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Evaluation of the Out-of-Plane Shear Properties of Cross-Laminated Timber

Yin Yang[1], Xiaoyan Cao[1], Zhiqiang Wang[1,*], Zhijun Liang[1] and Jianhui Zhou[2,*]

[1]School of Materials Science and Engineering, Nanjing Forestry University, Nanjing, 210037, China.

[2]Integrated Wood Engineering, University of Northern British Columbia, Prince George, V2L 1R7, Canada.

[*]Corresponding Authors: Zhiqiang Wang. Email: wangzhiqiang@njfu.edu.cn; Jianhui Zhou. Email: jianhui.zhou@unbc.ca.

Abstract: The out-of-plane shear properties of cross-laminated timber (CLT) substantially influence the overall mechanical properties of CLT. Various testing methods and theories related to these properties have recently been developed. The effects of the number of layers (three and five layers) and testing method (short-span three- and four-point bending tests) on the out-of-plane shear properties of CLT were evaluated. The out-of-plane shear strength values were calculated based on different theories for comparison. The failure mode in the short-span four-point bending (FPB) method was mainly the rolling shear (RS) failure in the cross layers, indicating that the FPB method was appropriate to evaluate the RS strength of CLT. The out-of-plane shear capacity obtained using the three-point bending (TPB) method was higher than that tested by the FPB method. The testing methods significantly influenced the out-of-plane shear capacity of the three-layer specimens but not that of the five-layer specimens. With an increase in the number of layers, the out-of-plane shear strength of the specimens decreased by 24%. A linear correlation was found among the shear strength values obtained from different theories.

Keywords: Cross-laminated timber; out-of-plane shear properties; testing methods; failure modes

1 Introduction

Cross-laminated timber (CLT) is a prefabricated solid engineered wood product made from solid sawn pieces of lumber for roof, floor, and wall applications [1]. Compared with solid timber and glued laminated timber, CLT has different configuration characteristics, such as gaps between pieces of lumber on the same layer, potential stress reliefs in the lumber and orthogonal layup of CLT. A normal CLT panel has layers oriented perpendicular to one another, whereas CLT in special configurations has consecutive layers placed in the same direction, resulting in a double layer (e.g., double longitudinal layers at the outer faces and additional double layers at the core of the panel) for specific structural capacities [2]. These configuration characteristics improve the physical and mechanical properties of CLT.

Generic CLT subjected to out-of-plane loading is prone to rolling shear (RS) failure and excessive deflection. Highly concentrated loads in a CLT floor supported by columns may lead to a critical RS zone in the supporting area, and high bending loads on short-span CLT floors may cause high RS stress [3]. RS strength and stiffness in CLT have been identified as key factors that can affect the design and performance of CLT floor systems [1]. To address these concerns, numerous studies have been conducted, including the measurement and prediction of the RS properties of CLT, enhancement of the RS properties of CLT, as well as the evaluation of test set-up configuration and methods [3-13].

No agreed standardized testing method currently exists for measuring the RS properties of full-size CLT specimens. Many testing approaches have been adopted to evaluate the RS (or planar shear) properties of wood, wood composites and CLT. Representative testing methods for the determination of the RS properties of CLT include short-span bending (shear) tests and planar shear tests. Short-span bending tests include the five-point bending test, four-points bending (FPB) test, and three-point bending (TPB) test.

