Variation of Density and Dynamic Modulus of Elasticity of Poplar Veneer and Its Impact on Grade Yield

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To maximize the value of poplar wood in manufacturing of laminated veneer lumber (LVL), its radial (from pith to bark) and longitudinal (from bottom to top) variations were examined in terms of the density and dynamic modulus of elasticity (E_D) of veneer. The veneer sheets were rotary-peeled from seven representative poplar butt bolts (the bottom part of a stem) and seven representative poplar second bolts (the middle part of a stem). A grading strategy for selecting veneer was proposed based on the requirements of LVL products. In this study, the E_D value of each poplar veneer sheet was non-destructively measured by the ultrasonic method. The results showed that there was a weak correlation between veneer density and ultrasonic wave velocity. The bolt class (butt or second bolt) did not significantly influence the variation of veneer density and E_D. However, the among-bolt variation played a significant role in the variability. A large difference in diameter between two ends of a bolt (*i.e.* the within-bolt variation) resulted in a low veneer E_D. According to the sorting criteria of Chinese Standard “Laminated Veneer Lumber”, the estimated grade yields of the poplar veneer studied were 45.2% for G1, 39.3% for G2, 13.1% for G3, and 2.4% for G4.

Keywords: Variation; Poplar; Veneer; Density; Dynamic modulus of elasticity

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INTRODUCTION

Fast-growing plantations play a critical role in the current global forestry. Poplar (*Populus×euramericana* cv) is the most widely planted fast-growing species in East China (Wu *et al.* 1998; Wei *et al.* 2013), where it provides great business opportunities and high economic value. The average harvesting age of this species is approximately seven years, which sometimes restricts its applications because of its low density, soft texture, and tendency to deform and decay. Over the past decade, Nanjing Forestry University and the Chinese Academy of Forestry performed numerous studies that investigated the properties and applications of poplar. They discovered that poplar wood was an ideal material for producing wood-based panels, most notably laminated veneer lumber (LVL), due to its unique manufacturing characteristics, *i.e.*, that it peels and bonds easily (Zhou 2006).

Laminated veneer lumber is a typical veneer-based wood composite exhibiting more uniform physical and mechanical properties than solid wood because of its reconstitution, densification, and use of an adhesive, allowing it to become one of the primary engineered wood products (Burdurlu *et al.* 2007; Kılıç 2011). Laminated veneer lumber has been widely used as I-joist flanges, headers, and beams in the construction of both residential and commercial buildings in North America. In China it has been used primarily in non-structural applications such as furniture, packaging, and transportation industries. With the development of the non-destructive evaluation (NDE) technique in recent decades (Ross 2002; Schimleck *et al.* 2002), the acoustic technique becomes the most feasible and practical method and has been widely used in enterprises in New Zealand and North America for many years (Brashaw *et al.* 2004; Chauhan and Walker 2006). For example, Director HM 200 (Fibre-gen Inc., Auckland, New Zealand) is usually used to sort logs in terms of their end-uses in mills, and the Metriguard Veneer Tester (Metriguard Inc., Pullman, WA, USA) is widely used to test and sort veneer sheets in the production of LVL. However, Chinese wood enterprises presently still evaluate logs using visual inspection based on diameter, knots, straightness, and decay. In particular, poplar veneer sheets are, without any inspection, used directly to make LVL/plywood products. Therefore, there is an urgent need to conduct research on stress grading for LVL manufacturers.

A previous study by Zhou *et al.* (2013) investigated the feasibility of using resonance-based acoustic technologies to site sort Chinese poplar logs for LVL products. Their results showed that there was a strong correlation between the resonance-based acoustic velocities of logs and the dynamic modulus of elasticity (E_D) of veneer and LVL. Thus, it is feasible to sort logs based on resonance-based acoustic measurement, which can help increase the grade outturn and, in turn, value recovery of Chinese poplar logs. The wood variation, however, was not taken into account, and this feature can no doubt affect the overall wood quality and the properties of the final products (Boever *et al.* 2007). It is generally known that the natural variation encountered in wood results from the combined influence of genetic origin and growing environment. In this case, the among-bolt and within-bolt variation must be evaluated. Nowadays, most studies have been primarily focused on the radial (from pith to bark) and longitudinal (from butt to top) variations of poplar wood in terms of anatomical and physical properties, such as fiber morphological features (Fang *et al.* 2006), wood density, and shrinkage (Pliura *et al.* 2005). Little information is available about the variation of the physical and mechanical properties of veneer, which is the basic element of veneer-based panels.

One of the most important properties of lignocellulosic material is density, due to its effect on strength, performance, and the general quality of final products (Anjos *et al.* 2014). Among mechanical properties, the modulus of elasticity (MOE) is one of the most important properties and is widely used as an indicator of the ability to support loads and resist bending deflection (Amishev and Murphy 2008). Thus, studies are needed to better understand the variation of veneer density and MOE and to provide a strategy for grading veneer sheets prior to use. The aim of this study was to evaluate the influence of sample position on poplar veneer density and E_D, and to examine the effect of poplar veneer density on ultrasonic wave velocity. The among-bolt and within-bolt variations were discussed in terms of the density and E_D of veneer.

EXPERIMENTAL

Sampling

Poplar I-72 (*Populus* × *euramericana* cv. I-72), which was the species used in this study, was 8 years old. The bolts were sampled from an LVL mill in Suqian City, Jiangsu Province, P. R. of China (118°18’E, 33°58’N). Seven representative butt bolts (the bottom part of a stem) were randomly selected from a pile of about 100 butt bolts, and seven representative second bolts (the second part of a stem) were obtained following the same approach, *i.e.* selected from a pile of about 100 second bolts. The mean bolt length was approximately 2.55 m, ranging from 2.52 to 2.59 m, which is the common merchantable length of Chinese poplar bolts for veneer-based panels. The mean small-end diameters of butt and second bolts were 24 cm and 25 cm, and ranged from 20 to 30 cm and 20 to 31 cm (Table 1). The moisture content (MC) of each log was determined from the MC samples using the oven-dry method, and ranged from 65 to 78% (on the dry basis).

