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The appropriacy of the analytical models for calculating the shear capacity of cross-laminated timber (CLT) under out-of-plane bending

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Abstract

Rolling shear, an inherent property of cross-laminated timber (CLT) due to the weak shear strength of cross layers, is always the determinant of load-bearing capacity for short-span CLT members subjected to out-of-plane bending. Many analytical models were developed to calculate the shear capacity of CLT members. Because of the difficulty to precisely model the complicated shear failure mechanisms, however, no model was universally accepted. This paper aims to study the appropriacy of the commonly used analytical models, namely, composite beam theory, shear analogy method, Gamma method, and simple beam theory, by tests and analytical calculations. A composite beam theory-based simplified method was proposed. Three-point loading tests for the short-span CLT panels with 3 and 5 layers were conducted, and the shear capacities of the test specimens were calculated using the above-mentioned analytical methods. Shear strength and modulus of cross layers of the test specimens, which were used as the inputs for calculating the shear capacities, were tested by modified planar shear method. By comparing the calculation results obtained from different analytical models and the test results as well, it can be concluded that: (1) composite beam theory, shear analogy method, and the proposed simplified method give almost the same calculation results, therefore, the proposed simplified method can be used as the replacement for the other models; (2) Gamma method is more appropriate for calculating the shear capacity in case the input shear strength is determined by planar shear test; (3) the simple beam theory that is used in CSA O86 provides significantly lower shear capacity predictions than those obtained by the other methods.

Introduction

Cross-laminated timber (CLT) panels consist of several layers of boards stacked crosswise (typically at 90 degrees) and glued together on their wide face, sometimes also on their edged face, but not mandatory [1]. Because of the orthogonal orientation of the adjacent layers within CLT and the low shear strength and modulus perpendicular to the grain of wood, rolling shear is an inherent property which could induce shearing failure in cross layers when CLT subjected to out-of-plane loading (bending). It has been confirmed by considerable tests that the strength of rolling shear ranges from 1.0 MPa to 2.0 MPa, and modulus is less than 100 MPa for most of

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the wood species made up CLT panels [2–5]. This property of wood leads to the fact that for CLT bending members with small span-to-depth ratio (usually less than 6), rolling shear could be the determinant which controls the load-bearing capacity of CLT beams. Even for CLT bending members with large span-to-depth ratio of which the load-bearing capacity depends on the bending strength of outer layers, the effects of rolling shear still have significant influence on the overall stiffness of CLT members [6]. For these reasons, the effects of rolling shear are always the key factor to be considered in the design philosophy of CLT members, and to be specifically, the determination of the strength of rolling shear of the cross layers and the prediction of shear capacity are always the two essential aspects for CLT structure designing.

It has been confirmed that the strength of rolling shear is a system property rather than an instinct material property because of the complicated failure mechanisms [7]. Considering the previous studies confirmed that the test-measured rolling shear quantities are rather apparent properties than the real rolling properties because the test results significantly depend on the saw patterns of cross layers, aspect ratio, size of test samples, test method, and so on [8–11].

In fact, the concept of rolling shear comes from the wood fibers oriented in the longitudinal direction rolling off each other due to the perpendicular-to-fiber shear stresses in TR plane (Tangential—Radial plane) [12]. Therefore, the strength and the modulus of rolling shear is theoretically determined by the interfacial properties of the fibers. For this reason, Perret et al. [13] suggested that the rolling shear properties should be experimentally determined on the scale of annual ring. However, the shear failure mechanisms of the cross layers of CLT bending member in real structures are not only rolling off between fibers, but also cracking intersecting the annual rings or/and debonding along the gluing interface. Each failure mechanism exhibits different shear properties, hence to measure the rolling shear properties on structural scale which includes all the possible failure mechanisms maybe more reliable for engineering design [14]. To achieve this goal, various methodologies were proposed to determine the strength and modulus of rolling shear on structural scale [10, 15]. Among them, modified planar shear test and short-span out-of-plane bending test are popularly accepted.

Modified planar shear test uses a pair of bearings to apply loads at the two opposite ends of the outer longitudinal layers of CLT to produce rolling shear stress in the middle cross layer. As no pressure is applied perpendicular to the cross layer, the test strength of rolling shear maybe closer to the actual strength produced by fibers rolling than that tested by short-span beam bending test, and furthermore, the shear modulus can be directly measured.

The short-span out-of-plane bending test is a more homogenized methodology across the standards [16–18]. The method employed a CLT panel of span-to-depth ratio less than 6 under three-point bending, specified by ASTM D 2718 [18], or of the span-to-depth ratio 12 under four-point bending, specified by EN 408 [16] and EN 16351 [17], to induce the shear stress in the cross layers. The test shear strength can be determined by composite beam theory, shear analogy method, and Gamma theory, etc. Obviously, for 3-point bending short-span CLT members, the model predicted shear capacity must be well in agreement with the test result if the input shear strength for calculation was determined by the same model. Hence, it naturally gives rise to the doubt about the confidence of the measured shear strength as the input for another analytical model.

With regard to the prediction of the shear capacity of CLT out-of-plane bending members, extensive studies based on the elastic beam theory have been carried out to establish the calculation models, as Chritovasilis et al. [19] reported. The models assume the shear stress, τ and the shear force, V in the cross section meets the relationship as shown in Eq. (1).

$$\tau = \frac{VS}{bI} \tag{1}$$

where, b and I are the width and the moment of inertia of the cross section, respectively; S is the static moment area. According to the different treatment of the cross layer and cross section, the analytical models were divided into different methods, such as Gamma method, shear analogy method, composite beam theory, and simplified beam theory. These methods were employed by current design codes [20, 21] and will be briefly summarized in "Summary of analytical methods" Section. Apart from the beam theories, Saavedra et al. [22] reported a multi-scale model to investigate the rolling shear property of CLT on the basis of numerical analysis, and Stürzenbencher et al. [23] developed the model to predict the mechanical property of CLT bending members by using advanced plate theory. However, because the complicated failure mechanisms cannot be precisely modeled, no model was universally accepted.

