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Advancing Timber for the Future Built Environment

PUNCHING SHEAR PERFORMANCE OF POINT SUPPORTED CLT

Houman Ganjali[1], Md Shahnewaz [2], Carla Dickof [3], Marjan Popovski [4], Thomas Tannert[5]

ABSTRACT: Cross-laminated timber (CLT) is a suitable material for point-supported floors where panels are directly supported by columns. Punching shear capacity is a key property in the design of point-supported CLT floors. CLT punching shear is directly related to the rolling shear (RS) strength of the boards and is enhanced by concurrent compression perpendicular to grain stresses. In this research, through punching shear tests on a total of 164 full-scale panels, the effect of various parameters on the punching shear capacity of CLT floors was investigated. Furthermore, the adjustment factor of RS strength in punching shear was determined. Having a center column, support area, timber species, and the out-of-plane stiffness of the load distribution plate were the main factors affecting the punching shear capacity of the panels.

KEYWORDS: mass timber floor systems, experimental investigation, point supports, cross laminated timber

1 – INTRODUCTION

Engineered mass-timber products are widely used in construction because of their smaller carbon footprint compared to other building materials. Cross-laminated timber (CLT) has gained popularity in recent years as a sustainable and cost-effective alternative to traditional construction materials, particularly for floor applications [1]. This application includes point-supported flat-slabs, where the panels are supported directly by columns, without the need for beams and their connections [2]. One of the key design properties in this application is the CLT punching shear resistance, which refers to its ability to resist concentrated loads or "punching" through the material, Figure 1a.

CLT punching shear resistance, R_{pu}, is directly related to the rolling shear strength, f_s, and impacted by the confinement of lamellas from adjacent layers and the presence of concurrent compression forces. These effects are accounted for in design by the rolling shear resistance in punching shear adjustment factor, $K_{r,pu}$, [3-5]. $K_{r,pu}$ is defined as the ratio of the maximum rolling shear stress from punching shear tests ($\tau_{r,max}$) to the average of the RS strength from in-plane shear tests ($f_{s,mean}$), Eq.(1). Mestek & Dietsch [3] proposed an adjustment factor of 1.2; in Annex D of prEN1995 [6] a $K_{r,pu}$ of 1.6 is recommended; and Muster [5] proposed $K_{r,pu}$ of 1.6 and 1.3 for centre and corner columns.

$$K_{r,pu} = \frac{\tau_{r,max}}{f_{s,mean}} \tag{1}$$

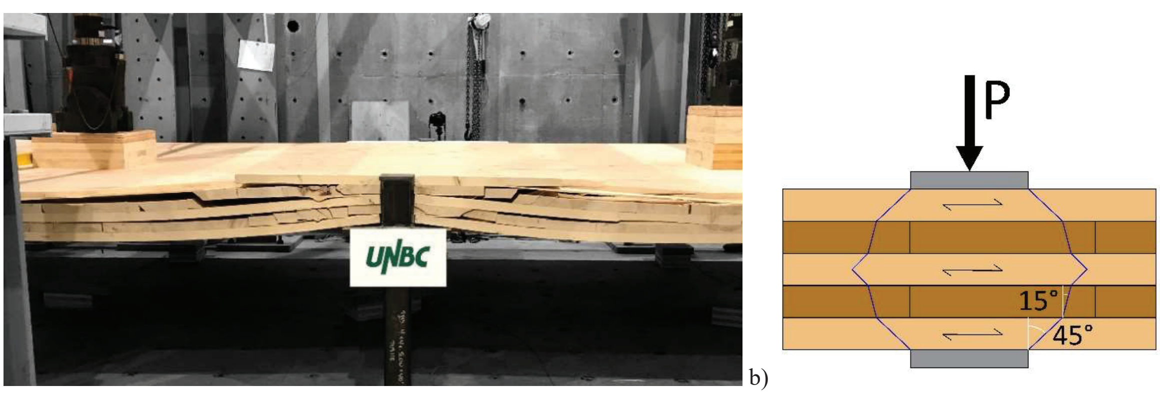
a) b)


Figure 1. Point-supported CLT punching shear failure (a); CLT load dispersion model (b).