Table 1. Dimensions of Bolt Specimens

Bolt class	Bolt Code	Length (m)	Diameter (mm)	
			Small-end	Large-end
Butt bolt	B-1	2.57	202	279
	B-2	2.59	203	283
	B-3	2.52	241	311
	B-4	2.57	259	298
	B-5	2.55	263	382
	B-6	2.57	277	400
	B-7	2.50	302	413
	mean	2.55	250	340
Second bolt	S-1	2.53	202	243
	S-2	2.54	204	242
	S-3	2.55	206	248
	S-4	2.53	233	264
	S-5	2.54	264	272
	S-6	2.56	269	301
	S-7	2.58	305	338
	mean	2.55	241	270

Each bolt was first debarked and then crosscut into two segments after its large- and small-end diameters and lengths were measured with a tape and recorded (Table 1), thus producing a total of 28 segments with a length of about 1250 mm. Each segment was peeled into veneer sheets 2.1 mm thick, 40.6 mm wide, and 1250 mm long, with a BQ1513/7 single hydraulic double shaft rotary-peeling veneer lathe. Three relatively complete veneer sheets were proportionally (90%, 50%, and 10% of the radius length, *i.e.* near the bark, in the middle, and near the pith of a bolt) sampled from each segment and then marked sequentially in the order of peeling from bark to pith. Each segment was rotary-peeled until reaching a core of 50 mm in diameter (Fig. 1). A total of 84 veneer sheets were obtained and air-dried, then further dried with a press dryer to achieve a target MC of 7 to 8% through controlling drying time, temperature, and pressure according to the production requirement.

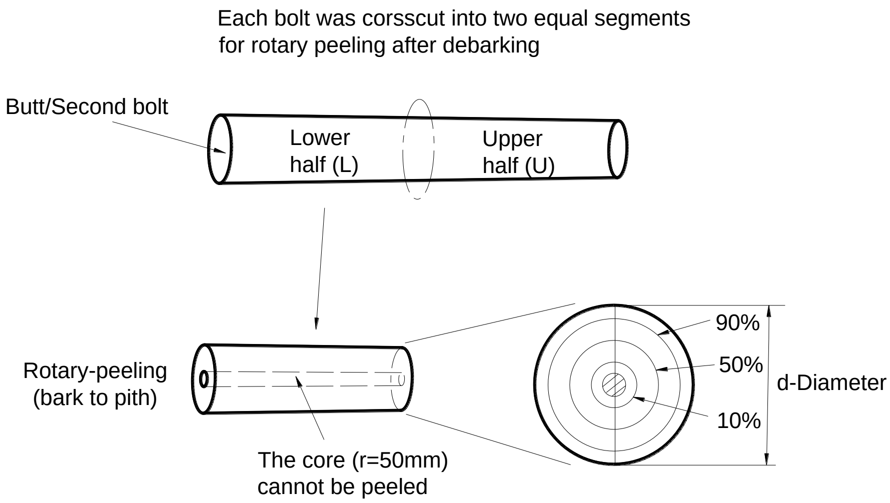


Fig. 1. Bolt sampling scheme

Veneer Density and E_D Measurements

Each veneer sheet was passed through a 2800 DME Digital Metriguard Veneer Tester (Metriguard Inc., Pullman, WA) for ultrasonic non-destructive testing. Because temperature of veneer is known to affect veneer grading (Sandoz 1993), temperature compensation was accomplished by the use of an infrared thermometer that measured the temperature of each sheet. This tester calculated the ultrasonic velocity by measuring ultrasonic propagation time (UPT) in a unit of μs within a given distance along the length of the veneer sheet. The density and MC were determined by using microwave and radio frequency technologies with measurement accuracy of 0.001 g/cm^{-3} and 0.1%, respectively. All of these measurements can be done at a speed up to 130 m/min in a production line.

The E_D of each veneer sheet was therefore determined using the following equation for an isotropic and homogeneous specimen with small lateral dimensions compared with the propagating wavelength (Beall 2000; Achim *et al.* 2011),

$$E_D = \rho c^2 \tag{1}$$

where E_D is the dynamic modulus of elasticity (GPa), ρ is density (g/cm^3), and c is the ultrasonic velocity (km/s).

Statistical Analysis

A multi-factor analysis of variance (ANOVA) was carried out to assess the influence of bolt class (butt and second), individual bolt, longitudinal location, and radial location on the density and E_D. Among these four influencing factors, the factor “individual bolt” was deemed as random effect, and the others were considered as fixed effects. All tests were performed at a level of significance of 0.05 using the software IBM SPSS Statistics 19.0 package (IBM Inc., Chicago, USA).

RESULTS AND DISCUSSION

Relationship between Density and Ultrasonic Wave Velocity

Table 2 summarizes the test results of the poplar veneer sheets in terms of density, ultrasonic wave velocity, and E_D. The average veneer density was 0.440 g/cm^3, ranging from 0.296 to 0.557 g/cm^3. The average ultrasonic wave velocity of veneer was 4.75 km/s, ranging from 3.89 to 5.37 km/s. As a result, the average E_D of poplar veneer was 10.05 GPa with a relatively higher coefficient of variation (COV) of approximately 20.13%.