The present study aims to investigate the appropriacy of the popular models, namely, composite beam theory, shear analogy method, Gamma method, and simple beam theory by comparing the calculation results of different models as well as the test results. Rolling shear properties, which were used as inputs to predict the shear capacity of the test specimens, were tested by means of modified planar shear test procedure so that the self-validation can be avoided. The CLT panels made from Canadian Spruce−Pine−Fir (SPF) and European Spruce (EUS) were tested, respectively.

Summary of analytical methods

Gamma method

Gamma method imagines the longitudinal layers as beams and the cross layers as continuously distributed connections. It assumes that the load on the panel only carried by longitudinal layers while the shear deformation is carried by cross layers which have the shear stiffness equal to the modulus of rolling shear. In order to consider the contribution of shear deformation to overall bending stiffness, $(EI)_{\text{eff}}$, a factor, γ_i is introduced to measure the connection efficiency of the cross layers. The relationship between the shear stress, τ and shear force, V, is expressed by Eq. (2).

$$\tau = \frac{(EQ)V}{(EI)_{\text{eff}}b} \tag{2}$$

where the effective bending stiffness, $(EI)_{\text{eff}}$ can be calculated by

$$(EI)_{\text{eff}} = \sum_{i=1}^{n}\left(E_iI_i + \gamma_iE_iA_iz_i^2\right) \tag{3}$$

where E_i is the modulus of elasticity for ith layer in longitudinal direction of the beam; I_i is the moment of inertia of the cross section for ith layer; A_i is the area of cross section for ith layer; Z_i is the space between the centroid of cross section of the ith layer and the neutral axis of global bending; γ_i is the connection efficiency factor for ith layer which can be given by

$$\gamma_i = \left(1 + \frac{\pi^2E_ib_ih_i}{L_{\text{eff}}^2G_{\text{r}j}b_j/h_j}\right)^{-1} \tag{4}$$

where L_{eff} is the effective length of the beam which equals to the length between two zero moment points; b_i and h_i are the width and depth of the ith longitudinal layer, respectively; $G_{\text{r}j}$ is the modulus of rolling shear for the jth cross layer that connecting ith longitudinal layer; b_j and h_j are the width and depth of jth longitudinal layer, respectively. The effective moment of area, $(EQ)_{\text{eff}}$ can be calculated by Eqs. (5) and (6) for 3- and 5-layer CLT panel, respectively.

$$(EQ)_{3\text{ - layer}} = \frac{1}{2}\gamma_1E_0bh(h+t) + \frac{1}{8}E_{90}bt^2 \tag{5}$$

$$(EQ)_{5\text{ - layer}} = \gamma_1E_0bh(h+t) + \frac{1}{2}E_{90}bt(h+t) + \frac{1}{8}\gamma_2E_0bh^2 \tag{6}$$

where E_0 and E_{90} are the MOEs (Modulus of Elasticity) parallel to grain and perpendicular to grain, respectively; h and t are thicknesses of longitudinal and cross layers, respectively.

Shear analogy method

Shear analogy method assumes the layered panel as a virtual system composed of two imaginary beams A and B. Beam A is given the sum of the inherent flexural stiffness of the individual layers along its own neutral axis, while beam B is given the combined flexural stiffness of all the layers and connections alone the neutral axis of overall bending as well as the sum of shear stiffness of all layers. The two beams are coupled by the virtual web that consists of a continuously distributed link element with infinite axial rigidity, hence, the equal deformation at any position along the beam must be validated when it carries the transvers load.

According to the above assumptions, for the CLT panel having the longitudinal layers of MOE parallel to grain E_i, width of b_i, and thickness of h_i, the bending stiffness of beam A, $(EI)_{\text{A}}$ and B, $(EI)_{\text{B}}$ can be given as Eqs. (7) and (8), respectively.

$$(EI)_{\text{A}} = \sum_{i=1}^{n}E_ib_i\frac{h_i^3}{12} \tag{7}$$

$$(EI)_{\text{B}} = \sum_{i=1}^{n}E_iA_iZ_i^2 \tag{8}$$

where $A_i = b_ih_i$, is the area of the ith longitudinal layer; Z_i is the space between the center of the ith layer and the neutral axis of global bending. When considering the assumption that the auxiliary web members have infinite flexural and shear stiffness, they must have the same deflections between the two beams at every same position. Therefore, the applied force and the moment must be proportionally carried by beam A and beam B in accordance with their bending stiffness, thus shear force, $V_{A,i}$ carried by the ith layer of beam A is given as

$$V_{\text{A},i} = \frac{E_iI_i}{(EI)_{\text{A}}}V_{\text{A}} \tag{9}$$

where V_A is the shear force carried by beam A. Accordingly, the shear stress of each individual layer of beam A, $\tau_{\text{A},i}$ can be given by

$$\tau_{\text{A},i} = \frac{3}{2bh_i}\frac{E_iI_i}{(EI)_{\text{A}}}V_{\text{A}} \tag{10}$$

where $I_i = b_i h_i^3/12$ is the moment of inertia for the ith longitudinal layer. The shear stress at the interface of the two layers of beam B, $\tau_{Bi,i+1}$ can be calculated by

$$\tau_{Bi,i+1} = \frac{V_B}{(EI)_B} \sum_{j=i+1}^{n} E_j A_j Z_j \tag{11}$$

where V_B is the shear force carried by beam B. For the CLT panel of knowing strength of rolling shear, τ_f, the maximum shear force carried by Beam B can be calculated form Eq. (11) by replacing $\tau_{Bi,i+1}$ with τ_f, and then the shear capacity of the beam can be calculated by

