Block Shear Strength and Delamination of Cross-Laminated Timber Fabricated with Japanese Larch

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Process parameters of cross-laminated timber (CLT) fabricated with Japanese larch were evaluated. The process parameters were designed by using an orthogonal test including pressure, glue consumption, and adhesive. Both delamination and block shear tests were conducted on CLT in accordance with GB/T 26899 (2011). The results showed that the optimum process parameters were $A_2B_3C_2$ including pressure (1.2 MPa), glue consumption (200 g/m^2), and amount of adhesive (one-component polyurethane). The weight loss and moisture absorption increased when the temperature increased, but the block shear strength decreased as the temperature was raised from 20 °C to 230 °C.

Keywords: Block shear strength; Delamination; Cross-laminated timber; Japanese larch; Heat treatment

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INTRODUCTION

With the recent rapid development of wooden structures in China, the demand for wood resources is increasing (Gong *et al*. 2016a). However, due to logging bans in the natural forests, effective in 2015 in China, wood resources have been in serious shortage. Therefore, plantation resources need to be developed and utilized in China (Gong *et al*. 2016b). Japanese larch (*Larix kaempferi* Carr.) is the main plantation tree species in China. It is distributed from 35 to 38° N and 136 to 140° E (Zhu *et al*. 2015a). Japanese larch has many advantages, such as fast growth, good mechanical performance, easy cultivation, and decay resistance. It has matured in Liaoning, Hubei, and Sichuan provinces (Xing *et al*. 2012; Zhang 2013; Zhu *et al*. 2015b). However, the lack of manufacturing engineered wood products using Japanese larch limits its application in building structures. Therefore, it is useful to explore the use of Japanese larch in cross-laminated timber applications for building structures as a green building material.

Cross-laminated timber (CLT) is a prefabricated solid engineered wood product dedicated to structural applications, and it is composed of orthogonally bonded layers of solid sawn lumber or structural composite lumber using adhesive, nails, or wooden dowels (Sturzenbecher *et al*. 2010; Laguarda and Espinoza 2015). CLT is an innovative-engineered wood product that was introduced in the early 1990s in Austria and Germany (Karacabey and Douglas 2013).

Compared with the raw material of other engineered wood products, the advantages of CLT are the homogenized mechanical and physical properties, which have gained popularity in residential and non-residential construction in roof, floor, and wall applications in Europe and North America (Zhou *et al*. 2014; Wang *et al*. 2015). In particular, CLT can be used to build high-rise wood structure buildings. For example, the 9-story CLT building named “Bridport House” was built in London. The bottom of the building is reinforced concrete, and the other levels are constructed of CLT (Gong and Ren 2016). An 18-story CLT apartment is being built at the University of British Columbia. It is the tallest wooden structure building in the world at present. However, there are no manufacturers of CLT in China, and it is still in the early stages of CLT research in universities and scientific research institutes in China. At the same time, there are significant differences in CLT production process because different countries have different tree species and adhesives. Therefore, parameters involved in the production of CLT fabricated with the local tree species, including pressure, glue consumption, and adhesive, should be explored.

As an innovative engineered wood product, the physical and mechanical properties of CLT have been studied. Previous studies were focused on the bending strength, rolling shear strength, numerical model, and connection performance for CLT (Shen *et al*. 2013; Schneider *et al*. 2014; Saavedra *et al*. 2015). However, there is little information on delamination and block shear strength of CLT treated by impregnation, boiling, and heat. The block shear strength is an important evaluation index of process parameters (Sikora *et al*. 2016). However, there is currently no suitable standardized test method for determining the block shear strength for CLT.

The objective of this study was to determine process parameters of CLT fabricated with Japanese larch including pressure, glue consumption, and adhesive. The process parameters were designed using an orthogonal test. The effect of heat treatment on the performance of CLT was studied. The research on the process parameters will provide basic data for the application of CLT fabricated with Japanese larch in building structures in China.

EXPERIMENTAL

Materials

Japanese larch was harvested from Dagujia Forest Farm of Liaoning Province, China. The diameters of logs were 250 to 320 mm. A total of 351 logs with 3 m length were cut into dimension lumber using the four sawing method; the lumber sizes were 25 mm in thickness and 90 mm in width. The average density and moisture content of the lumber were 0.615 ± 0.07g/cm^3 and 12 ± 0.96%, respectively. To ensure random and representative samples, 150 lumber pieces were cut to 450 mm in length to manufacture CLT.