Table 2. Summary of Results from Ultrasonic Tests on 84 Poplar Veneer Sheets

	Density	Velocity	E_D*
Min	0.296 g/cm^3	3.89 km/s	4.55 GPa
Max	0.557 g/cm^3	5.37 km/s	13.86 GPa
Average	0.440 g/cm^3	4.75 km/s	10.05 GPa
COV*	11.61%	7.29%	20.13%
*E_D dynamic modulus of elasticity, COV coefficient of variation			

Comparing the two bolt classes, the average density values of poplar veneer sheets from butt and second bolts were 0.427 and 0.454 g/cm^3 (Table 3), respectively, and the difference between them was generally small. The density of veneer sheets peeling from the second bolt (0.454 g/cm^3) was about 6.3% higher than that of the butt bolts (0.427 g/cm^3). The difference between the E_D values of poplar veneer sheets peeling from the butt bolt and second bolt, however, was relatively large, such that the E_D of veneer sheets peeling from the second bolt (10.61 GPa) was approximately 12% higher than that of the butt bolt (9.48 GPa), and the variation within the butt bolts (2.34 GPa) was larger than that within the second bolts (1.46 GPa) (Table 3).

Table 3. Average Density and E_D Values of Veneer Sheets from Two Classes of Bolts

Bolt class	Density (g/cm^3)	E_D* (GPa)
Butt	0.427±0.057	9.48±2.34
Second	0.454±0.041	10.61±1.46
*E_D dynamic modulus of elasticity		

The ultrasonic wave velocity of veneer was found to be weakly correlated to the density (Fig. 2). The weak correlation between density and wave velocity can be explained by the fact that density is a measure of the relative amount of solid cell wall (Machado *et al.* 2014); wave velocity depends on not only the relative amount of solid cell wall, but also the microfibril angle (MFA) of the cell wall (Yang and Evans 2003; Lasserre *et al.* 2009), the grain angle (Hernández 2007), and some other factors (Hasegawa *et al.* 2011; Liu *et al.* 2014) that influence the propagation of wave. In addition, the correlation between density and wave velocity is highly dependent on species (Baar *et al.* 2012; Machado *et al.* 2014).

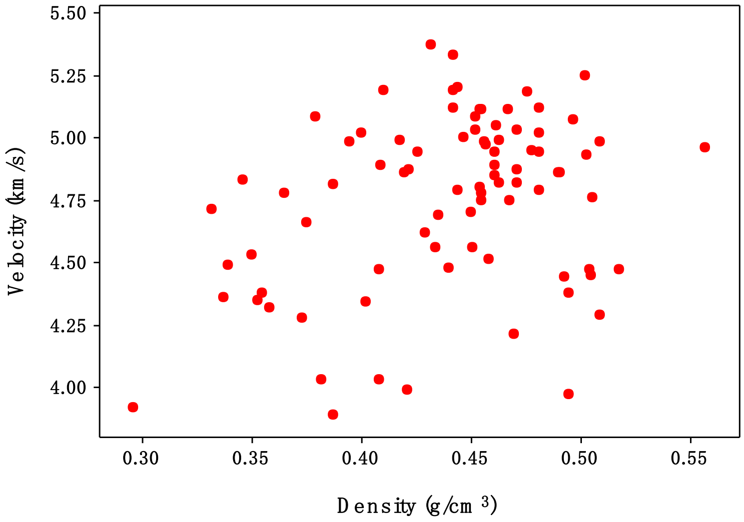


Fig. 2. The relationship between density and ultrasonic wave velocity of 84 poplar veneer sheets

Variation of Veneer Density and *E*D

From Table 4, it can be seen that bolt class (*i.e.*, butt or second bolt) was not a significant factor influencing the variation of veneer density of poplar bolts with similar-sized small-end diameters. The among-bolt variation, however, played a significant role in the variability (P-value is 0.002), suggesting that the genetic difference of each individual bolt to a large degree caused the variation of veneer density. As a result, the selection of bolts, rather than of bolt classes, was an important determinant of poplar veneer sheet quality in the production of veneer-based panels.

Table 4. Influence of Different Factors on Density and *E*D of Veneer

Variation source*	df*	Density			*E*D*		
		Mean square	F-value	P-value	Mean square	F-value	P-value
Bolt class	1	.015	1.422	.256	26.782	1.542	.238
Bolt (Bolt class)	12	.011	8.102	.002	17.364	8.755	.000
Longitudinal	1	.000	.301	.593	12.608	10.843	.006
Longitudinal* Bolt class	1	4.876E-5	.038	.849	1.636	1.407	.259
Longitudinal* Bolt (Bolt class)	12	.001	1.602	.148	1.163	3.125	.006
Radial	2	.005	6.084	.007	17.154	13.851	.000
Radial* Bolt class	2	.002	2.023	.154	.737	.595	.559
Radial* Bolt (Bolt class)	24	.001	1.059	.439	1.238	3.329	.001

**E*D – dynamic modulus of elasticity, df – degrees of freedom, Bolt class –butt or second bolt, Bolt (Bolt class) – Bolt nested within Bolt class, Longitudinal – the longitudinal position of a bolt (*i.e.* upper or lower segment), Longitudinal* Bolt class – the interaction between Longitudinal and Bolt class, Longitudinal* Bolt (Bolt class) – the interaction between Longitudinal and Bolt (Bolt class), Radial – the radial position of a bolt (90%, 50%, or 10% of the radius length), Radial* Bolt class – the interaction between Radial and Bolt class, and Radial* Bolt (Bolt class) – the interaction between Radial and Bolt (Bolt class).