$$V = V_b \left[1 + \frac{(EI)_A}{(EI)_B}\right] \tag{12}$$

Composite beam theory

Because the longitudinal layers and the cross layers have different moduli in the principal axis of bending, the CLT bending members can be treated as the beams of different materials according to the elementary beam theory. This can be dealt by using an equivalent width technique [24], in which the width of each component parallel to the principal axis of bending is proportional to the modulus of elasticity of the component material. For a CLT beam having MOE of longitudinal layers and cross layers as E_0 and E_{90}, respectively, then the equivalent width of cross layer, b_r can be determined by

$$b_r = \frac{E_{90}}{E_0} b \tag{13}$$

The rolling shear stress, τ in the cross layers of the bending specimen can be calculated by

$$\tau = \frac{VS}{I_{eq} b} \tag{14}$$

where I_{eq} is the moment of inertia of the equivalent cross section; S is static moment of area. Figure 1 show the cross section of a 3-layer and a 5-layer CLT bending member with width b, longitudinal-layer thickness h, and cross layer thickness t. According to the previous studies [25, 26], the failure of rolling shear usually takes place at the interface between outer layer and its adjacent cross layer, i.e., the point 1 for 3-layer and point 1 or 2 for 5-layer CLT bending members. However, for CLT bending members, the shear stress is almost uniformly distributed over the depth of cross layer, as Hojat [27] found. Therefore, only the static moment of the area outside the cross layer needs to be calculated for determining the maximum shear force of the panel, which can be calculated as Eqs. (15) and (16), respectively.

$$S_{1,\,3\text{ - layer}} = \frac{1}{2} bh(t+h) \tag{15}$$

$$S_{1,\,5\text{ - layer}} = bh(t+h) \tag{16}$$

the moment of inertia of the cross section can be calculated by

$$I = \sum_{i=1}^{n} \left(I_i + A_i z_i^2\right) \tag{17}$$

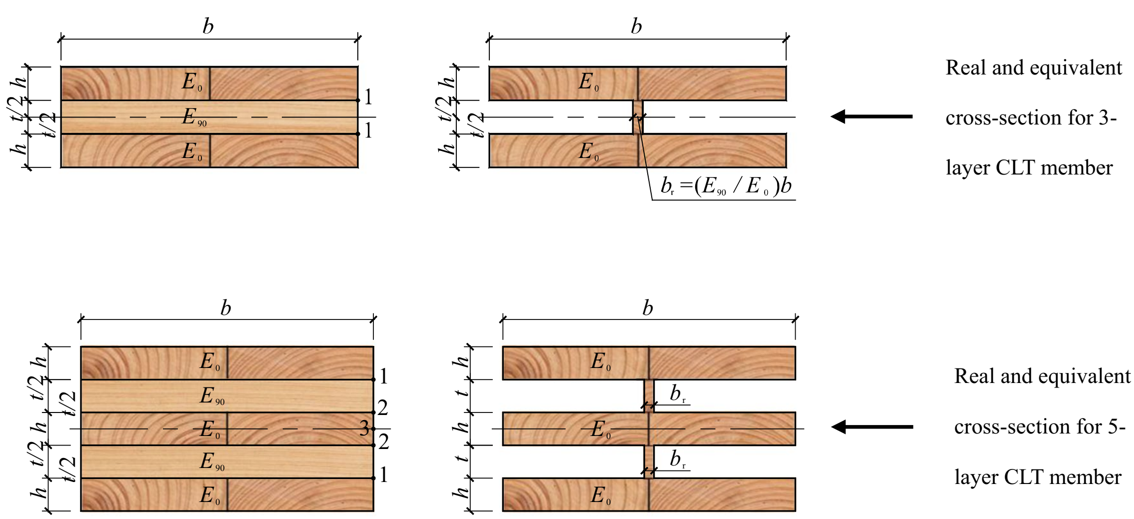


Fig. 1 Equivalent cross section for 3-layer and 5-layer of a CLT beams based on composite beam theory

Simple beam theory

Canadian design code CSA O86-14 [20] adopts a simple method based on elementary beam theory for isotropic materials to calculate the shear resistance of CLT panels. It specified that the factored shear resistance, V_r of CLT panels shall be calculated by

$$V_r = \phi F_s \frac{2A_g}{3} \tag{18}$$

where $\phi = 0.9$; F_s is the factored strength of rolling shear of laminations; and A_g is the gross cross-sectional area of the panel for the major strength axis. Equation (18) implies that the shear strength of the material equals to the rolling shear strength and the failure of rolling shear takes place at the middle of the cross section where the shear stress reaches its maximum value.

Simplified composite beam method

The formulas to determine the shear capacity of the CLT bending members by using Gamma method or shear analogy method are complicated while the calculation results may not be the best. The simple beam theory provides the simplest formula to calculate the shearing capacity, however, it ignores the differences between the longitudinal layers and cross layers and treats the layered cross section as homogenous section, which may lead to unacceptable errors.

In fact, because the transverse MOE of the cross layer is only around 1/30 of MOE parallel to grain of longitudinal layer [4], the contribution of the stresses in cross layers to the overall bending is tiny. If we further ignore this contribution, the bending of CLT panel can be simply modeled as the cross section shown in Fig. 2. The shear stress along the interface of longitudinal and cross layers given as Eq. (1) can be further simplified according to the equilibrium condition of the longitudinal layer (Fig. 2).