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Meanwhile, compression shear tests include the two-plate planar shear test and the modified compression shear test in which steel plates are replaced with lumber plates. Numerous studies have adopted different testing methods to measure the RS strength of CLT. These studies indicate that different RS strengths of CLT could be obtained using different approaches. Zhou [8] conducted the short-span bending test and the two-plate shear test to evaluate the RS properties of the cross layer in CLT, suggesting that adopting the two-plate shear test for determining the RS modulus and strength of a cross layer in CLT was feasible. Aicher et al. [14] performed bending shear, two-plate planar shear and modified compression shear tests to determine the RS properties of the beech cross-layer in hybrid CLT. Their experiment results showed that the mean and characteristic RS strength evaluated using the modified compression shear test agreed well with the result of the bending shear test. However, the two-plate planar shear tests resulted in roughly 30%-50% higher strength distribution throughout. Lam et al. [15] conducted torque loading tests on CLT shear blocks. The torque loading test method also yielded RS strength results differently from the results based on short-span beam bending tests in their previous research. Li [3] used short-span three-point bending test and modified planar shear test to evaluate the RS strength of CLT made of Radiata pine (*Pinus radiata*) grown in New Zealand. Comparable strength properties were obtained by both methods.

Recent research mainly applies four theories to calculate the out-of-plane shear strength of CLT, i.e., traditional beam theory, layered beam theory, gamma beam theory and shear analogy. The traditional beam theory calculates the out-of-plane shear properties of CLT documented in ASTM D 198 [16]. Bodig and Jayne [17] presented the layered beam theory, which does not consider the shear deflections of each layer. The gamma method in Eurocode 5 [18] can be used to predict the bending performance of CLT beams. Kreuzinger proposed the shear analogy method, which considers the shear deformations of a beam [1]. Fellmoser and Blaβ [19] evaluated the influence of the span-to-depth ratio on the RS properties of a three-layer CLT panel via shear analogy method. They found that shear deformation was strongly influenced when the span-to-depth ratio was smaller than 20. Li [20] calculated the RS stress in different beam theories (the layered beam theory, gamma beam theory and shear analogy) for three- and five-layer CLT beams. Shear analogy was also used by Li to evaluate the RS strength of CLT products made from Radiata pine (*Pinus radiata*) [3].

Apart from the testing methods, other factors also affect the RS strength of CLT. These factors include the wood species, gaps, layer thickness and manufacturing technology of CLT [10,14,21-22]. Some studies indicate that the macro and micro characteristics of wood, such as the growth ring, sawing pattern, and so on, exert significant effects on their RS strength. The edge gluing and gap size significantly influence the RS strength rather than the apparent RS modulus determined using the modified planar shear test method [23]. The RS strengths of CLT specimens with lamination thickness of 35 and 20 mm were significantly affected by the lamination thickness. Niederwestberg et al. [24] evaluated the RS strength of three- and five-layer hybrid CLT fabricated with lumber and structural composite lumber. The RS strengths were evaluated using short-span center-point loading tests. Compared with the three-layer hybrid CLT, the five-layer hybrid CLT exhibited a larger increase in RS strength than that of regular CLT.

In the present study, short-span FPB and TPB methods were used to evaluate the out-of-plane shear property of non-edge-glued CLT made of SPF (*Spruce-pine-fir*) dimension lumber. CLT specimens with different numbers of layers (three and five) were tested. This study aimed to experimentally evaluate the effects of testing methods and the number of layers on the out-of-plane shear capacity of CLT as well as the different RS strength value calculated using different calculation theories.

2 Material and Methods

2.1 CLT Specimens

The CLT shear specimens were fabricated using J-grade SPF (*Spruce-pine-fir*) lumber pieces imported from Canada. All test specimens had a cross-section measuring 38 mm (thickness) × 89 mm (width). The lumber pieces had a mean value of density of 410 kg/m^3 and an average moisture content of 14% at test. A total of fifty-nine pieces of SPF dimension lumber with a lengths of 2000 or 2450 mm were selected for the dynamic elastic modulus parallel to grain by the transvers beam vibration method. The dynamic elastic modulus (MOE_d) parallel to grain were obtained by measuring the fundamental nature frequency of a free-free beam. The MOE_d can be calculated using Eq. (1). The testing setup is presented in Fig. 1. The linear relationship between the MOE_d and the static modulus of elasticity (MOE_s) of the SPF dimension lumber established by Wang et al. [25] was employed in this study (Eq. (2)). Finally, MOE_s was used in the calculation of the out-of-plane shear strength of CLT.