Within bolts, the radial variation rather than the longitudinal variation was the important source of veneer density variation. The radial variation was independent of "Bolt class" and "Bolt" see Table 4, in which, "Radial* Bolt class" means the interaction between Radial and Bolt class and "Radial* Bolt (Bolt class)" the interaction between Radial and Bolt which is nested within Bolt class.

Table 5. Influence of Bolt Classes (Butt and Second) among Bolts and Longitudinal and Radial Position within-bolt for Density and E_D of Poplar Veneer

Variation source	df*	Density			E_D*		
		Mean square	F-value	P-value	Mean square	F-value	P-value
Butt bolt							
Bolt	6	.015	16.057	.000	25.814	24.529	.000
Longitudinal	1	8.010E-5	.085	.772	11.639	11.060	.002
Radial	2	.006	6.252	.005	12.341	11.727	.000
Second bolt							
Bolt	6	.006	7.356	.000	8.909	13.929	.000
Longitudinal	1	.000	.404	.529	2.590	4.049	.053
Radial	2	.001	1.135	.334	5.535	8.653	.001

*E_D – dynamic modulus of elasticity, df – degrees of freedom, Bolt – Bolt individual, and Longitudinal – the longitudinal position of a bolt (*i.e.* upper or lower segment),

When considering each bolt class individually, ANOVA results (Table 5) showed that the longitudinal position for butt bolts was not a significant factor influencing veneer density, and the radial position showed a weak but significant impact. From the main effects plot (Fig. 3c), it can be seen that veneer density decreased from pith to bark. For second bolts, neither longitudinal nor radial variation of veneer density was significant. These results did not conform with several previous studies of this species in Canada, where it was reported that the wood density of poplars tended to be high at the bottom of the tree, decreased to a minimum at mid-height, then increased again near the top of the tree, and, in the radial direction, wood density was higher near the pith, dropped at mid-diameter, and increased in the mature wood zone (at all heights) (Yanchuk *et al.* 1983; Hernández *et al.* 1998; Pliura *et al.* 2005). In fact, bolts in the present study seemed to be entirely composed of juvenile wood, as the age of demarcation between juvenile and mature wood of Chinese poplar is approximately 10 years (Jiang and Yin 2003). Wang and Gong (1994) have also reported that the wood density of Chinese poplar has no correlation with the growth rate, resulting in wood density remaining nearly constant in the radial direction. In conclusion, neither the radial nor the longitudinal variation was a significant factor influencing the veneer density of the Chinese poplar in the juvenile phase.

