Evaluation of the Uniformity of Density and Mechanical Properties of Bamboo-Bundle Laminated Veneer Lumber (BLVL)

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The objective of this study was to evaluate the uniformity of density distribution for Bamboo-bundle Laminated Veneer Lumber (BLVL) and its relationship to the stability of mechanical performance. A novel assembly style called one-piece veneer formation technology was developed to enhance the density uniformity, and four different density levels for BLVL were examined by X-ray scanning. The results indicated that the homogeneity of density, the stability of mechanical performance, and the mechanical properties for BLVL could be effectively improved by assembling the bamboo bundles into layers and then combining the layers to make the lumber. The density uniformity in width and thickness directions increased with increasing target density. A negatively linear correlation between density and Coefficient of Variation (COV) of MOR and shearing strength was observed. Partial correlation analysis revealed that when controlling for the variability of density, the linear relationship between density and the COV of MOR became insignificant, and the degree of linear correlation between density and the COV of shearing strength decreased.

Keywords: Bamboo bundle laminated veneer lumber; Density uniformity; Vertical density profile; Stability of mechanical properties; Coefficient of variation

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INTRODUCTION

As an import non-wood resource, bamboo has been widely used for construction, in such applications as low-rise buildings, footbridges, scaffoldings, and long-span roofs (Wang *et al.* 2011; Jiang *et al.* 2012). Bamboo is also well-known as a low-cost material that is used especially in the regions of Southeast Asia, South America, Africa, *etc.*, where bamboo grows in abundance while economic development is relatively slow. Due to its ample availability, fast growth rate (3 to 5 years mature), high specific strength and stiffness, and low cost of processing, bamboo has played a vital role in improvement of local economies (Wong *et al.* 2010; Abdul Khalil *et al.* 2012).

Especially, with a decrease in the large-size timber supply in the world, interest has recently arisen in using bamboo fiber as an eco-friendly material for the manufacture of composite panels, including non-structural and structural components (Zhang *et al.* 2000; Lee 2012).

Recently, a new type of bamboo composite panel (over 90% bamboo) called laminated bamboo fibrillated-veneer lumber (LBL) has been extensively promoted in China, because of its high strength and stiffness (Yu *et al.* 2011; Meng *et al.* 2011). However, some drawbacks of LBL, *e.g.*, high density (1.2 g/cm^3 and over) and uneven stress distribution, severely limit its application as a structural material (Chen *et al.* 2013; Jiang *et al.* 2013). As an engineering material, the composites are required not only to possess high mechanical properties, but also to present superior stability and uniformity for the structural design (Wei *et al.* 2013; Chen *et al.* 2013).

The density uniformity within a panel has been considered as one of the most key attributes in determining the mechanical properties and quality control (Winistorfer *et al.* 2000; Ribeiro *et al.* 2009; Vengala *et al.* 2011). Particularly for the biomass resource, reasonable density distribution and homogenous control are essential to make products with high performance and low cost (Winistorfer *et al.* 1996; Qiu *et al.* 2013). Taking the example of the vertical density profile (VDP), *i.e.*, a density gradient through the panel thickness with high-density face layers and low-density core layers, increased surface density is conducive to the improvement of bending strength and dimensional stability, while higher core density could be beneficial to the edge machining and fastener performance (Xu and Winistorfer 1996; Painter *et al.* 2006; García *et al.* 2008; Cheng *et al.* 2011). Therefore, the modulus of rupture, modulus of elasticity, and internal bond strength of a panel along with the stability of these mechanical properties are strongly dependent on panel density distribution and uniformity.

