Feasibility of Predictive Assessment of Bending Performance of CLT Plates of Canadian Hemlock

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The correlation between the bending elastic modulus of lumbers along the primary direction and that of the resultant cross-laminated timber (CLT) plates in the full size suitable for slabs or wallboards was investigated to verify the feasibility of predicting the bending performance during the manufacturing of heavy building structures of this new type of material. A batch of Canada hemlocks lumber was graded based on a vibrational test that measures longitudinal elastic modulus. The elastic modulus and shear modulus in the transverse direction were also measured using the scheme of a torsional modal analysis of a cantilever plate. CLT were fabricated using the graded lumbers in sizes suitable for slabs or wallboards. The elastic moduli of these CLT products were measured using a conventional four-point static bending test. Finally, the static measurements of the elastic moduli of the CLT were compared with their predicted values that were calculated with the aforementioned data collected from the lumber pieces. The predicted elastic modulus along the primary direction of a CLT product agreed with the measured values. Therefore, the mathematical model of the CLT plate and the equation of its elastic modulus are feasible for the bending performance prediction in industrial production of CLT.

Keywords: Canadian hemlock; Lumber; Cross-laminated timber; Transverse vibration method; Bending performance; Prediction and evaluation; Application

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INTRODUCTION

Cross-laminated timber (CLT) is a solid engineered wood product made of at least three layers of lumber or structural composite (SCL), bonded in a way that adjacent layers have orthogonal primary directions. Cross-laminated timber is a new-generation engineering material for wood products and heavy-duty wood structures for building systems that has the advantages of high strength-to-weight ratio, good load-bearing performance, anti-vibration, sound insulation, fire prevention, heat preservation, design flexibility, comfort and beauty, energy savings, and environmental friendliness, *etc*. Cross-laminated timber panels are modularized and prefabricated in a factory and then assembled onsite of construction, so that the building process is shortened. This is effective for shorter buildings, and it is suitable for buildings of intermediate height or even tall buildings over 20 stories. It is a competitive alternative to the traditional reinforced concrete and brick-concrete structures. Cross-laminated timber panels can be used in steel or reinforced concrete structures for partial replacement, making it very suitable for demonstration and promotion for China's urbanization, holiday tourism, and rural construction (Fu 2012; Que *et al.* 2015; Yin 2015; Cao *et al.* 2016; Wang *et al.* 2019).

Western hemlock is widely grown in the coastal forests of British Columbia, Canada, and it is one of its main product species. Compared with spruce-pine-fir (SPF) and other species, western hemlock has the advantages of being inexpensive and having high flexural strength. It is better suited for a country like China, which lacks timber resources and relies on imports. However, hemlock is currently widely used in low value-added industries such as paper and plywood, not the construction industry. Although CLT is widely used in Europe and North America, CLT manufacturers are now limited to a few tree species in the production of CLT, such as Canadian SPF specifications, European red pine, and North American Douglas fir.

To provide a technical reference of CLT production in China, the feasibility and reliability of CLT sheet performance prediction and evaluation methods were verified.

EXPERIMENTAL

Dynamic Test of the Elastic Modulus of the Serratus Sawn Timber and Its Quality Grading

Material and equipment

The test materials were 550 samples of Western hemlock lumber, each 5500 mm × 140 mm × 40 mm in size and with an average dry density of 490 g/cm^3 in and 16% to 19% in water content.

The instruments included a set of CRAS vibration and dynamic signal acquisition and analysis system (Nanjing Analyzer Software Engineering Co., Ltd., Nanjing, China), containing a signal acquisition box, signal conditioning box, and supporting analysis software, *etc*.; a CA-YD-125acceleration sensor (Sinocera Piezotronics Inc., Jiangsu, China), 1.5 g in mass, with sensitivity coefficient of 0.089 pc/ms^{-2}; a CA-YD-127 accelerometer (Sinocera Piezotronics Inc., Jiangsu, China), 38 g in mass, with a sensitivity coefficient of 3.2 pc/ms^{-2}; a rubber hammer; a free beam suspension; a scale (with a range to 100 kg and accuracy of 0.01 kg); and a steel tape measure (0 m to 10 m).

Test principles and methods

According to the lateral bending theory of the beam, the relationship between the first-order bending frequency of the free beam and the elastic modulus is,

$$E = 0.9462\frac{\rho l^4 f_1^2}{h^2} \tag{1}$$

where E is the dynamic elastic modulus of the free beam test material (Pa); ρ is the air-dry density (g/m^3); f_1 is the first-order bending frequency value of the free beam (Hz); l is the free beam length (mm); and h is the free beam thickness (mm).