Theoretically, the maximum shear stress over a rectangular cross section must take place at middle of the depth. However, for CLT bending members, the shear stress is almost uniformly distributed over the depth of cross layer, as Hojat [27] found, hence it is reasonable to assume the failure of rolling shear take place at the interface between longitudinal and cross layers. Accordingly, we have static moments of area and the moments of inertia for 3- and 5-layer CLT members, as shown in Eqs. (19–22).

$$S_3 = \frac{1}{2}bh(h+t) \tag{19}$$

$$I_3 = 2\left[\frac{1}{12}bh^3 + \frac{1}{4}bh(h+t)^2\right] \tag{20}$$

$$S_5 = bh(h+t) \tag{21}$$

$$I_5 = \frac{1}{4}bh^3 + 2bh(h+t)^2 \tag{22}$$

If the strength of rolling shear, f_r is determined, the shearing capacity of the CLT bending members can be calculated by

$$V_{3-layer} = \frac{b\left[h^2 + 3(h+t)^2\right]f_r}{3(h+t)} \tag{23}$$

for 3-layer CLT panel and

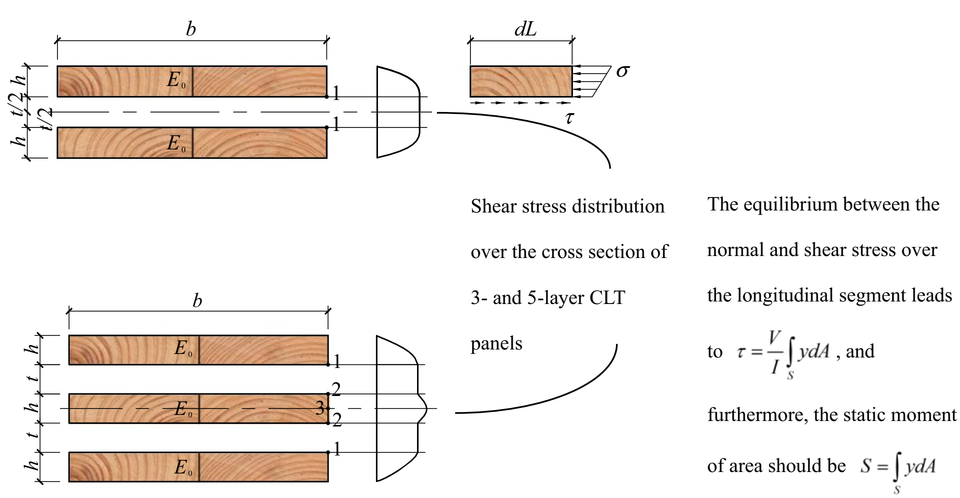


Fig. 2 Simplified beam model for the calculation of shearing capacity

$$V_{5-layer} = \frac{b\left[h^2 + 8(h + t)^2\right]f_r}{4(h + t)} \quad (24)$$

for 5-layer CLT panel.

Test program for rolling shear

To investigate the appropriacy of the methods mentioned above, 3-point bending tests for short-span CLT panels was conducted in this study. CLT panels made from Canadian SPF and EUS were selected. The grade of SPF and EUS were visually graded No. 2 and SF, respectively, according to National Lumber Grades Authority (NLGA). The cross section of SPF and EUS were 35 mm in thickness and 140 mm in width. The 3-layer and 5-layer CLT panel were manufactured by Zhongjia Low Carbon Co. Ltd. at Ningbo, China. All the specimens were stored in room condition for approximately 2 months before test. The densities and the moisture contents are 0.45 g/mm^3 and 12.54% for SPF, and 0.47 g/mm^3 and 12.45% for EUS, respectively.

Determination of material and rolling shear properties

To obtain the input parameters for calculating the shear capacity of the test samples, the mechanical properties of SPF and EUS, including tensile and bending, were tested in accordance with ASTM D 143 [28] and EN 789 [29]. For each property; in total, 15 timber specimens were tested.

The rolling shear properties were tested by modified compression shear test method, which has been recognized in several standards, such as EN 789 [29], EN 408 [16], and ASTM D2718 [18], for the determination of the planar shear strength and modulus of wood-based panels. In this study, the test procedures specified in ANSI/APA PRG 320–2019 [30] were used to determine the planar shear properties of the CLT panels. 3-layer CLT segments, 330 mm in length, 105 mm in thickness, and 140 mm in width were used as the test samples. Planar shear stress was introduced by applying the opposite pressures on the longitudinal layers, as shown in Fig. 3. A steel plate was mounted on the longitudinal layer to introduce the test load while a displacement sensor was used to measure the relative displacements between longitudinal layers which are considered equal to the shear deformation of cross layer. Both the deformation and the applied load were simultaneously recorded via TDS 650 data acquisition system. The planar shear stress, τ, and modulus, G_r, were calculated as $G_r = \frac{t}{lb} \cdot \frac{P}{\Delta} \cos\alpha$, $\tau = \frac{P}{lb} \cos\alpha$, where t is the thickness of cross layer; l and b are the length and width of the CLT segments; P is the applied load; Δ is the shear deformation of the cross layer; $\alpha = 14^o$ is the angle between the load axis and longitudinal layer.

