

Torque loading tests on the rolling shear strength of cross-laminated timber

Frank Lam¹ · Yuan Li² · Minghao Li^{3,4}

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Abstract In this study, torque loading tests on small shear blocks were performed to evaluate the rolling shear strength of cross-laminated timber (CLT). The CLT plates in the tests were manufactured with Mountain Pine Beetle-afflicted lumber boards and glued with polyurethane adhesive; two types of layups (five-layer and three-layer) with a clamping pressure 0.4 MPa were studied. The small block specimens were sampled from full-size CLT plates and the cross layers were processed to have an annular cross section. These specimens were tested under torque loading until brittle shear failure occurred in the middle cross layers. Based on the test results, the brittle shear failure in the specimens was evaluated by detailed finite element models to confirm the observed failure mode was rolling shear. Furthermore, a Monte Carlo simulation procedure was performed to investigate the occurrence probability of different shear failure modes in the tests considering the randomness of the rolling shear strength

and longitudinal shear strength properties in the wood material. The result also suggested the probability of rolling shear failure is very high, which gives more confident proof that the specimens failed dominantly in rolling shear. It was also found that the torque loading test method yielded different rolling shear strength values compared to the previous research from short-span beam bending tests; such a difference may mainly be due to the different stressed volumes of material under different testing methods, which can be further investigated using the size effect theory in the future.

Keywords Torque loading test · Rolling shear · Cross-laminated timber · Brittle fracture · Finite element model

Introduction

Rolling shear stress in wood is defined as the shear stress in the radial-tangential plane perpendicular to the grain direction; rolling shear strength and stiffness of wood are much lower than its longitudinal shear strength and stiffness [1]. According to the literature [1–6], rolling shear strength normally varies between 18 and 28 % of parallel-to-grain shear strength based on limited test data. In Eurocode 5 [7], a characteristic rolling shear strength value of 1.0 MPa is used for wood independent of its strength class. In timber design, high rolling shear stresses should always be avoided due to the low rolling shear strength of wood.

Cross-laminated timber (CLT) consists of crosswise oriented layers of wood boards that are either glued by adhesives or fastened with aluminum nails or wooden dowels [8]. For general timber design, rolling shear strength and stiffness are not major design properties. For

✉ Yuan Li
ubcli@interchange.ubc.ca

Frank Lam
frank.lam@ubc.ca

Minghao Li
minghao.li@canterbury.ac.nz

¹ Department of Wood Science, University of British Columbia, 4041-2424 Main Mall, Vancouver, BC V6T1Z4, Canada

² Department of Wood Science, University of British Columbia, 2843-2424 Main Mall, Vancouver, BC V6T1Z4, Canada

³ University of British Columbia, Vancouver, Canada

⁴ University of Canterbury, CNRE, Private Bag 4800, Christchurch 8140, New Zealand

CLT, however, rolling shear strength and stiffness must be considered in some loading scenarios due to the existing cross layers. For example, when a CLT floor panel is supported by columns, highly concentrated loads in the supporting area may cause high rolling shear stresses in cross layers; the same concerns may arise for designing short-span floors or beams. Therefore, there is a need to evaluate the rolling shear strength and stiffness properties for more practical applications of CLT structures.

ASTM D2718-00 stipulates two test methods (short-span bending test and planar shear test) to evaluate shear properties of wood products [9]. The short-span bending test is to load the specimen with small span-depth ratios to encourage shear failure mechanism; in the planar shear test, shear loads are applied by two metal plates face-glued onto the specimen. Norlin et al. [10] used a short-span bending test to study longitudinal and rolling shear strength properties of a laminated veneer product. Using non-destructive bending vibration tests, Fellmoser and Blass [4] studied the influence of rolling shear modulus on CLT stiffness as well as the relationship between shear deformations and beam span-depth ratios. Mestek et al. [11] studied the influence of shear deformations in cross layers on the load-carrying capacity of CLT beams. Zhou et al. [12] used both planar shear tests and short-span bending tests to study rolling shear strength and stiffness properties of CLT specimens made by black spruce. Li [6] performed short-term ramp loading tests in the research of the rolling shear behaviour of CLT; five-layer and three-layer CLT products were investigated in the tests. In this research, basic short-term rolling shear strength distribution was established by short-term ramp loading.

The objective of this study is to evaluate the rolling shear strength properties of non-edge-glued CLT plates by the torque loading tests. The CLT plates were manufactured mainly by Mountain Pine Beetle-killed lodgepole pine, which is one of the major species in the Spruce-Pine-Fir group in Canada. Another important reason to study CLT made out of the beetle-afflicted wood is to utilize the trees from the beetle-attacked forests [6].