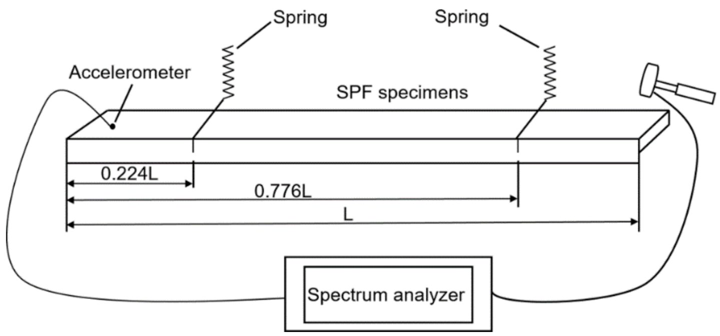


Figure 1: Setup illustration of the free-free beam vibration test

$$MOE_d = 0.95\frac{\rho f_2^2 l^4 \rho}{h^2}$$

$$MOE_d = 0.95\frac{\rho f_1^2 l^4}{h^2} \quad (1)$$

$$MOE_s = 0.975 MOE_d - 186.18 \quad (2)$$

where MOE_d is the dynamic modulus of elasticity (MPa), ρ is the density (kg/m^3), f_1 is the first natural frequency (Hz), l is the length of the specimen (m), h is the depth of the specimen (m), and the MOE_s is the static modulus of elasticity (MPa).

The converted MOE_s were used to calculated other elastic constants needed for the calculation of shear strength. The modulus of elasticity in the minor strength direction $E_\perp$ is assumed to be 1/30 of that in the major strength direction $E_\parallel$; in addition, shear modulus $G_0 \approx E_\parallel/15$, and the RS modulus $G_{RT} \approx G_0/10$ (Tab. 1) [1].

Table 1: Input elastic properties of the CLT laminations

Lamination grade	$E_\parallel$(MPa)	$E_\perp$(MPa)	G_0(MPa)	G_{RT}(MPa)
J	9920	331	620	62

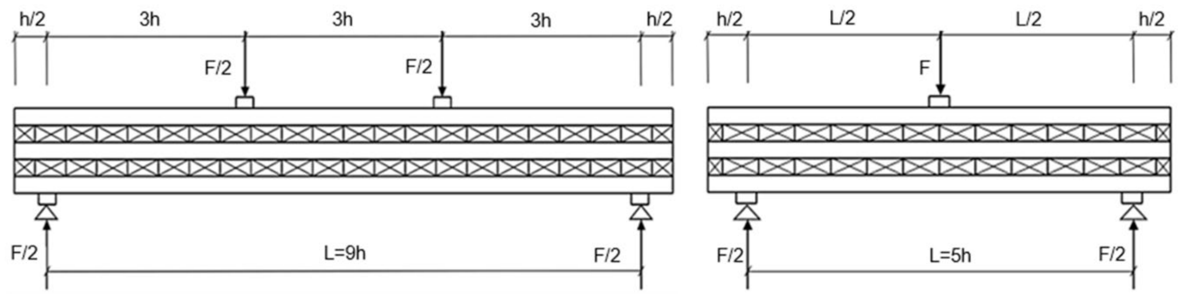
The adhesive was applied at a rate of 180 g/m^2 on the surface of each layer, and the maximum assembly time was set at 30 min. The specimens were pressed without applying side pressure under the following conditions: ambient temperature, 15°C; duration, 1.5 h; pressure, 1.0 MPa. All test specimens were stored under the same conditions for more than three weeks. In accordance with EN 16351 [2], four groups of CLT specimens with different numbers of layers (three or five) and different testing methods (FPB and TPB) were prepared in this study (Tab. 2).

