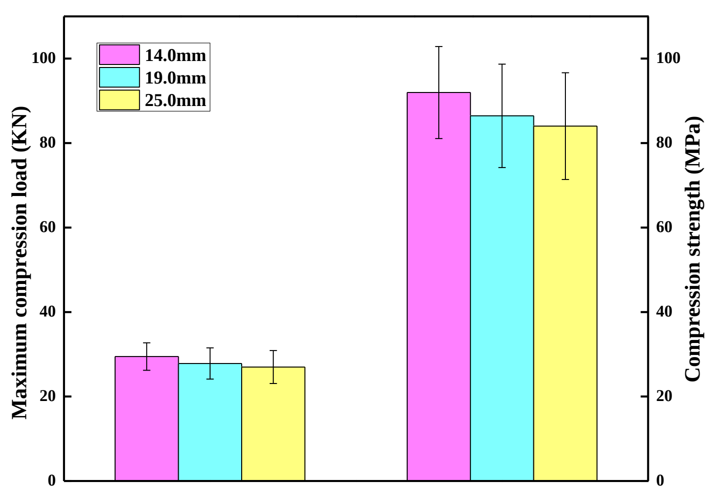

Fig. 4. Compression properties of BLVL with different finger lengths. Data presented as the mean ± standard deviation

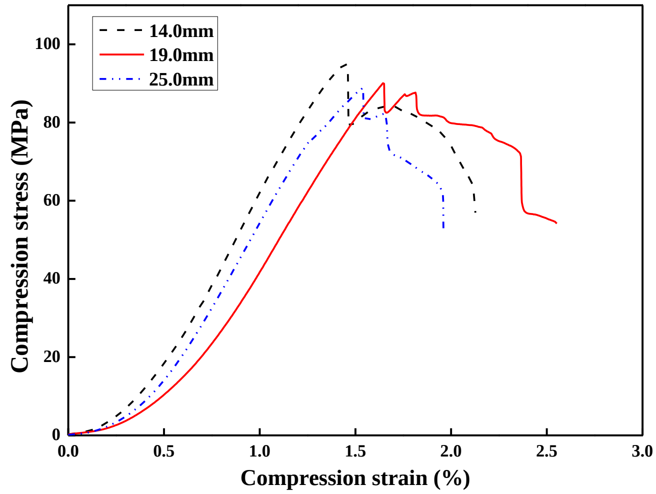

Fig. 5. The compression stress-strain curves of BLVLs with different finger lengths

Bending properties with different finger lengths

The bending properties of jointed BLVL are shown in Fig. 6. It can be seen that the modulus of rupture (MOR) was 79.36, 53.13, and 69.21 MPa for specimens with finger lengths of 14, 19, and 25 mm, respectively, while the modulus of elasticity (MOE) was 20.27, 19.53, and 19.58 GPa. For MOR, the mean value of the 19 and 25 mm finger-jointed BLVL members were 33.05% and 12.79%, respectively, which was smaller than that of the 14 mm finger-jointed groups.

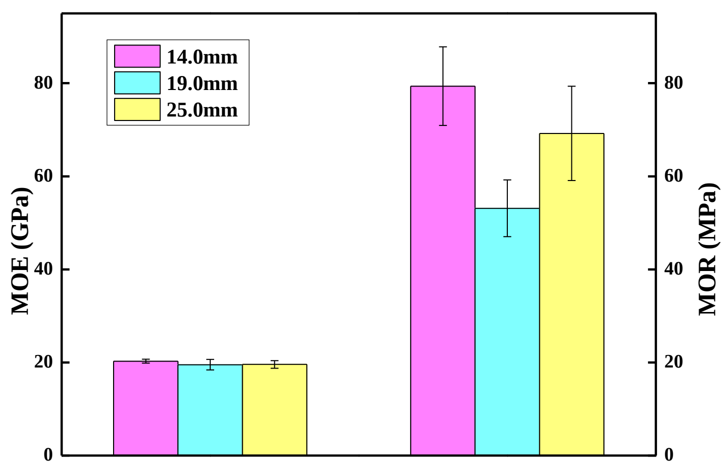

Fig. 6. Bending properties of BLVLs with different finger lengths. Data presented as the mean ± standard deviation