In this study, torque loading tests were performed on CLT tube specimens. Brittle shear failure mode was observed in the CLT tube specimens. To further investigate the observed failure mode and the shear stress distribution in the cross layers, a detailed finite-element method was then adopted to simulate the structural behaviour of the CLT tube specimens under the testing conditions. A Monte Carlo simulation procedure was further performed to investigate the probability of different shear failure modes in the tests considering the randomness of the rolling shear strength and longitudinal shear strength in wood material.

Experimental methods

CLT test specimens are shown in Fig. 1, and two categories of the non-edge-glued CLT plates laminated with polyurethane adhesive, i.e., five-layer Spruce-Pine-Fir (SPF5) plates and three-layer Spruce-Pine-Fir (SPF3) plates, were studied. Within each category, one rigid mechanical clamping pressure level (i.e., 0.4 MPa) was applied for manufacturing [13]. For convenience, a five-layer Spruce-Pine-Fir plate is simply denoted as an SPF5 plate. Considering the 0.4 MPa pressure applied, this plate is further denoted as SPF5-0.4. Similarly, a three-layer Spruce-Pine-Fir plate pressed under 0.4 MPa is denoted as an SPF3-0.4 plate. Table 1 shows the configurations of these CLT plates, including the board grades, the thickness of laminations, the width of laminations, and the plate dimensions [13, 14]. The grade of lamination in Table 1 follows the NLGA (National Lumber Grade Authority) Standard Grading Rules for Canadian Lumber [15], and the Mountain Pine Beetle-afflicted lumber boards in both No.2 and stud grades in Table 1 were used for the CLT manufacturing.

To investigate the rolling shear failure, CLT tube specimens were prepared for the torque loading test, as shown in Fig. 2.

The torque tube specimen included three layers of laminated wood. First, small CLT cubic block specimens were sampled from full-size CLT plates. Then, the middle cross layer was cut and shaped into cylinder volume with an outer diameter of 52 mm by a computer numerical control (CNC) machine. The whole cylinder middle layer came from one piece of cross-laminated board, and this middle layer was continuous with no gaps guaranteed by the quality control process. Then, one hole with an inner diameter of 19.0 mm was drilled throughout the torque specimen crossing all the three layers of laminated wood. Table 2 shows the detailed information for the CLT torque tube specimens.



Fig. 1 Cross-laminated timber (CLT) panels

After one torque tube specimen was fixed on the loading machine platform, the upper layer of the specimen was locked on a steel frame with lever welded, as shown in Fig. 3. Then, vertical load was applied to the other end of the lever. The force arm from the centre of test specimen to the loading point is 0.5 m. The jack kept loading vertically at a constant loading rate until the specimens failed. The vertical load on the lever transformed into the torque load on the specimen, leaving the middle cylinder layer in a shear status. The loading test adopted the displacement control method, and the speed was about 4.8 mm/min (0.2 inch/min). The total time to failure for one tube specimen was about 4 min. The specimen would fail when the shear stress from the torque loading exceeded the rolling shear strength in the timber material, as further discussed in following sections investigating the failure modes in the torque tests. In the test, the loading history and the failure modes for the specimens were recorded.

Finite-element model

To investigate the stress distributions in the torque tube specimens, further modeling work was performed and summarized as follows with consideration of different shear stress components (longitudinal shear).

Considering the anisotropic material property in timber material and the grain influences on strength, the evaluation of the stress status of CLT torque tube specimens requires finite-element method for further investigation, since the elementary mechanical torque theory equations (calculated by hand) are not able to accurately evaluate the structural response of the tube specimens. Therefore, a linear elastic finite-element analysis was carried out.

The finite-element model, as shown in Fig. 4, was developed in ANSYS platform [16], considering the glue line shear stiffness and anisotropic wood properties. Dimensions of the tube models are the same as those in the

Table 1 Grades and configurations of the CLT plates

CLT category	Lamination grade	Lamination thickness (mm)	Lamination board width (mm)	Plate dimension $L \times W \times H$ (mm)
SPF5-0.4	No.2/Stud/No.2/Stud/No.2	34/19/34/19/34	140	3658 × 1219 × 140
SPF3-0.4	No.2/Stud/No.2	34/34/34	140	3658 × 1219 × 102



Fig. 2 CLT torque tube specimens

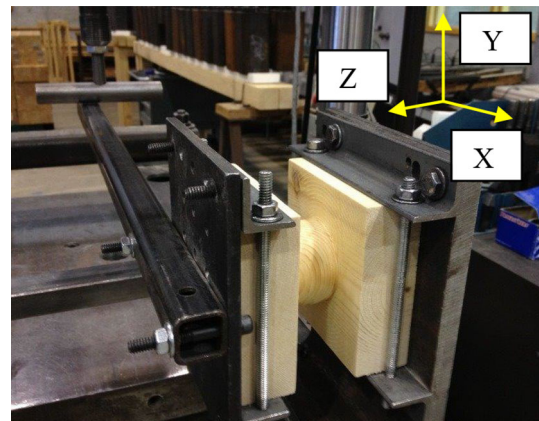


Fig. 3 Torque test setup (with Y direction as the direction of wood fibre in the middle cross layer)