Table 2: Dimensions and numbers of the CLT specimens

Groups	Method	Dimension (mm)			Count
		Length	Width	Thickness	
3A	FPB	1140	356	114	10
5A	FPB	1900	356	190	10
3B	TPB	684	356	114	10
5B	TPB	1140	356	190	10

2.2 Out-of-Plane Shear Strength Test

FPB tests were conducted with reference to EN 16351 [2], which specifies the measurement of the RS strength of cross layers. Groups 3A and 5A were under the third-point loading. The bending spans for three- and five-layer CLT specimens were 1026 and 1710 mm, respectively, and the span-to-depth ratio (L/h) was 9. The load speed used for the three- and five-layer CLT specimens were 5 and 3 mm/min, respectively. TPB tests were performed in accordance with ASTM D198 [16]. Groups 3B and 5B were under the center-point loading and their test spans were 570 and 950 mm, respectively, with a span-to-depth ratio (L/h) of 5. The load was applied perpendicular to the face layer of the CLT beam at 2 and 3 mm/min to ensured reaching the maximum load within 2-7 min. The test setup is illustrated in Fig. 2.



(a) (b)

Figure 2: Experimental setup for the OP bending shear tests, (a) FPB test and (b) TPB test

All failure modes and load-displacement curves were recorded during testing. The out-of-plane shear strength values of the CLT specimens were then calculated with reference to four theories: the traditional beam theory, layered beam theory, gamma beam theory and shear analogy.

