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Experimental investigation on the effect of openings on the in-plane shear strength and stiffness of cross-laminated timber panels

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A R T I C L E I N F O

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Diagonal-compression test
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A B S T R A C T

The high in-plane shear strengths of cross-laminated timber (CLT) make it a good candidate for use as shear walls in buildings in areas of high seismicity such as Japan. One important aspect of CLT walls, and one that is presently poorly understood, is the influence of openings on the in-plane shear carrying capacity. The main purpose of this paper is to experimentally evaluate the effect of openings on the in-plane strength and stiffness of CLT panels with openings. In this study, 24 CLT panels were tested using a diagonal compression test configuration. In particular, they were three identical replicates of eight CLT panels. One of these eight panels was a solid panel, while the other seven panels had openings with different sizes and aspect ratios. The results showed that the panels with openings with the same area but different aspect ratios had different failure directions and reduction factors for panel shear strength and stiffness. Panels with rectangular openings with different orientations relative to the panel's major and minor shear direction had different failure direction and reduction factors. In addition, the effect of openings on the reduction of initial stiffness for CLT panels was found to be greater than their effect on the reduction of shear strength. This paper's findings will help clarify the reduction in strength and stiffness of CLT panels with openings, which is an important aspect of the seismic design of buildings.

1. Introduction

Cross-laminated timber (CLT) has been gaining popularity in residential and non-residential applications around the world. CLT is a wood-based material with relatively high strength and load transfer ability on all sides, which makes it a potential replacement for concrete or steel in some mid-rise and high-rise buildings. In Japan, the use of CLT as a building material is recent compared to Europe; however, the CLT industry in Japan is growing rapidly and gaining more attention since CLT is a natural and carbon storage product, takes less construction time compared to other types of structures such as reinforced concrete buildings (due to the prefabrication), and also produces little waste during the assembly process. CLT panels have a relatively high in-plane shear strength and are therefore becoming a good alternative for use as shear walls in timber structures to maximize the shear resistance of the structure. One construction method for CLT buildings is by connecting narrow panels together to be able to construct a wall with the required opening. However, although the narrow CLT panel configuration may have higher ductility and energy dissipation compared to a single CLT panel with the same size, higher stiffness and strength were observed in single-wall configuration [1]. This higher ductility can be achieved only if the steel connections used could allow high rocking deformation. Also, in the narrow CLT panels construction method, many steel connections are needed to connect the panels, which results in high construction cost and also time. For these reasons, understanding the behaviour of a single wide CLT panel with openings is of a great interest in seismic design practice.

The seismic performance of multi-story CLT structures has been the focus of several research projects all over the world, with projects testing CLT buildings such as recent studies in Europe [2–3] and studies in

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Japan [4–6] and the US [7–9]. In those projects, several types of openings are incorporated in the tested buildings. Openings in CLT shear walls are very common either as windows or doors or as openings for installation of building services. Those full-scale projects have concentrated on the performance of the entire structure rather than the performance of each CLT shear wall at a component level with or without openings. Even though there was intensive research of CLT structures, the studies concerning the influence of openings on CLT walls are still limited, and this influence on in-plane shear strength and stiffness of walls are still not well understood.

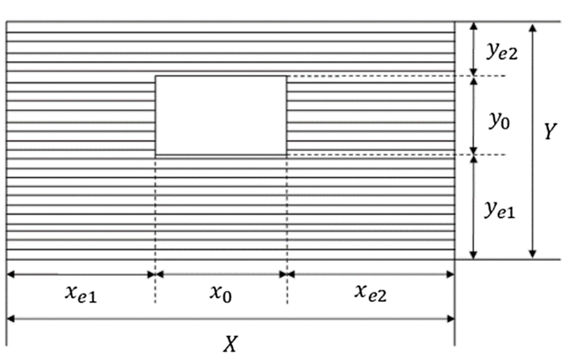
In Japan, the limitations of opening size in structural CLT elements described in the Japanese CLT Guidebook [10] are indicated in Fig. 1. The concept used in the guideline is based on an older study [11] on experiments on plywood sheathed wooden frames rather than CLT walls. These regulations are relatively strict, and if the opening dimensions exceed these described limits, the entire wall must be considered a non-structural element. For example, if the distance from the edge of the opening to the edge of the CLT wall in any direction is less than 500 mm (as shown in Fig. 1), the entire wall is considered a non-structural wall. These strict limitations are due to the concern of the high seismic loads in Japan, as well as the lack of academic research regarding the reduction of strength and stiffness due to openings in CLT shear walls.