Table 2 Information for the torque tube specimens

CLT category	Lamination grade	Number of specimen	Lamination thickness (mm)	Upper and bottom layers	Middle cylinder layer	
				Length × width (mm)	Outer diameter (mm)	Inner diameter (mm)
SPF5-0.4	No.2/Stud/No.2	33	34/19/34	100 × 100	52	19
SPF3-0.4	No.2/Stud/No.2	33	34/34/34	100 × 100	52	19

CLT specimens, as introduced in Tables 1 and 2. Table 3 gives the input elastic orthotropic properties of wood material [6, 13]. Poisson's ratios for Spruce-Pine-Fir were obtained from the Wood Handbook [2].

Solid volume elements were used to model the wood boards. The metal part of the test jig was also simulated. The fibre direction of the cross layer in the model was the same as that in the test setup, i.e., the grain direction (Y direction) was perpendicular to the longitudinal direction of the steel lever (X direction in Figs. 3 and 4).

For modeling the glue line strength between different layers, the glue line shear stiffness was obtained from one test database [17]. In Schaaf's study, torsional shear tests were conducted to study the shear strength and stiffness properties of glue lines in three-layered wood composites glued by polyurethane adhesive, as shown in Fig. 5. Table 4 shows the input shear line stiffness value for the finite-element models. COMBIN14 linear x–y–z spring pairs were used to model the glue line bonding stiffness. The x-springs and y-springs considered the glue line shear stiffness, and the z-springs were assigned with high stiffness value representing rigid vertical bonding between wood layers. The boundary condition for the model was the same as the support condition in the test setup.

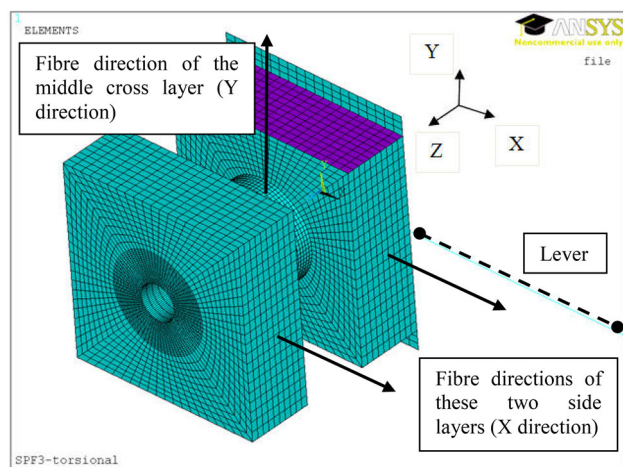


Fig. 4 Finite element modeling of three-layer CLT tube test specimens (orthotropic wood properties with Y direction as the direction of wood fibre in the middle cross layer)

Table 3 Input orthotropic properties of the wood boards

Species	Grade	Elastic properties (GPa)				Poisson's ratios		
		E_L	E_T and E_R	G_{LR} & G_{LT}	G_{RT}	ν_{LR}	ν_{LT}	ν_{RT}
Spruce–pine–fir	No. 2/better	11.43	0.381	0.714	0.071	0.316	0.347	0.469
	Stud	10.66	0.355	0.666	0.067			

Test results and data analysis

There were two failure modes in the torque tests, shown in Figs. 6 and 7; blue stains in the beetle-afflicted lumber boards may also be found in Fig. 6. Most of the tube specimens failed in brittle shear failure mode; the shear failure showed the typical brittle failure behaviour with 45° inclined angle observing from the top or bottom face of the tube specimen. The resistance of the specimens to carry load suddenly dropped to zero, when the failure occurred. The other specimens (two specimens at SPF5-04 group and

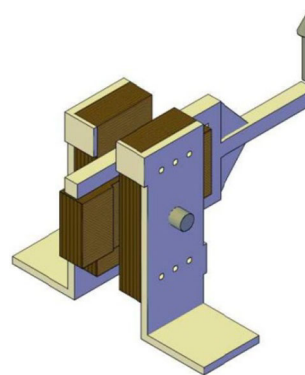


Fig. 5 Schaaf's study for the torsional shear test

Table 4 Input shear stiffness of the glue lines

Species	Clamping pressure	Stiffness (N/mm ³)
Spruce–Pine–Fir	0.4 MPa	20.6

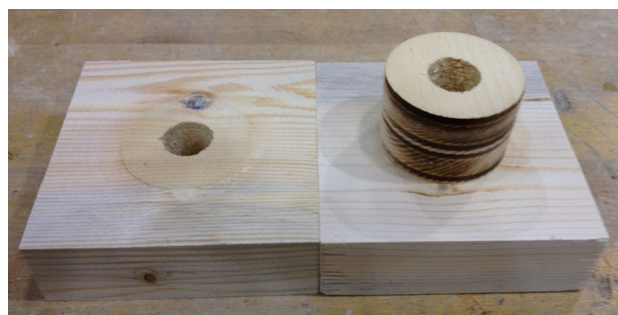


Fig. 6 Glue failure in the torque test

Fig. 7 Shear failure in the torque test (with Y direction as the direction of wood fibre in the middle cross layer)