[1] Houman Ganjali, School of Engineering, University of Northern British Columbia, Prince George, Canada, ganjali@unbc.ca
[2] Md Shahnewaz, Fast + Epp, Vancouver, Canada, mshahnewaz@fastepp.com
[3] Carla Dickof, Fast + Epp, Vancouver, Canada, cdickof@fastepp.com
[4] Marjan Popovski, FPInnovations, Vancouver, Canada, marjan.popovski@fpinnovations.ca
[5] Thomas Tannert, School of Engineering, University of Northern British Columbia, Prince George, Canada, thomas.tannert@unbc.ca

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Maximum shear stress occurs in mid CLT thickness; thus, shear stresses should be checked at an effective shear plane width, b_{eff}, to account for load dispersion angles of 45° and 15° parallel and perpendicular to grain, respectively (Fig. 1b). For simplicity, an average angle of 35° has been suggested [3,5]. PrEN1995 [6] also recommends checking the rolling shear stress at an effective perimeter of the loaded area defined at 35° to the centre line of the CLT thickness (t_{CLT}), determined with Eq.(2). However, this provision lacks a clear analytical basis and does not provide any adjustment factors for support-condition, i.e. the effect of column location and geometry, which are required for efficient CLT punching shear design.

$$b_{\mathrm{eff,i}} = b_{\mathrm{A,i}} + t_{\mathrm{CLT}} \cdot tan\,35° \qquad (2)$$

Adopting an appropriate shear stress distribution model to estimate the actual stresses close to point-supports is crucial. The shear analogy (SA) method [1,7] is based on the parallel axis theorem for determining the moment of inertia of a body about a given axis and is widely used to determine the effective bending stiffness of CLT. SA is capable of accounting for the effect of transverse layers on the shear stress profile in CLT. However, SA method has many steps and could make the design process laborious [8]. The transformed-section method [9] can be more readily adopted to determine the stress distributions in composite material sections. These shear stress distribution models give the stress profile across the thickness while assuming a constant profile along the width. This assumption only holds true in one-way bending problems. In a point supported CLT, the two-way bending of the panel leads to a different shear stress profile along the support dimensions demanding adjustment factors in design. Mestek [3] proposed a model based on an adaptation of SA method and a shear stress distribution adjustment factor (K_A) as a function of point support width to CLT thickness. Muster [5], proposed adopting plane beam shear stress equation for asymmetrical CLT layups and when required, based on point support location, using Mestek [4] adjustment factor, K_A, as well as an edge column at opening adjustment factor (K_{edge}). While limited design guidance for point-supported CLT floors is provided in prEN1995 [6], the current CSA O86 [10] and NDS [11] do not include such guidance. To close this gap and address the needs of the industry, a research project is being conducted by Fast + Epp structural engineers in collaboration with UNBC to study all factors relevant to punching shear design of CLT floors. The objective of this contribution is to investigate the effect of various support-condition-related parameters and to propose a new CLT punching shear design approach.

2 – MATERIALS AND METHODS

2.1 EXPERIMENTAL INVESTIGATION

The punching-shear resistance of 164 CLT panels from four Canadian manufacturers was evaluated to study the impact of: i) column geometry and size (square, rectangle, round), see, Fig. 2, ii) grade (E1, V2), species, and layup (5-ply 175 mm thick and 7-ply 245 mm thick); and iii) column location (edge, centre, corner, and perimeter Fig. 3. The E1 series had 1950 Fb-1.7E SPF and No.3 SPF in longitudinal and transverse layers, respectively. The V2 series had No.1/2 SPF and No.3/Stud SPF in in longitudinal and transverse layers, respectively, produced in accordance with ANSI/APA PRG 320 [12]. The panels in series S4, S5, and S6 were edge glued. The panels were sized 1.7 m × 1.8 m, 1.5 m × 1.8 m, and 1.5 m ×1.5 m

