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EVALUATING ROLLING SHEAR STRENGTH PROPERTIES OF CROSS LAMINATED TIMBER BY TORSIONAL SHEAR TESTS AND BENDING TESTS

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ABSTRACT: This paper presents a study on evaluating rolling shear (RS) strength properties of cross laminated timber (CLT) using torsional shear tests and bending tests. The CLT plates were manufactured with Spruce-Pine-Fir boards and glued with polyurethane adhesive. Two types of layups (3-layer and 5-layer) and two clamping pressures (0.1 MPa and 0.4 MPa) were studied. For the torsional shear tests, small shear block specimens were sampled from the CLT plates and the cross layers were processed to have an annular cross section. Strip specimens were simply sampled from the CLT plates for the bending tests. Based on the failure loads, RS strength properties were evaluated by torsional shear formula, composite beam formulae as well as detailed finite element models, respectively. It was found that the two different test methods yielded different average RS strength value for the same type of CLT specimens. The test results showed that the CLT specimens pressed with the higher clamping pressure had slightly higher average RS strength. The specimens with thinner cross layers also had higher RS strength than the specimens with thicker cross layers.

KEYWORDS: Cross laminated timber, rolling shear strength, torsional shear tests, bending tests

1 INTRODUCTION

Rolling shear (RS) stress in wood is defined as the shear stress in the radial-tangential plane perpendicular to the grain direction. RS strength and stiffness of wood is much lower than its longitudinal shear strength and stiffness. According to the Wood Handbook (FPL, 2010), RS strength normally varies between 18% and 28% of parallel-to-grain shear strength based on limited test data. In Eurocode 5 (2004), a characteristic RS strength of 1.0 MPa is used for wood independent of its strength class. Therefore, in timber design, high RS stresses should always be avoided due to the low RS capacity of wood.

Cross laminated timber (CLT) consists of crosswise oriented layers of wood boards that are often glued by adhesives. RS strength and stiffness are not major design properties for timber. For CLT, however, RS 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 RS stresses in cross layers; the same concerns may arise for designing short-span floors or beams. Therefore, there is a need to evaluate the RS strength and stiffness properties of CLT products to provide technical support for more robust designs.

ASTM D2718-00 (2006) stipulates two test methods (planar shear test and short-span bending test) to evaluate shear properties of wood products. In the planar shear test, shear loads are applied by two metal plates face-glued onto the specimen. The short-span bending test is to load the specimen with small span-depth ratios to encourage shear failure mechanism. Norlin et al. (1999) used a short-span bending test to study longitudinal and RS shear strength properties of a laminated veneer product. Using non-destructive bending vibration tests, Fellmoser and Blass (2004) studied the influence of RS modulus on CLT stiffness as well as the relationship between shear deformations and the span-depth ratios. Mestek et al. (2008) studied the influence of shear deformations in cross layers on the load carrying capacity of CLT beams. Zhou et al. (2014) used both planar shear tests and short-span bending tests to study RS strength and stiffness properties of CLT specimens made by black spruce.

The objective of this study is to evaluate the RS strength properties of non-edge-glued CLT plates by two test methods: torsional shear tests and short-span bending tests. The CLT plates were manufactured mainly by mountain pine beetle killed lodgepole pine, which is a major species

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in the Spruce-Pine-Fir (SPF) group in Canada. Another important motivation for this study is to help recover the wood resource from the beetle attacked forests. This study is also focused on understanding the influence of the clamping pressure for curing adhesives and the thickness of cross layers on the RS strength properties of the CLT products.

2 METHOD

2.1 CLT PLATE SPECIMENS

As shown in Figure 1, 5-layer Spruce-Pine-Fir (SPF5) plates and 3-layer S.P.F. (SPF3) plates were manufactured for the experimental studies. For each layup, two clamping pressures (0.1 MPa representing vacuum press and 0.4 MPa representing mechanic press) were used for the pressing process. Thus, combining the layup and the curing pressure, four types of CLT plates were studied. For each type, three full-size plates were sampled. In the following context, a SPF5-0.4 represents the 5-layer S.P.F. panel pressed under 0.4 MPa. Similarly, a 3-layer S.P.F plate pressed under 0.1 MPa is labeled as SPF3-0.1.