There was little difference between the three kinds of jointed BLVLs in MOE. It can be accepted that the jointed ones with 14 mm finger length possessed the best bending properties in this study. The testing results were different from that by Huang (2012), who found that 25 mm finger-jointed larch lamina had a higher MOR than the 12.7 and 19 mm groups. For laminated bamboo members (Yeh and Lin 2012), the 15 mm finger-joints provided better flexural performance than the 12 and 18 mm ones. In both studies mentioned above, there was no significant influence of finger length on MOE of jointed members. The different results in the studies may indicate that finger length was just one of the main influencing factors for jointed material, and the role of other parameters including profile orientation, finger spacing, and tooth top width cannot be neglected.

In terms of bending failure mode, BLVL was basically subjected to the damage of glue line at finger-joints with a low bamboo failure ratio (Fig. 7), which is probably due to high material strength of bamboo itself. The bending failure mode of finger jointed wooden material differed with density differences, and can be classified into two categories: pure glue-line damage and compound damage (Lin 2005).

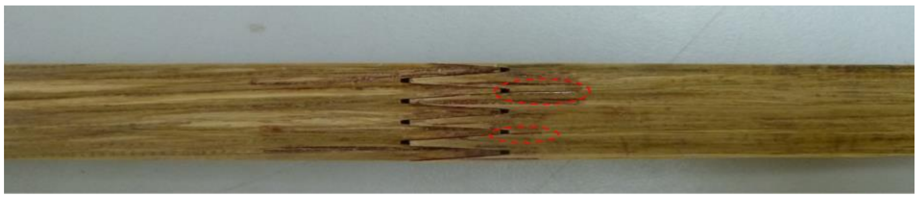

Fig. 7. Bending failure mode of finger-jointed BLVL. Failure zones are outlined with dashed red ovals.

Tensile properties with different finger lengths

Figure 8 presents the testing results of tensile properties of finger-jointed BLVL. The jointed BLVL members with a 14-mm finger length achieved the highest tensile properties, *i.e.*, 44.97 MPa for tensile strength, and 20.65 GPa for tensile modulus. In comparison, the 19- and 25-mm groups had 15.54% and 10.72% less tensile strength, and 6.30% and 1.79% smaller mean value of tensile modulus, respectively.

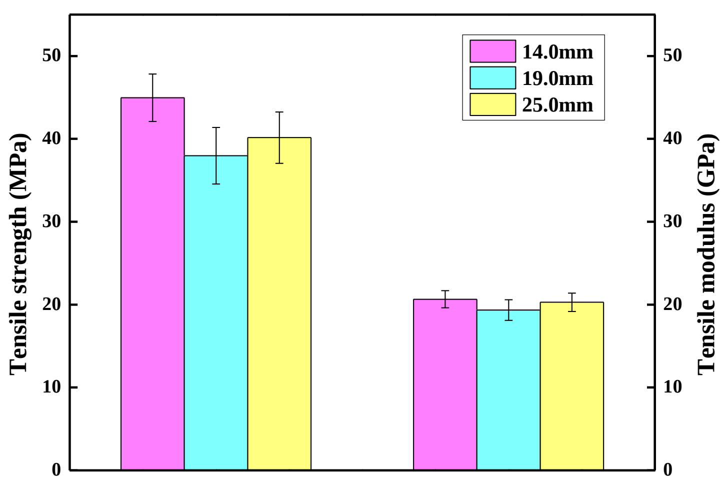

Fig. 8. Tensile properties of BLVLs with different finger lengths. Data presented as the mean ± standard deviation

For tensile modulus, the multiple variance analyses were performed between the three groups of finger-jointed BLVLs, and no significant difference was observed ($p > 0.05$). When finger-jointed composites were in the state of tension, the bearing capacity was determined by the combined action of the tensile capacity of the joint root's net section and the joints' glue line strength. Theoretically, a larger finger length leads to a wider bonding area, and in turn a greater joint strength. However, joint parameters interact. As finger length increases, finger spacing enlarges and there is a decrease in the numbers of joints within a defined width range. Therefore, the advantage of the numbers of 14 mm joints counteracts the disadvantage caused by smaller finger length in comparison to 25 mm joints. In addition, greater numbers of joints brings about increased adjacent-finger meshing force, which contributes to better tensile performance.

