EXPERIMENTAL RESEARCH ON POINT-SUPPORTED CLT PANELS: PHASE 1: ROLLING SHEAR STRENGTH

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ABSTRACT: Rolling shear strength is one of the key design parameters for point-supported cross-laminated timber (CLT) flat-slab system where the panels are directly supported by columns without any beams. The specified rolling shear strength of CLT in the current Canadian design standard could be conservative estimates considering the variability in wood species, stress grade, thickness of lamellas, layups and grain orientations. To address these gaps in knowledge for the North American market, a Post + Plank research project is being undertaken by Fast+Epp structural engineers in collaborations with the University of Northern British Columbia. In the first phase of the project, presented herein, CLT rolling shear strength under in-plane shear loading was evaluated. A total of 330 specimens (11 series with 30 replicate each, sized 100 mm (width) × 300 mm (length) were tested. The parameters varied were thickness: 3-ply of 89 mm and 105 mm, and 5-ply of 139 mm and 175mm with multiple species and fabricators, and both visual and machine stress graded CLT. The mode of failure was crack development along the growth ring. The results show that the mean rolling shear strength of various Canadian CLT species was between 0.94 MPa to 1.8 MPa. Although thin layers exhibited relatively higher rolling shear strength, these differences were found not to be statistically significant.

KEYWORDS: Point-supported Floors, Cross-laminated Timber, Rolling Shear Strength, Punching Shear Failure.

1 INTRODUCTION

1.1 BACKGROUND

Cross-laminated timber (CLT) has become popular construction material for mid- to high-rise buildings because of its benefits to sustainability, fast installation, design flexibility and overall good acoustic, thermal, fire and seismic performances. Point-supported CLT is a flat-slab building system, where CLT panels are supported directly on columns without drop beams, as designed in the 18 storey Tall Wood House in Vancouver (Figure 1) [1]. This configuration is appealing due to its ease of construction, ease of mechanical and electrical distribution, and reduction of the floor assembly depth. However, the transfer of force at the column faces leads to high shear stress near supports [2].

The strength of CLT in shear is governed by the rolling shear strength in the lamella perpendicular to the direction of loading. In this context, rolling shear refers to stresses causing tension perpendicular to the wood grain in layer perpendicular to the loading, creating a tendency for lamella to roll over each other [3].

Rolling shear strength values adopted in Canadian and American wood design standards [4,5] are much lower than longitudinal shear, and will often govern the capacity of point-supported panels. However, recent studies on [3,6,] suggested that the short-term rolling shear values specified by different standards are overly conservative.

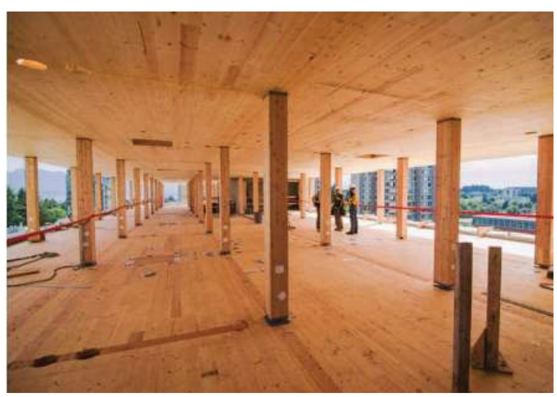

Figure 1: *Point supported CLT floor*

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1.2 ROLLING SHEAR STRENGTH IN CLT

Wood is an anisotropic material with three major axes: longitudinal, tangential, and radial relative to the log. Rolling shear occurs in the tangential-radial plane perpendicular to grain direction; failure occurs when the longitudinal fibers roll over each other. Rolling shear strength (f_s) is lower than longitudinal shear strength parallel to grain (f_v), and often "taken as approximately one-third" [3]. The specified CLT rolling shear strengths in Canadian Standard for Engineering Design in Wood [4] range from 0.43 to 0.63 MPa, the allowable stress design values in American Design Standard [5] is between 0.24 to 0.41 MPa depending on the base-material stress grade. For both edge-glued and non-edge-glued CLT made of laminations with a minimum width-to-depth ratio of 4, the recommended rolling shear strength in Europe is 1.4 MPa [7]. If the minimum width-to-depth ratio requirement is not met, then a value of 0.7 MPa is recommended instead.