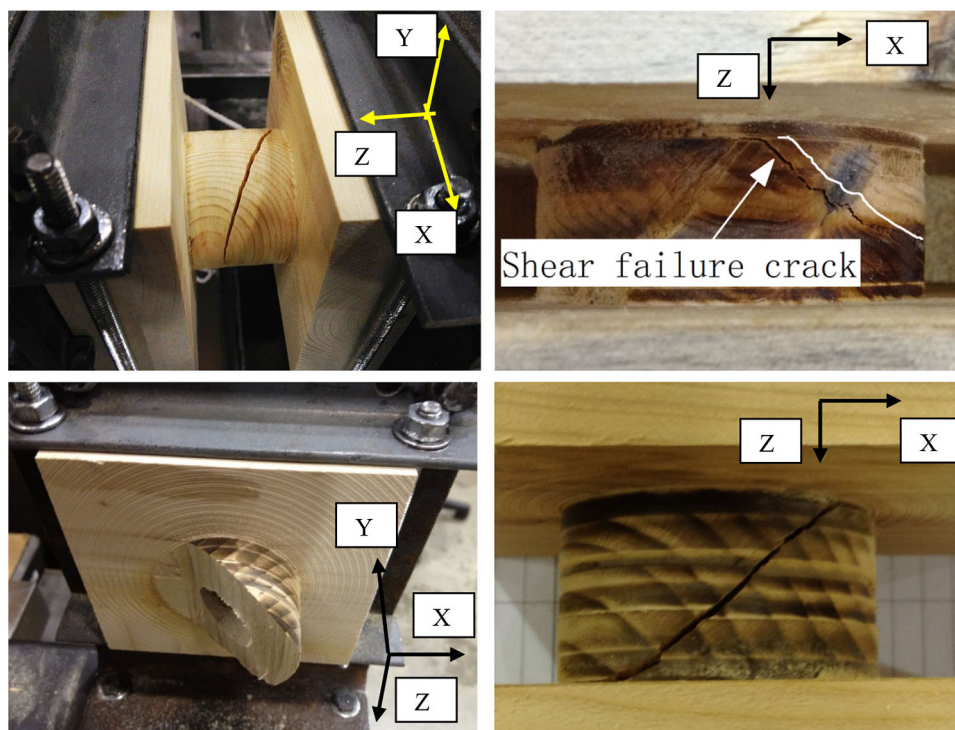


Table 5 Summary of the torque test results

CLT type	Peak failure torque load (N × mm)			Weibull fitting parameters			No. of specimen with rolling shear failure	Calculated shear strength (N/mm ²)
	Mean	Standard deviation	Coefficient of variation (%)	Location	Scale	Shape		Mean
SPF5-0.4	103,989	17,058	16.40	0.00	110,378.29	7.42	31	3.79
SPF3-0.4	84,561	14,048	16.61	0.00	89,210.22	7.86	25	3.36

eight specimens at SPF3-04 group) showed the glue strength failure in the tests; the average glue failure peak loads for the two specimens at SPF5-04 group and the eight specimens at SPF3-04 group are 52,258 and 52,117 N × mm. Only those specimens with the shear failure were included in the analysis in Table 5. The typical curve between the recorded applied load and displacement at the lever end is given in Fig. 8.

In Table 5, the mean value, standard deviation, and coefficient of variation of the measured torque failure loads are given. Table 5 also includes the Weibull fitting parameters for the cumulative distribution of the torque test results. Shear strength τ can be calculated using equation $\tau = T/I_p \times r$, where τ is the shear strength in N/mm², T is the peak failure torque load in N × mm from Table 5, $I_p = \pi D_{\text{outer}}^4/32 - \pi D_{\text{inner}}^4/32$ is the polar moment of area in mm⁴, D_{outer} is the outer diameter, D_{inner} is the inner diameter, and $r = D_{\text{outer}}/2$ is the outer radius in mm.