The Effect of Scarf Angle on Mechanical Properties of Jointed BLVL

Longitudinal compression properties with different scarf angles

The compression properties of scarf-jointed BLVL are shown in Fig. 9. It can be seen that the maximum compression load was 22.19, 13.23, and 29.79 kN for specimens with scarf angle of 30°, 45°, and 60°, respectively, while the compression strength was 74.18, 46.43, and 101.94 MPa, respectively. This may indicate that 60° scarf-jointed BLVL exhibited better longitudinal compression properties than 30° and 45° scarf-jointed groups.

When considering scarf-jointed composites under a parallel-to-grain loading condition, the bearing capacity is determined by the combined effect of the shearing capacity of the joints' glue layers and the longitudinal compressive resistance of the bamboo fibers. In comparison with a 45° scarf-jointed BLVL, the 30° joints had a larger bonding area, so that the joints' glue layers provided greater compressive capacity; the opposite was the case for 60° scarf-jointed BLVL. Instead, the bearing capacity of 60° scarf-jointed BLVL depended mainly on the properties of bamboo fibers when experiencing longitudinal compression, and the failure mode (Fig. 10a) was different from that of 45° and 60° scarf-joints in which the phenomenon of detachment fault occurred (Fig. 10b).

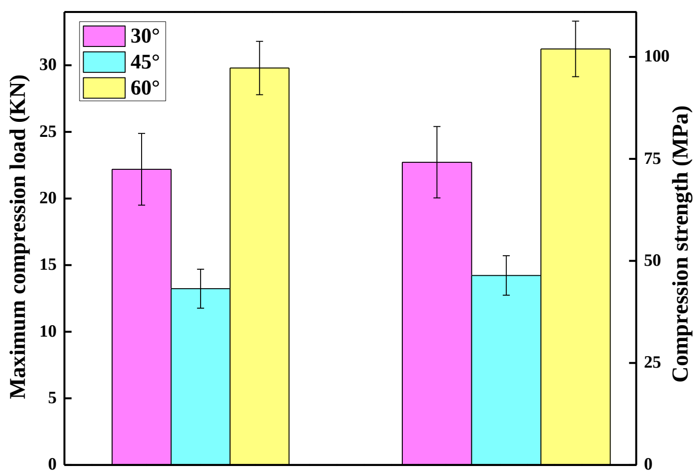

Fig. 9. Compression properties of BLVLs with scarf joints at 30°, 45°, and 60°. Data presented as the mean ± standard deviation

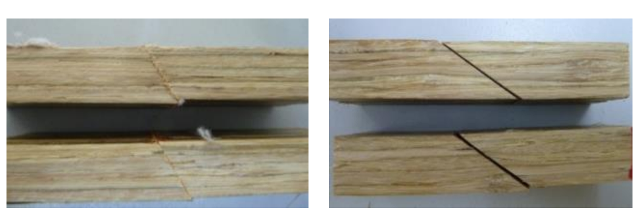

Fig. 10. Compression failure of scarf-jointed BLVL

Bending properties with different scarf angles

The bending properties of scarf-jointed BLVL are shown in Fig. 11. It can be seen that there was a certain difference between different scarf-jointed BLVL in MOR, while there was little difference in MOE. For MOR, the 45° and 60° scarf-jointed BLVL members were 56.80% and 74.07%, respectively, which were smaller values than that of the 30° scarf-jointed groups.