Rolling shear properties of CLT do not currently have universally standardized test configurations and methods, primarily short span bending tests and in-plane shear tests are conducted. In-plane shear test apply load to a specimen at a 14° angle on the outer lamellas, similar to EN408 [8]. Four-point bending tests for CLT allow to indirectly determine the rolling shear strength. Kumar et al. [9] reported that the in-plane shear test resulted 10-20% higher strength compared to rolling shear estimated from bending tests. EN 16351 [7] adopts both methods and ANSI PRG 320 [10] refers to short span bending tests.

Amongst the several factors that influence the rolling shear properties of CLT: wood species, density of wood, annual ring orientation, the lamella aspect ratio (width to thickness of lamella), knots, and edge gluing or edge gaps, species appears to have the largest impact [9]. Previous studies completed on European species reported the mean rolling shear strength to range from 1.5 MPa to 2.8 MPa for softwoods and up to 5.6 MPa for hardwoods [5]. The mean rolling shear strength observed in North American species ranged from 1.3 MPa to 2.3 MPa [11-13]. The mean rolling shear strength observed for various Australian/New Zealand wood species ranged between 2.0 MPa to 3.6 MPa [3].

Further research found that the shear strength of CLT is increased near column supports [14, 15]. This increase is largely due to two effects: i) the lamella confinement of adjacent layers; and ii) additional confinement against rolling from compression forces. In North America, there have been few tests to confirm these findings, nor has the increase in rolling shear capacity due to confinement s been evaluated for a variety of support conditions. At time of writing, only one research program has completed full-scale panel test [2].

1.3 RESEARCH PROGRAM OVERVIEW

To address these gaps in knowledge for the North American market, a Post + Plank research project is being conducted by Fast+Epp structural engineers in collaborations with the University of Northern British Columbia. This research program will expand industry knowledge on point-supported CLT floors by experimentally testing a wide range of variables critical for point supported CLT construction.

The Post+Plank project will investigate the structural performance of North American CLT panels in point-supported construction through a series of numerical analyses and experimental testing. The experimental testing program will consist of four phases. Phase 1 of testing will use small CLT billets to test short-term rolling shear strength and stiffness of a variety of species, layups, and grades. The results to date from this phase will be reported in-depth in this paper.

In phase 2, the CLT rolling shear strength under 4-point bending loading will be determined for both short-term and long-term duration of load. In phase 3, the punching-shear strength will be evaluated under variation of following parameters: a) support condition (columns at the panel centre, edge, and corner; b) CLT lamella species and grade; c) column support geometry; and d) level of screw reinforcement. Panels sized 1.7×1.8 m, 1.5×1.8 m, and 1.5×1.5 m will be used. Six repetitions per test series for a total of 180 specimens will be tested. Phase 4 will be completed on full-scale floor systems to validate the strength predictions from phases 1 and 3. Six two-span continuous panels will be tested with varying parameters including panel width and presence of penetrations.

2 PHASE 1: SHORT-TERM ROLLING SHEAR STRENGTH

2.1 MATERIALS

In Table 1, and overview of all test series including wood species, stress grade, test layer orientation, and thickness is provided. Tests are completed for E and V rated CLT samples for different species, including Black Spruce and SPF. Each species and grade is tested in both major and minor layer orientations for 3-ply of 89 mm and 105 mm thicknesses and 5-ply of 175mm and 139mm thicknesses CLT panels to evaluate the impact of lamella aspect ratio. The numbers in bold and underlined show the layup, orientation, and thickness of the tested layers.

Table 1: *Test series overview*

Series	Stress Grade	Layup	Species	Tested layer
S1	E1	35/**19**/35	Spruce	Minor
S2	E1	35/**35**/35	Spruce	Minor
S3	E1	35/35/**35**/35/35	Spruce	Major
S4	V2	35/**19**/35	SPF	Minor
S5	V2	35/**35**/35	SPF	Minor
S6	E1	35/35/**35**/35/35	SPF	Major
S9	V2	35/17/**35**/17/35	SPF	Major
S10	V2	35/17/35/**17**/35	SPF	Minor
S11	V2	35/**19**/35	SPF	Minor
S12	V2	35/**35**/35	SPF	Minor
S13	E1	35/35/**35**/35/35	SPF	Major

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2.2 METHODS

The specimens were prepared and tested at the University of Northern British Columbia Wood Innovation and Research Laboratory in Prince George. All specimens were conditioned at 20 °C and 65% relative humidity prior to testing. The nominal length and width of each specimen was 300 mm and 100 mm, respectively. The thickness of the lamella of interest varied depending on the layup of the specimen; test specimens of different width are presented in Figure 2. The exact dimensions of the lamellas within the shear plane were measured for each specimen by means of a calliper prior to testing.