Currently, research methods for measuring density distribution of a panel mainly include sawing methods, model procedure, and X-ray computerized tomography (Echols 1973; Candan *et al.* 2013). Among these above methods, X-ray scanning is an effective testing procedure whereby one evaluates the variation of attenuation count rate of X-ray when it passes through the samples. In addition, the density distribution of a panel can be accurately and quantitatively represented in the form of visual curves (Du *et al.* 2010). Considerable work has been focused on the mechanical properties of bamboo-based composites and density distribution of wood-based panels, such as medium density fiberboard (MDF), oriented strand board (OSB), and particleboard (PB) (Wong *et al.* 1999; Kruse *et al.* 2000; Xu 2007; Du *et al.* 2009). However, limited studies have been done for investigating the relationship between density uniformity and mechanical stability of BLVL.

It would be more convenient for the constructional design if the mechanical variance of BLVL could be quantified by an optimal manufacturing method devoted to the improvement of density uniform of board. A novel integral veneer technology linking separate fibrillated bamboo bundles together was adopted herein to improve the uniformity of bamboo bundle veneer. The term "veneer" is used in this work to denote a layering of cellulosic materials to form a board. The overall purpose of this project was to manufacture BLVL from bamboo bundles and phenol formaldehyde(PF) resin, and to evaluate the stability of physical properties as affected by various density of the panels.

The specific objectives were: 1) to explore the technical feasibility of the manufacturing of BLVL with bamboo bundle veneer integral technology, 2) to compare the density and mechanical uniformity of BLVL with different bamboo bundle veneer preparation, 3) to evaluate the effect of density levels on the characteristics of density distribution in thickness and width directions of BLVL, and 4) to investigate the relationship between density levels and the variability of mechanical properties of BLVL.

MATERIALS AND METHODS

Bamboo Bundle Sheet

Three-year-old Cizhu bamboo (*Neosinocalamus affinis*) was obtained from Yibin, Sichuan Province, China. With an initial moisture content (MC) of about 65%, the bamboo tubes were first split into four pieces of approximately the same size. After bamboo nodes were removed using a hatchet, an untwining machine was used for brooming and rolling the bamboo strips into a loosely laminated reticulate sheet. The laminated sheet was cross-linked in the width direction with no fracture along the length direction, and was nearly uniform in thickness, maintaining the original bamboo fiber arrangement (Fig. 1). The bamboo bundle sheets were finally cut into pieces having a length of 300 mm in length. The cut pieces were then air-dried to about 10% MC. More than 90% bamboo yield could be produced by using this brooming method.

One-Piece Veneer Formation Technology

After the bamboo bundles with the similar thickness (about 5 to 7 mm) were selected, they were arranged at regular intervals of 75 mm along the width direction by use of cotton thread. The bamboo bundles were tied together with the help of a sewing approach, linking separated and loose bundles to a uniform one-piece veneer (Fig. 1). A comparison with the manufacturing process of LBL using separated bamboo bundles and irregular assembly shows that this simple improvement could be beneficial to the subsequent procedures of impregnating adhesive, drying, veneer assembly, and hot-pressing. More importantly, it could be favorable for promoting the overall uniformity of panels by quality control of each bamboo bundle veneer used for the BLVL manufacturing.