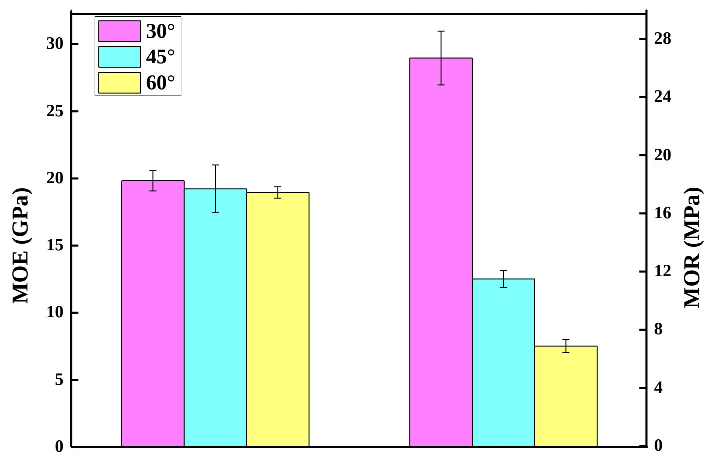

Fig. 11. Bending properties of BLVLs with different scarf joint angles. Data presented as the mean ± standard deviation

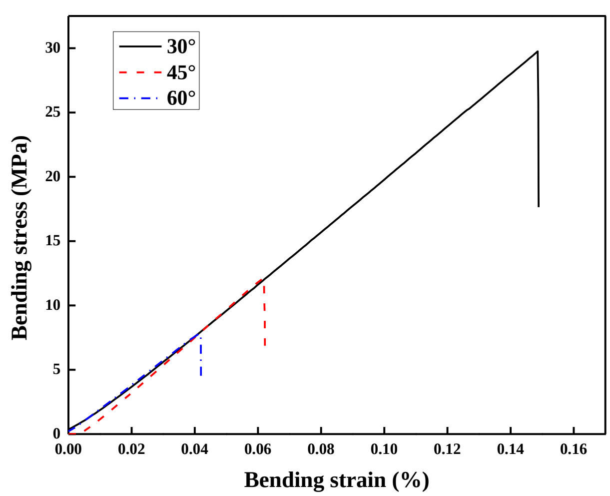

Fig. 12. The bending stress-strain curves of BLVLs with different scarf joint angles

During the bending tests, flexural load was mainly born by the glue layers at the scarf joints, and the failure process can be considered as brittle fracture (Fig. 12). The bonding strength was positively correlated with the size of bonding area. Therefore, the MOR was reduced in succession, as the bonding area decreased from the scarf angle of 30° to 45° and 60°.

Properties with different scarf angles

Figure 13 shows the testing results of tensile properties of scarf-jointed BLVL. The larger scarf angle led to poorer tensile properties of BLVL members. In comparison with 30° scarf-jointed BLVL, the 45° and 60° scarf-jointed BLVL were 50.66%, and 77.88% smaller, respectively, in tensile strength.

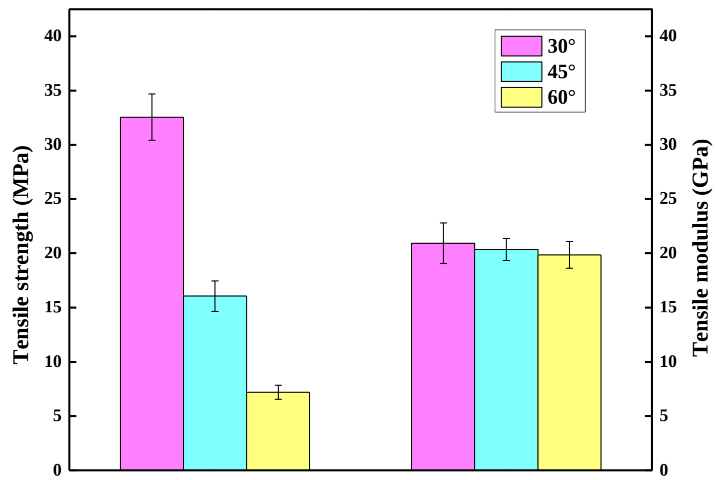

Fig. 13. Tensile properties of BLVLs with different scarf joint angles. Data presented as the mean ± standard deviation