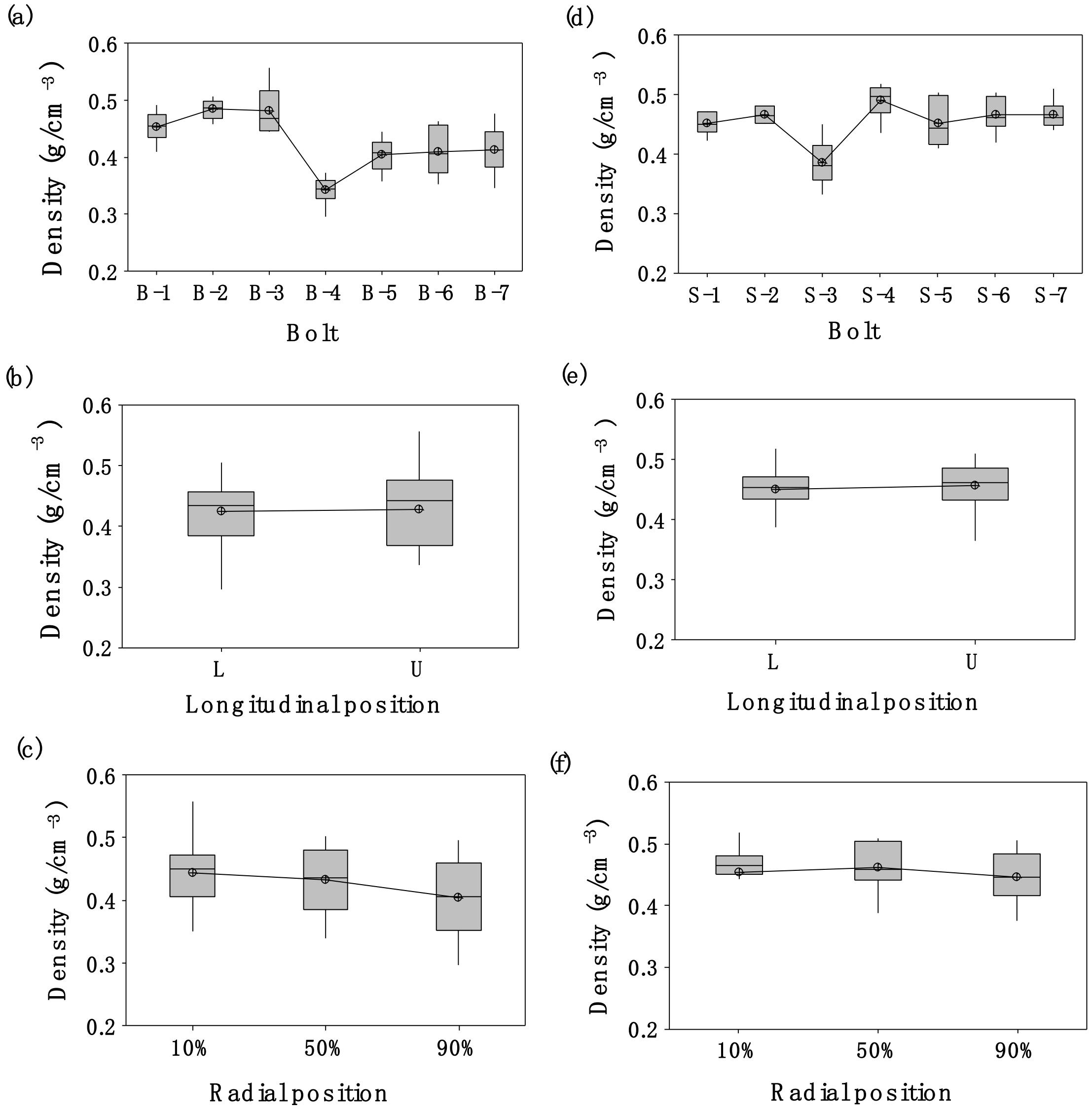


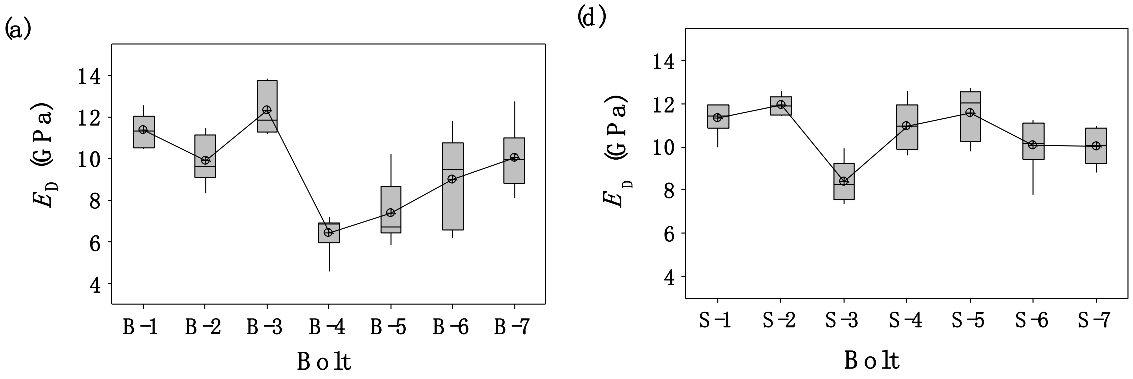
Fig. 3. Main effects (Bolt, Longitudinal, and Radial) plot for the veneer density from (a, b, c) butt and (d, e, f) second bolt

Like veneer density, the among-bolt variation within a bolt class was an important source of the variation for veneer E_{D}, but bolt class was not. Within bolts, both the radial and the longitudinal variation of veneer E_{D} were significant. These two variations were independent of bolt class but varied between bolts (Table 4). In all cases, the among-bolt variation was a significant source of variation (P = 0.002 and 0.000 for veneer density and E_{D}, respectively). As a result, selection of bolts was important in determining the veneer quality of poplar in the production of veneer-based panels.

With regard to bolt classes, ANOVA results (Table 5) revealed that, as for butt bolt, the longitudinal and radial variations of E_{D} were both highly significant (P = 0.002 and 0.000, respectively). As for the second bolt, only radial variation was significant. In both bolt classes, E_{D} modestly decreased from the 10% to 50% radial position, but substantially decreased to 90% of the distance from pith to bark (Fig. 4c, f). The longitudinal variation was highly significant for the butt bolts (P = 0.002), though not for the second bolts. From Fig. 4b, it appears that the E_{D} of poplar veneer increased from the lower to upper half for butt bolt. This discrepancy had a link with the difference between the two ends of individual bolt specimens (Table 1). Table 1 shows that the diameter difference of the butt bolts was obviously larger than that of the second bolts. The peeling of veneer occurred on a cylindrical surface. In general, if the diameter difference between the two ends of the bolt was larger, the grain angle of its veneer increased in the longitudinal direction in which the ultrasonic wave propagated. The direction of wave propagation (*i.e.*, grain direction – longitudinal, radial, or tangential) has the greatest influence on velocity. The wave velocity in the longitudinal direction is larger than that in other two directions (Gerhards 1982; Smith 2001). The larger the grain angle of the veneer in longitudinal direction, the more time is needed for a wave to propagate, thus a lower E_D of veneer results. This analysis attempted to explain the pattern of the radial variation, relying on the fact that the grain angle in each veneer sheet increased from pith to bark.

Overall, the radial position had a more significant influence on the E_D of Chinese poplar (P = 0.000 and 0.001 for veneer E_D of butt and second bolt, respectively) than the longitudinal position. A similar pattern was found by Machado *et al*. (2014), who reported that, for blackwood (*Acacia melanoxylon* R. Br.), wood density varied considerably over the radial profile but very little along the height direction. As for the mechanical properties of blackwood, the significant influence on variation was the radial position, and no significant influence on tree height was found.

The analysis of radial and longitudinal variations within the merchantable trunk is another important study in the selection of veneer in order to improve the quality of veneer-based panels. The above analysis suggested that a large difference in the diameters of two ends of a bolt resulted in a low E_D for poplar veneer (Table 1 and 3). All in all, the bolt with high wave velocity and small difference in diameter between two ends gives high quality veneer.