In the Japanese CLT Guidebook [10], Eq. (1) is used to calculate a single reduction factor to reduce both the shear strength and stiffness of CLT shear walls with openings, with reference to the limitations in Fig. 1. CLT wall's strength and stiffness reduction for different openings area ratios based on [10] are illustrated in Fig. 2a and b, respectively.

$$R_0 = \frac{r}{8-7r}, \quad r = \frac{1}{1+\alpha/\beta}, \quad \beta = \frac{y_{e1}+y_{e2}}{Y}, \quad \alpha = \frac{x_0 \bullet y_0}{X \bullet Y} \tag{1}$$

where R_0 is the reduction factor, r is the opening coefficient, x_0, y_0, y_{e1}, y_{e2}, X and Y are as defined in Fig. 1.

One way of testing CLT shear walls to get their shear strength and stiffness is by using a cantilevered wall configuration, where steel connections are provided at the base of the CLT panel. Okabe et al. [12] and Araki et al. [13] tested several CLT shear walls with openings of different sizes in a cantilevered wall configuration. The base-to-wall connections used in these tests were strong enough to ensure failure in the CLT panels. A comparison between the reduction obtained from the results of



The length parallel to outer layer fiber $:x_0 \leq 1100mm$

The length perpendicular to outer layer fiber $:y_0 \leq 740mm$

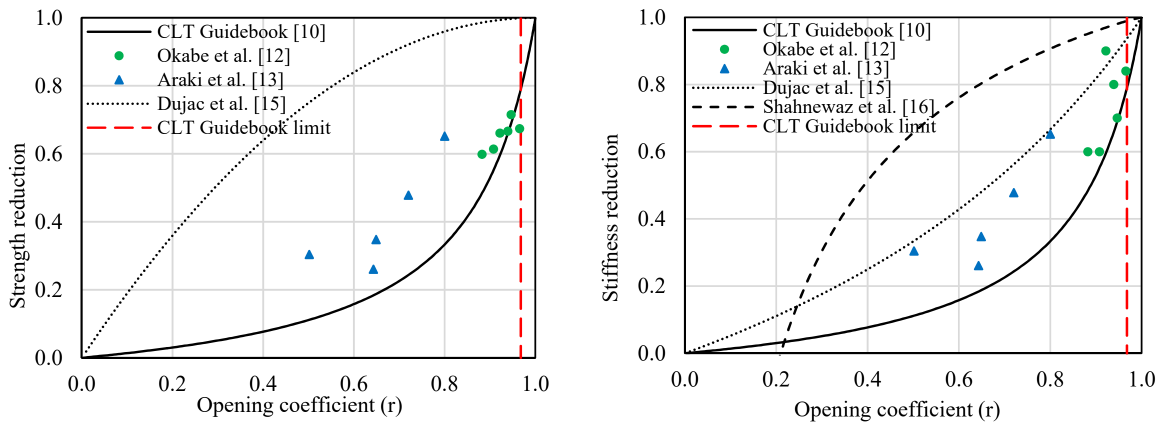
$$x_{e1}, x_{e2}, y_{e1}, y_{e2} \geq 500mm$$

Fig. 1. Regulation of the opening size in the Japanese CLT Guidebook [10].