Small-scale in-plane shear tests following EN 408 [8] were conducted with the modification where the specimen is inclined against the vertical axis by 14° [16], as shown in Figure 3. The tests were performed using a universal test machine with a calibrated 100kN load cell, at a loading rate of 1 mm/min.

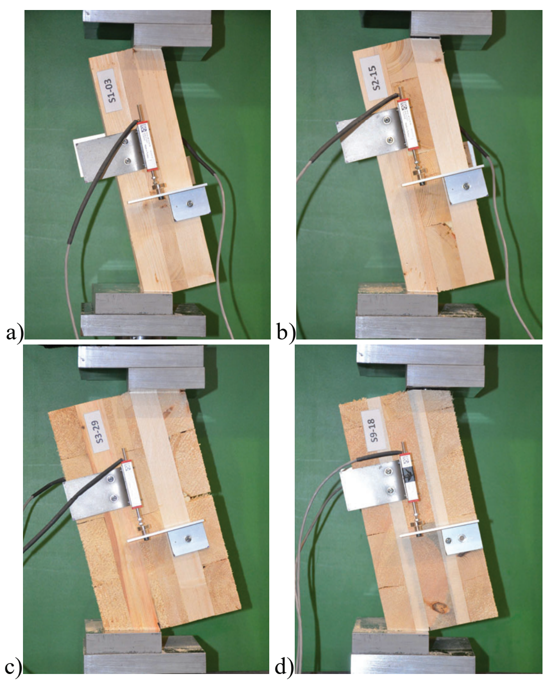

Figure 2: *Test specimen of different width: a) 89mm; b) 105mm; c) 175mm; d) 139mm*

Each specimen was loaded to failure and the rolling shear strength (τ) and shear modulus (G) were calculated by Equation (1) and Equation (2), respectively:

$$\tau = \frac{P_{max} \cos\alpha}{L\, w} \tag{1}$$

$$G = \frac{t_c}{L\, w} \frac{P}{\Delta} \cos\alpha \tag{2}$$

Where, P_{max} is the peak load, L and w are the length and the width of the specimen, t_c is the thickness of cross layer, P/Δ is the slope of the linear range of the load deformation curve between 10% and 40%, and $\propto$ is the angle between the shear plane and the force (14°).

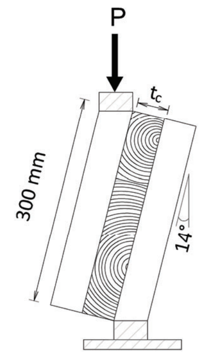

Figure 3: *Modified planar-shear test*

To calculate the average rolling shear modulus of each test series, two linear variable differential transformers (LVDTs) were used to measure the relative displacement between CLT layers adjacent to the loaded layer, on both front and back faces on 15 randomly selected specimens from each series. Load vs. the relative displacement curves of the specimens from S10 are shown in Figure 4. Most specimens exhibited quasi-linear behaviour until failure and sustained some load after peak and failure.

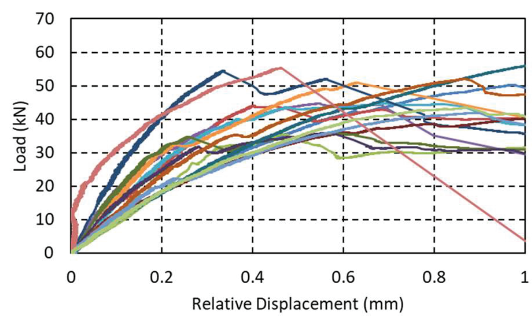

Figure 4: *Load vs. the relative displacement curves of S10.*

Since CSA 086 [4] gives the same value for rolling shear strength of 0.5 MPa for both strength grades, all 13 series were grouped together and the corresponding characteristic rolling shear strength is calculated. Nonparametric percent point estimate (NPE) and parametric tolerance limit (PTL) approaches described in EN 789 [17] were evaluated to calculate the 5th percentile rolling shear strength values. The NPE approach requires fewer assumptions and is deemed more conservative, while the PTL assumptions may lead to inaccurate results, thus NPE is adopted in the rest of this report.

EN 16351 [7] provides rolling shear strength values of CLT panels based on their lamination width-to-depth ratio. Therefore, all specimens with a tested layer thickness of 35 mm were considered as one group called "Thick" and the specimens having tested layer thicknesses of 19 mm and 17 mm were considered as a second group called "Thin". Outliers are excluded from each individual group of specimens. To further groups based on the stress grade of the specimens, E1 and V2, are also created and named accordingly.