Figure 1: Full-size CLT plates

Table 1 shows the board grades, laminate thickness, and dimensions of the CLT plates. In the SPF5 plates, No. 2 or better boards were used for two face layers and the core layer while stud grade boards were used for two cross layers. In the SPF3 plates, No. 2 or better boards were used for two face layers and stud grade boards were used for the crosswise core layer. All the laminates were 34 mm x 138 mm boards except that the cross layers in the SPF5 plates were 19 mm x 138 mm boards. The average moisture content of the boards was about 13% with a coefficient of variation (COV) of 0.18. Modulus of Elasticity (MOEs) of the boards were also measured by transverse vibration tests following a test standard (ASTM D6874-03, 2009) before they were glued to the CLT plates. Table 2 shows the vibration MOE results which showed that the No.2 and better grade boards had higher stiffness than stud grade boards.

Table 1: *CLT layup and lamination grade*

Type	Laminate Grade	Laminate thickness (mm)	Plate size L×W×H (mm)
SPF5-0.1 & SPF5-0.4	No.2/Stud/No.2 /Stud/No.2	34/19/34/ 19/34	3658×1219 ×140
SPF3-0.1 & SPF3-0.4	No.2/Stud/No.2	34	3658×1219 ×102

Table 2: *Vibration MOE of wood boards*

Grade	MOE		Sample size
	Mean (GPa)	COV	
No. 2 or btr.	11.43	16.4%	256
Stud	10.66	18.5%	280

2.2 TORSIONAL SHEAR TESTS

Figure 2 shows the schematics of a torsional shear specimen, in which the mid-layer, i.e., the cross layer in a CLT plate, has a milled-down annular cross section. The reason to have such a cross section is to facilitate the RS failure mechanism and reduce the stress concentrations typically experienced by a square-shaped shear plane.

The specimens were processed in three steps. In the 1st step, 3-layer blocks were sampled from the full-size CLT plates. For the SPF5 specimens, two layers of wood needed to be removed. In the 2nd step, the 3-layer blocks were press drilled from the centre of the top face to the bottom face; in the 3rd step, the blocks were further processed by a CNC machine to achieve the annular cross section. It should also be noted that for each torsional shear specimen, the mid-layer was cut out from one piece of wood in order to eliminate the influence of gaps on the torsional shear stress distributions.

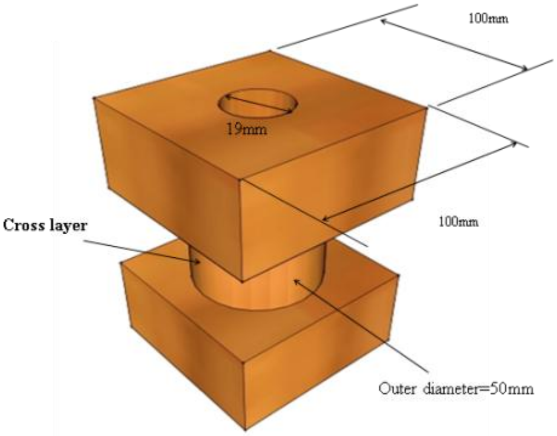

Figure 2: Torsional shear specimens

Figure 3 shows the test setup in which the torsional moment was applied via a steel arm firmly connected with one face layer of the specimen. The moment arm length was 500 mm. The other face layer of the specimen was fully restrained onto the test table. The test to failure time for was kept in 5 ~ 10 minutes for each specimen.

Figure 3: *Test setup of torsional shear test*

Figure 4 shows an example of RS failure mode observed in the cross layer. Most of the specimens had brittle failures and the cracks were developed at an inclined angle with respect to the top or bottom face of the specimen. Load-displacement curves from the actuator also indicated an approximate linear relationship up to the peak load followed with a sudden drop of the load due to failure.