Three kinds of adhesives including emulsion polymer isocyanate (Guangxi Jiamei Environmental Protection Co., Ltd., Guangxi, China; 30% solids content, 10 Pa.s viscosity), one-component polyurethane (Haerbin Chengfeng Adhesive Co., Ltd., Haerbin, China; 100% solids content, 9 Pa.s viscosity), and phenol-resorcinol formaldehyde (Shenyang Aike Haobo Chemical Co., Ltd., Shenyang, China; 65% solids content, 15 Pa.s viscosity, pH 7.5) were selected.

The design of process parameters using an orthogonal test is shown in Table 1. Finally, the dimensions for the orthogonally bonded three layers of CLT were 450 (length) × 450 (width) × 75 mm (thickness).

The dimensions of the specimens used for block shearing testing are shown in Fig. 1, and the dimensions of the specimens used for delamination testing were 80 (length) × 75 (width) × 75 mm (thickness).

Table 1. $L_9\,(3)^3$ Orthogonal Test Design

Matrix	Factors					
	(A) Glue consumption (g/m^2)		(B) Pressure (MPa)		(C) Adhesive	
1	A_1	275	B_1	0.8	C_1	EPI
2	A_1	150	B_2	1.0	C_2	PUR
3	A_1	375	B_3	1.2	C_3	PRF
4	A_2	200	B_1	0.8	C_2	PUR
5	A_2	400	B_2	1.0	C_3	PRF
6	A_2	325	B_3	1.2	C_1	EPI
7	A_3	425	B_1	0.8	C_3	PRF
8	A_3	375	B_2	1.0	C_1	EPI
9	A_3	250	B_3	1.2	C_2	PUR

Note: EPI, PUR, and PRF represent emulsion polymer isocyanate, one-component polyurethane, and phenol-resorcinol formaldehyde, respectively.

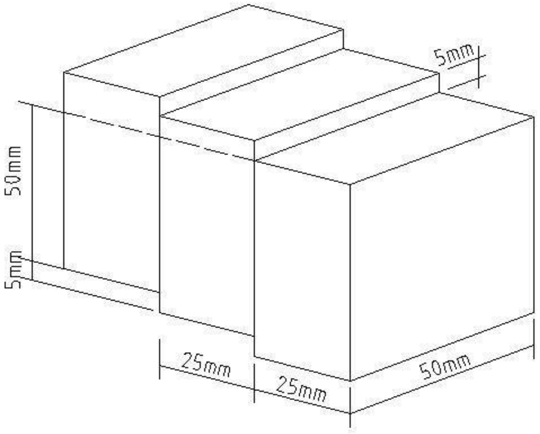

Fig. 1. Dimensions of the specimens for block shearing testing

Heat Treatment

The samples were placed in a drying oven for 2 h at 20 °C, 50 °C, 80 °C, 110 °C, 140 °C, 170 °C, 200 °C, or 230 °C. All specimens were conditioned at 20 °C and 65% relative humidity (RH) for 24 h. The weight loss after heat treatment was calculated using following equation,

$$WL = \frac{m_0 - m_1}{m_0} \times 100\% \tag{1}$$

Moisture absorption was estimated by the following equation,

$$MA = \frac{m_2 - m_1}{m_1} \times 100\% \tag{2}$$

where m_0 is the initial mass of the sample before heat treatment, m_1 is the oven-dry mass of the sample after heat treatment, and m_2 is the mass of treated samples at 20 °C and 65% relative humidity (RH) for 24 h.

Static Test Methods

The block shear tests were performed in accordance with GB/T 26899 (2011; Fig. 2). The loading speed was adjusted to 5 mm/min for block shearing testing. The specimens were tested using an Instron 5582 machine (50 KN load limit; Instron Corporation, Grove City, USA), and the maximum load was taken as the failure load. The block shear strength of CLT was calculated using following equation,

$$\sigma = \frac{F_{\max}}{bt} \tag{3}$$

where σ is the block shear strength (MPa), $F_{\max}$ is the maximum block shear force applied to the specimens during the test (N), b is the width of the shear area (mm), and t is the length of the shear area (mm).

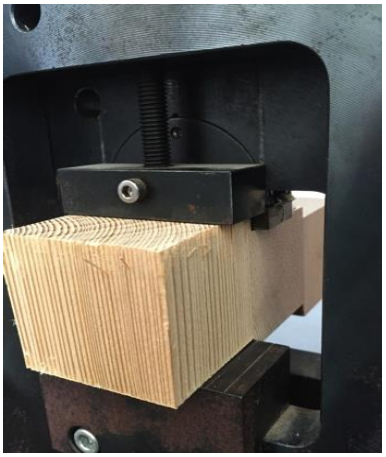

Fig. 2. Test set-up of block shear strength

The delamination tests were performed in accordance with GB/T 26899 (2011). The delamination tests included two methods: impregnation cycle and boiling cycle. The samples of impregnation cycle were covered in water at a temperature of 10 to 25 °C for 24 h. The samples of boiling cycle were covered in water at a temperature of 100 °C for 4 h and then removed to water at a temperature of 10 to 25 °C for 1 h. After impregnation and boiling treatment, all samples were placed in a drying oven at 70 ± 3°C. When the test specimens had returned to within 100 to 110% of their original test weight, the delamination was measured. The delamination of CLT was calculated using following equation,