3 Results and Discussion

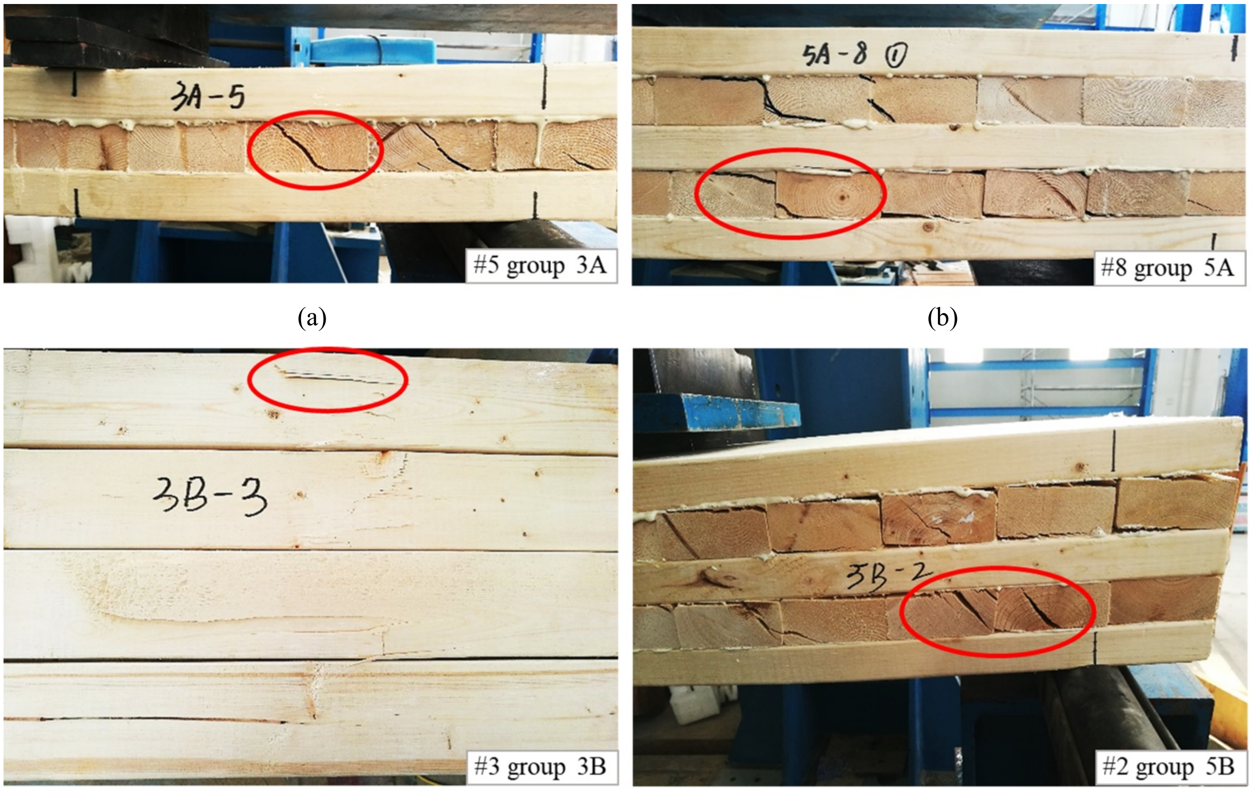
3.1 Failure Modes

The initial and main failure modes of all test specimens observed in this study are the RS failure of cross layers, tensile failure of bottom layers and delamination failure between layers. The main failure modes and proportion of the specimens obtained using different testing methods are listed in Tab. 3.

Table 3: Initial and main failure modes and proportions of the CLT specimens

Groups	Failure modes		
	Rolling shear of cross layers	Tensile of bottom layers	Delamination between layers
3A	9/10[a]	—[b]	1/10
5A	9/10	—	1/10
3B	5/10	4/10	1/10
5B	10/10	—	—

Fig. 3 shows the representative failure modes of the different CLT specimens. The rolling shear failure first appeared in the cross layers and some further extended to the glue lines between layers, with the specimens being mainly in a brittle state. Most CLT specimens, particularly for five-layer specimens tested by the FPB method, failed in RS. However, for Group 3B, 40% of the specimens exhibited tensile failures at the bottom layers, particularly near knots. Nearly no specimens exhibited shear delamination between layers. In addition, RS failure was more evident in five-layer specimens than under TPB testing. Compared with TPB testing, FTB testing is more likely to result in RS failure in the cross layers and an out-of-plane shear capacity closer to the RS properties of CLT. Therefore, with an increase in the number of layers, the possibility of the RS failure of CLT specimens increased relative to those of the three- and five-layer CLT specimens. Fig. 3 presents the representative failure modes of the CLT specimens.



(a) (b) (c) (d)

Figure 3: Typical failure modes of four groups, (a)-(d) correspond to Group 3A, 5A, 3B and 5B, respectively

3.2 Out-of-Plane Load Bearing Capacity of CLT Specimens

The maximum load bearing capacity of all specimens are listed in Tab. 4.

Table 4: The out-of-plane ultimate load of the CLT specimens

Groups	Maximum (kN)	Minimum (kN)	Average (kN)	COV (%)
3A	98.97	57.38	76.72	13
5A	127.25	95.89	111.48	8
3B	103.49	73.89	96.13	10
5B	131.86	101.57	120.63	9

For the CLT specimens with the same number of layers, the maximum load obtained by TPB testing was higher than that obtained by FPB testing. The average maximum load obtained for the three-layer CLT specimen using the TPB testing method was 25% higher than that obtained using the FPB testing method. However, the values determined using the TPB and FPB testing methods were much closer for the five-layer CLT specimens. The mean value of Group 5B was only 8% higher than that of Group 5A. The reason is the high percentage of rolling shear failure of the five-layer CLT specimens in both testing methods, where RS strength governs the peak load. The out-of-plane shear strength is considered as the RS strength of the CLT specimens. From the perspective of material mechanics, the shear-to-span ratio (the ratio of the bending moment of the component to the product of shear force and effective height) obtained using the TPB test method was 2.5, and that obtained using the FPB testing method was 3. The higher the shear-to-span ratio, the lower the shear resistance. This finding is in consistent with the conclusion that the test results by the FPB testing method were smaller than those by the TPB testing method. In addition, one-way ANOVA of the maximum load of the three- and five-layer CLT specimens was conducted using the SPSS software at 95% significance level. As shown in Tab. 5, the p value is lower than 0.05 for three-layer CLT specimens, while higher than 0.05 for the five-layer CLT specimens, indicating that the testing method significantly affects the maximum load of the three-layer specimens. However, no significant effect is observed for the five-layer specimens.

