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EXPERIMENTAL INVESTIGATIONS ON CLT PANELS WITH OPENINGS

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ABSTRACT: The design of cross-laminated timber (CLT) shear walls demands careful consideration. In order to reduce cost and speed up construction time, large panel sizes are often preferred, yet sometimes openings are required for architectural purposes. However, the Canadian Standard for Engineering Design in Wood (CSA O86-19) prohibits openings in CLT shear walls due to a lack of research quantifying the reduction of stiffness as a function of opening size. To address this research gap, the impact of opening size on the stiffness of CLT panels was investigated. A total of 43 tests were conducted on panels with two different aspect ratios, two different thicknesses, and various opening sizes. The results indicate that the panel stiffness decreases non-linearly with an increase in opening size. However, even opening sizes large in relation to the panel width have only a minimal impact on the panel stiffness. These findings provide valuable insights for future design provisions for openings in CLT shear walls.

KEYWORDS: Cross-laminated timber, Push-over test, In-plane stiffness, Opening size

1 INTRODUCTION

1.1 CLT SHEAR WALLS WITH OPENING

The use of cross-laminated timber (CLT) in construction has significantly increased in the 21st century, with numerous structures built worldwide demonstrating the benefits of this material [1]. One emerging application of CLT is as shear walls, which commonly feature openings for doors and windows. However, such openings create stress concentrations that can reduce the panel's in-plane stiffness and load-carrying capacity.

While previous research has largely focused on the mechanical properties of CLT panels, limited work has been conducted on openings to determine a reduction coefficient. Dujic et al. [2] utilized a combination of experiments and numerical analysis to investigate how the size and shape of openings affect the strength and stiffness of shear walls. Through a parametric study, the authors proposed Equations (1) and (2) to estimate the stiffness and strength of panels with openings:

$$K_{opening} = K_{full} \cdot \frac{r}{2-r} \tag{1}$$

$$F_{opening} = F_{full} \cdot r(2-r) \tag{2}$$

Where $K_{opening}$ and K_{full} denote the stiffness of a CLT wall with and without and openings, respectively. The panel area ratio, r, is calculated using Equation (3):

$$r = \frac{1}{1+\frac{\alpha}{\beta}} \cdot \frac{H\Sigma L_i}{H\Sigma L_i + \Sigma A_i} \tag{3}$$

In this equation, H is the height of wall, ΣL_i is the sum of length of full height wall segments (excluding length of openings from the total length), and ΣA_i is the sum of the openings area. The parameters used in these equations are illustrated in Figure 1.

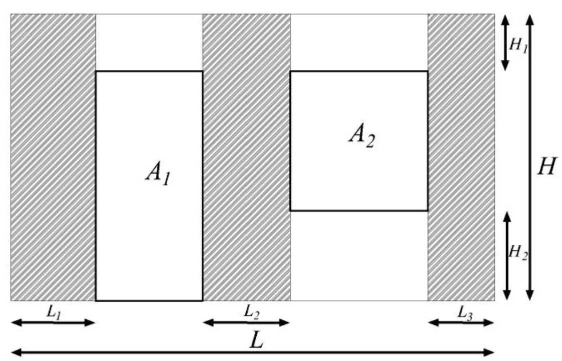

Figure 1: *Opening parameters for Equations (1) and (2)*

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Ashtari [3] investigated the in-plane stiffness of four configurations of CLT floor diaphragms, with and without openings, utilizing a numerical model. The study determined that several key factors significantly influenced the in-plane stiffness, including the panel-to-panel connections of the CLT, the in-plane shear modulus of the CLT panels, the stiffness of the shear walls, and the configuration of the floor diaphragm. The numerical model was considered to be appropriate for CLT shear walls with openings, but it was noted that the findings require further experimental validation.

Pai et al. [4] studied the force transfer mechanism around openings in CLT shear walls and identified reinforcement requirements for the opening corners. The study revealed high concentrations of shear stress, indicating a likelihood of shear failure. To mitigate this issue, the authors recommended adding reinforcement to the opening.

Yasamura et al. [5] created 3D models and examined the mechanical properties of full-size CLT structures subjected to reverse cyclic horizontal loads. The results highlighted the importance of considering panel failure when designing CLT plates with openings.