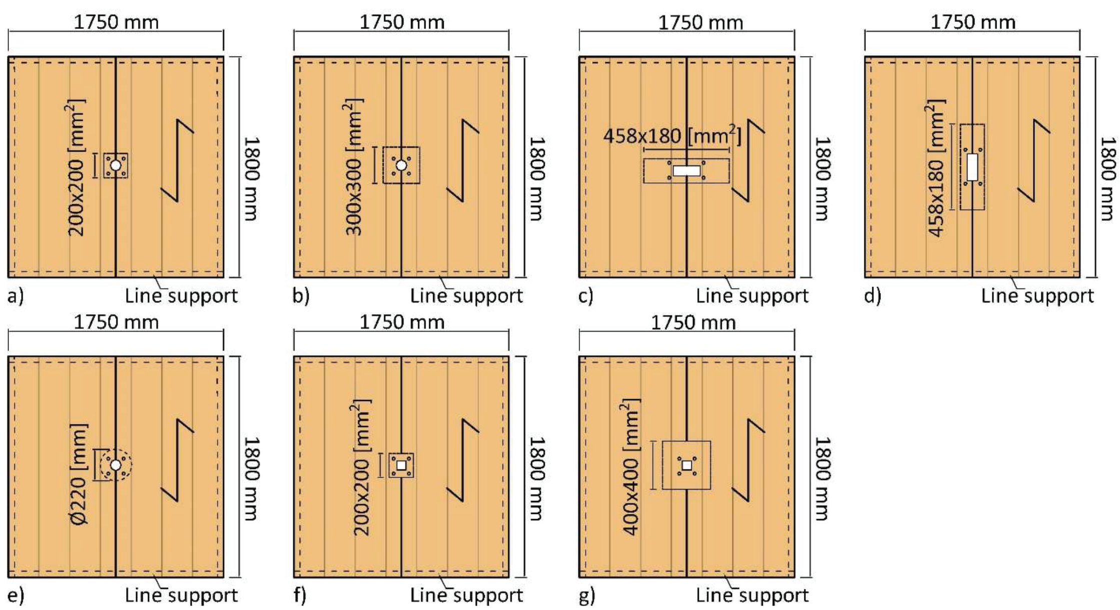

Figure 2. Different column geometries: a) square plate with stub (S1-S4, S6-S9, S15-S16); b) square plate with wood stub (S5); c) rectangular plate with wood stub (S10); d) rectangular plate with wood stub (S11); e) round column (S12); f) square plate and HSS (S13); and g) square plate and HSS (S14)

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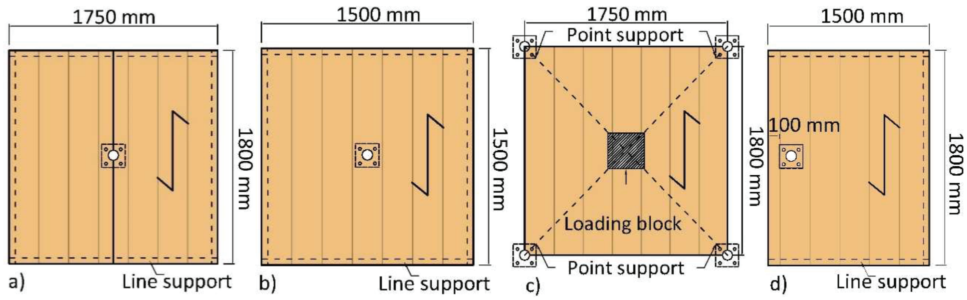

Figure 3. Punching shear test support locations: a) edge; b) centre; c) corner; and d) perimeter.

Table 1: Overview of punching shear tests and results.