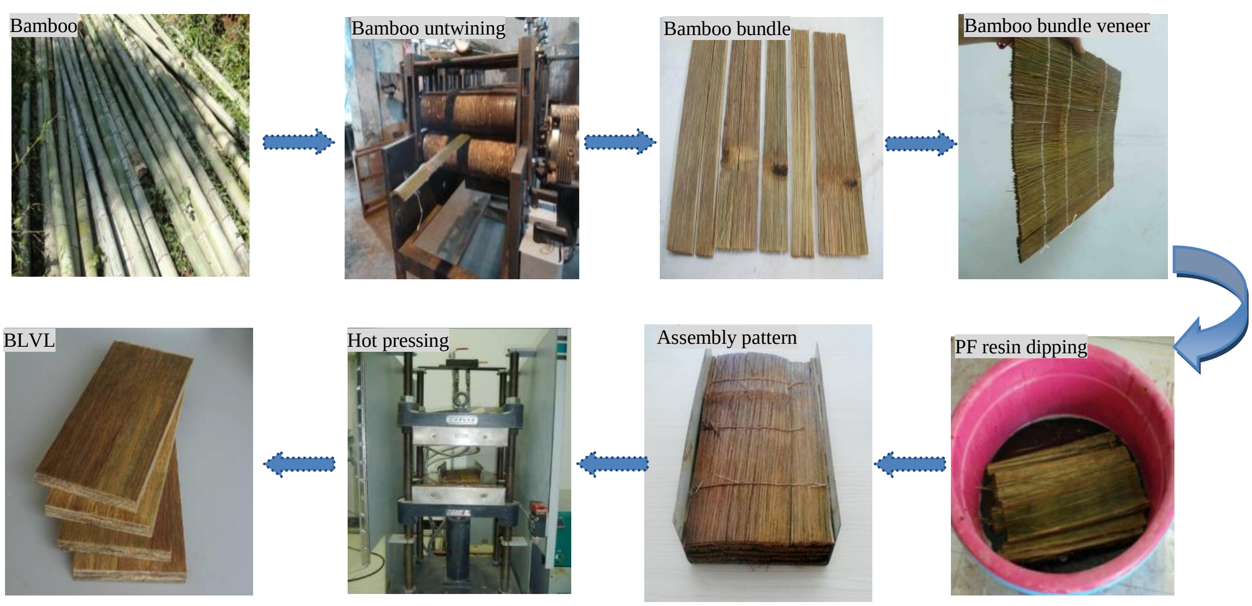

Fig. 1. Production of bamboo bundle laminated veneer lumber (BLVL)

Preparation of BLVL

A commercial phenol formaldehyde (PF) resin obtained from the Taier Corporation (Beijing, China) was used for the composite fabrication. The PF resin was diluted with water to a solids content of 15%. The bamboo veneer assemblies were immersed in the PF resin for 7 min and then dried to a MC between 8% and 12% in an ambient environment. A 300 mm × 300 mm CARVER Auto M-3895 hot press with a PressMAN control system (Carver Inc., USA) and a custom designed mold was used to press the BLVL at a platen temperature of 155 °C. The dimensions of the BLVL layers were 300 mm (length) × 150 mm (width) × 12.5 mm (thickness). The hot pressing time was 30 min (10 min for press closing, 10 min for the pressure maintained at the target thickness, and 10 min for the press opening).

The special processing of BLVL is shown in Fig. 1. Bamboo bundles without the use of one-piece veneer formation technology to fabricate BLVL served as the control specimens. The experiments were carried out as follows: (1) To evaluate the effect of density levels on the characteristics of density distribution in both thickness and width direction for BLVL, comprised of five samples with density levels of 0.7 g/cm^3, 0.8 g/cm^3, 0.9 g/cm^3, 1.0 g/cm^3, and 1.1 g/cm^3 were made; (2) To compare the density uniformity of panels processed with the one-piece veneer formation technology and control specimens, ten specimens with 50 mm× 50 mm× 12.5 dimensions were made of two board types, for a total of 20 samples with the target density 1.0 g/cm^3; (3) To compare the stability of mechanical properties between BLVL and control samples at four different density levels, nine replicates for each testing index were prepared; (4) To investigate the relationship between density and the variability of MOE, MOR, and shearing strength of BLVL, there were nine repeats for each density level.

Density Distribution Testing

A Dense-LabX (Germany, GreCon) device (Fig. 2) with a measurement accuracy of ±0.5% was used for testing the density distribution of the panels. The samples were clamped on the track, and then the cabinet was moved at a speed of 0.5 mm/s. X-ray computerized tomography is able to provide remarkably precise images of density variations of the board without destroying it. X-rays are electromagnetic waves with a wavelength range of 0.06 Å to 10 Å. When they pass through the panel, the radiation will be absorbed by the matter, leading to decreases in intensity of the X-ray beam.