Shahnewaz et al. [6] utilized numerical methods to calculate the in-plane stiffness of fenestrated three-ply single CLT walls. Through a parametric study, the authors evaluated the impact of changing the size and shape of openings and proposed Equation (4) to calculate the stiffness reduction as function of opening size and shape.

$$K_{opening} = K_{full} \cdot \left(1 - \frac{r_{o/w}\left({A_0}/{A_w}\right)}{\sqrt{r_{o/w} + r_o\left({A_0}/{A_w}\right) - 2\left({r_{off}}/{r_w}\right)}}\right) \qquad (4)$$

Where $K_{opening}$ and K_{full} represent the stiffness of walls with and without opening, respectively. A_0 and A_w represent the areas of walls with and without opening, respectively. The aspect ratio of the opening, r_o , is defined as the ratio of the smaller to larger dimension of the opening. The maximum aspect ratio of opening to wall dimension, $r_{o/w}$ is calculated as the maximum of l_0/L or h_0/H, where L and H are the wall length and height, respectively, and l_0 and h_0 are the opening length and height, respectively. The wall aspect ratio, r_w , is defined as L/H, and the ratio of wall offset to wall dimension, r_{off} ,is defined as x_{off}/L or y_{off}/H, respectively). These parameters are illustrated in Figure 2.

Mestar et al. [7] and Casagrande et al. [8] studied CLT shear walls with openings and found that for large lintel slenderness, bending failure occurred. Additionally, a numerical calculation method was proposed for simulating laminated plates using homogeneous shell elements with effective moduli of elasticity and shear.

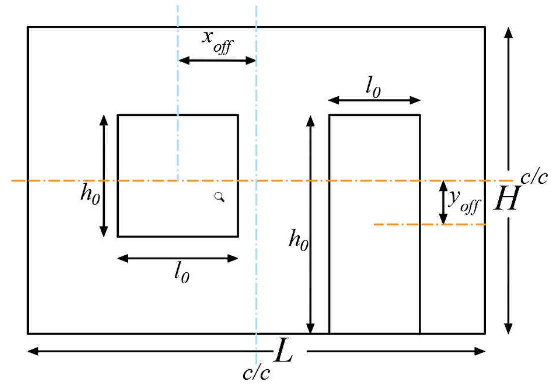

Figure 2: *Opening parameters for Equation (4)*

1.2 OBJECTIVES

Due to a lack of research on the strength and stiffness reduction as a function of the size and location of openings, the current CSA O86 provisions do not allow for any openings in CLT shear walls [9]. To address this knowledge gap, the objective of this study was to investigate experimentally how the size of openings affect the stiffness of CLT panels with different panel thicknesses and aspect ratios.

2 EXPERIMENTAL INVESTIGATIONS

2.1 MATERIALS

CLT panels with two different thicknesses were used in the experiments, namely: 1) 139mm 5-ply grade E1M4; and 2) 175mm 5-ply grade E1M5. The CLT panels were fabricated in accordance with ANSI/APA PRG 320 [10] and were supplied by Structurlam Products Ltd [11]. The wood species used were SPF MSR2100 (major layer)/No. 3 (minor layer). Based on the weight and volume of the CLT panels, the average apparent density of the panels was calculated to be 490 kg/m^3. The moisture content of the wood products was determined to be 12% (±3%) using portable electric resistance meters.

2.2 TESTS ON SINGLE PANELS

Two CLT panels of each layup measuring 1.5 x 3.0m were subjected to testing. Initially, the panels were tested without any opening, and then with gradually increasing opening sizes. The opening sizes were increased in increments of 200mm, up to a maximum size of 1200 x 1200mm, as shown in Figure 3. The panel was fixed at the bottom by three hold-downs, with one placed on each end and one in the panel centre. For ease of preparation, only slots were cut instead of completely removing the material from the opening.