Series	Support size [mm]	Column location	$R_{pu,avrg}$ [kN]	$f_{s,avrg}$ [MPa]	$\tau_{r,max,FEA}$ [MPa]	$K_{r,pu,FEA}$ [-]	$K_{TW,FEA}$ [-]
S1	200 × 200	Edge	259.8	1.12	2.99	2.7	1.5
S2	200 × 200	Edge	273.9	1.48	3.12	2.1	1.5
S3	200 × 200	Edge	262.3	1.06	2.95	2.8	1.5
S4	200 × 200	Edge	321.1	1.51	3.66	2.4	1.5
S5	300 × 300	Edge	347.6	1.51	2.61	1.7	1.4
S6	200 × 200	Edge	221.2	1.14	2.54	2.2	1.5
S7	200 × 200	Edge	231.2	1.62	2.64	1.6	1.5
S8	200 × 200	Edge	322.2	1.44	3.70	2.6	1.5
S9	200 × 200	Edge	243.7	1.06	2.80	2.6	1.5
S10	460 × 180	Edge	335.0	1.62	2.06	1.3	1.2
S11	180 × 460	Edge	324.0	1.62	3.37	2.1	1.5
S12	Ø 219	Edge	259.4	1.62	2.73	1.7	[-]
S13	200 × 200	Edge	265.8	1.62	2.67	1.6	1.4
S14	400 × 400	Edge	352.5	1.62	2.27	1.4	1.3
S15	300 × 300	Edge	209.2	1.62	2.39	1.5	1.6
S16	200 × 200	Edge	259.2	1.62	2.96	1.8	1.5
S17	300 × 300	Edge	463.2	1.62	2.46	1.5	1.2
S23	200 × 200	Edge	217.8	1.62	2.48	1.5	1.5
S24	200 × 200	Centre	268.0	1.62	2.50	1.5	1.1
S25	Ø 219	Centre	271.5	1.62	2.75	1.7	1.1
S26	300 × 300	Centre	363.0	1.62	2.44	1.5	1.1
S27	200 × 200	Centre	307.4	1.62	2.78	1.7	1.1
S28	200 × 200	Centre	288.5	1.62	2.61	1.6	1.1
S29	300 × 300	Centre	566.5	1.62	2.42	1.5	1.1
S30	200 × 200	Perimeter	151.8	1.62	1.40	0.9	1.0
S31	200 × 200	Perimeter	195.0	1.47	2.7	1.3	1.1
S41	200 × 200	Corner	255.0	1.62	4.20	2.6	1.7
S42	200 × 200	Corner	387.8	1.62	2.97	1.8	1.5

The edge and centre specimens were line-supported on four edges along the length, while the perimeter condition specimens were line-supported on three edges. The corner condition specimens were point-supported on four corners having the same bearing area, ensuring an equal possibility of failure for all corners. The test series overview is shown in Table 1. The tests were conducted according to ISO 6891 [13] using a hydraulic actuator at a monotonic loading rate of 5 mm/min. The displacement of the tension side of the panels (underside for the edge, centre, and perimeter series and top for corner series) was recorded using string pots at various points throughout the tests.

2.2 NUMERICAL MODELING

To determine the shear stresses through finite element analysis (FEA), the panels were modelled as 2D plates in Dlubal's RFEM adopting RF-Laminate [14]. The panel geometry was defined as a rectangular surface in accordance with the experimental setups. All loaded areas and the point-supports (corner series only) were modeled as separate surface elements integrated with the rest of the panel. The boundary conditions of edge, centre, and perimeter supports was modelled as roller line-supports with locked in-plane displacement and released vertical tension in accordance with Fig. 2.

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The supports in the corner-series, however, were modelled as surface supports having the effective bearing areas calculated with Eq.(2) and adopting a support stiffness, $C_{u,z}$, of 1.7 N/mm^3 [8]. Test loads of edge, centre, and perimeter condition series were applied on a surface equal to the effective bearing area of point supports calculated with Eq.(2) as shown in Fig. 2. For the edge series, due to symmetry only a half panel was modeled. The test load of the corner series was applied on a 600 mm × 600 mm surface in the centre of the panel. The material properties were assigned using RF-Laminate modules by entering the layers' thickness and their manufacturer-provided material properties. In RF-Laminate, details of composites, the option for considering coupling effect was selected for all series, and cross laminated timber without glue at narrow sides was unchecked for series S4, S5, and S6. The local X-axis was set to be parallel to the major direction of the panels. The mesh size was 30 mm with refinements around point supports.

3 – RESULTS AND DISCUSSION

3.1 PUNCHING SHEAR RESISTANCE

The average punching shear resistance, $R_{pu,avrg}$, of each series and the corresponding COV are summarized in Table 1. The results show CLT panels having the same CLT thickness, grade, species, and manufacturer, supported on different locations had substantially different resistances. This highlights the necessity of a proper shear stress distribution adjustment factor. The setup used for series S30 did not activate two-way bending action. Therefore, two additional panels were tested with clamped ends at the line support in the minor direction; series S31.