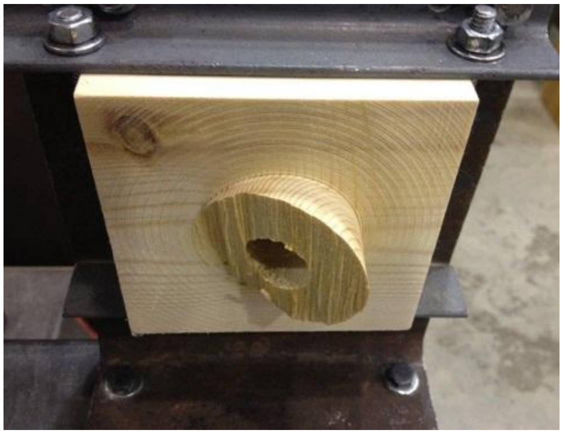

Figure 4: *Rolling shear failure mode*

Figure 5 shows the cumulative distributions of the failure torsional moments for four types of specimens. Table 3 also lists the mean and COV for each type. It was found that the SPF5 specimens with 19 mm thick cross layers had much higher torsional shear capacity than the SPF3 specimens with 34 mm thick cross layer although the annular cross sections of these specimens are the same. On average, the SPF3 specimens pressed with 0.1 MPa and 0.4 MPa had almost the same torsional capacity. The SPF5 specimens pressed with 0.4 MPa had slightly higher torsional capacity.

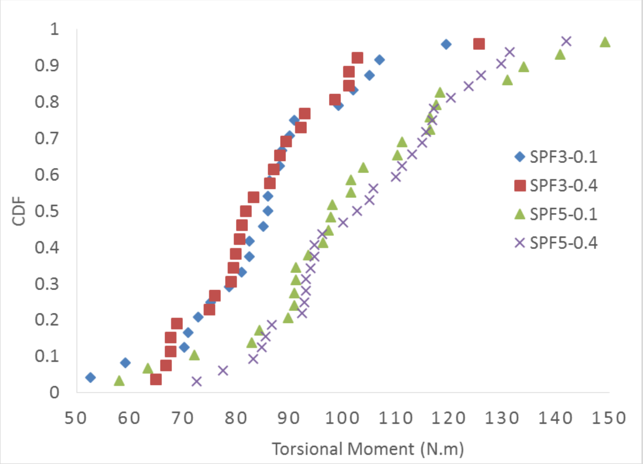

Figure 5: *Cumulative distributions of peak torsional moments*

Table 3: *Summary of torsional shear results*

CLT	Cross layer thickness (mm)	Sample size	Failure torque (N.m)	
			mean	COV
SPF3-0.1	34	23	85.1	17.8%
SPF3-0.4	34	25	84.6	16.6%
SPF5-0.1	19	28	101.7	21.1%
SPF5-0.4	19	31	104.0	16.4%

Assuming rigid glue line bonding and homogeneous isotropic material properties, the maximum torsional shear stresses on an annular cross section can be calculated by the torsional shear formula:

$$\tau_{max} = \frac{T r_o}{\frac{\pi}{2}(r_o^4 - r_i^4)} \qquad (1)$$

where T is the peak torsional moment, r_o and r_i are the outer radius and inner radius of the annular cross section.

In this study, finite element models were also developed in finite element software ANSYS v14 (2011) to model the torsional shear specimens in order to consider the glue line shear stiffness and the orthotropic wood properties. Solid elements were used to model the wood boards and linear spring elements were used to model the glue line shear stiffness. Table 4 lists the input wood material properties. Poisson's ratios of lodgepole pine were obtained from the Wood Handbook (FPL, 2010). The parallel to grain modulus E_L were obtained from the transverse vibration tests. Additional assumptions on other wood properties were given as follows. The perpendicular to grain modulus E_T/ E_R was assumed to be 1/30 of E_L. The parallel to grain shear modulus G_{LR} or G_{LT} was assumed to be 1/16 of E_L. The rolling shear modulus G_{RT} was assumed to be 1/10 of G_{LR} or G_{LT}. These assumptions are also consistent with commonly adopted assumptions for CLT strength and stiffness calculations in Europe (FPInnovations, 2011). Table 5 lists the shear stiffness of glue lines which were experimentally obtained by Schaaf (2010) using torsional shear testing methods.

***Table 4:** Wood orthotropic properties for FE models*

Grade	Elastic properties (GPa)				Poisson's ratios		
	E_L	E_T/E_R	G_{LR}/G_{LT}	G_{RT}	ν_{LR}	ν_{LT}	ν_{RT}
No. 2/ btr	11.43	0.381	0.714	0.071	0.316	0.347	0.469
stud	10.66	0.355	0.666	0.067			

***Table 5:** Shear stiffness of glue lines*

Species	Clamping pressure (MPa)	Shear stiffness (N/mm^3)
S.P.F.	0.1	19.0
	0.4	20.6

Figure 6 shows the meshed FE model for the torsional shear specimen. The metal part of the test jig was also modelled. Figure 7 shows the RS stress distributions in the cross layers of the SPF3-0.1 and SPF5-0.1 specimens loaded under the average peak torsional loads. Apparently, the stresses were not uniformly distributed along the perimeter of the annular rings due to the orthotropic wood properties.