Fig. 2. Specimens of BLVL and profile density analysis apparatus

The attenuation of X-rays follows the exponential equation (1),

$$I_{(E)} = I_{0(E)} e^{-(\rho \mu t)} \tag{1}$$

$$\rho = \frac{1}{t(\mu/\rho)} \ln\left[\frac{I_{0(E)}}{I_{(E)}}\right] \tag{2}$$

where $I_{0(E)}$ represents the initial intensity of radiation, $I_{(E)}$ denotes the attenuated intensity after the X-rays have passed through the panel with a thickness of t and a density of ρ, and u is the mass attenuation coefficient, which is dependent only on the wavelength of the X-ray beam and elemental constitution of the object. Since the u is independent of the chemical and physical state of the matter, the density of ρ could be obtained from Eq. 2.

RESULTS AND DISCUSSION

Evaluation of Density Uniformity with Different Density Levels

The density distribution curves at both thickness and width directions for BLVL with different density levels are shown in Fig. 3. In the thickness direction, the altitudes of vertical density profile (VDP) curves were overall lifted, and the fluctuation amplitude of VDP generally decreased as the target density increased. This could be mainly attributed to the decreasing of the effects of internal flaws and the gaps between bamboo bundles as the compacting degree of bundles was increased.

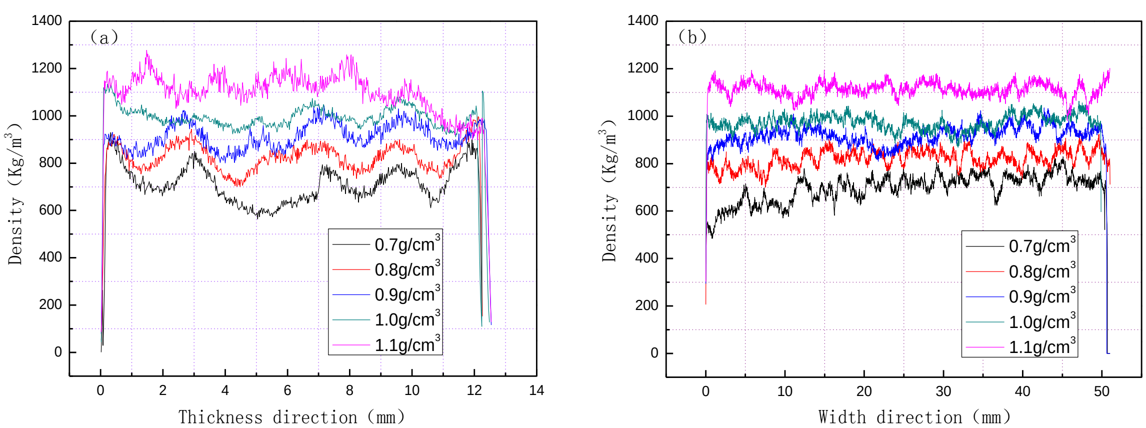

Fig. 3. Vertical density profile curves of BLVL at different density levels (a) thickness (b) width

As shown in Fig. 3(a), the density beside the surface layer was slightly higher than the parts next to the core layer. The highest density point did not occur at the outermost layer, but was located in the position about 1 to 3 mm distance from the outermost surface of the panel, and the density gradually decreased from this position to the core layer. In general, the density distribution from the outermost layer (a thin layer about 0.5 to 1 mm thickness) to the core layer of BLVL reflected a "low-high-low-high-low" density gradient. The outermost PF resin firstly contacted with the hot-pressing plate and immediately was subjected to a pre-curing phenomenon, resulting in a low density layer. Bamboo has been considered as a viscoelastic material with both elastic and plastic behaviors. During the initial stage of hot-pressing, the temperature at the surface was much higher than that at the core, so that the surface bamboo bundles would have a greater degree of being softened, resulting in a greater compression rate. As the curing of resin progressed continuously, this deformation became consolidated. Meanwhile, the bundles in the core were not easily compressed, leading to a lower compression rate. Therefore, the density near the surface of BLVL was slightly higher than near the core.