Among the 175 mm SPF edge column series, S05 (manufacturer B) had a 40% larger resistance than S07 (manufacturer F). Grade E1 series was 5% stronger than grade V2 series (S06 vs. S07) since punching shear failure is accompanied by the tensile failure, and E1 grade has boards with higher tensile strength in the longitudinal layers. A 45% and 40% increase was attained when X- and Y-oriented rectangular columns were adopted.

The softer (thinner) load distribution plate in S13 resulted in a 13% increase in $R_{pu,avrg}$; this can be attributed to the reduced stress concentration. In the edge column series, using a round column increased the capacity by 12%. However, the results of the round column series with center column condition, S25, showed no increase when compared to S24 with a square load distribution plate. Results shows that a bigger support width in the governing direction did not necessarily result in a higher capacity, but 4 times larger support area, regardless of geometry, predicted up to 50% higher punching shear resistance.

The maximum rolling shear stress values determined through FEA ($\tau_{S,max,FEA}$), and the adjustment factor for rolling shear resistance in punching from FEA ($k_{r,pu,FEA}$) are reported in Table 1. The values of $\tau_{S,max,FEA}$ were considerably higher than RS strength values reported by Ganjali et al. [15]. The $k_{r,pu,FEA}$ values calculated with Eq.(1) for the edge-column series averaged 2.0; for the centre column series 1.6; for the perimeter series 1.0 and 1.3; and for the corner series 2.2.

The plane beam equation and the model proposed by Muster [5] assumes a parabolic shear profile across CLT thickness, thus, not accounting for the difference between the contribution of minor and major axis layers to CLT shear profile and overestimating the maximum shear stress. Besides, in symmetric CLT layups, major and minor directions do not have equal shares in the punching shear resistance of the point supports; this also should be reflected in the design.

Herein, the Transformed Composite Section (TCS) method is adopted to calculate the rolling shear stress (τ_r):

$$\tau_r = \frac{V_i \cdot Q_{trans}}{I_{trans} \cdot b_{eff}} \qquad (3)$$

Where V_i is the shear force from force analysis; Q_{trans} is the first moment of inertia of the transformed section, I_{trans} is the moment of inertia of the transformed section; and b_{eff} is the effective width of the shear plane determined with Eq.(2). Herein, an adjustment factor for shear stress distribution in two-way bending (K_{TW}) was defined as the ratio of $\tau_{r,max,FEA}$ to $\bar{\tau}_{r,FEA}$:

$$K_{TW} = \frac{\tau_{r,max,FEA}}{\bar{\tau}_{r,FEA}} \qquad (4)$$

The $K_{TW,FEA}$ of the tested series are reported in Table 1. $K_{TW,FEA}$ for the edge-column series averaged 1.5; for the centre column series averaged 1.1; for the perimeter* series averaged 1.1; and for the corner series 1.6. Using the proposed K_{TW} is contingent on the ability of adopted stress distribution model in giving the same $\bar{\tau}_r$ as those of from FEA.

The shear stress distribution of S29 in both directions through SA, plane beam equation, and TCS methods are compared to each other in Fig. 4a and b. The simpler TCS method resulted in the same shear profile and the ultimate shear stress as SA method and plane beam equation overestimating the maximum shear stress in both directions.

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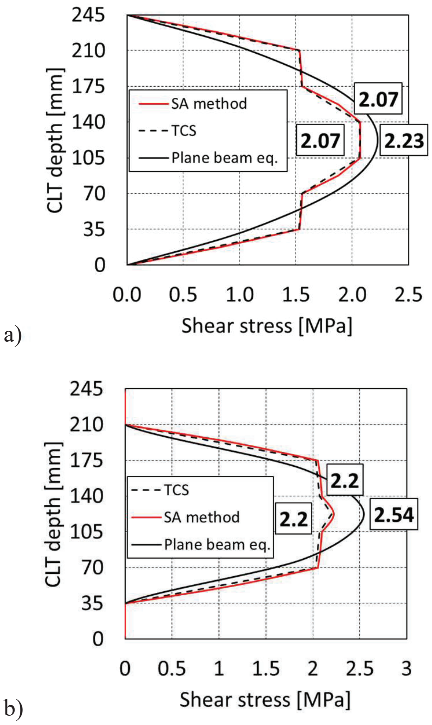

Figure 4. SA vs. TCS vs. plane beam equation methods in major (b) and minor (c) directions of a 7-ply CLT (S29).