In this paper, the transient beam excitation method was used to test the grain elastic modulus value E (Wang *et al.* 2015) of the hemlock sawn timber (CLT substrate) by using the free beam test piece. By testing the spectrum of the hemlock free beam test piece, it was identified from the spectrogram. The first-order bending frequency f_1 of the free beam test piece was calculated using formula (1), and the test block diagram and the tested spectrum are shown in Figs. 1 and 2, respectively.

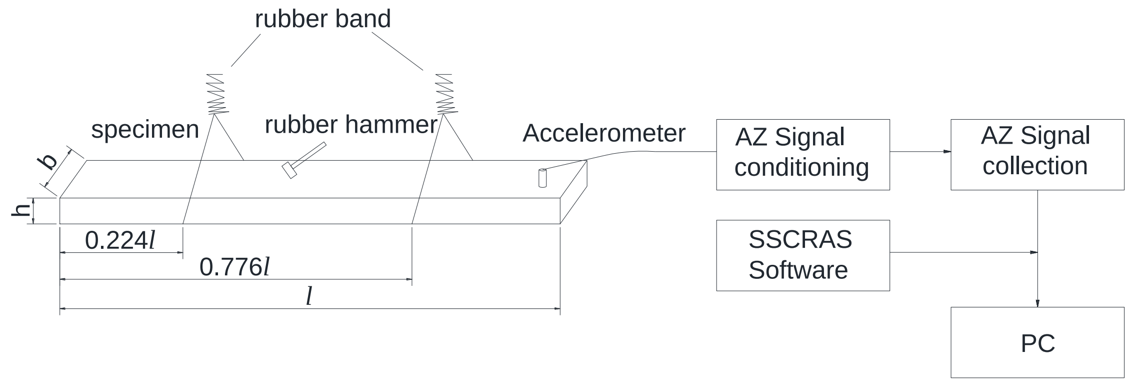

Fig. 1. Dynamic test block diagram of elastic modulus of lumber under free beam conditions

Figure 1 shows how first the free beam restraint was set up for the hemlock lumber specimen, which was wired with the dynamic signal acquisition and analysis system, and the accelerometer was firmly attached to the surface of the specimen. The parameters were set at 200 Hz analysis frequency, 4,096 FFT length, negative trigger acquisition mode, and ±5,000 mV voltage range. The hammer piece was struck with a rubber hammer to produce lateral free vibrations. After the accelerometer picked up the vibration, the mechanical vibration signal of the test piece was converted into an analog electric signal, and the lateral vibration spectrum of the sawn piece was obtained by signal amplification, filtering, A/D conversion, *etc*. Figure 2 is a spectrogram obtained by in the dynamic test of the specimen No. 101, and the first-order bending frequency value f_1 of the lateral vibration was obtained according to the spectrum identification method.

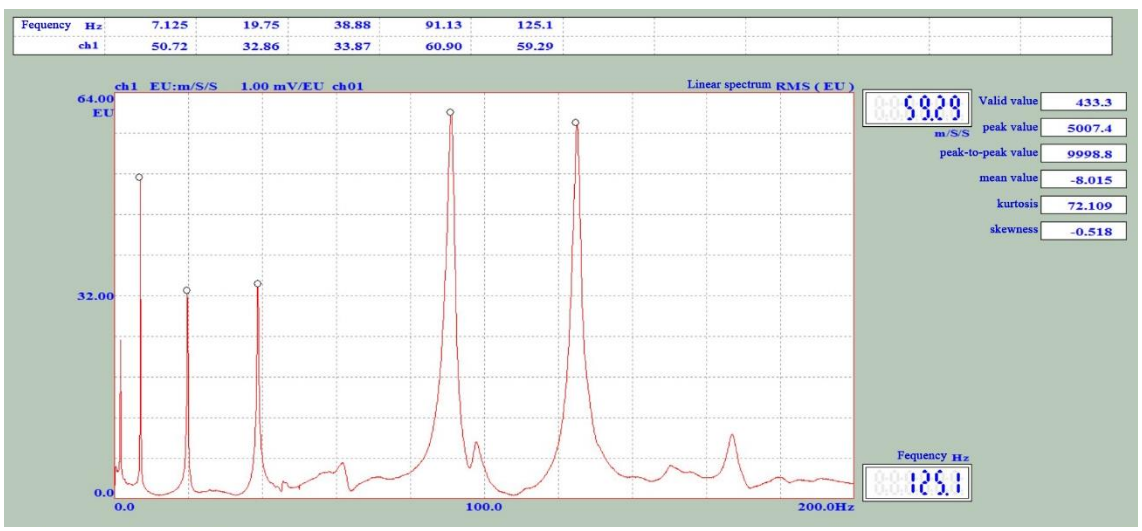

Fig. 2. Specimen 101 test spectrum of hemlock sawn timber

Quality grading of elastic modulus of hemlock sawn timber

The principle and method described above were used to test the dynamic elastic modulus of the same batch of 550 pieces of hemlock sawn timber specimens under free beam, and the probability distribution map was drawn (see Fig. 3 for details). The hemlock sawn timber specimens were divided into three grades according to their elastic modulus: less than 8,500 MPa for the CLT vertical layer laying materials; 8,500 MPa to 11,500 MPa for the wall panel CLT parallel layer laying materials, and more than 11,500 MPa for slab CLT parallel layers laying materials. The measured average elastic modulus of 550 hemlock sawn timber was 10,681 MPa, the standard deviation was 2,942 MPa, and the coefficient of variation was 27.5%. Among them, the amount of sawn timber with an elastic modulus of less than 8,500 MPa accounts for about 23% of the total.