The results of rolling shear together with the timber properties are provided in Table 1, where, E_0, E_b, G_r, and f_r are MOE parallel to grain, modulus of bending,

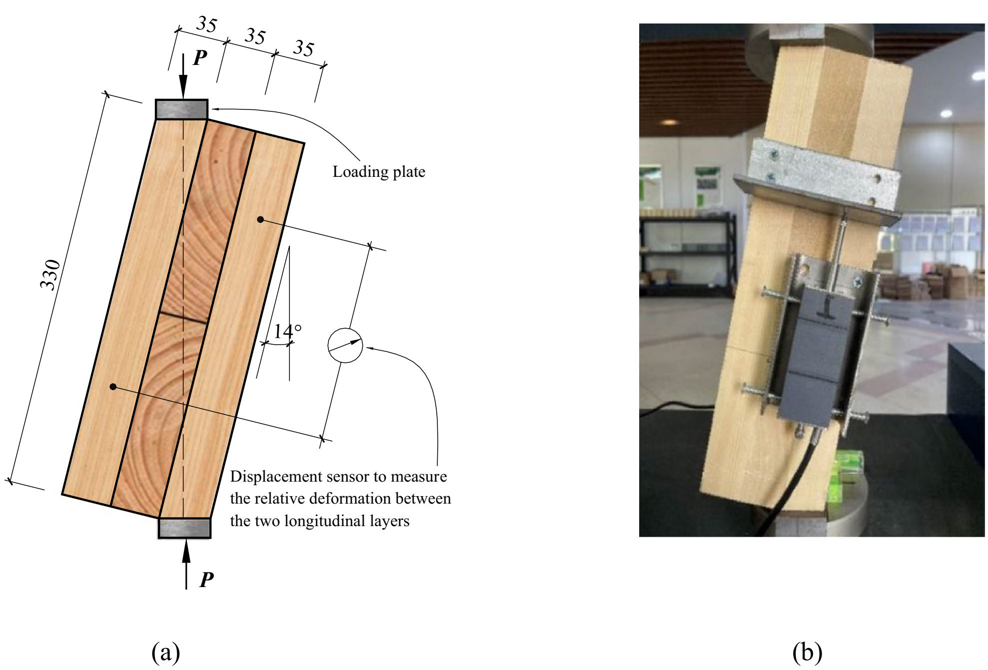


Fig. 3 Test setup to measure the strength and modulus of rolling shear: **a** sketch; **b** photo

modulus of rolling shear, and strength of rolling shear, respectively.

Short-span bending test

Shear capacities of the CLT panels were teats by 3-ponit loading test. A total of six 3-layer and six 5-layer CLT panels were tested for SPF and EUS panels, respectively. The dimensions of the specimens are shown in Table 2. Load was applied with an actuator having capacity of 300 kN and accuracy of ± 0.1 kN. The test setup is shown in Fig. 4. The specimen was installed on the machine using a roller supporter at one end and a knife supporter at the other end so that the two ends of the beam can rotate freely. The space of the center between the two supports were calibrated to precisely align with the vertical line demarcated on side surface of the specimens to ensure the test specimen having expected span, as shown in Fig. 4. The test load was applied at the mid-span of the specimens at a constant speed of 2 mm/min for 3-layer CLT panels and 2.5 mm/min for 5-layer CLT panels so that the maximum load can be reached in 5 min. A laser displacement sensor was installed below the mid-span to measure the deflection of the mid-span. The applied load was measured by the force cell on the actuator of the test machine. Both the applied load and the mid-span deflection were simultaneously recorded at 1 Hz.

Test results

Typical failure modes are shown in Fig. 5. The rolling shear crack firstly appeared between the loading position and supporter, and then extended to the loading position or supporter as the applied load increases. The crack path went along or intersected the annual rings, and extent through the glued interface between the longitudinal and cross layers. This phenomenon validated that the shear failure mode of CLT out-of-plane bending

Table 1 The properties of materials and rolling shear

Material	E_0		E_b		Test specimen number	G_r		f_r		Test specimen number
	Mean (MPa)	COV (%)	Mean (MPa)	COV (%)		Mean (MPa)	COV (%)	Mean (MPa)	COV (%)	
SPF	14015	9.15	8360	11.71	15	92.71	16.08	1.16	16.61	15
EUS	9759	3.47	7398	13.78	15	101.49	17.53	1.29	9.54	15

Table 2 Dimensions of test specimens

Specimen label	Number of layers	Thickness of longitudinal layer (mm)	Thickness of longitudinal layer (mm)	Total thickness (mm)	Width (mm)	Span (mm)	Ratio of span to depth
SPF3	3	35	35	105	310	630	6
SPF5	5	35	35	175	310	1050	6
EUS3	3	35	35	105	310	525	5
EUS5	5	35	35	175	310	875	5