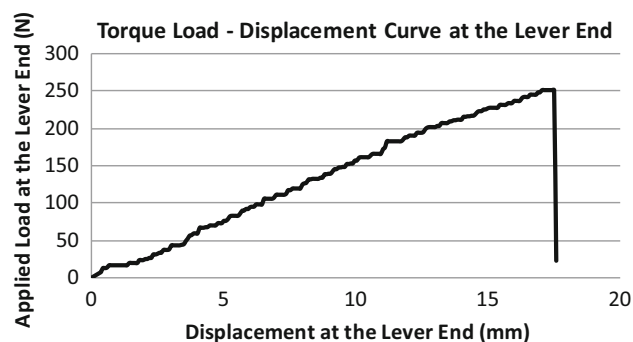


Fig. 8 Typical curve between the recorded applied load and displacement at the lever end

Table 5 gives the mean value of the calculated shear strength τ ; the given shear strength τ in Table 5 from equation $\tau = T/I_p \times r$ is based on the assumption of isotropic material property which is not true for timber, and

more accurate results can be evaluated based on the developed finite-element models introduced in the next section.

Analysis and discussion on the rolling shear failure in torque loading tests

Finite-element model results

In the torque loading tests, most of the CLT tube specimens had brittle shear failure. Once failure occurred, the resistance to carry load sharply dropped to zero. The cracks were developed at an inclined angle in the middle layer of the specimen. The brittle shear failure mechanism in the torque tube specimens was not as clear as the rolling shear failure observed in the short-span beam specimens [6]. To investigate and confirm that the observed shear failure mode was rolling shear failure in the torque tube specimens, a linear elastic finite-element analysis was performed to evaluate the rolling shear stress distribution with consideration of the orthotropic wood material properties; the results were summarized as follows with consideration of different shear stress components (longitudinal shear and rolling shear).

Figures 9, 10, and 11 show the shear stress (τ_{xz} , τ_{xy} , τ_{yz} in Pa in the figures) distributions in the cross layer of three-layer CLT tube specimens, when the applied load level is the mean peak failure load (84,561 N \times mm from Table 5) for three-layer CLT. The shear stress τ_{xz} (the same as engineering definitions in Cartesian coordinate system in terms of directions) is the shear stress directed parallel to a given plane (YZ plane) which is perpendicular to the X direction, and this τ_{xz} is parallel to the Z direction. Therefore, since rolling shear is defined as a shear stress leading to the shear strain in the planes perpendicular to the grain, τ_{xz} is the rolling shear stress, and τ_{xy} and τ_{yz} are the longitudinal shear stresses. These two longitudinal shear stresses (τ_{xy} and τ_{yz}) are also uncoupled according to the defined wood orthotropic material property [18]. The maximum value of the shear stress (τ_{xz} , τ_{xy} or τ_{yz}) is also given in the figures (in Pa).

Figure 9 shows that the maximum rolling shear stress (3.86 MPa) occurred near the ring-edge of the cross layer volume close to the top or bottom layer of the tube specimen, where the initial shear crack typically started in the tests (brittle shear failure mode as given in Fig. 7). As shown in Fig. 10, the maximum longitudinal shear stress is 7.04 MPa.

Similarly, when the applied load level is the mean value of peak failure load (103,989 N \times mm from Table 5) for five-layer CLT, the maximum rolling shear stress

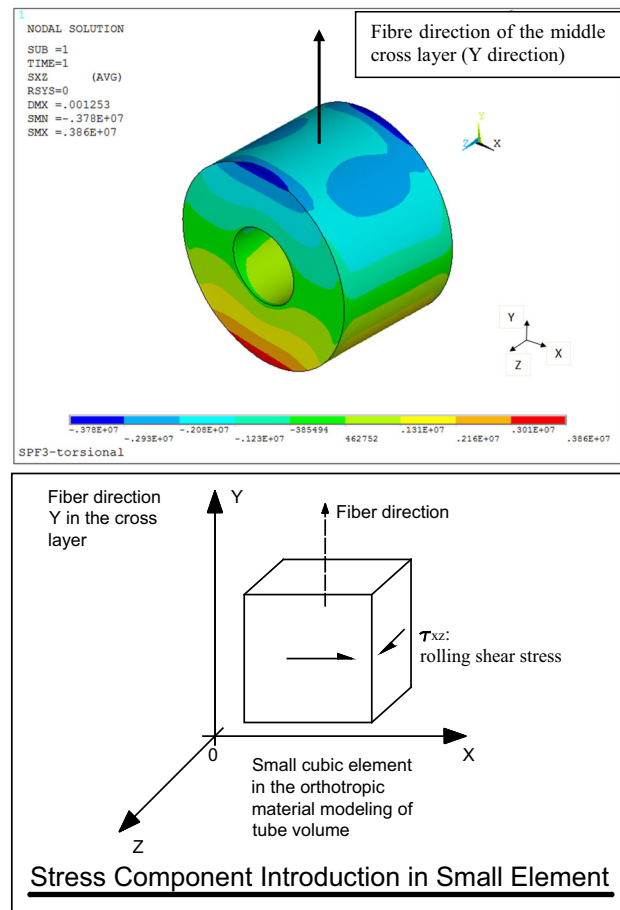


Fig. 9 Shear stress (τ_{xz} in Pa, rolling shear in orthotropic material modeling) distribution in the cross layer of three-layer tube specimen (maximum $\tau_{xz} = 3.86 \times 10^6$ Pa)

(4.83 MPa) occurred near the ring-edge of the cross layer volume; the maximum longitudinal shear stress was 10.30 MPa.