Table 6 lists the average RS strength for each type of CLT specimen evaluated by the torsional shear formula and the FE model simulations. It was found that the torsional shear formula gives unreasonably high RS strength due to the assumption of homogenous isotropic material property. The FE models give rational evaluations which are in a reasonable range of RS strength compared with available test data.

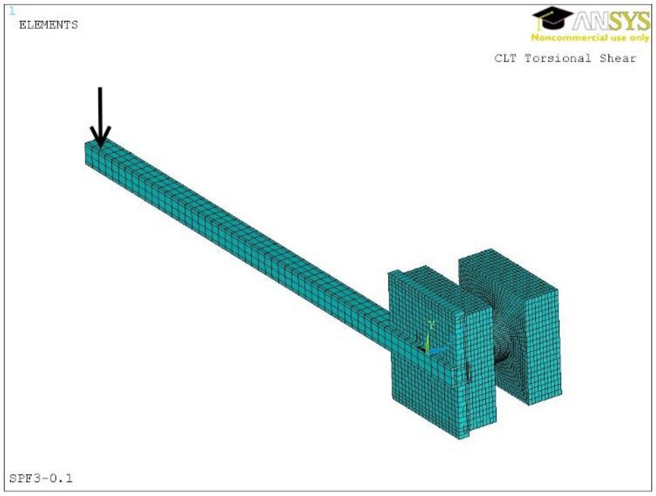

***Figure 6:** FE model of a torsional shear test*

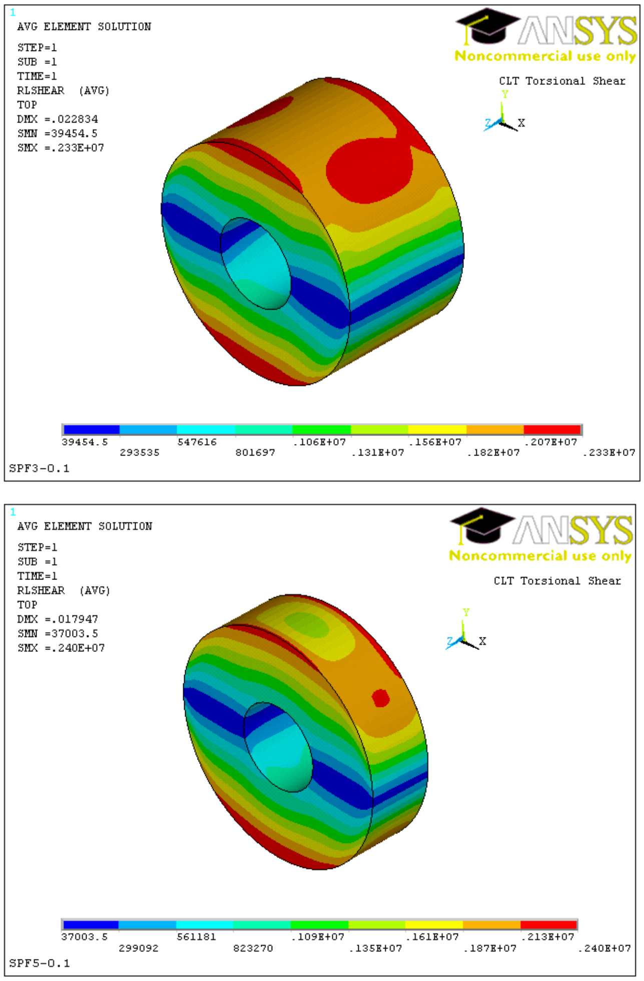

***Figure 7:** RS stress distributions in cross layers of SPF3-0.1 and SPF5-0.1 specimens (Pa)*

***Table 6:** Summary of average RS strength from torsional shear tests (MPa)*

CLT	Cross layer thickness (mm)	Shear Formula	FE model
SPF3-0.1	34	3.54	2.33
SPF3-0.4	34	3.52	2.31
SPF5-0.1	19	4.23	2.40
SPF5-0.4	19	4.33	2.46