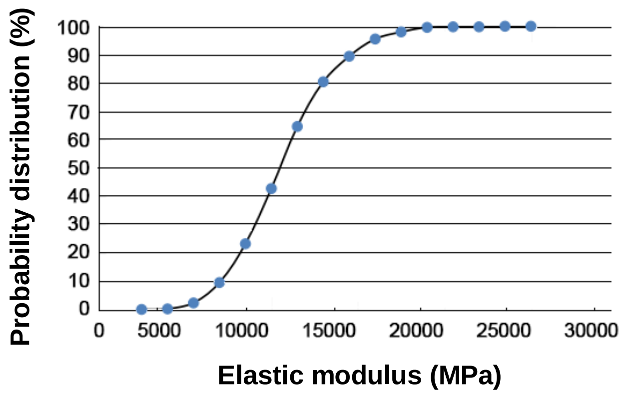

Fig. 3. Probability distribution diagram of elastic modulus of hemlock lumber

Dynamic Test of Transverse Elastic Modulus and Shear Modulus of Hemlock Sawn Timber

Material and equipment

The test materials were 15 pieces of Western hemlock sawn timber used in previous test, 190 mm × (38.36 to 40.50) mm × (6.05 to 9.03) mm in size, 490 g/cm^3 average air dry density ρ ρ, and 16% to 19% in water content. The instruments for this test were the same as the ones used for the dynamic test of the elastic modulus of the serratus sawn timber described above.

Test principle and method

According to the cantilever beam bending vibration theory, the first-order bending frequency and elastic modulus of the cantilever beam conform to Eq. 2 (Gao *et al.* 2016),

$$E' = \frac{48\pi^2 \rho l^{4'} f_b^2}{(1.875)^4 h^2} \tag{2}$$

where E is the dynamic shear modulus of the cantilever plate test material (Pa); f_b is the first-order bending frequency value of the cantilever plate (Hz); l is the specimen length of cantilever (mm); and h is the test piece thickness (mm).

From the theory of torsional modal vibration of solid cantilevered rectangular members, the first-order torsional frequency and shear modulus are in accordance with Eqs. 3 through 6 (Wang *et al.* 2016),

$$G = \frac{\rho\pi^2 l^2 b^2 f_t^2}{C_1 \beta h^2} - C_2 E' \tag{3}$$

$$\beta = \left\{1/16\left[16/3 - 3.36h/b(1-1/12(h/b)^4\right]\right\} \tag{4}$$

$$C_1 = 7.089\,6 + 6.021\,2b/l - 0.512\,1h/b \tag{5}$$

$$C_2 = -0.000\,5 + 0.064\,26 b/l - 0.007\,31 h/b \tag{6}$$

where G is the cantilever plate test material dynamic shear modulus (Pa) and C_1 and C_2 are the vibration mode coefficient of the torsional vibration of the cantilever plate, respectively. β is the rectangular section factor.

The spectrum block diagram of the cantilever plate test piece is shown in Fig. 4. According to the spectrum of the cantilever plate specimen (Fig. 5), the first-order bending frequency f_b and the first-order torsional frequency f_1 are obtained from the spectrum by cross-power spectrum identification.

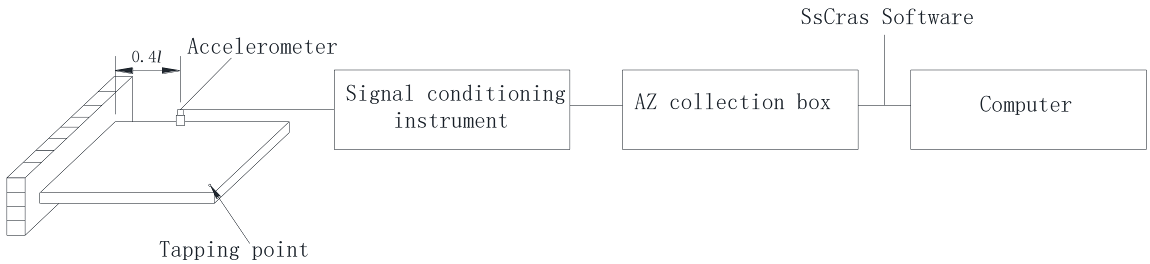

Fig. 4. Dynamic test block diagram of shear modulus of fir lumber under cantilever plate