In Table 5, the calculated mean shear strength for the three-layer CLT from equation $\tau = T/I_p \times r$ is 3.36 MPa and the calculated mean shear strength for the five-layer CLT is 3.79 MPa. In the developed finite-element models, the evaluated mean rolling shear strength is 3.86 MPa for the three-layer CLT and is 4.83 MPa for the five-layer CLT. The results are close but different; the difference is due to that the finite-element modeling can simulate the timber anisotropic material property, and it can give more accurate results in terms of shear stress concentrations and distributions in volumes by considering both longitudinal and rolling shear components. The results in Table 5 are based on the assumption of isotropic material property which is different in timber; the finite-element result shows the shear stress distribution is highly non-uniform by simulating the specimens' detailed geometry giving a better understanding of the structural behaviour of specimens.

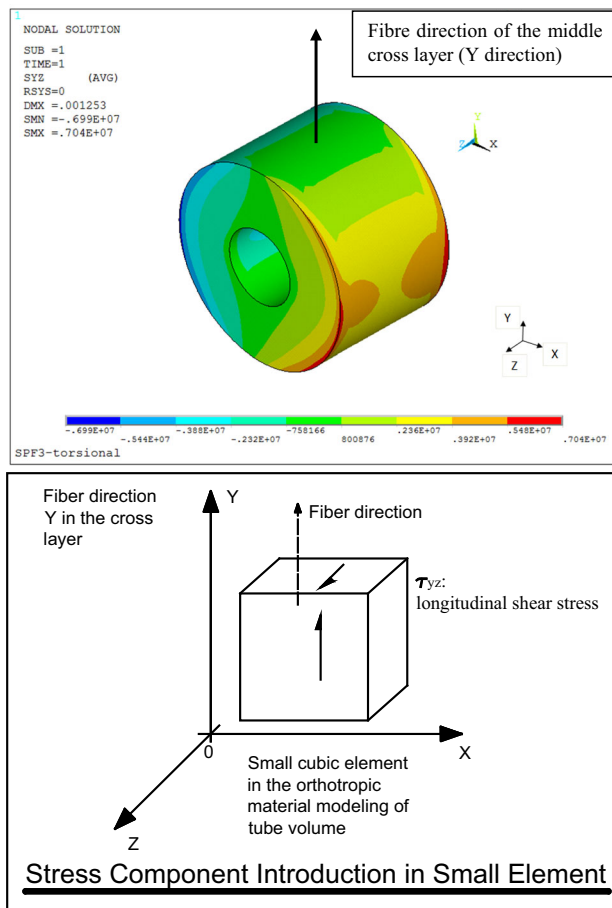


Fig. 10 Shear stress (τ_{yz} in Pa, longitudinal shear in orthotropic material modeling) distribution in the cross layer of three-layer tube specimen (maximum $\tau_{yz} = 7.04 \times 10^6$ Pa)

For the three-layer CLT tube specimens, the ratio between the maximum rolling shear stress and longitudinal shear stress is $R_{\text{Shear}}^{\text{Three-layer}} = \frac{\tau_{xz}^{\text{max}}}{\tau_{yz}^{\text{max}}} = \frac{3.86}{7.04} = 0.55 \approx 1/1.82$. For the five-layer CLT tube specimens, the ratio between the maximum rolling shear stress and longitudinal shear stress is $R_{\text{Shear}}^{\text{Five-layer}} = \frac{\tau_{xz}^{\text{max}}}{\tau_{yz}^{\text{max}}} = \frac{4.83}{10.30} = 0.47 \approx 1/2.13$.