For tensile strength and tensile modulus, the multiple variance analyses were performed between the three groups of scarf-jointed BLVLs. No significant difference was observed for tensile modulus ($p > 0.05$), while the opposite ($p < 0.05$) was the case for tensile strength. When the scarf-jointed composite was in tension, the joint's glue layer was the main load bearing object, which suffers not only shearing force parallel to the glue line, but tensile force perpendicular to the glue line. As the scarf angle decreases, the size of the bonding area increases, along with the reduction of tensile force perpendicular to the glue line, thus enhancing the bearing capacity of the joint's glue layer. The trend was consistent with that observed in the bending properties of BLVLs with different scarf joint angles.

The Effect of Joint Form on Mechanical Properties of BLVL

Analysis of the above testing results revealed that jointed BLVLs with a 14-mm finger length yielded better mechanical properties, as well as those with 30° scarf angle. In this section, the effect of joint form on mechanical properties of BLVL is discussed. For all the tests, the BLVLs without joints act as the control samples.

The test results of mechanical properties of BLVLs with different joint forms are presented in Table 1. In contrast with the control sample, the finger-jointed and scarf-jointed groups were 58.5% and 84.9% smaller in MOR, respectively, while 16.9% and 18.7% smaller in MOE. From Table 1, it is observed that the highest tensile strength (157.94 MPa) and compression strength (124.7 MPa) were obtained in the control samples (BLVLs without joints). As a result, it may be accepted that the presence of a joint contributes to the extension of a composites' size, but brings a negative effect on mechanical properties in comparison to original material. With regard to BLVLs with joints, finger-jointed ones achieve better mechanical performance than scarf-jointed ones, as presented in Table 1. This case may arise from the lock-catch effect by finger-joint form, in which the fingers lean against each other and show a slightly similar buckle-loop state when being loaded.

Table 1. Mechanical Properties of BLVLs with Different Joint Forms

Samples	Bending properties		Tensile strength (MPa)	Compression Strength (MPa)
	MOR (MPa)	MOE (GPa)		
Control sample	191.34[A] (19.08)	24.38[A] (0.94)	157.94[A] (8.48)	124.71[A] (6.62)
Finger-jointed BLVL	79.36[B] (8.44)	20.27[B] (0.41)	44.97[B] (2.87)	84.01[B] (12.63)
Scarf-jointed BLVL	28.97[C] (2.00)	19.83[B] (0.76)	32.55[B] (2.14)	74.18[B] (8.75)

Note: The control sample is a BLVL without joints; Finger-jointed BLVL is a jointed BLVL with a 14-mm finger length; Scarf-jointed BLVL is a jointed BLVL with a 30° scarf angle
Data in parentheses are standard deviation of the eight replicates. Different capital letters indicate a significant difference ($p < 0.05$) in mechanical properties for different jointed BLVLs.

CONCLUSIONS

1. Finger length had a significant effect on the mechanical properties of finger-jointed BLVLs. The BLVL member with 14-mm fingers achieved the highest compressive strength, bending modulus of rupture (MOR) and tensile strength, followed by the 19 and 25 mm ones. There was little difference in bending and tensile modulus (MOE) between the three kinds of finger-jointed BLVLs.
2. Scarf angle played an important role on the mechanical properties of scarf-jointed BLVLs. The 30° scarf-jointed members exhibit the best bending and tensile modulus of rupture (MOR) in this experiment, followed by the 45° and 60° ones. For compression strength, the 60° scarf-jointed BLVL is better than the 30° and 45° groups.
3. The presence of a joint contributes to the extension of composites' size, but causes a negative effect on mechanical properties in comparison to the original material. With regard to BLVLs with joints, finger-jointed BVLVs achieve better mechanical performance (bending modulus of rupture) than scarf-jointed ones.

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