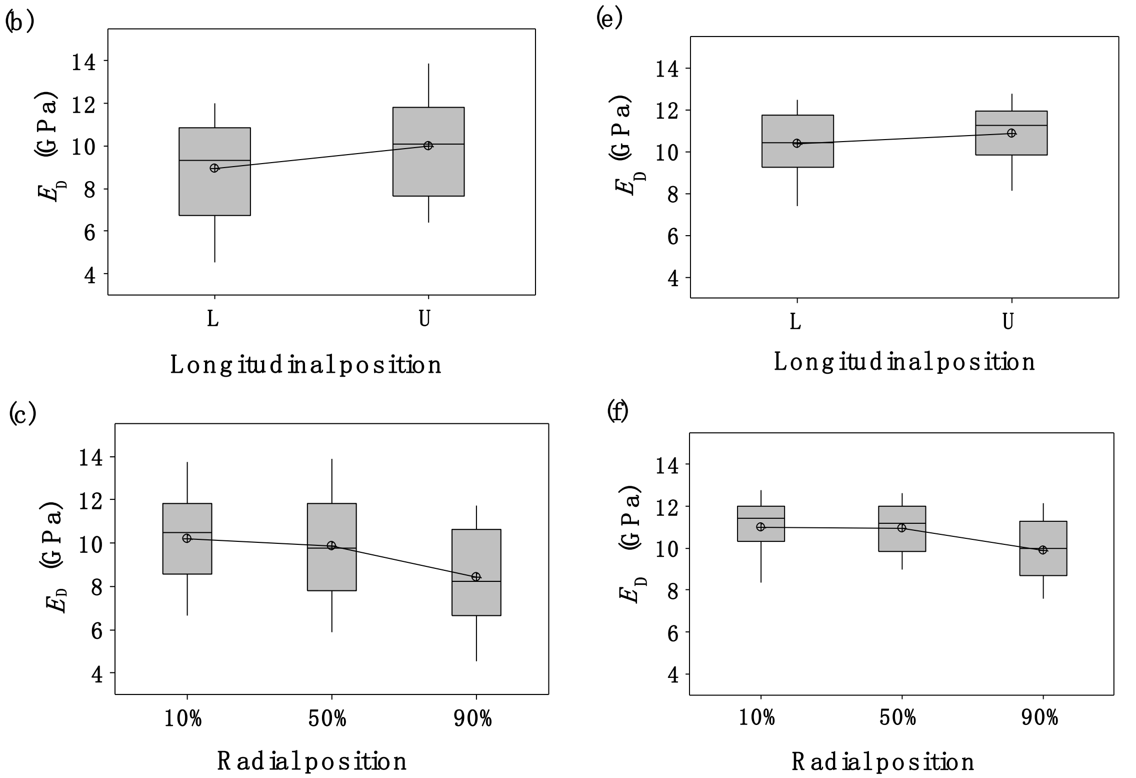


Fig. 4. Main effects (Bolt, Longitudinal, and Radial) plot for veneer E_D from (a, b, c) butt and (d, e, f) second bolt

Veneer Sheets Grading Based on E_D

Figure 5 shows the distribution of ultrasonic dynamic MOE for 84 poplar veneer sheets. The average veneer E_D was 10.05 GPa with a standard deviation of 2.022 GPa.

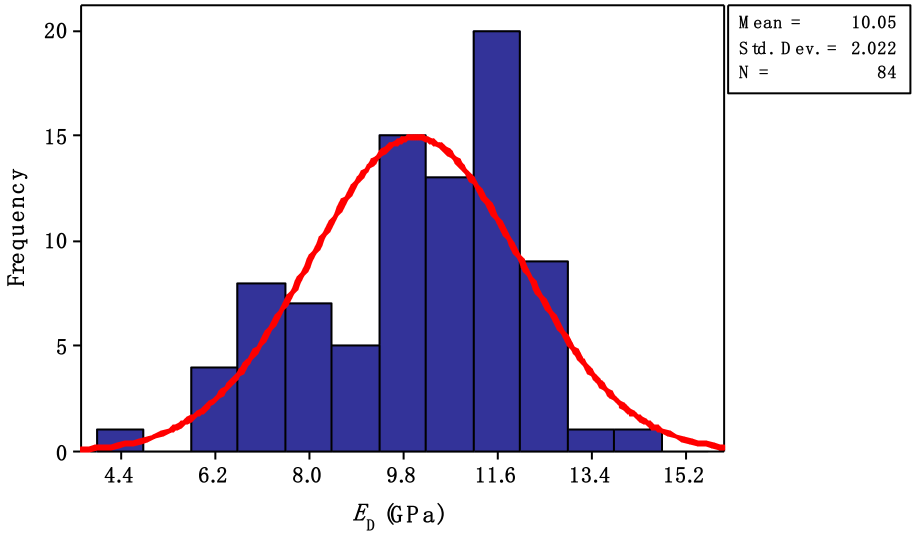


Fig. 5. Sample distribution of veneer E_D

As illustrated in the previous study by the authors (Zhou *et al.* 2013), the correlation of E_D between LVL and veneer was in good agreement, with an R^2 of 0.93. On average, Wang and Dai (2005) suggested that a conversion factor of 1.15 could be used to link poplar product E_D with veneer E_D using normal pressing schedules for a panel compression ratio (CR) ranging from 7 to 13%. According to GB/T 20241-2006 (2006), the Chinese "Laminated Veneer Lumber" standard, there are requirements for both the average MOE and minimum MOE for each grade of LVL. As a result, two constraints can be established for each veneer stress grade: one for the average veneer E_D, and the other for the minimum veneer E_D. Table 6 gives the veneer E_D requirements for each stress grade by dividing the corresponding LVL grade by the conversion factor of 1.15.