The characteristics of density profile curves in the width direction displayed greater consistency, with a slight degree of fluctuation around the target density level, as shown in Fig. 3(b), and the degree of fluctuation was reduced with increasing target density. Furthermore, in comparing the density distribution curves in the thickness direction, the uniformity of width direction provided a better result because of the differences in stress for different layer bundles during hot-pressing process.

Comparison of Density Uniformity with Different Veneer Preparation

The effects of different bamboo bundles veneer preparation methods on the density uniformity distribution in different parts of the panels are shown in Fig. 4. The control samples were processed in the same general manner with the bundles lined up lengthwise, but without obvious stacking of layers along the thickness direction of the board. In comparison with the density distribution curves of the control specimen, a significant improvement of repeatability was observed for the ten specimens of BLVL manufactured with one-piece veneer formation technology, as shown in Fig. 4(b). This clearly demonstrates that the density uniformity of the BLVL could be effectively improved by the improvement of bamboo bundles veneer uniformity. Without one-piece veneer formation technology, however, the bamboo bundles alignment within the control samples was considerably more irregular in its arrangement, resulting in the augmentation of variability of existing bamboo bundles.

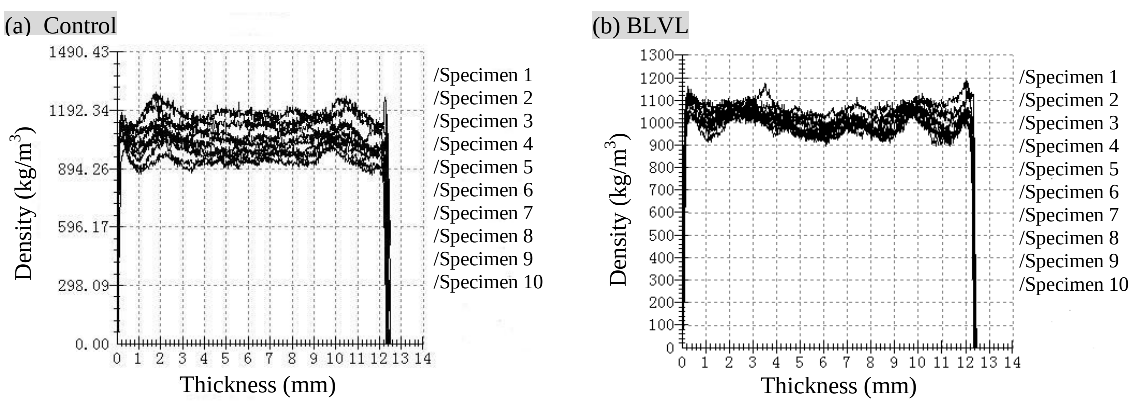

Fig. 4. Effect of veneer preparation on the density uniformity of panel

Comparison of Mechanical Uniformity with Different Veneer Preparation

The relationships between mechanical properties and density of the control and BLVL with different density levels are shown in Fig. 5. The statistical results for the density and modulus of elasticity (MOE), modulus of rupture (MOR), and shearing strength (SS) of the control and BLVL are presented in Table 1.

As the target density increased, each performance index of mechanical properties increased linearly, excepting for the MOR of the control samples. Fitting equations were determined as follows:

MOE *vs.* density for Control: Y=13.41X+8.51， R^2=0.85,
MOE *vs.* density for BLVL: Y=19.79X+6.17， R^2=0.92;

MOR *vs.* density for Control: Y=194.38-0.05*(X-0.67)^2, R^2=0.96,
MOR *vs.* density for BLVL: Y=302.29X-51.58， R^2=0.96;
SS *vs.* density for Control: Y=37.90X-17.90， R^2=0.96,
SS *vs.* density for BLVL: Y=44.24X-22.60， R^2=0.97.