$$p = \frac{l}{L} \times 100\% \tag{4}$$

where p is delamination percentage of CLT (%), L is the length of glue line (mm), and l is the stripping length of glue line (mm).

Range Analysis

Range analysis can be used to estimate the most significant factors, determining the optimum technological parameters (Zhao 2008). The formula can be expressed as follows,

$$\begin{aligned} K_{ij} &= \frac{(\sum_{n=1}^{m} y_{ij})}{m} \qquad \{i = 1,2,3 \ldots m, j = 1,2,3 \ldots m\} \\ R_j &= \max K_{ij} - \min K_{ij} \end{aligned} \tag{5}$$

where y_{ij} is the experiment data corresponding to the i level of the j column, m the numbers of i level, K_{ij} is the mean value of y_{ij}, R_j is the range value of the j column. The greater R_j indicated the factor corresponding to the j column had greater influence on the experimental results.

RESULTS AND DISCUSSION

Delamination

Delamination is defined as the separation of layers at the interface between the adhesive and the adherent. It is an important index to evaluate bonding properties. The mean values of delamination for CLT in the different conditions are shown in Table 2. The delamination of 1 cycle for impregnation and boiling was obviously lower than that of 2 cycles, and the minimum delamination in the four different conditions were 0, 6.2, 4.3, and 11.3%, respectively. However, the best technological parameters could not be selected based only on these outcomes in Table 2. Therefore, the experimental data for delamination were analyzed using range analysis and *K* and *R* values listed in Table 3.

Table 2. Delamination of CLT in Different Conditions

Test No.	Delamination (%)										
	Parameters			Impregnation				Boiling			
	A	B	C	1 cycle		2 cycles		1 cycle		2 cycles	
				Max	Mean	Max	Mean	Max	Mean	Max	Mean
1	A_1	B_1	C_1	84.5	15.3	100	21.3	38.2	11.9	100	29.8
2	A_1	B_2	C_2	0	0	45.8	6.2	44.7	4.3	56.5	11.3
3	A_1	B_3	C_3	40.2	18.3	100	41.7	83.4	15.8	85.9	37.8
4	A_2	B_1	C_2	50.6	2.5	53.4	16.1	79.9	6.2	86.7	18.1
5	A_2	B_2	C_3	72.1	33.4	100	46.1	100	15.6	100	32.7
6	A_2	B_3	C_1	45.8	7.3	100	21.1	100	16.9	100	22.3
7	A_3	B_1	C_3	80.7	24.8	100	44.0	100	21.3	100	47.8
8	A_3	B_2	C_1	43.3	4.1	100	24.5	80.4	5.2	87.5	11.4
9	A_3	B_3	C_2	41.4	2.1	79.1	15.5	66.3	7.9	91.1	14.6

According to the R-values shown in Table 3, the influence on the mean delamination of CLT in the different conditions decreased in the order: C >B >A. The adhesive had the most influence on delamination. The delamination of CLT in the different conditions decreased at first and then increased as the pressure increased from 0.8 MPa to 1.2 MPa. The glue consumption also influenced the outcomes.

Table 3. Range Analysis of Experimental Data for Delamination

Statistical parameter	Impregnation						Boiling					
	1 cycle			2 cycles			1 cycle			2 cycles		
	A	B	C	A	B	C	A	B	C	A	B	C
K_{1j}	11.2	14.2	8.9	23.1	27.1	22.3	10.7	13.1	11.3	26.3	31.9	21.2
K_{2j}	14.4	12.5	1.5	27.8	25.6	12.6	12.9	8.4	6.1	24.4	18.5	14.7
K_{3j}	10.3	9.2	25.5	28.0	26.1	43.9	11.5	13.5	17.6	24.6	24.9	39.4
R_j	4.1	5.0	24.0	4.9	1.5	31.3	2.2	5.1	11.5	1.9	13.4	24.7
Optimal level	A_3	B_3	C_2	A_1	B_2	C_2	A_1	B_2	C_2	A_2	B_2	C_2