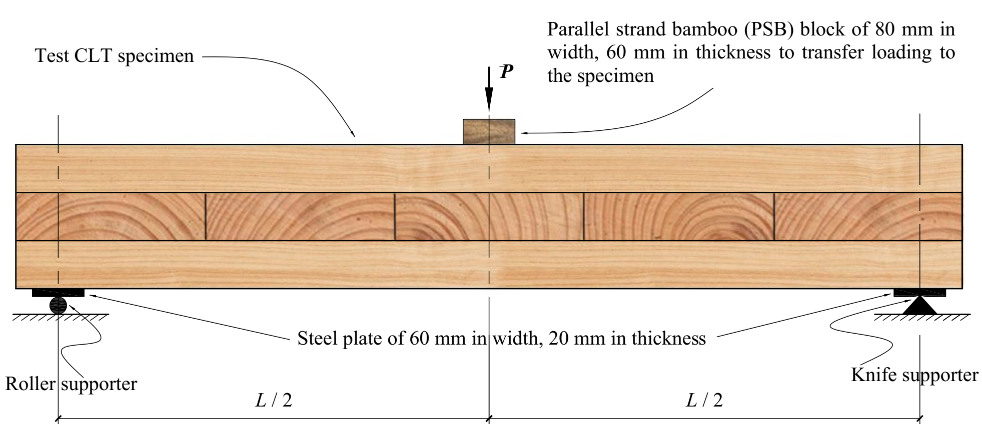
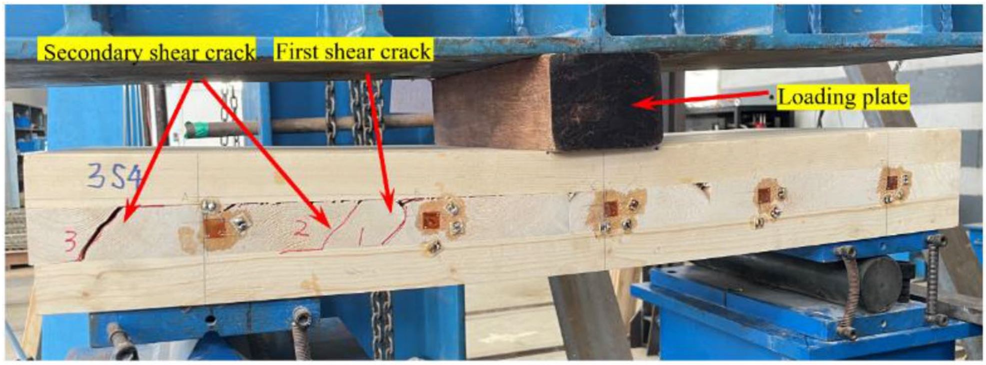
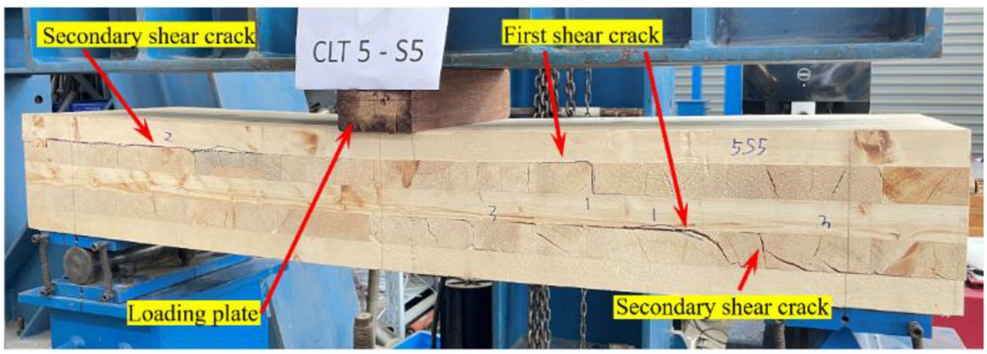


Fig. 4 Test setup of three-point bending of CLT panels



(a)



(b)

Fig5 Typical failure modes of rolling shear: **a** three-layer CLT panel; **b** five-layer CLT panel

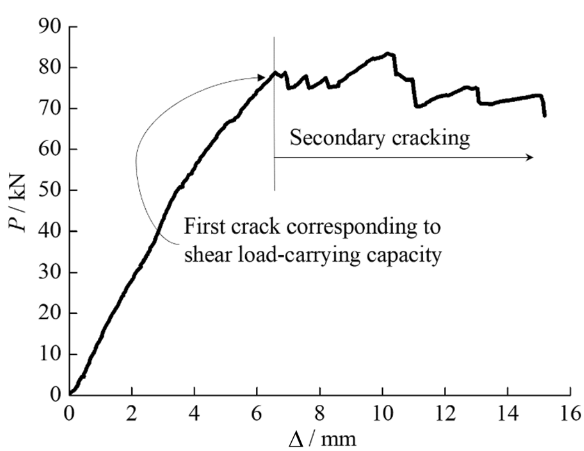


Fig. 6 Typical load–deflection curve (SPF5-S5)

member includes many mechanisms, such as fiber rolling and interfacial debonding.

Figure 6 shows a typical load–deflection curve. It indicated that the damage of rolling shear shows a progressive process. Before the first crack appeared, the specimen behaves elastically until crack occurs, and the slope represents the initial bending stiffness of the specimen. Point 1 at the end of straight linear corresponds to the onset of initial crack, and the corresponding load can be defined as the shear capacity of the specimen. The post linear curve is associated with the shear crack expansion and secondary cracking. Load–deflection curves of the specimens in SPF are shown in Fig. 7.

Table 3 presents the test results of each specimen. Because debonding took place between the layers of specimens SPF5-3 and SPF5-4, rolling shear did not happen. Hence, the test results of these two specimens are excluded from Table 3. The test results show that the average rolling shear capacity of the groups SPF3 and SPF5 are 35.76 kN with a COV of 5.65% and 40.94 kN with a COV of 2.45%, respectively. The shear capacity of 5-layer SPF CLT panel is roughly 15.7% higher than that of 3-layer SPF CLT panels. This is consistent with the common understanding that the shear capacity of CLT panels is positively related to the quantity of layers. For CLT panels with more layers, higher capacity is obtained. However, the shear capacities of groups EUS3 and EUS5