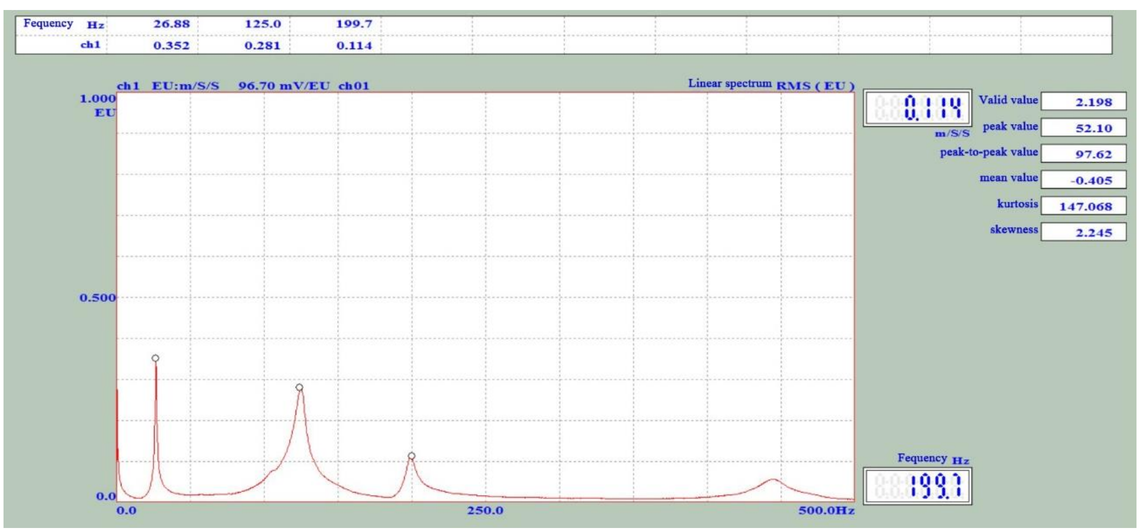

Fig. 5. Test spectrum of horizon of hemlock sawn timber specimens 12

Substituting the relevant parameters of the hemlock sawn timber into Eqs. 2 and 3, the elastic modulus value E' and the shear modulus G of the 15 pieces of the hemlock sawn timber transverse test piece were obtained, and the test results are shown in Table 1.

Table 1. Elastic Modulus and Shear Modulus of Horizontal Specimens of Hemlock Lumber under Cantilever Boar

Test piece number	*Cantilever length* *l*/(mm)	*Specimen width* *b*/(mm)	*Specimen thickness* *h*/(mm)	*Density* ρ/(kg·m^{-3})	*One bend frequency* f_b/(Hz)	*Elastic Modulus* *E'*/(MPa)	*One twist frequency* f_t/ (Hz)	*Shear modulus* *G* (MPa)
1	190	39.94	7.55	530.31	37.19	641.53	164.41	51.37
2	190	38.96	7.19	506.13	33.13	535.75	155.92	46.92
3	190	39.84	6.85	633.98	30.63	632.56	163.13	75.25
4	190	39.92	6.69	523.95	27.50	441.80	146.61	52.69
5	190	39.93	6.72	522.20	29.69	509.17	160.93	63.02
6	190	39.54	7.01	545.30	30.63	519.52	148.84	49.94
7	190	38.50	9.03	510.85	31.88	317.74	190.00	47.85
8	190	40.47	7.11	509.98	25.00	314.64	148.45	49.01
9	190	40.34	7.42	510.46	26.56	326.08	161.61	53.62
10	190	38.57	6.24	630.93	29.38	698.70	135.96	56.45
11	190	39.90	6.24	525.53	26.88	486.63	125.03	42.30
12	190	38.36	8.37	521.64	37.56	524.60	168.13	41.11
13	190	40.37	6.05	509.27	22.19	341.50	132.65	52.52
14	190	40.50	6.52	507.74	23.13	318.87	137.91	49.57
15	190	40.38	7.37	504.42	26.56	326.62	143.63	41.62
Average value						462.38		51.55
Standard deviation						132.99		8.72
Coefficient of variation						29%		17%

CLT Structural Design and Performance Prediction and Evaluation Normal Stress of Three-Layer CLT Beam

CLT blanking scheme and structural design

The sawn timber pieces used to make six CLT plates were randomly selected from the classified sawn timbers, three of which were used as floor slabs and three as wall slabs. The CLT was a three-layer structure with a plate size of 5,500 mm × 1,200 mm ×105 mm.