3.2 PROPOSED ANALYTICAL MODEL

For punching shear design of CLT, Eq.(5) should be satisfied, where the rolling shear strength of CLT should be increased by $K_{r,pu}$ factor and the maximum rolling shear stress can be calculated through a TCS based model Eq.(6) at an effective shear width determined based on the column location, applying the adjustment factor for shear stress distribution in two-way bending (K_{TW}).

$$\tau_{r,d} = K_{r,pu} \cdot f_s \geq \tau_{r,max} \quad (5)$$

Where $\tau_{r,d}$ is the design rolling shear stress; f_s is rolling shear strength; and $k_{r,pu}$ based on Table 2.

The maximum rolling shear stress ($\tau_{r,max}$) in the decisive layer can be calculated by:

$$\tau_{r,max} = \frac{V_i \cdot Q_{trans} \cdot K_{TW}}{I_{trans} \cdot b_{eff}} \quad (6)$$

Where $b_{eff,i}$ is determined with Eq.(7) and (8) according to Fig. 5 for the cases where the panel is continuous on the both sides of the point support and when it is not, respectively; and K_{TW} is based on Table 3.

Table 2: RS resistance in punching shear adjustment factor ($k_{r,pu}$).

Column location	Centre	Edge	Corner	Perimeter
$k_{r,pu}$	1.6	2	2.2	1.3

Table 3: Adjustment factor for shear stress distribution (K_{TW}).

Column location	Centre	Edge	Corner	Perimeter
K_{TW}	*1.1*	*1.5*	*1.6*	*1.1*

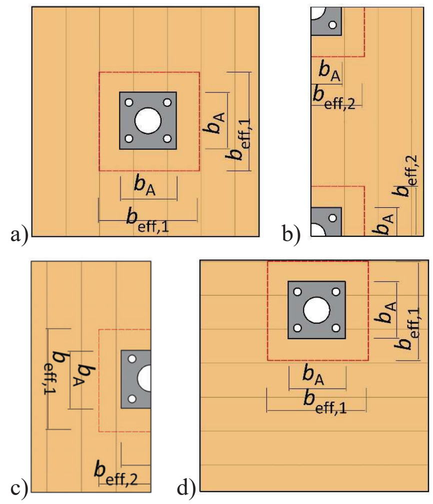

Figure 5. b_{eff} in centre (a); corner (b); edge (c); perimeter (d) columns.

$$b_{eff,1} = b_{A,i} + t_{CLT} \cdot tan\, 35° \quad (7)$$

$$b_{eff,2} = b_{A,i} + 0.5 t_{CLT} \cdot tan\, 35° \quad (8)$$

4 – CONCLUSIONS

Based on the punching shear tests on 164 full-scale CLT panels, and subsequent analytical and numerical analyses, the following conclusions can be drawn:

- CLT punching shear resistance, R_{pu}, was impacted by column location.
- CLT panels from different manufacturers with the same grade and species were up to 40% stronger.
- A larger support area (regardless of geometry) and softer (thinner) load distribution plate increased the resistance by 50% and 13%, respectively. Overall, the E1 series were slightly (5%) stronger than V2 series.
- Round column geometry increased the resistance of the edge column panels while it had no effect on $R_{pu,avrg}$ of the centre column series.
- The adjustment factor for rolling shear resistance in punching shear, $k_{r,pu,FEA}$, for edge-columns averaged 2.0; for the centre columns 1.6; for the perimeter supports 1.0 and 1.3; and for the corner series it was 2.2.
- An adjustment factor for shear stress distribution in two-way bending (K_{TW}) was suggested as 1.5 for the edge-column series; 1.1 for the centre column series; 1.1 for the perimeter series; and 1.6 for the corner series.
- To avoid the laborious SA method, the TCS method, that leads to the same shear stress profile, is proposed.
- A model for punching shear design of CLT is proposed with the required adjustment factors accounting for the effect of concurrent RS and compression perpendicular stresses as well as the effect of two-way bending on the maximum RS shear.

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