Rolling shear strength and stiffness of wood are much lower than its longitudinal shear strength and stiffness. According to limited test data [1–6], rolling shear strength is typically between 18 and 28 % of parallel-to-grain shear strength. In this study, the ratio $R_{\text{Shear}} = 0.47 \approx 1/2.13$ (i.e., the minimum of $R_{\text{Shear}}^{\text{Three-layer}}$ and $R_{\text{Shear}}^{\text{Five-layer}}$) is much higher than the ratio of rolling shear strength and longitudinal shear strength (18–28 %, which is about 1/5–1/3). Therefore, in the torque loading tests, the rolling shear stress should reach the material strength limit earlier than longitudinal shear and the brittle failure mode observed in the cross layers of the CLT tube specimens should be rolling shear failure. The calculation from the finite-

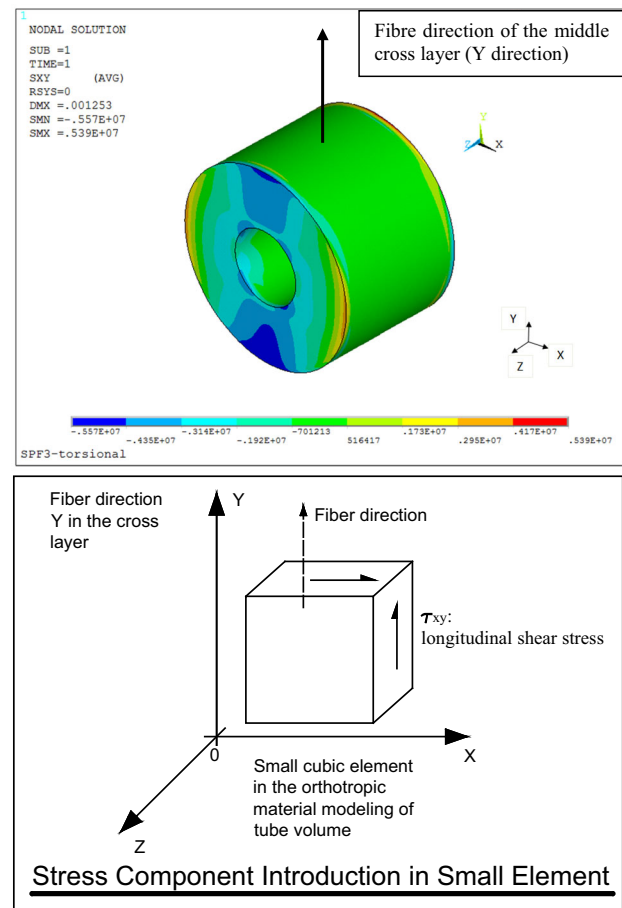


Fig. 11 Shear stress (τ_{xy} in Pa, longitudinal shear in orthotropic material modeling) distribution in the cross layer of three-layer tube specimen (maximum $\tau_{xy} = 5.57 \times 10^6$ Pa)

element models under applied peak torque load from the experiments shows the longitudinal shear stress not failed meaning that the failure is not longitudinal shear failure; therefore, the ratio R_{Shear} shows much higher than the reference data.

Further investigation on the shear failure mode in torque loading tests based on a Monte Carlo simulation procedure

Test results show that the longitudinal shear strength of Spruce-Pine-Fir, a Canadian softwood species category, ranges from 6.94 to 8.08 MPa [5]. Spruce-Pine-Fir species comprises timber from white spruce, engelmann spruce, lodgepole pine, and alpine fir species in western Canada (British Columbia and Alberta states, Canada). According to the Wood Handbook [2], the longitudinal shear strength of lodgepole pine grown in Canada is 8.50 MPa in 12 % moisture content, and the white spruce grown in Canada has the lowest longitudinal shear strength (mean value of

6.80 MPa in 12 % moisture content) among Spruce-Pine-Fir species. There is also research informing the average longitudinal shear strength (mean value of 7.27 MPa) of Mountain Pine Beetle-afflicted lodgepole pine, based on the test data [19]. Therefore, the values of 6.80 and 7.27 MPa were selected in the following simulation process.

In this section, a Monte Carlo simulation procedure was performed as follows to investigate the probability of different shear failure modes in torque loading tests, considering the randomness of the rolling shear strength and longitudinal shear strength in wood material, and this process was as follows:

1. The mean values of rolling shear strength τ_{RS}^m (for example, $\tau_{RS}^m = 1.0$ MPa) and longitudinal shear strength τ_{LS}^m (for example, a lower longitudinal shear mean strength $\tau_{LS}^m = 6.80$ MPa) were chosen, and a coefficient of variation of 18 % was also chosen.
2. Assume the rolling shear strength and longitudinal shear strength were lognormally distributed, and based on the initial distribution parameters chosen in step 1), a random sample size of $N_{\text{Rnd}} = 1000$ sets of τ_{RS} and τ_{LS} was generated. τ_{RS} and τ_{LS} represent the rolling shear strength and longitudinal shear strength in wood material of this given random set.
3. For each random set, the ratio (i.e., $\text{Ratio}_{\text{Random}}$) between τ_{RS} and τ_{LS} was calculated as $\text{Ratio}_{\text{Random}} = \tau_{RS}/\tau_{LS}$.
4. As investigated in the previous section, if $\text{Ratio}_{\text{Random}} < \min(R_{\text{Shear}}^{\text{Three-layer}}, R_{\text{Shear}}^{\text{Five-layer}})$, where

$$R_{\text{Shear}}^{\text{Three-layer}} = 0.55 \approx 1/1.82, R_{\text{Shear}}^{\text{Five-layer}} = 0.47 \approx 1/2.13;$$

there is rolling shear failure occurred in this random set; otherwise, the failure mode will be longitudinal shear failure.