Table 6. Veneer E_D Requirements for Fabricating Chinese Commercial LVL Grades

Target LVL products	Required MOE of LVL* (GPa)		Required E_D of veneer* (GPa)		Veneer stress grade
	Average	Minimum	Average	Minimum	
180E	18.0	15.0	15.6	13.0	G1
160E	16.0	14.0	14.0	12.2	
140E	14.0	12.0	12.0	10.5	
120E	12.0	10.5	10.5	9.0	G2
110E	11.0	9.0	9.6	8.0	
100E	10.0	8.5	8.7	7.5	
90E	9.0	7.5	7.8	6.5	G3
80E	8.0	7.0	7.0	6.0	
<80E LVL	<8.0	<7.0	<7.0	<6.0	G4 (or rejected)

*LVL (laminated veneer lumber), MOE (modulus of elasticity), E_D (dynamic modulus of elasticity)

Based on the above analysis, the grade yields of veneer sheets in terms of E_D are summarized in Table 7. There are four veneer grades with different E_D requirements. Based on the range of each veneer grade, the thresholds of veneer E_D are estimated to determine the number of veneer sheets and veneer grade yield. It can be estimated that the veneer grade yields were approximately 45.2% of G1, 39.3% of G2, 13.1% of G3, and 2.4% of G4. G1 can be used to manufacture structural LVL, both G2 and G3 with a grade recovery of 52.4% can be used for nonstructural purpose, whereas G4 should be rejected. The low grade recovery of the high grade was due to the significant variation of density and E_D of poplar veneer.

Table 7. Estimated Grade Recovery of Poplar Veneer in Terms of E_D

Chinese veneer Stress grade	Grading threshold* (GPa)	Number of veneer sheets	Grade recovery (%)
G1	$E_D \geq 10.5$	38	45.2%
G2	$7.5 < =E_D < 10.5$	33	39.3%
G3	$6.0 < =E_D < 7.5$	11	13.1%
G4	$E_D < 6.0$	2	2.4%

*E_D dynamic modulus of elasticity

CONCLUSIONS

1. A weak correlation between the density and ultrasonic wave velocity of poplar veneer was observed.
2. The bolt class (*i.e.*, butt or second bolt) was not a significant factor impacting the variation of the veneer density and the E_D of poplar bolts with similarly sized small-end diameters. The among-bolt variation significantly contributed to the variability.
3. The within-bolt position had a limited impact on the veneer density (P>0.05). Within the bolt, neither the radial nor the longitudinal variation was a significant factor influencing the density of veneer (P>0.05). The variation of E_D of the poplar veneer was larger in the radial direction (P = 0.000 and 0.001 for veneer E_D of butt and second bolt, respectively) than in the longitudinal direction.
4. The larger difference in diameter between two ends of a bolt resulted in a lower veneer E_D. This suggests that the bolt having a higher wave velocity and a smaller difference in diameter could produce better quality veneer.
5. The grade yields of the poplar veneer studied were, in terms of the Chinese Standard "Laminated Veneer Lumber", 45.2% of G1, 39.3% of G2, 13.1% of G3, and 2.4% of G4. G1 can be used to manufacture structural LVL. Both G2 and G3 with a grade recovery of 52.4% can be used for nonstructural purpose, whereas G4 should be rejected.

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REFERENCES CITED

Achim, A., Paradis, N., Carter, P., and Hernández, R. E. (2011). "Using acoustic sensors to improve the efficiency of the forest value chain in Canada: A case study with laminated veneer lumber," *Sensors* 11(6), 5716-5728. DOI: 10.3390/s110605716

Amishev, D., and Murphy, G. E. (2008). "In-forest assessment of veneer grade Douglas-fir logs based on acoustic measurement of wood stiffness," *Forest Products Journal* 58(11), 42-47.

Anjos, O., Rodrigues, C., Morais, J., and Pereira, H. (2014). "Effect of density on the compression behaviour of cork," *Materials and Design* 53(1), 1089-1096. DOI: 10.1016/j.matdes.2013.07.038

Baar, J., Tippner, J., and Gryc, V. (2012). "The influence of wood density on longitudinal wave velocity determined by the ultrasound method in comparison to the resonance longitudinal method," *European Journal of Wood and Wood Products*, 70(5), 767-769. DOI: 10.1007/s00107-011-0550-2

Beall, F. C. (2000). "Subsurface sensing of properties and defects in wood and wood products," *Sensing and Imaging,* 1(2), 181-204. DOI: 10.1023/A:1010135009428

Boever, L. D., Vansteenkiste, D., Acker, J. V., and Stevens, M. (2007). "End-use related physical and mechanical properties of selected fast-growing poplar hybrids (*Populus trichocarpa* × *P. deltoides),*" *Annals of Forest Science* 64(6), 621-630. DOI: 10.1051/forest:2007040

Brashaw, B. K., Wang, X., Ross, R. J., and Pellerin, R. F. (2004). "Relationship between stress wave velocities of green and dry veneer," *Forest Products Journal* 54(6), 85-89.

Burdurlu, E., Kılıç, M., Ilce, A. C., and Uzunkavak, O. (2007). "The effects of ply organization and loading direction on bending strength and modulus of elasticity in laminated veneer lumber (LVL) obtained from beech (*Fagus orientalis* L.) and lombardy poplar (*Populus nigra* L.)," *Construction and Building Materials* 21(8), 1720-1725. DOI: 10.1016/j.conbuildmat.2005.05.002

Chauhan, S. S., and Walker, J. C. F. (2006). "Variations in acoustic velocity and density with age, and their interrelationships in radiata pine," *Forest Ecology and Management* 229(1-3), 388-394. DOI: 10.1016/j.foreco.2006.04.019

Fang, S., Yang, W., and Tian, Y. (2006). "Clonal and within-tree variation in microfibril angle in poplar clones," *New Forests* 31(3), 373-383. DOI: 10.1007/s11056-005-8679-7

GB/T 20241-2006 (2006). "Laminated veneer lumber," Standardization Administration of China, Beijing, China.

Gerhards, C. C. (1982). "Longitudinal stress waves for lumber stress grading: Factors affecting applications: State of the art," *Forest Products Journal,* 32(2), 20-25.