2.3 SHORT-SPAN BENDING TESTS

As shown in Figure 8, a series of three-point bending tests on strip specimens sampled from the full-size CLT plates have also been conducted by Yawalata and Lam (2011) following a test standard (ASTM, D198-05a, 2005). A span-to-depth ratio of 6 was used to encourage the RS failure mode. The wood fibres of the top and bottom layers of the specimens were parallel to the beam span. Table 7 lists the dimensions and the test results in terms of the mean and standard deviation of the failure loads. The bending test results showed that for the specimens with the same layup, the increased clamping pressure from 0.1 MPa to 0.4 MPa seemed to slightly increase the load-carrying capacity on average.

Figure 8: *Short-span bending test and RS failure mode*

Table 7: *Summary of bending test results*

CLT	Span x depth (mm x mm)	Sample size	Failure loads (kN)	
			mean	COV
SPF3-0.1	612x102	30	15.13	10.8%
SPF3-0.4	612x102	30	16.51	19.1%
SPF5-0.1	840x140	30	20.98	16.2%
SPF5-0.4	840x140	30	21.78	7.2%

Assuming rigid glue line bonding and material continuity in the cross layers, the RS strengths of the bending specimens were evaluated by three composite beam theories: Layered beam (Bodig and Jayne, 1982); Gamma beam method (Eurocode 5, 2004); and Shear analogy method (Kreuzinger, 1999). Meanwhile, as shown in Figure 9, considering orthotropic wood properties, gaps between the wood boards in the cross layers and the glue line shear stiffness, detailed FE models were also developed in ANSYS v14 (2011) to study the RS stress distributions under the failure loads. The wood properties given in Table 4 and the glue line shear stiffness given in Table 5 were used for the FE model simulations. Similar to the torsional shear FE models, solid elements and linear spring elements were used for the wood members and the glue lines, respectively. Figure 10 shows the RS stress distributions of the SPF5-0.1 and SPF3-0.1 specimens under the average failure loads. It can be seen that the RS stress distribution was not continuous in the cross layer due to the gaps. The stresses in the vicinity of the gaps were much smaller than those in the central parts of the boards due to the shear stress release around the free edges. This type of RS stress distribution also agreed with the test observation that the RS failures of the specimens tended to occur at a certain distance (comparable to the thickness of the cross layers) from the location of the gaps.