5. The probability of rolling shear failure p_f^{RS} can be evaluated based on the number of sets with rolling shear failure mode.

In the simulation, different variables were also included and investigated, considering the variable mean values of rolling shear strength τ_{RS}^m (1.0, 1.5, 2.0, 2.5, and 3.0 MPa) and longitudinal shear strength τ_{LS}^m (6.80 and 7.27 MPa), and the coefficient of variation (16 and 18 %).

It needs to be emphasized that the selected longitudinal shear strength category of 6.80 MPa in step (1) of the simulation has already been an under-estimation, considering the longitudinal shear strength of lodgepole pine grown in Canada is 8.50 MPa, and considering that the lodgepole pine, rather than white spruce species, was mainly adopted in the related CLT manufacture process [13].

Table 6 shows the probability of rolling shear failure p_f^{RS} based on different ratios (τ_{RS}^m/τ_{LS}^m) between the chosen mean values of rolling shear strength τ_{RS}^m and longitudinal shear strength τ_{LS}^m . Although the criterion was strict in the longitudinal shear strength simulation, in most cases, it still shows $p_f^{\text{RS}} > 94$ %, and this gives more confidence on the

Table 6 Results for the Monte Carlo simulation

τ_{RS}^m/τ_{LS}^m	Rolling shear mean strength τ_{RS}^m	Longitudinal shear mean strength τ_{LS}^m	Coefficient of variation (%)	Probability of rolling shear failure p_f^{RS} (%)
1/6.8	1.00	6.80	18	100.0
1/4.8	1.50	7.27	16	100.0
1/4.8	1.50	7.27	18	100.0
1/4.5	1.50	6.80	16	100.0
1/4.5	1.50	6.80	18	100.0
1/3.6	2.00	7.27	16	99.6
1/3.6	2.00	7.27	18	99.1
1/3.4	2.00	6.80	16	98.2
1/3.4	2.00	6.80	18	97.3
1/2.9	2.50	7.27	16	93.3
1/2.9	2.50	7.27	18	90.3
1/2.7	2.50	6.80	16	88.9
1/2.7	2.50	6.80	18	85.9
1/2.4	3.00	7.27	16	75.4

observed rolling shear failure mode in the tube specimens. The cases with $p_f^{RS} \leq 94\%$ only occurred when the ratio between τ_{RS}^m and τ_{LS}^m was larger than 1/3. This is not realistic considering rolling shear strength is recognized to be between 18 and 28 % (about 1/5–1/3) of longitudinal shear strength. When the ratio τ_{RS}^m/τ_{LS}^m is between 1/5 and 1/3, the $p_f^{RS} > 97\%$. Even when the ratio τ_{RS}^m/τ_{LS}^m is impractically larger than 1/3 ($\tau_{RS}^m/\tau_{LS}^m = 1/2.4$ and with assumed rolling shear strength to be 3 MPa), p_f^{RS} is still in a high confidence level (75.4 %).

Conclusions

In this study, the rolling shear behaviour of CLT was investigated by the torsional shear tests on CLT shear blocks with processed tubular cross layers. The rolling shear strength values were evaluated by finite-element modeling of the test specimens subjected to the failure loads. Simple analytical equations to calculate the rolling shear strength is not applicable in this study due to the complicated orthotropic wood properties and the torsional shear loading scheme. A Monte Carlo simulation procedure was performed to investigate the occurrence probability of longitudinal shear and rolling shear failure modes in the specimens considering the randomness of the rolling shear strength and longitudinal shear strength of wood material. The simulation results further confirmed that the observed brittle shear failure was indeed rolling shear. Therefore, the torque loading test is a viable method to investigate the rolling shear behaviour of the CLT specimens.

The evaluated rolling shear strength values by the finite-element modeling results were very different from other test results from bending tests or planar shear tests available in literature. In this study, much higher rolling shear strength values were obtained, i.e., 3.86 and 4.83 MPa, for the three-layer and the five-layer CLT tube specimens, respectively. Apparently, these values cannot be directly used for design purpose, because it involved a significant size effect and rolling shear stress concentration was observed in the cross layers. However, together with short-span bending test results, these test results can be a useful data source to study the size effect on rolling shear strength properties of CLT with common structural sizes under normal loading scenarios. In addition, to consider the size dependence and to explain the strength differences between the CLT beam bending tests and the torque loading tests, Weibull's weakest link theory will be applied to evaluate the size effect on the rolling shear strength of CLT in the future.

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