Block Shear Strength

Block shear strength reflects the quality of the bonding process parameters. The mean values and coefficient of variation (COV) of block shear strength for CLT in the different conditions including dry, impregnation, and boiling treatment are shown in Table 4. The block shear strength of CLT in the dry condition was higher than in the impregnation and boiling treatment because the strength of wood decreased as the moisture content increased below the fiber saturation point (Barrett and Lau 1991; Zhou *et al*. 2012). There was no remarkable difference in the block shear strength for CLT in the dry condition. The failure model of block shear for CLT is shown in Fig. 3. The interface strength of adhesive and wood was higher than that of wood. The maximum block shear strength for CLT in the dry, impregnation, and boiling conditions were 3.80, 3.21, and 3.44 MPa, respectively. Zhao *et al*. (2015) reported that the shear strength of structural glulam fabricated with China larch was about 10.25 MPa. Because wood is an anisotropic material, the fiber direction of the bonding interface has a great influence on the shear strength. The shear strength of perpendicular fiber direction is only 2/3 to 3/4 times lower than that of parallel fiber direction (Qin 2014). Thus, the block shear strength obtained in this study was similar to previously reported values. The COV of block shear strength for CLT in the different conditions ranged from 12.2 to 28.7%; the characteristic of large variability for wood was reflected by the test data. To select the best technological parameters, the experimental data of block shear strength were analyzed using range analysis and the *K* and *R* values listed in Table 5.

Fig. 3. The failure model of block shear strength for CLT

According to the *R* values in Table 5, different conditions had different main influence factor on the block shear strength. The block shear strength of CLT in the different conditions increased at first increased and then decreased as the glue consumption increased. Considering the economic benefit and production cost, the optimum process parameters were $A_2B_3C_2$ based on the analysis above.

Table 4. Block Shear Strength of CLT in Different Conditions

Test No.	Block Shear Strength (MPa)								
	Parameters			Dry		Impregnation		Boiling	
	A	B	C	Mean	COV (%)	Mean	COV (%)	Mean	COV (%)
1	A_1	B_1	C_1	3.38	24.8	2.89	23.6	3.04	22.6
2	A_1	B_2	C_2	3.63	23.3	2.94	26.5	3.18	15.5
3	A_1	B_3	C_3	3.29	21.4	2.91	15.9	2.82	18.1
4	A_2	B_1	C_2	3.52	23.8	3.07	24.7	2.86	19.9
5	A_2	B_2	C_3	3.59	22.8	3.15	17.6	3.22	17.9
6	A_2	B_3	C_1	3.70	23.1	3.21	25.6	3.27	22.9
7	A_3	B_1	C_3	3.16	26.7	2.83	28.7	2.87	14.8
8	A_3	B_2	C_1	3.51	19.9	3.06	21.4	3.08	12.2
9	A_3	B_3	C_2	3.80	18.4	3.17	22.2	3.44	19.8

Table 5. Range Analysis of Experimental Data for Block Shear Strength

Statistical Parameter	Dry			Impregnation			Boiling		
	A	B	C	A	B	C	A	B	C
K_{1j}	3.43	3.35	3.53	2.19	2.93	3.05	3.01	2.92	3.13
K_{2j}	3.60	3.57	3.65	3.14	3.05	3.06	3.12	3.16	3.16
K_{3j}	3.49	3.60	3.35	3.02	3.10	2.96	3.13	3.18	2.97
R_j	0.17	0.25	0.30	0.23	0.17	0.10	0.12	0.26	0.19
Optimal level	A_2	B_3	C_2	A_2	B_3	C_2	A_3	B_3	C_2

Heat Treatment

To study the influence of temperature on CLT performance, the optimum process parameters $A_2B_3C_2$ were selected to manufacture CLT. The process parameters included pressure (1.2 MPa), glue consumption (200 g/m^2), and adhesive (PUR). Weight loss, moisture absorption, and block shear strength for heat-treated CLT are shown in Fig. 4.

As shown in Fig. 4, the weight loss increased as the temperature increased. The increase of weight loss for CLT below 170 °C may be caused by evaporation of water, and weight loss for CLT with increasing temperature in the range 170 °C to 230 °C increased greatly. This may be caused by degradation of the chemical components of wood including cellulose, lignin, and hemicellulose at high temperature. There was no noticeable change in moisture absorption for CLT below 140 °C, while it increased progressively as the temperature ranged from 140 °C to 230 °C. This result reflected that the crystal structure of cellulose is damaged at high temperature, allowing water to enter the amorphous areas; thus the moisture absorption increased greatly (Liu and Zhao 2004). The block shear strength for CLT decreased as the temperature increased. The block shear strength decreased by 41.3% as the temperature was increased from 20 °C to 230 °C. A previous study reported that the tensile and bending strength of softwood was reduced by 15% and 24% as the temperature was raised from 25 to 50 °C (Tomak *et al*. 2014).