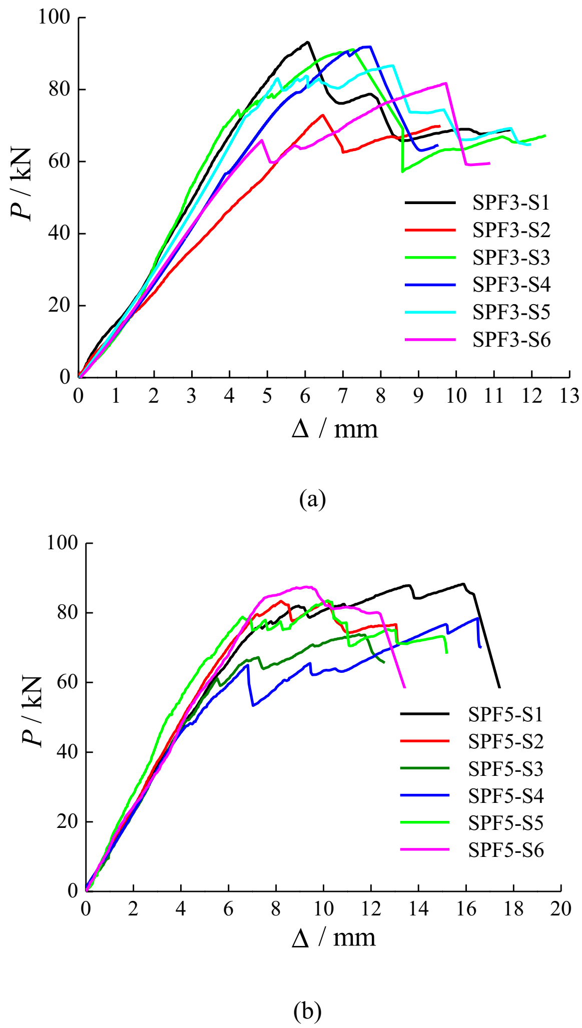


Fig. 7 Load–deflection curves of SPF CLT panels: **a** 3-layer; 5-layer

Table 3 Test results of the rolling shear capacities of SPF and EUS CLT panels

Specimen count	Load when first shear crack appears (*P*)/kN	Shear capacity/kN	
		Test values (*P*/2)	Mean/COV
SPF3-S1	71.48	35.74	35.76/5.65%
SPF3-S2	72.89	36.45	
SPF3-S3	78.37	39.19	
SPF3-S4	67.62	33.81	
SPF3-S5	72.95	36.48	
SPF3-S6	65.85	32.93	
SPF5-S1	81.99	41.00	40.94/2.45%
SPF5-S2	82.13	41.06	
SPF5-S5	78.86	39.43	
SPF5-S6	84.51	42.26	
EUS3-S1	119.45	59.73	56.16/4.80%
EUS3-S2	106.73	53.37	
EUS3-S3	108.22	54.11	
EUS3-S4	106.21	53.11	
EUS3-S5	116.05	58.03	
EUS3-S6	117.25	58.63	
EUS5-S1	107.13	53.57	56.92/7.54%
EUS5-S2	102.45	51.23	
EUS5-S3	109.79	54.90	
EUS5-S4	122.21	61.11	
EUS5-S5	114.19	57.11	
EUS5-S6	127.27	63.64	

are almost the same. This may be caused by imperfection of specimen manufacturing.

Comparison of analytical models and test results

The shear capacities of the test specimens predicted by composite beam theory, simplified composite beam method, shear analogy method, Gamma method, and CSA O86 [20] method as well as those obtained by the test are compared in Fig. 8. The errors of model prediction are compared in Fig. 9. It can be observed that the predicted results of simplified method, composite beam theory, and shear analogy method are almost the same. The maximum difference of these calculation results is less than 3%. This implies that the error induced due to omitting the effects of cross layers is tiny, and the simplified method can be used as the replacement of composite beam theory and shear analogy method to evaluate the shear capacity of CLT members.

Figure 8 shows that the shear capacities calculated by Gamma method are significantly different from those calculated by the other analytical models. The prediction results of Gamma method are apparently higher for 3-layer CLT specimens while lower for 5-layer CLT specimens when comparing with those predicted by simplified method, composite beam theory, and shear analogy method. The shear capacities calculated by simple beam theory specified by CSA O86 [20] are quite lower than those calculated by the other analytical methods.

The details of the data regarding to the model prediction shear capacity, test results, and the differences among them are presented in Table 4. Because the strengths of rolling shear of the cross layers, as shown in Table 1, were tested by modified planar shear test method, self-validation in calculation can be avoided. The results indicate that the predicted results of Gamma method for SPF are well in agreement with the test results, whereas for EUS the predicted results of Gamma method deviated from the results with the largest error of 19.53%. Comparing the results of other methods with the test results indicated that, apart from specimen EUS-5, the calculation results were

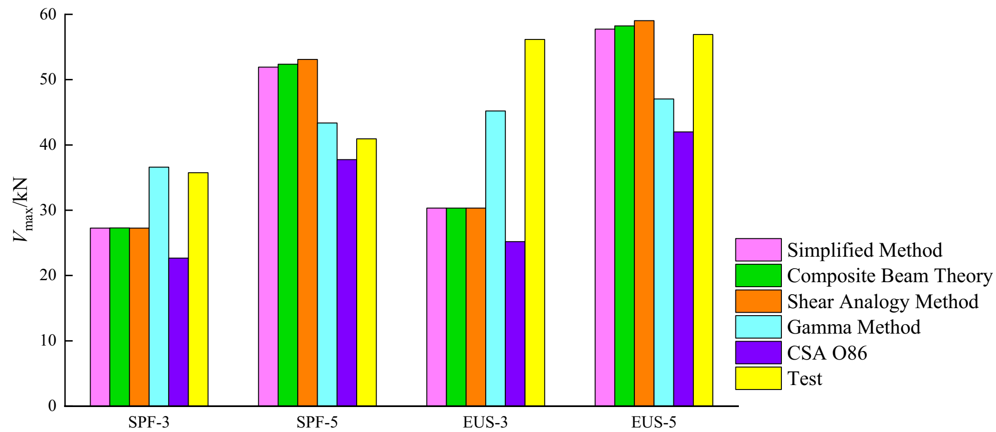


Fig. 8 Comparison of the mean values of shear capacities of the test specimens obtained by different analytical models