Table 2. Performance Parameters of Sawn Timber Used in CLT

CLT Number	CLT Type	Elastic Modulus ofParallel Layer Laying Material (MPa)	Vertical Layer Elastic Modulus Laying Material (MPa)	Average Density (kg·m^{-3})
1	Floor	15,459	7,972	493
2	Floor	14,826	8,312	492
3	Floor	14,463	6,889	483
4	Wall panel	10,970	6,898	484
5	Wall panel	10,916	8,070	475
6	Wall panel	10,633	9,210	498

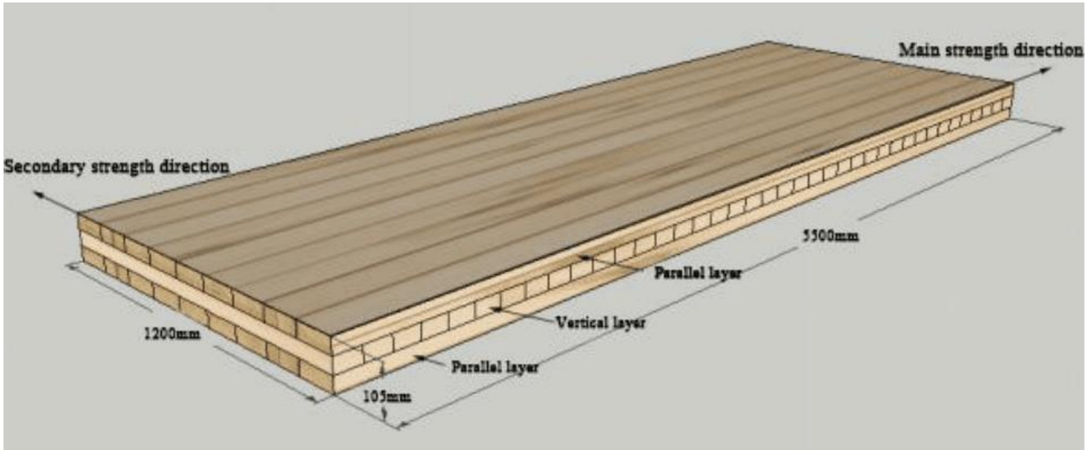

Fig. 6. Schematic diagram of CLT structure

According to the sawing material specification and the board size, each CLT board requires 18 units for each parallel layer and 9 units for the vertical layer of the sawn timber. The structure is shown in Fig. 6. The performance parameters of the sawn timber used in each CLT are shown in Table 2.

CLT Manufacturing and Bending Performance Test

Manufacture of CLT

According to Gagnon *et al.* (2012), the CLT test piece used in the conventional CLT manufacturing method was processed, including the processing of sawn timber, the control of the moisture content of the sawn timber, the appearance of the sawn timber, the stress of the sawn timber, *etc*. The main processing flow of the CLT substrate selection, planing, sizing, blanking, and cold pressing process is shown in Fig. 7 (Gagnon *et al.* 2012).