Table 5: ANOVA on the effect of different test methods on maximum load of the CLT specimens

Number of Layer	Sources of Variation	Sum of Squares	d_f	Mean Square	F	P
3-layer	Between Groups	1896	1	1896	17.013	0.001
	Within Groups	2006	18	111		
	Total	3901	19			
5-layer	Between Groups	419	1	419	3.551	0.076
	Within Groups	2122	18	118		
	Total	2540	19			

3.3 Out-of-Plane Shear Strength of CLT Specimens Using Different Theories

The average out-of-plane shear strength of the CLT specimens was calculated based on different theories (i.e., the traditional beam theory, layered beam theory, gamma method, shear analogy method) as shown in Fig. 4). The out-of-plane shear strength value calculated based on the traditional theory was higher than those determined based on the other three theories. The transverse layer in the CLT specimens has considerably lower modulus of elasticity and shear modulus. However, the layered beam theory does not consider shear deflections and assumes that cross-section always remain plane [26]. Similarly, the traditional beam theory ignores the shear deformations of cross layers. The gamma beam theory is adopted to calculate wood composite beams in Eurocode 5 [18]. It provides a closed (exact) solution for the differential equation only for simply supported beams panels with a sinusoidal load distribution. The shear analogy method considers the shear deformation of cross layers [1]. Although no unified calculation model for the CLT structural performance exists at present, a significant amount of research shows that shear analogy method is more suitable for the theoretical analysis and accurate strength prediction of CLT. The American and Canadian standard for CLT products adopted the shear analogy method to calculate the bending and shear properties of CLT [1].

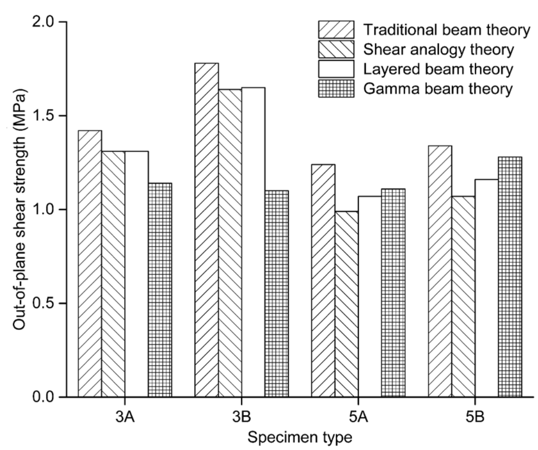


Figure 4: Comparison of the out-of-plane shear strength values calculated by different theories

The average out-of-plane shear strength values of CLT specimens calculated based on shear analogy method using the maximum load from FPB and TPB tests were 1.15 and 1.36 MPa, respectively. These values agree well with the values of the three-layer CLT specimens obtained from the modified compression shear testing method in previous studies [11,27]. The RS strength of 2 × 4’’ and 2 × 6’’ SPF dimension lumber obtained by Gong et al. [11] were 0.92 and 1.29 MPa, and the RS strength of SPF dimension lumber measured by Wang et al. [27] was 1.41 MPa.

Further, the out-of-plane shear strength values decrease with an increase in the number of layers tested by the same method. The calculated value using the shear analogy method for Groups 3A and 3B were 32% and 53% higher than those for Groups 5A and 5B, respectively. The cross layers comprise a larger proportion of CLT as the number of layer increases, which greatly increases the homogeneity of CLT. The difference between the results of the three- and five-layer CLT increased accordingly. Other studies reported similar conclusions. Sikora et al. [28] examined the effect of thickness on the out-of-plane shear properties of CLT and found that the out-of-plane shear strength of spruce varied between 1 and 2 MPa; in addition, an increase in thickness caused a decrease in RS strength. Similarly, Li [20] demonstrated that a decrease in thickness led to an increase in RS strength.