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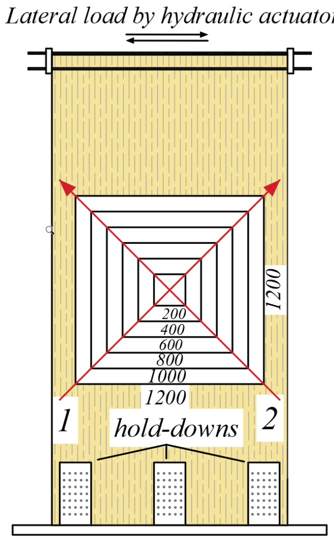

Figure 3: *Size of openings in single panels*

A lateral load was applied at the top end of the panel using a hydraulic actuator. The actuator was attached to steel plates with four pre-stressed rods. For each opening size, the panels were loaded three times to 100kN in both directions. The quasi-static monotonic load was applied at a constant rate of displacement of 10mm/min [12]. To measure the panel distortion, two string pots were used to span diagonally over the opening. In-plane panel movement was prevented by using an HSS profile, which was placed on a Teflon sheet to prevent friction. The experimental setup is illustrated in Figure 4.

Figure 4: *Set-up of single-panel test*

2.3 RESULTS OF SINGLE PANEL TESTS

Figure 5 shows the applied force versus opening distortion for all opening sizes. Figure 6 illustrates the maximum opening distortions as a function of opening size. It can be found that the panel stiffness decreased slightly with increasing opening size, with distortions of around 4mm for opening sizes of up to 800 x 800mm. Only when the opening size reached 1000mm was a significant increase of approximately 10mm observed.

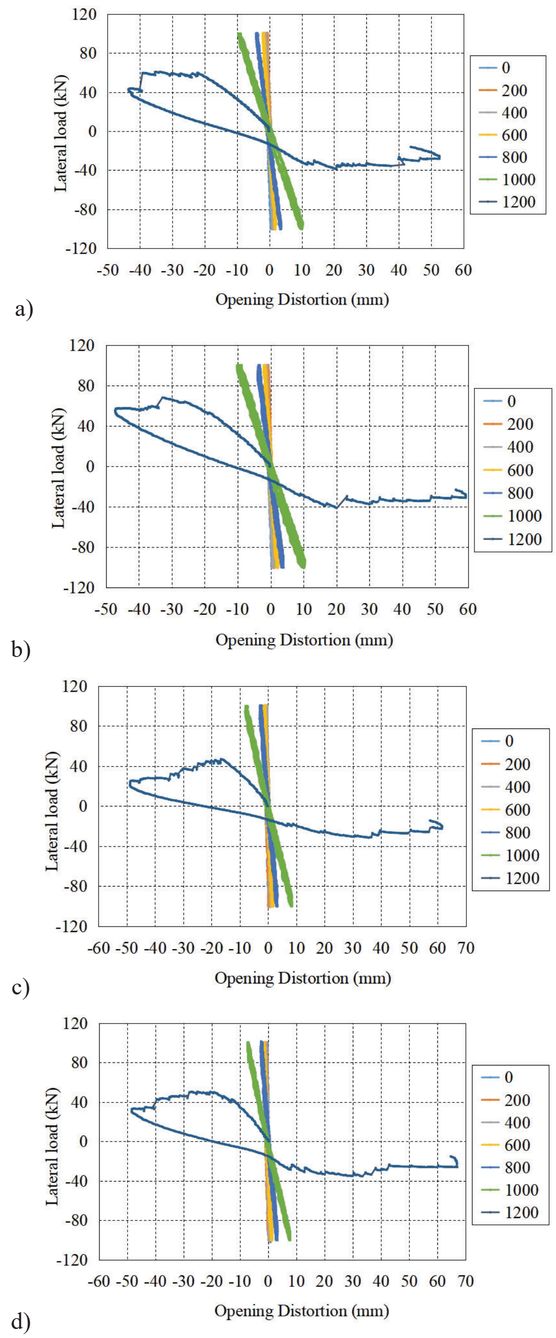

Figure 5: *Lateral load vs Opening distortion curves: (a)139-1; (b)139-2; (c)175-1; (d)175-2*

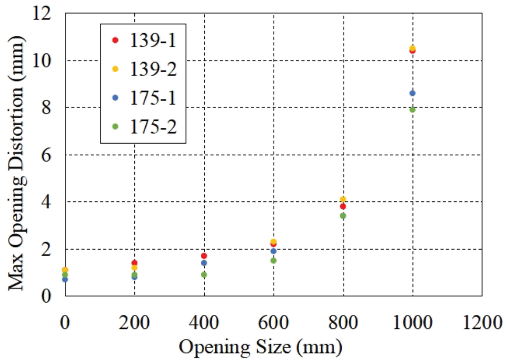

Figure 6: *Maximum opening distortion vs opening size*

The typical failure mode of the panels, when tested with a 1200 x 1200mm opening, is depicted in Figure 7. It be observed that cracks developed in the CLT panels near the corners of the openings, where the stresses peaked.