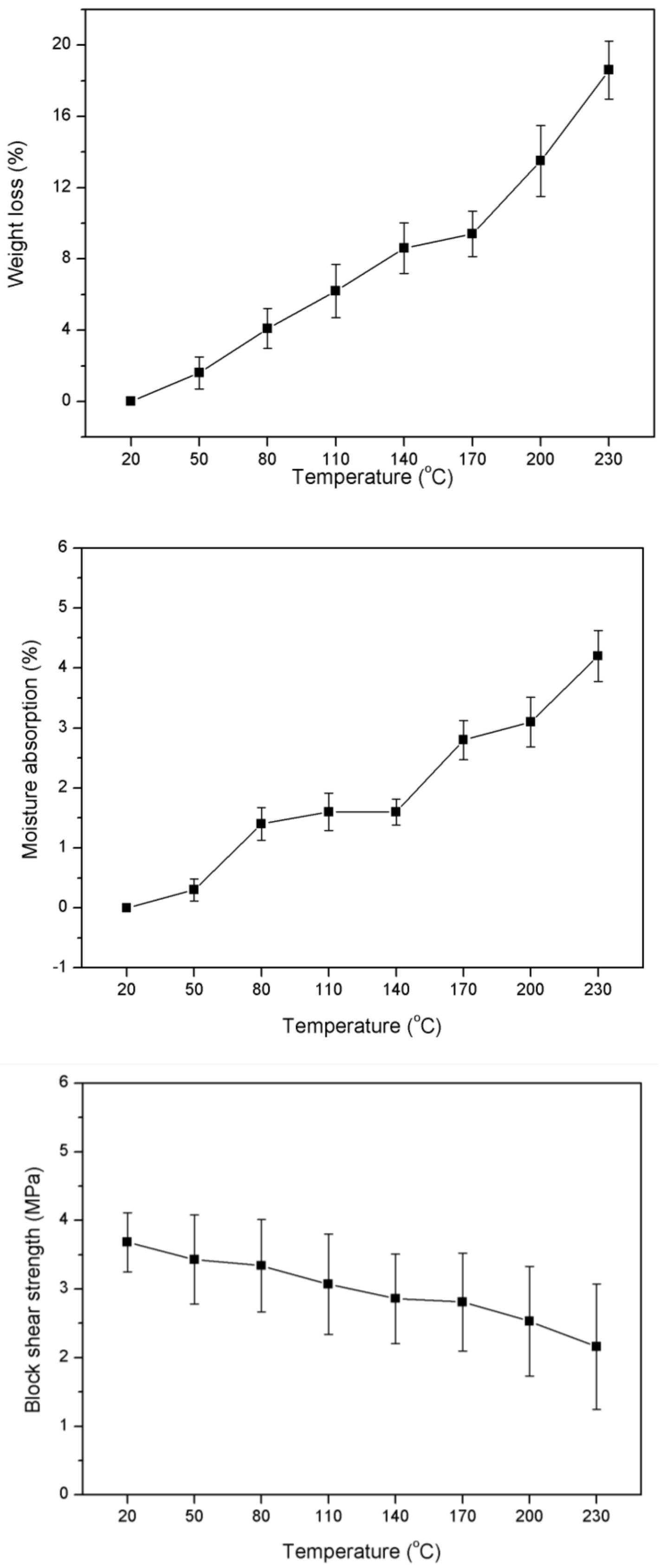

Fig. 4. Weight loss, moisture absorption, and block shear strength at different temperatures

The changes in wood chemical components including lignin and cellulose after heat treatment caused the decreased mechanical strength of wood. The results obtained in this study are similar to those of previous researchers (Chen *et al*. 2013).

CONCLUSIONS

The objective of this study was to determine the process parameters of CLT fabricated with Japanese larch. The results will provide fundamental parameters for the utilization of CLT in the building structure field as a green building material. The conclusions are as follows:

1. The delamination of 1 cycle for impregnation and boiling was obviously lower than that of 2 cycles. The block shear strength of CLT in the dry condition was higher than those of the impregnation and boiling treatment.
2. The experiment data of delamination and block shear strength were analyzed using range analysis, which indicated that the optimum process parameters were $A_2B_3C_2$ including pressure (1.2 MPa), glue consumption (200 g/m^2), and adhesive (PUR).
3. The weight loss and moisture absorption increased as the temperature increased, but the block shear strength decreased as the temperature was increased from 20 °C to 230 °C.

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