The out-of-plane shear strength values of three- and five-layer CLT, calculated using the traditional theory and the shear analogy method, were fitted in Fig. 5. A considerably strong linear correlation of calculated values between the two theories was observed, regardless of the number of layers.

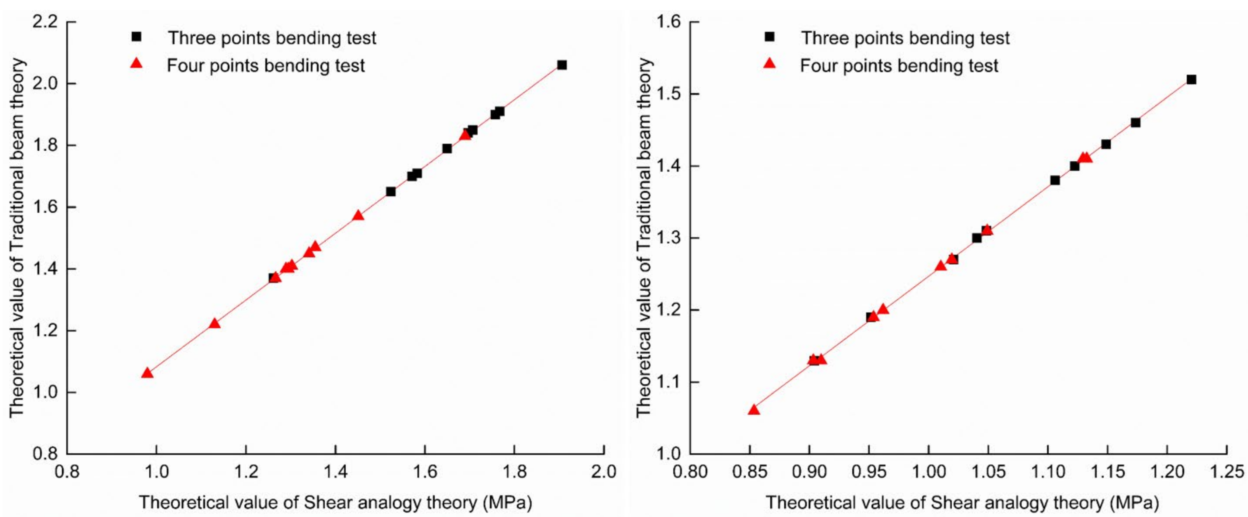


Figure 5: Correlation between the calculated values of the traditional beam theory and shear analogy, (a)three-layer CLT and (b) five-layer CLT

The relationship between theoretical values of 3- and 5-layer CLT can be expressed by linear regression Eqs. (3) and (4), respectively.

$$f_3 = 1.08\tau_3 \ (R^2 = 0.9998) \quad (3)$$

$$f_5 = 1.24\tau_5 \ (R^2 = 0.9995) \quad (4)$$

where f and τ represent the theoretical value of traditional beam theory and shear analogy theory, respectively, subscripts indicate layer number.

4 Conclusions

In this study, the out-of-plane shear strength values of three- and five-layer CLT specimens were evaluated using two short-span bending test methods. The test results were analyzed using different theories. The main conclusions can be summarized as follows:

1. The failure modes of all the specimens observed in the FPB tests were mainly subjected to RS failure in the cross layers. However, both tensile failure and delamination of the individual specimens were observed in the TPB tests. Thus, the FPB method is more suitable for evaluating the RS strength of CLT.

2. The shear bearing capacity of the CLT specimens determined using the TPB method was higher than that obtained using the FPB method. Moreover, the testing methods used significantly affected the out-of-plane shear capacity of the three-layer CLT specimens.

3. Apart from the testing method, the number of layers also affected the evaluation of out-of-plane shear properties. The out-of-plane shear strength decreased markedly as the number of layers increased.

4. The values calculated using the traditional theory was the highest among all four theories. Moreover, the out-of-plane shear strengths of CLT calculated using the traditional beam theory and shear analogy were highly correlated. Therefore, theoretical values can be converted based on their high linear correlation in engineering applications.

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