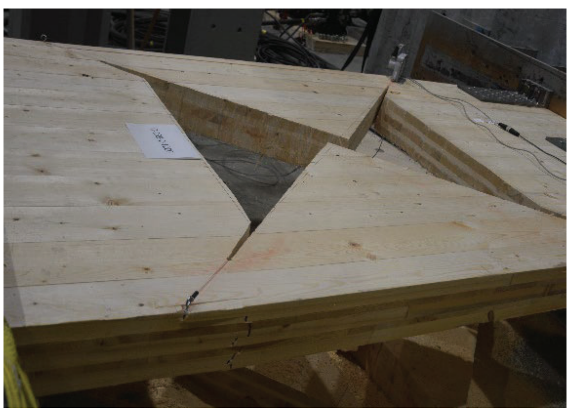

Figure 7: *Typical failure mode in single-panel test*

2.4 TESTS ON COUPLED PANELS

In the second part of the tests, the impact of different aspect ratios on CLT panels was examined with dimensions of 3 x 1.5 m and 3 x 1 m, corresponding to aspect ratios of 2:1 and 3:1, respectively. Only 139 mm 5-ply CLT panels were utilized for these tests.

Two CLT panels were tested next to each other, initially without any openings and subsequently with openings increasing in size from 150 x 150mm in increments of 150mm. The maximum opening sizes were 750 x 750mm for 1000mm wide panels and 1200 x 1200mm for 1500mm wide panels. To simplify the preparation process, only slots were cut rather than completely removing the material from the openings. The openings were placed eccentrically, with their centers 750mm and 500mm away from the long side of the panels, as depicted in Figure 8.

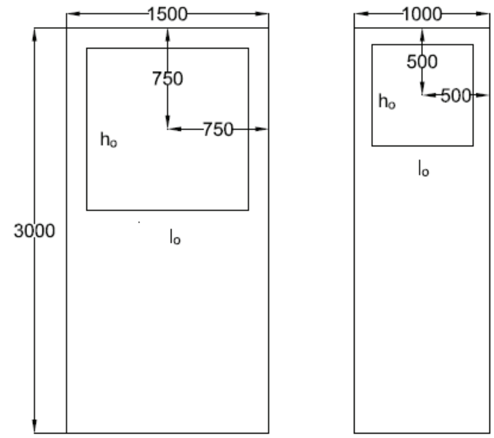

Figure 8: *Size of openings in coupled panels*

A hyperelastic hold-down system, presented by Asgari et al. [13] was used on the outside corners of the panels, and a pin-type shear connector was mounted at the midpoint, as shown in Figure 9. There was no further shear connection between the two panels. A hydraulic actuator was used to apply lateral load to the top of the two CLT panels via pins. A steel frame was used to hold the panels in-plane and to apply a constant dead load to the panels. For each opening size, the panels were subjected to three cycles of lateral loading in both directions, up to 50kN for the 1000mm wide panels and up to 75kN for the 1500mm wide panels. The quasi-static monotonic load was applied at a constant rate of displacement of 10mm/min.

The following parameters were measured during the tests: horizontal panel displacement, individual panel uplifts at both corners, horizontal sliding at the bottom of the panels, and panel distortion. Two string pots were mounted on each panel, spanning diagonally over the openings, to measure the panel distortion.

Figure 9: *Set-up of coupled-panel test*

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2.5 RESULTS OF COUPLED PANEL TESTS

Figure 10 illustrates the typical failure mode of the CLT panels when tested with a 1200 x 1200 mm opening. Similar to the single panel test, cracks developed in the panels near the corners of the openings, where the stresses were highest.

Figure 10: *Typical failure mode in single-panel test*

The force versus displacement curves for all opening sizes are depicted in Figure 11, while the panel distortions are illustrated in Figure 12. It is evident that an increase in opening size resulted in a corresponding increase in the maximum displacement, coupled with a decrease in stiffness. Notably, the curves for small to mid-sized openings overlap, indicating that the reduction in stiffness was minimal. The relationship between opening size and maximum distortion is displayed in Figure 13.