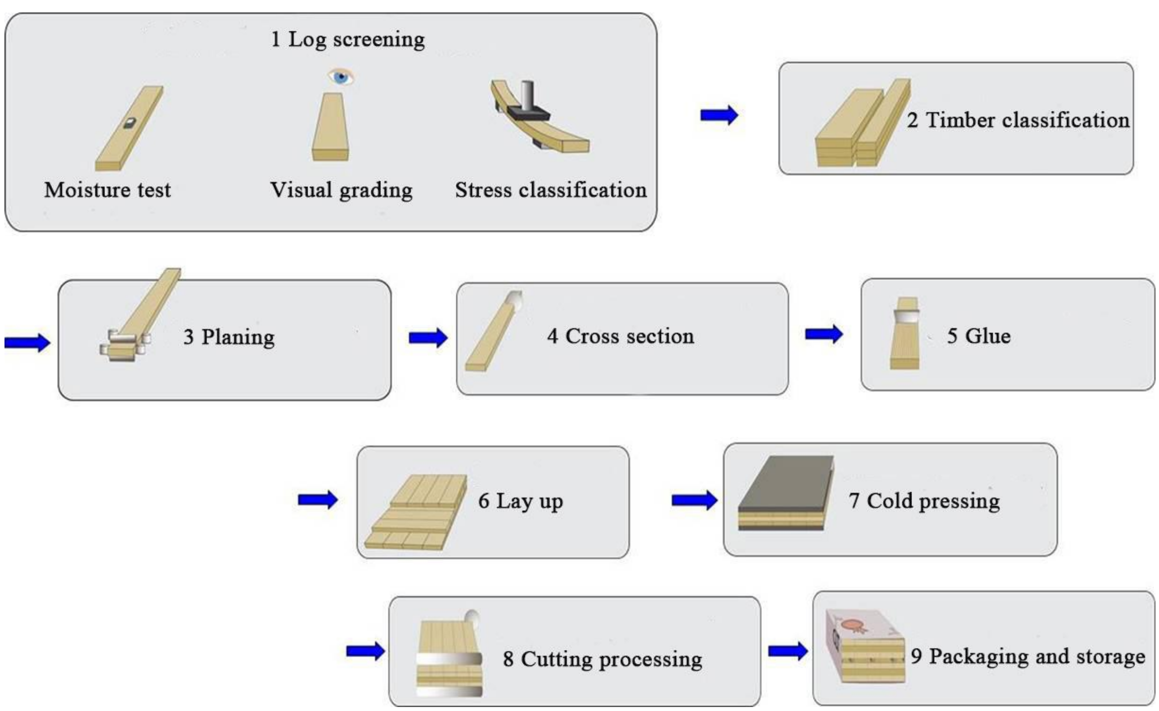

Fig. 7. CLT manufacturing flow diagram

The thickness of the CLT unit was controlled to 35 mm, and the glue was sprayed within 24 h after the thickness was cut to prevent the surface passivation of the wood from affecting the quality of the glue. One-component polyurethane (PUR) was used as the adhesive, and the sizing process was carried out with a sizing amount of 180 g/m^2. The opening time from the start of the leaching to the start of the cold pressing was controlled to within 30 min. The plate surface pressure at cold pressing was 1.2 MPa, the measured surface pressure was 0.08 MPa, and the cold pressing time was 90 min.

CLT bending performance test

A total of 12 pieces of CLT specimens were cut from floor and wall panels. Three pieces of CLT specimens were cut from each panel. The specimen size was 3300 mm×300 mm×105 mm. The moisture content of the specimen was 16% to 17%. The four-point bending test equipment included a Tianchen 30 t long-span beam test machine (Shanghai, China); Tianchen load-displacement analysis software (Shanghai, China); 300 mm displacement extensometer; 1 L-shaped steel; 10 m tape measure, *etc.*

Fig. 8. Four-point bend test site

After the CLT sheet was processed and manufactured, the CLT bending performance was tested using the four-point bending method with reference to the American standard ASTM D198-15 (2015). The span of the test piece was taken to be 30 times that of the thickness of the test piece, that is, 3,150 mm. The distance between the two loading points was 1/3 of the span, which was 1,050 mm, and the loading direction was perpendicular to the surface of the test piece. During the test, the displacement extensometer was vertically fixed to the center position in the span and thickness direction of the test piece at a loading speed of 4 mm/min, as shown in Fig. 8 (Sikora *et al.* 2016). The load-displacement curve of the CLT bending test is shown in Fig. 9.

According to the North American ANSI/APA PRG320-2012 (2012) standard, the relationship between the slope of the CLT four-point bending linear phase load-displacement curve and the CLT elastic modulus is in accordance with Eq. 7 (ANSI/APA PRG 320-2012),

$$E = \frac{23\Delta P l^3}{108\Delta y b h^3} \tag{7}$$

where E is the CLT elastic modulus (MPa); ($\Delta P/\Delta y$) is the linear phase slope of the CLT load displacement curve; l is the test span (mm) for the CLT four point bending; b is the CLT test piece width (mm); and h is the thickness of the CLT specimen (mm). After the test was completed, the elastic modulus value of the CLT sheet was obtained by calculation. The final result in the text was taken as the average of the two tests (Table 3).