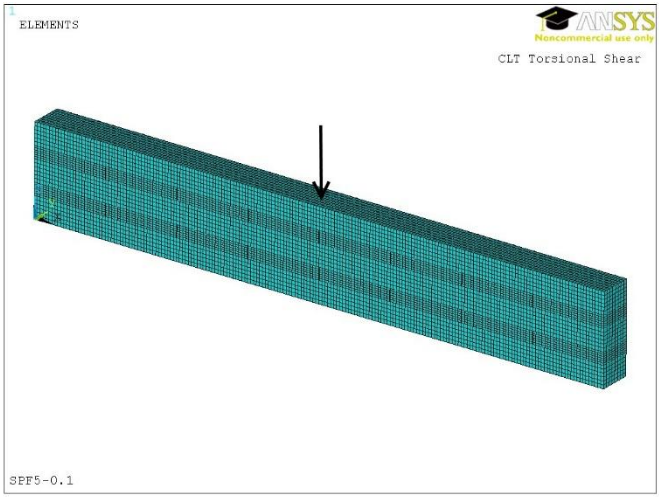

Figure 9: *FE model of a SPF5 bending specimen*

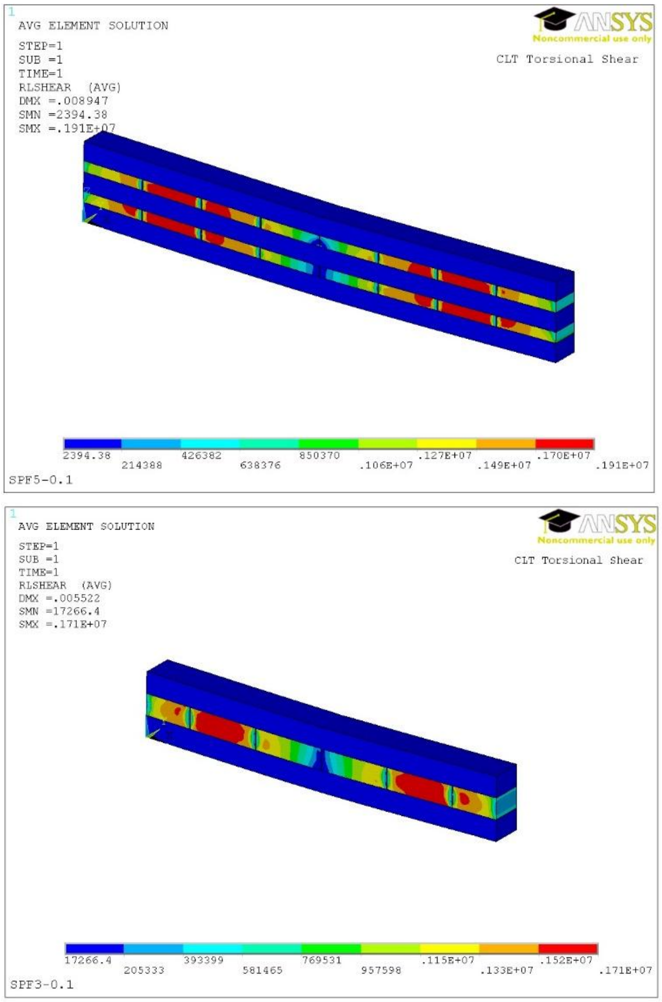

Figure10: *RS stress distributions in cross layers of SPF5-0.1 and SPF3-0.1 specimens (Pa)*

Table 8 lists the average RS strengths evaluated by the composite beam theories and the FE modeling for each type of the specimens. For the SPF5 specimens, the calculations by the beam theories agreed reasonably well with the FE results. However, for the SPF3 specimens, the beam theories significantly over-estimated the RS strength compared with the FE results. According to the composite beam calculations, the average RS strength of the SPF3 specimens with 34 mm thick cross layers was about 18 % higher than the SPF5 specimens with 19 mm thick cross layers. However, the FE results showed that the average RS strength of the SPF3 specimens was actually 8 % lower than that of the SPF5 specimens. The FE models are believed to be more accurate and the FE findings were also consistent with the torsional shear test results. If one considers the size effect on the RS strength of the cross layers, it is understandable that thick cross layers tend to have more volume of wood stressed under RS stresses than thin cross layers. Therefore, thick cross layers will normally have lower RS strength properties.

Table 8: *Average RS strength calculated by beam theories and FE models*

CLT type	Layered beam	Gamm a beam	Shear analogy	FE model
SPF3-0.1	2.04	2.15	2.02	1.71
SPF3-0.4	2.22	2.34	2.20	1.87
SPF5-0.1	1.85	1.74	1.78	1.91
SPF5-0.4	1.93	1.81	1.85	1.98

3 CONCLUSIONS

In this study, RS strength properties of CLT plates manufactured by S.P.F. boards and polyurethane adhesive were evaluated by torsional shear tests and short-span bending tests. The test results were analysed by torsional shear formula, composite beam theories and detailed FE modelling. Based on the test and modelling results, some conclusions are drawn as follows:

- Two different test methods yielded very different RS strength properties of the CLT specimens. Torsional shear tests gave higher average RS strength range (2.31 ~ 2.46 MPa) than that obtained from the short-span bending tests (1.71 ~ 1.98 MPa). Besides the different mechanism of the test methods, one reason might be that the bending specimens had gaps between the adjacent wood boards in the cross layers. However, the torsional shear specimens eliminated the influence of the gaps.

- On average, the SPF5 specimens with thin (19mm thick) cross layers had about 7 % higher RS strength than the SPF3 specimens with thick (34 mm) cross layers although the cross layers consisted of the same stud grade material. The thickness of cross layers seemed to affect the RS strength properties for the CLT specimens.

- For specimens with the same layup configuration, the increased clamping pressure from 0.1 MPa to 0.4 MPa increased the average RS strength of the CLT specimens by 4% approximately.

- The torsional shear formula is not suitable for evaluating RS strength properties of the torsional shear specimens. The composite beam theories should also be used with caution to evaluate the RS strength of the bending specimens.

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