The values of positive slope in the linear equations for BLVL were higher than that of control, revealing a greater improvement for BLVL on the mechanical properties with increasing density. Additionally, from the determining coefficient of linearly fitting R^2, a higher value for BLVL was observed compared to the control. This indicated that the stability of linear correlation between the mechanical properties and density for BLVL was more significant.

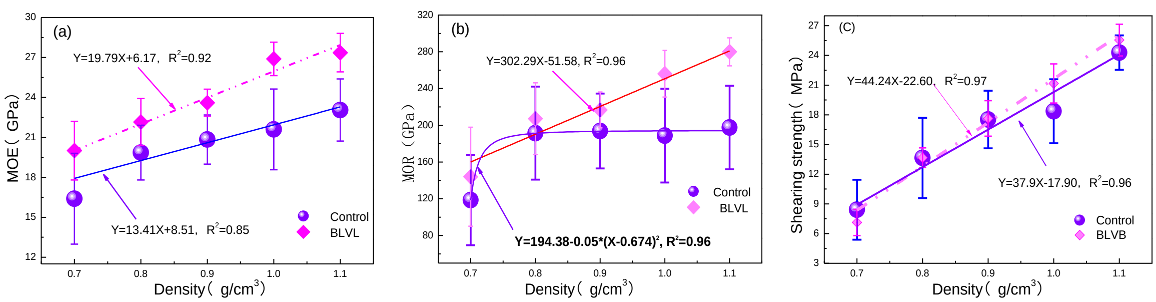

Fig. 5. The relationship between density and mechanical properties of BLVL

Table 1 shows that the coefficients of variation (COV) of each index for BLVL at different density levels were much lower than that of the control specimens. These results clearly reflected that the stability of mechanical performance for BLVL was effectively improved by the one-piece veneer formation technology, which was consistent with the analysis above. However, the uneven distribution of bamboo bundles and irregular arrangement within the control specimen resulted in an increase of flaws and nonuniform density distribution in the panel, which resulted in increasing variability of mechanical behaviors for the control.

Table 1. Comparison of the Uniformity of Physical and Mechanical Properties of the Control Specimen and BLVL

Target density (g/cm^3)	Coefficient of variation (COV) for the properties of Control (%)				Coefficient of variation (COV) for the properties of BLVL (%)			
	Density	SS	MOR	MOE	Density	SS	MOR	MOE
0.7	9.05	35.97	41.43	20.79	3.59	18.71	28.99	10.99
0.8	8.51	29.79	26.43	12.19	3.65	16.65	17.97	6.89
0.9	4.54	16.64	21.03	10.44	2.16	10.14	13.33	4.32
1.0	4.74	12.44	18.17	10.43	2.72	9.33	11.15	4.66
1.1	5.87	7.18	17.11	10.12	1.22	6.26	5.44	5.27

Relationship between the Uniformity of Mechanical Properties and Density

The relationships between density and the stability of mechanical properties of BLVL are shown in Fig. 6. As the target density of BLVL increased, the COV of panel density (Table 1), and COV of mechanical properties, *i.e.*, shearing strength (SS), modulus of rupture (MOR), and modulus of elasticity (MOE) all showed a declining tendency (Fig. 6). Fitting equations for the relationship between COV of mechanical properties and density levels are shown below:

Between COV of SS and density： $Y=-32.22X+41.22$, $R^2=0.93$;
Between COV of MOE and density：$Y=2.11+562*\exp(-X/ 0.229)$, $R^2=0.95$;
Between COV of MOR and density： $Y=36015-36011*\exp((-X-0.98)/14.3)^2$, $R^2=0.99$.

The stability of the mechanical properties of the BLVL was related not only to the density levels but had much to do with the variability of density. In order to quantitatively evaluate the linear relationship between the uniformity of mechanical performance of BLVL and the density levels, the Pearson correlation analysis was performed, based on the Coefficient of variance (COV) of shearing strength and density, the COV of MOR and density, and the COV of MOE and density, respectively. Considered with the effect of the variance of density on the uniformity of mechanical properties, a partial correlation analysis was also conducted to control for the COV of density, as shown in Table 2.