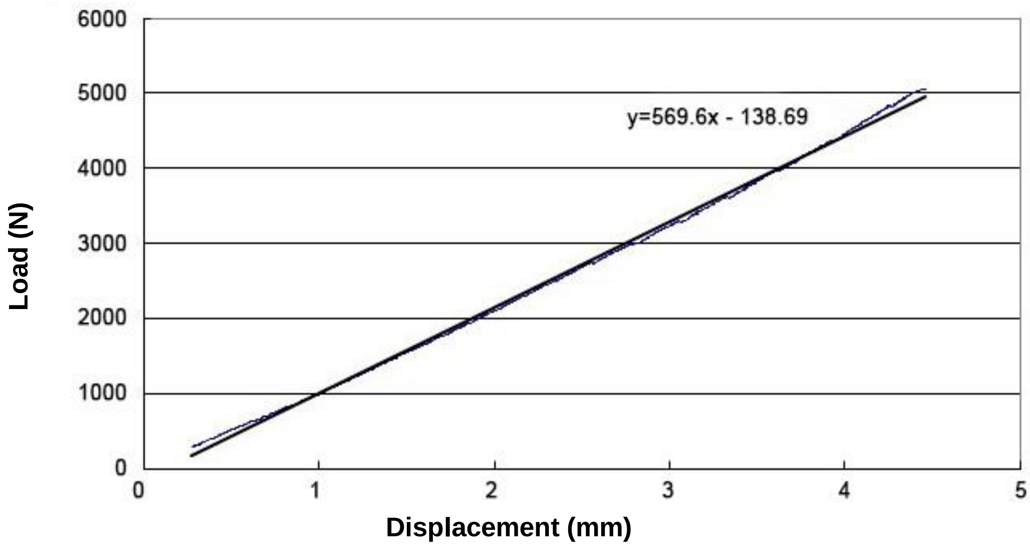

Fig. 9. CLT four-point bending test load displacement diagram

CLT effective bending stiffness prediction

The gamma method (Wang *et al.* 2016) was used for predicting the effective bending stiffness of CLT. When calculating the effective bending stiffness of CLT, the gamma method simplifies the vertical layer unit to the interface connecting the upper and lower parallel layers and accounts for the influence of the transverse shear effect in the actual calculation, which is more in line with practical engineering applications and the stress conditions of the CLT. After considering the lateral shear effect of CLT, the relationship between the effective bending stiffness and the elastic modulus of the sawn timber is in accordance with Eq. 8:

$$EI_{\mathrm{eff}} = \sum_{i=1}^{(n+1)/2} (E_i I_i + \gamma_i E_i A_i a_i^2) \tag{8}$$

In Eq. 8, EI_{eff} is the CLT effective bending stiffness prediction value (N·mm^2); E_i is the parallel layer hemlock specification material elastic modulus (MPa); A_i is the CLT single layer cross-sectional area (mm^2); I_i is the CLT single layer section moment; n is the the number of layers of the CLT unit; a_i is the the sum of half the thickness of the parallel layer and half the thickness of the vertical layer, *i.e.* the cell thickness; and γ_i is the correlation coefficient of transverse shear modulus, the specific relationship of which accords with Eq. 9.

$$\gamma_i = \frac{1}{1+\pi^2 \cdot \frac{E_i \cdot A_i}{l^2} \cdot \frac{\bar{h}_i}{G_R \cdot b}} \tag{9}$$

In Eq. 9, l is the CLT span (mm); b is the CLT width (mm); h is the CLT unit thickness (mm); and G_R is the transverse shear modulus of hemlock specification material (MPa).

Substituting the average elastic modulus and the transverse shear modulus of each CLT blank unit into Eqs. 6 and 7, the predicted bending stiffness of CLT can be obtained as shown in Table 3.

CLT bending elastic modulus prediction

For predicting the calculation of the CLT flexural modulus of elasticity, the K method described in Chapter 3 of the Canadian CLT handbook (Gagnon *et al.* 2012) was used. When the K method predicts the bending elastic modulus of CLT, the correlation coefficient between the elastic modulus of the CLT blank unit sawing material and the elastic modulus of the CLT main strength direction is calculated. The relationship between the correlation coefficient and the average value of the elastic modulus of the blank of the blank unit is in accordance with Eq. 8.

$$k_1 = 1-\left(1-\frac{E_{90}}{E_0}\right)\times\frac{h_{m-2}^3 - h_{m-4}^3 + \ldots \pm h_1^3}{h_{tot}^3} \tag{10}$$

where k_1 is the CLT main strength direction elastic modulus and CLT unit sawn timber elastic modulus correlation coefficient; k_2 is the CLT secondary strength direction elastic modulus and CLT unit sawn timber elastic modulus; E_0 is the average modulus of the elastic modulus of the hemlock sawn timber (MPa); E_{90} is the average elastic modulus of the hemlock sawn timber (MPa); h_{tot} is the total thickness of CLT(mm); and m is the CLT unit layer number.

After calculating the coefficient k_1 by using the equation above, multiplying the average modulus of the elastic modulus of the hemlock sawn timber of each CLT unit, the predicted value of the elastic modulus of the main strength direction of the CLT can be obtained. In the calculation process, the length, width, and thickness parameters are in accordance with Canadian Standard CSA O122-06-CAN/CSA UPD 2-2009 (2009) and ASTM D198 (2015). The calculation of the CLT bending test piece size was compared with the actual measured value. The elastic modulus E and the elastic modulus values E' of the transverse test specimens were taken as the average values of the elastic modulus and the transverse elastic modulus in Tables 1 and 2, and the calculation results are shown in Table 3.

RESULTS AND DISCUSSION

The predicted and measured values of the effective bending stiffness and elastic modulus of the CLT panels are shown in Table 3. The effective bending stiffness average for the floor slab CLT was 1003×10^9 N·mm^2, which meets the required 958×10^9 N·mm^2 by the Canadian standard ANSI APA PRG320-2012 (2012). The average effective bending stiffness for the wallboard CLT was 879 x 10^9 N·mm^2, meeting the required 772 x 10^9 N·mm^2 (ANSI/APA PRG 320-2012) by the standard E2 rating. The data in Table 3 were used to obtain a comparative analysis chart as shown in Fig. 10, which shows that the coefficient of determination between the predicted value of the bending elastic modulus of CLT and the measured value reached 0.887, a strong correlation. The error between the predicted value and the measured value was within 10%. Considering the anisotropic characteristics of CLT panels, the predicted values of CLT are predicted to be a reliable guide for the quality control of CLT production.