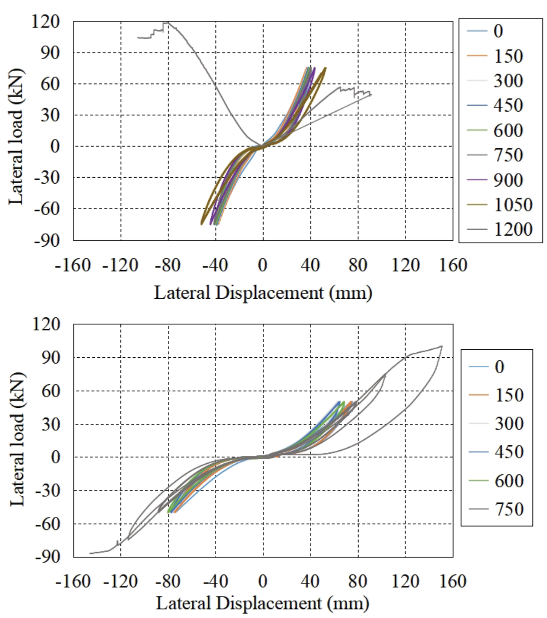

Figure 11:*Load vs displacement curves. Top: 2:1 aspect ratio; bottom: 3:1 aspect ratio*

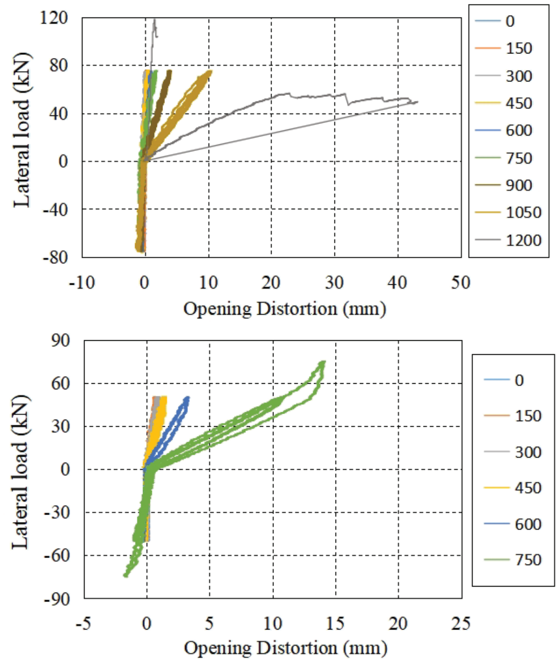

Figure 12: *Opening distortion curves. Top: 2:1 aspect ratio; bottom: 3:1 aspect ratio*

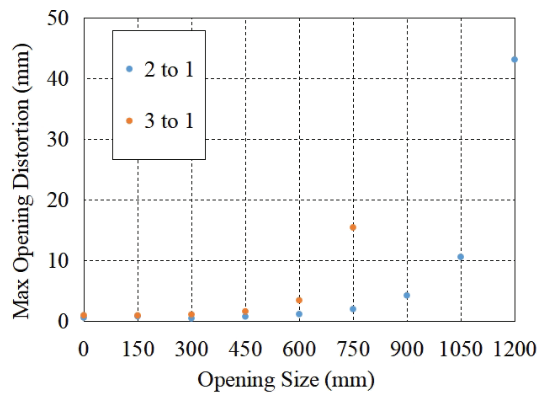

Figure 13: *Maximum opening distortion vs opening size*

3 CONCLUSIONS

The impact of different opening sizes on the in-plane stiffness of CLT panels was investigated experimentally, and the following main conclusions were drawn:

1) Openings do have an impact on the in-plane stiffness of CLT panels, but this impact is minimal for small opening sizes, and only becomes significant for very large opening sizes.

2) From the experimental results of coupled panels, it can be concluded that small openings in CLT shear walls only marginally reduce their stiffness. However, very large openings can reduce the stiffness by up to 35% and significantly reduce the shear resistance, leading to brittle panel failure at small loads.

3) The aspect ratio is a significant factor affecting the stiffness of CLT panels, and panels with different aspect ratios exhibit a considerable difference in stiffness under the same size of CLT panel openings.

4) These findings, once analysed in more depths and used to validate a numerical model for extended parameters studies can guide the development of future design provisions regarding openings in CLT shear walls.

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