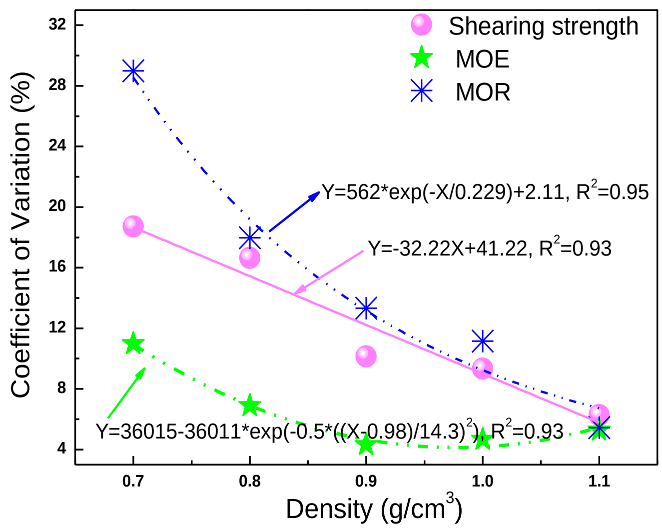

Fig. 6. Relationship between COV of mechanical properties and density levels of BLVL

Pearson's correlation coefficients between density and COV of shearing strength, MOR, and MOE were -0.9717(P <0.01), -0.9640(P <0.01), and -0.7901(P >0.05, insignificant) when not controlling for COV of density. The statistical results indicated that density had a significant negative linear correlation with the variability of shearing strength and MOR, except for MOE. The reason for the difference in MOE is mainly due to elastic modulus as the inherent properties of the matter only determined by the material itself.

Table 2. Bivariate and Partial Correlation Analysis for the Density COV and Mechanical Properties of BLVL

Model type	Properties of BLVL		Coefficient of variance (COV)		
			Shearing strength	MOR	MOE
Uncontrolled model for COV of density	Density	Pearson correlation Significance (2-tailed)	-0.9717** (P=0.006)	-0.9640** (P=0.008)	-0.7901 (P=0.112)
Control model for COV of density	Density	Pearson correlation Significance (2-tailed)	-0.9491* (P=0.049)	-0.9381 (P=0.062)	-0.7792 (P=0.221)

NOTE: *correlation is significant at 0.05 level,**correlation is significant at the 0.01 level.

After controlling for density COV, Pearson's correlation coefficient between density and the COV of shearing strength and MOR decreased to -0.9491 (P <0.05) and -0.9381 (insignificant, P > 0.05). This indicated the density variation might have a negative effect on the stability of the mechanical properties. The statistical analysis also revealed that the effect of density levels on the variability of MOR was not significant at the 95% confidence level, after considering the density COV itself. These results clearly demonstrated that the controlling for density variability would weaken the linear relationship between target density and the variability of mechanical properties. Thus, the linear relationship between density and the uniformity of mechanical behavior of BLVL could be relatively improved. The possibility for above changes in linear correlations was that the dispersion of board strength related to average density was largely eliminated by density uniformity improvement.

CONCLUSIONS

1. A novel bamboo bundle laminated veneer lumber (BLVL) using one-piece veneer formation technology was successfully fabricated, and its density and mechanical uniformity were investigated.
2. By using the one-piece veneer method for bamboo bundles, the uniformity of density, stability of mechanical properties as well as MOE, MOR, and shearing strength of BLVL could be effectively improved.
3. The uniformity of density distribution in both thickness and width directions for BLVL increased with increasing target density. A negative linear relationship was found between density and Coefficient of Variation (COV) of MOR and shearing strength. Controlling the variation of density would have a positive effect on the uniformity of mechanical properties of BLVL.

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