Table 3. Predicted and Measured Values of Elastic Modulus of CLT Sheet

CLT Number	CLT Sheet Type	Effective Bending Stiffness (10^9N·mm^2)	Predicted Value (MPa)	Measured Value (MPa)
1	floor	1039.7	12681.98	13243.9
2	floor	1000.1	12119.00	11246.68
3	floor	970.0	11696.40	10930.24
4	wall panel	888.8	10777.95	10648.22
5	wall panel	884.9	10157.09	10010.09
6	wall panel	864.8	9900.28	11793.1
Average value		941.38	11222.12	11312.04

The data in Table 3 show that for the floor slab CLT, the mean value of the flexural modulus of elasticity was higher than the measured mean value by 3%, while for the wallboard CLT, the mean value of the flexural modulus of elasticity was lower than the measured mean by 5%.

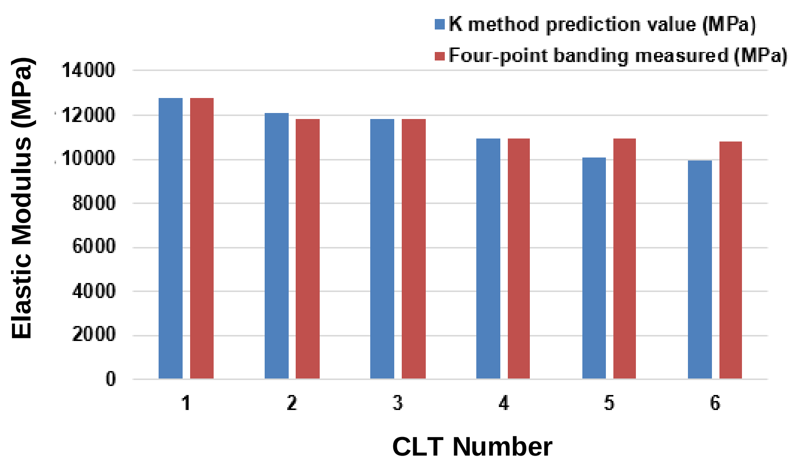

Fig. 10. Predicted and measured elastic modulus of CLT in primary strength direction

In the calculation of the effective bending stiffness and the CLT principal strength direction elastic modulus and the CLT unit sawn timber elastic modulus correlation coefficient k_1, the elastic modulus and shear modulus of the hemlock horizontal sawn timber measured in this paper were used. The mean values were 462.4 MPa and 51.6 MPa, and the predicted value of the elastic modulus, 51.6 MPa, of the main strength direction of CLT was consistent with the measured value. This not only shows the correctness of the elastic modulus and shear modulus test value of the hemlock horizontal sawn timber but also provides fundamental data for further study of CLT performance. For example, in CLT, there are elastic moduli of parallel and vertical layers. In CLT, the elastic modulus of parallel layers is clearly the elastic modulus of the sawn timber. However, what is the elastic modulus of the vertical layer in CLT? How could it be tested? It is neither defined clearly nor easy to test directly. However, the results show that in the CLT main strength direction, the predicted elastic modulus and the measured value were consistent, indicating that the elastic modulus of the CLT vertical layer can be taken as the elastic modulus of the sawn timber of the transverse stripes. As a preliminary estimate, according to the test results of this paper, the average E_1 mean value and the transverse elastic modulus E_2 of the hemlock sawn timber were 10,680 MPa and 462.4 MPa, respectively, so that the ratio of the elastic modulus of the parallel layer to the vertical layer of $E_1 / E_2 = 23$ is obtained. This can be used to calculate the normal stress and shear stress of the hemlock CLT beam at three-point bending and provides reliable performance parameters for testing the inter-layer shear strength of CLT beams (Lu *et al.* 2018).

CONCLUSIONS

1. The predicted bending elastic modulus has a strong correlation with the measured value using a four-point bending test.
2. The accuracy of the transverse vibration method coupled with the K method to predict the bending performance of CLT is feasible for quality control and performance prediction in CLT manufacturing.
3. Canadian hemlock sawn timber can be used for CLT processing and manufacturing. Canadian hemlock CLT panels are of bending performance, which meets the engineering grade requirements of floor slabs, wall panels, *etc.*
4. The parameters of transverse shear modulus and elastic modulus of the hemlock coupled with the cantilever plate torsion mode method provide a reliable basis for further study of the performance of Canadian hemlock CLT.

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