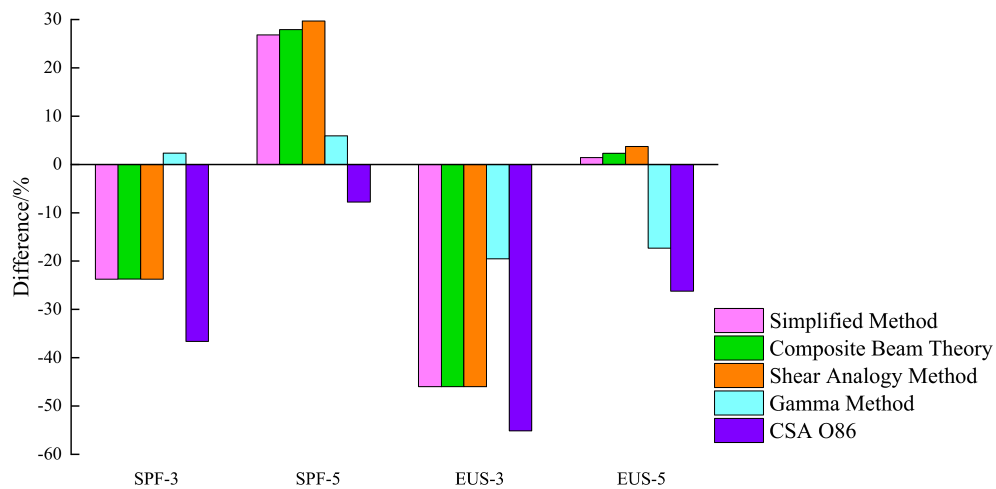


Fig. 9 The errors of model prediction

Table 4 Comparation of prediction rolling shear capacity with test results

CLT	f_r (MPa)	V_{max} (kN)/Errors					
		Simplified method	**Composite beam theory**	**Shear analogy method**	**Gamma Method**	**CSA O86**	**Test**
SPF-3	1.16	27.27/−23.74%	27.28/−23.71%	27.27/−23.74%	36.60/2.35%	22.66/−36.63%	35.76
SPF-5	1.16	51.92/26.82%	52.37/27.92%	53.09/29.68%	43.36/5.91%	37.76/−7.77%	40.94
EUS-3	1.29	30.33/−45.99%	30.34/−45.98%	30.33/−45.99%	45.19/−19.53%	25.19/−55.15%	56.16
EUS-5	1.29	57.74/1.44%	58.24/2.31%	59.04/3.72%	47.05/−17.34%	41.99/−26.23%	56.92

significantly deviated from the test results, and the errors are greater than 22%, some of them are greater than 50%. Regarding to the results of the method in CSA O86 [20], apart from SPF5, all the other calculation errors are greater than 25%. Hence it can be concluded that in case the input shear strength was determined by planar shear test, Gamma method is more appropriate than the other methods in calculation the shear capacity for CLT members.

To further compare composite beam theory, shear analogy method, and Gamma method, test and calculation results reported by Sikora [31] and Navaratnam [2] were adopted in this study. They used short-span loading test for 3- and 5-layer CLT panels to measure the rolling

Table 5 Comparation of the rolling shear strength obtained by calculation based on short-span loading test

CLT	*b*/mm	*L*/mm	*h*/mm	*t*/mm	V_{max}/kN	f_r (MPa)/Difference		
						Composite beam theory	Shear analogy Method	Gamma Method
3-layer [34]	520	1260	35	35	78.67	2.0	2.0	1.89
5-layer [34]	520	1740	35	20	106.20	1.76	1.76	1.76
S-3–20 [35]	270	720	20	20	24.25	2.08	2.07	1.91
S-3–24 [35]	288	864	24	20	25.57	1.71	1.71	1.57
S-3–40 [35]	584	1440	40	40	55.10	1.09	1.09	1.00
S-5–20 [35]	576	1200	20	20	49.06	1.03	1.03	1.04

shear strength of cross layer. Table 5 compares the rolling shear strength of cross layer obtained by the composite beam theory, shear analogy method, and Gamma method. It shows that the rolling shear strength obtained by composite beam theory and shear analogy method are almost the same. For 3-layer CLT panels, the rolling shear strengths obtained by Gamma method exhibit 5.8% to 9.0% higher than those obtained by composite beam theory and shear analogy method, whereas for 5-layer CLT panels the two results are the same. These findings are approximately in agreement with the findings obtained from Table 4.

Conclusions

Test results in this study indicated that the shear failure mode of CLT out-of-plane bending member includes many complicated mechanisms, such as fiber rolling and interfacial debonding. Damage of rolling shear shows a progressive process. The load associated to the first shear crack can be defined as the shear capacity of CLT members under out-of-plane bending.

The simplified method proposed in this study gives the shear capacity of CLT panel almost as same as that given by composite beam theory and shear analogy method. Hence the proposed simplified method can be use as replacement of composite beam theory and shear analogy method to calculate the shear capacity for CLT members under out-of-plane bending.

The shear capacities predicted by Gamma method are more reliable in case the strength of rolling shear, which used as the input parameter, is tested by modified planar shear method.

The method that is used in CSA O86 [20] provides the lowest shear capacities among all the analytical methods studied in this paper, and they also significantly lower than test results. Therefore, CSA O86 [20] provides the most conservative prediction for shear resistance of CLT out-of-plane bending members.

Abbreviations

CLT	Cross-laminated timber
TR	Tangential radial
SPF	Spruce—Pine—Fir
EUS	European spruce
MOE	Modulus of elasticity
COV	Coefficient of variation
PSB	Parallel strand bamboo
NLGA	National lumber grades authority

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Author contributions

ZH accomplished all the theoretical analysis and the manuscript writing work. LJ programmed the short-span bending test, and was the actual operator of all tests. CN provided theoretical and technical support of the whole research work presented in the manuscript. All test operation were carried out under the guidance of ZC. All authors have read and approved the final manuscript.

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Availability of data and materials

Not applicable.

Declarations

Competing interests

The authors declare no competing interests.

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