Hasegawa, M., Takata, M., Matsumura, J., and Oda, K. (2011). "Effect of wood properties on within-tree variation in ultrasonic wave velocity in softwood," *Ultrasonics* 51(3), 296-302. DOI: 10.1016/j.ultras.2010.10.001

Hernández, R. E. (2007). "Influence of accessory substances, wood density and interlocked grain on the compressive properties of hardwoods," *Wood Science and Technology* 41, 249-265. DOI: 10.1007/s00226-006-0114-5

Hernández, R. E., Koubaa, A., Beaudoin, M., and Fortin, Y. (1998). "Selected mechanical properties of fast-growing poplar hybrid clones," *Wood and Fiber Science* 30(2), 138-147.

Jiang, X. M., and Yin, Y. F. (2003). "Variation within tree of wood anatomical properties and basic density of I-214 poplar in Beijing area and their relationship modeling equations [in Chinese]," *Scientia Silvae Sinicae* 39(6), 115-121. DOI: 10.11707/j.1001-7488.20030619

Kılıç, M. (2011). "The effects of the force loading direction on bending strength and modulus of elasticity in laminated veneer lumber (LVL)," *BioResources* 6(3), 2805-2817. DOI: 10.15376/biores.6.3.2805-2817

Lasserre, J. P., Mason, E. G., Watt, M. S., and Moore, J. R. (2009). "Influence of initial planting spacing and genotype on microfibril angle, wood density, fibre properties and modulus of elasticity in *Pinus radiata* D. Don corewood," *Forest Ecology and Management* 258(9), 1924-1931. DOI: 10.1016/j.foreco.2009.07.028

Liu, H., Gao, J., Chen, Y., and Liu, Y. (2014). "Effects of moisture content and fiber proportion on stress wave velocity in cathay poplar (*Populus cathayana*) wood," *BioResources* 9(2), 2214-2225. DOI: 10.15376/biores.9.2.2214-2225

Machado, J. S., Louzada, J. L., Santos, A. J. A., Nunes, L., Anjos, O., Rodrigues, J., Simões, R. M. S., and Pereira, H. (2014). "Variation of wood density and mechanical properties of blackwood (*Acacia melanoxylon* R. Br.)," *Materials and Design* 56(4), 975-980. DOI: 10.1016/j.matdes.2013.12.016

Pliura, A., Yu, Q., Zhang, S. Y., Mackay, J., Périnet, P., and Bousquet, J. (2005). "Variation in wood density and shrinkage and their relationship to growth of selected young poplar hybrid crosses," *Forest Science* 51(5), 472-482.

Smith, W. R. (2001). "Wood: Acoustic properties," in: *Encyclopedia of Material Science & Technology (Second Edition)*, Buschow K. H. J., Elsevier, Oxford, UK, pp. 9578-9583. DOI: 10.1016/B0-08-043152-6/01733-2

Ross, R. J. (2002). "Nondestructive evaluation of green materials - Recent research and development activities," in: *Nondestructive Evaluation of Wood* (FPL-GTR-238), Forest Products Laboratory, Madison, WI, pp. 149-171.

Sandoz, J. L. (1993). "Moisture content and temperature effect on ultrasound timber grading," *Wood Science and Technology,* 27(5), 373-380. DOI: 10.1007/BF00192223

Schimleck, L. R., Evans, R., and Matheson, A. C. (2002). "Estimation of *Pinus radiata* D. Don clear wood properties by near-infrared spectroscopy," *Journal of Wood Science* 48(2), 132-137. DOI: 10.1007/BF00767290

Wang, B. J., and Dai, C. (2005). "Hot-pressing stress graded aspen veneer for laminated veneer lumber (LVL)," *Holzforschung* 59(1), 10-17. DOI: 10.1515/HF.2005.002

Wang, W. H., and Gong, M. (1994). "Study on the definition of juvenile wood and mature wood of *Populous delloules* and *Paulownia elomgata* [in Chinese]," *China Forestry Science and Technology* 1, 18-20. DOI: 10.13360/j.issn.1000-8101.1994.01.010

Wei, P. X., Wang, B. J., Zhou, D., Dai, C., Wang, Q., and Huang, S. (2013). "Mechanical properties of poplar laminated veneer lumber modified by carbon fiber reinforced polymer," *BioResources* 8(4), 4883-4898. DOI: 10.15376/biores.8.4.4883-4898

Wu, Z. H., Furuno, T., and Zhang, B. Y. (1998). "Properties of curved laminated veneer lumber made from fast-growing species with radiofrequency heating for use in furniture," *Journal of Wood Science* 44(4), 275-281. DOI: 10.1007/BF00581307

Yanchuk, A. D., Dancik, B. P., and Micko, M. M. (1983). "Intraclonal variation in wood density of trembling aspen in Alberta," *Wood and Fiber Science* 15(4), 387-394.

Yang, J. L., Evans, R. (2003). "Prediction of MOE of eucalypt wood from microfibril angle and density," *Holz als Roh- und Werkst* 61(6), 449-452. DOI: 10.1007/s00107-003-0424-3

Zhou, D. G. (2006). "Research and development of poplar composites in Jiangsu province [in Chinese]," *Journal of Nanjing Forestry University (Natural Sciences Edition)* 30(4), 1-4. DOI: 10.3969/j.issn.1000-2006.2006.04.001

Zhou, Z. R., Zhao, M. C., Wang, Z., Wang, B. J., and Guan, X. (2013). "Acoustic testing and sorting of Chinese poplar logs for structural LVL products," *BioResources* 8(3), 4101-4116. DOI: 10.15376/biores.8.3.4101-4116

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