2.3 ROLLING SHEAR STRENGTH RESULTS

The results from the in-plane rolling shear tests of all series are summarized in Table 2. The average of the rolling shear strength varied from 0.94 MPa to 1.81 MPa with a coefficient of variation (COV) between 14% to 37%. The average shear moduli range from 84 MPa to 157 MPa with a COV between 11% to 35%. When compared to those obtained in previous research, the measured mean value from this study is in a good agreement with those of the previous studies on the same softwood species.

The characteristic rolling shear strength values of each series are also presented in Table 2. It should be noted that these values need to be adjusted for normal duration of load, i.e., they should be divided by 1.15, if they are to be compared with the specified values in CSA O86 [4].

Table 2: *Summary of test results*

Series	Rolling shear strength			Rolling shear modulus	
	Mean [Mpa]	COV [%]	$\tau_{0.05}$ (NPE), [MPa]	Mean [Mpa]	COV [%]
S1	1.55	18	1.02	157	21
S2	0.94	19	0.60	87	22
S3	1.06	21	0.73	135	32
S4	1.81	23	1.27	104	23
S5	1.72	22	1.23	126	20
S6	1.51	14	1.23	150	11
S9	0.96	24	0.61	140	34
S10	1.54	20	1.10	85	35
S11	1.69	37	0.70	87	21
S12	1.10	20	0.67	102	34
S13	1.48	20	1.08	138	20

Previous findings suggest that the width to thickness ratio of the CLT lamellas influences its rolling shear strength where thinner boards with a higher width to thickness ratio have a greater rolling shear strength were confirmed. For instance, the thinner series, S1 (19 mm) has a greater average rolling shear strength value than the series having thicker test layer from this provider, S2 (35 mm). Similar finding can be observed by comparing values of the series from the panels provided by the same manufacturer.

The cumulative distribution of the rolling shear strength of all E1 and V2 series and the two other combined groups (Thin and Thick) are shown in Figures 5-8. The characteristic rolling shear strength value of E1 and V2 series combined groups are 0.73 MPa and 0.79 MPa, while the characteristic rolling shear strength value of Thin and Thick combined groups are 0.85 MPa and 0.72 MPa respectively.

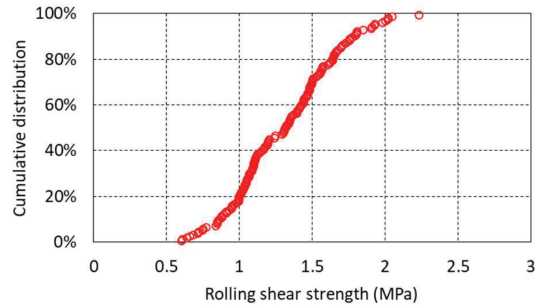

Figure 5: *Cumulative distribution for rolling shear strength of all E1 panel series.*

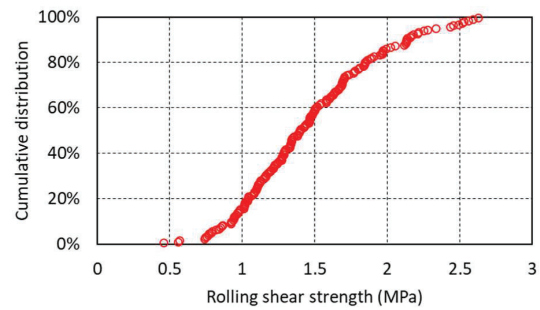

Figure 6: *Cumulative distribution for rolling shear strength of all V2 panel series.*

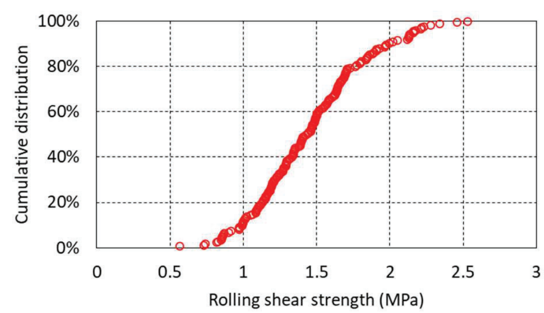

Figure 7: *Cumulative distribution for rolling shear strength of all "Thin" width-to-depth ratio.*

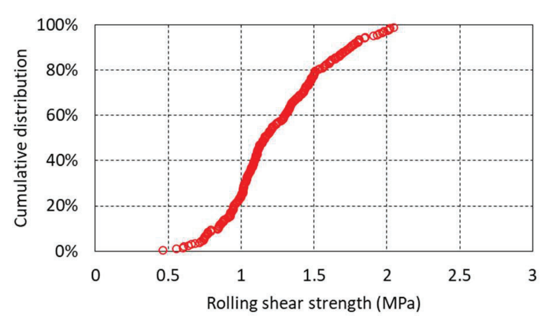

Figure 8: *Cumulative distribution for rolling shear strength of all "Thick" width-to-depth ratio*

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For an in-depth investigation of the measured values, one-way ANOVA test [18] was performed with a significance level of 95% and a cut-off p-value of 0.05. The obtained p-value <0.001 showed that there were statistically significant differences between the test series. Therefore, a Tukey's multiple comparison test was conducted, see Table 4. It can be observed that despite the difference in their average rolling shear strength values, not all *"Thin"* series are different from *"Thick"* series. For instance, it cannot be claimed that S1 is different from S5, S6, and S13. Similarly, it also cannot be claimed that all *"Thick"* are not different from each other; as shown in Table 4, there is a significant difference between S2 and S5.

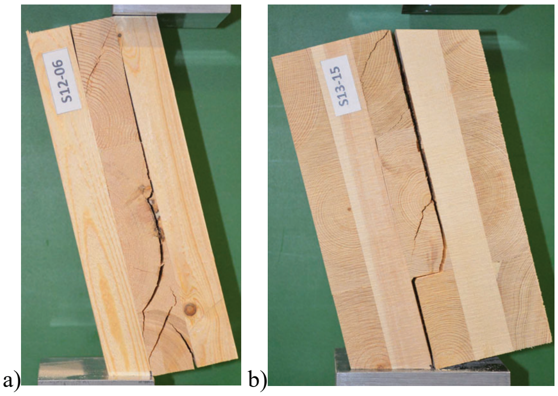
Table 4: *Tukey's multiple comparison test results.*

Series	Grouping[1]	Grade	Thickness
S1	ca	E1	Thin
S2	b	E1	Thick
S3	b	E1	Thick
S4	c	V2	Thin
S5	ca	V2	Thick
S6	a	E1	Thick
S9	b	V2	Thick
S10	a	V2	Thin
S11	ca	V2	Thin
S12	b	V2	Thick
S13	a	E1	Thick

[1] There is no significant difference at the 0.05 level between groups having at least one letter in common.

2.4 FAILURE MODES

The typical rolling shear failure mechanisms are illustrated in Figure 9. In the most common failure mechanism, cracks formed and propagated along the growth ring and led to a separation. In most tests, the crack(s) stopped at the bonding surface of loading plates and test layer, which resulted in the ultimate fracture. This was occasionally interrupted by steps along the wood ray. The presence of a pith in a specimen also led to the rolling shear failure, where a crack suddenly formed around the pith and then propagated along either the growth ring or a wood ray direction. Same scenario might happen when the wood ray which is a weak zone in a wood section is present. As shown in Figure 9, cracks were caused by tension perpendicular to grain stresses and propagated along the wood ray. During the tests, each or any combination of the above-mentioned mechanisms may have been the reason for initiation of failure, but as the load increased a combination of all three failure mechanisms was likely to be observed.



a) b)

Figure 9: *Typical rolling shear failure of (a) 3-ply, (b) 5-ply*

3 CONCLUSIONS

The Post+Plank program will assess the punching shear capacity of CLT flat slab systems through a large of experimental program. Results for the first phase of testing is overviewed in this paper, showing the base rolling shear strength for North American manufacturers of CLT. The following observations were made:

1. The predominant mode of failure was due to the development and extension of cracks along the growth ring, eventually resulting in separation. Additionally, the presence of a pith in the specimen results in rolling shear failure, wherein a crack abruptly initiates around the pith and extends either along the growth ring or along a wood ray direction.
2. The average of the measured rolling shear strength varied from 0.94 MPa to 1.81 MPa and the average shear moduli ranged from 84 MPa to 157 MPa.
3. The CLT series with a thinner layer exhibited higher average rolling shear strength than the thicker ones, corroborating earlier research that established a positive correlation between width-to-thickness ratio (lamella aspect ratio) and rolling shear strength; however, ANOVA showed these differences not to be consistently statistically significant.
4. The characteristic rolling shear strength values of the combined groups of E1 and V2 series after adjustment for normal duration loading were 0.63 MPa and 0.69 MPa, respectively. These values are 26% and 37% higher than what is specified in the CSA O86 standard [4].

The ongoing structural testing program at Fast + Epp and the University of Northern British Columbia will provide design inputs for point supported CLT.

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