[12,13] experiments and the reduction obtained from CLT Guidebook [10] are shown in Fig. 2. All the specimens tested in these two studies are out of the scope of the CLT Guidebook reduction equation. Although base-to-wall connections were designed so that the CLT wall fails first, these connections will still affect the overall behaviour of the CLT shear wall system and its stiffness. Mestar et al. [14] also used the cantilevered wall configuration to investigate the kinematic behaviour of CLT shear walls with openings. Dujic et al. [15] used the same testing method in an experimental and numerical study to investigate the effect of opening on the strength and stiffness of CLT shear walls. From the experimental campaign, it was found that with openings equal to 30% of the wall area, the maximum strength of the wall with openings almost did not change while the stiffness was reduced to around 50% of that of the solid wall. The strength did not change as the failure of both CLT walls happened in the base-to-wall connections. Based on a numerical study, Dujic et al. [15] proposed two empirical equations to calculate strength and stiffness reduction due to openings. The reduction obtained from these equations is illustrated in Fig. 2. For stiffness reduction, Dujic et al. [15] proposal underestimates the reduction compared to the experimental results obtained from [12,13], and for strength reduction, a big difference was found. That is thought to be because of the effect of base-to-wall connections, as the failure in Dujic et al. experiments occurred in these connections, while for [12,13], the failure happened in the CLT panel itself. In addition to that, analytical studies using finite element analysis were conducted by [16–19]. Shahnewaz et al. [16] performed a parametric finite element analysis and proposed empirical equations to calculate the stiffness reduction of CLT walls with openings. The reduction based on the proposal of [16] is illustrated in Fig. 2b. The reduction calculated based on this proposal has higher values than [10,12,13,15], and that is although thought to be due to the base-to-wall connections used in the numerical study. In all the previous studies, CLT walls had base-to-wall connections, which contribute to the stiffness and strength of CLT walls. Thus, the effect of openings on the strength and stiffness characteristics of only the CLT walls (without other influence of connections) is not clear in the previous studies. The influence of base-to-wall connections is important, but it also depends on the ratio of lateral strength of the connections to the lateral strength capacity of the panel itself. The effect of the connections used on the behavior of CLT structures was investigated by Flatscher et al. [20]. For example, if a relatively weak connection is used (relative to the strength of the CLT wall), a small opening in the CLT wall will not affect the stiffness and strength since the failure, and the deformation is concentrated in the connections. On the other hand, using relatively strong connections, then adding an opening in the CLT wall may cause the failure to precede in the wall before the connections. In summary, the influence of openings on walls depends not only on the connections but also on the reduction of strength and stiffness of walls. The reduction of stiffness and strength due to openings on walls alone (without the influence of opening) is unclear with no previous experimental studies.

Since the in-plane shear test cannot be conducted without including the effect of steel connections [21], an alternative method for testing CLT panels under in-plane loads to assess their strength and stiffness could be done by performing a component diagonal compression test. By using this test configuration, the in-plane loads can be induced in the CLT walls without the need for base-to-wall connections. Several researchers have performed this test on CLT panels with the primary objective of determining the CLT shear modulus (G) [15,22–25]. However, none of these previous diagonal compression tests have considered such a loading set-up to investigate the effect of openings on the CLT panel performance.

The main objective of this study is to investigate the key opening parameters that affect the reduction of in-plane strength and stiffness of CLT shear panels with openings without the influence of base-to-wall connections. To achieve this, an experimental programme consisting of monotonic diagonal compression tests of CLT panels with different openings was undertaken.



(a) Strength reduction for CLT walls with different opening sizes

(b) Stiffness reduction for CLT walls with different opening sizes

Fig. 2. Strength and stiffness reduction for CLT walls with openings obtained from the literature vs. opening area ratio calculated by Eq. (1).

2. Experimental programme

2.1. Material properties

All the CLT panels were 5-layer 150 mm thick panels made from Japanese cedar with Mx-60-5-5 (5-ply 5-layer) grade and composition, where "60" refers to the average nominal Young's modulus of one board in the major direction (6 GPa). The CLT density was around 400 kg/m^3, and the average moisture was around 14.9%. This average moisture value represents the average value for the moisture of each specimen which was measured at three points of the specimen before the test started. Material tests were conducted to obtain compression, bearing, and shear strength in the major and manor direction of the CLT panels based on testing procedures mentioned in [26]. In these tests, 18 CLT specimens were tested in total, three specimens for each type of test, and results are shown in Table 1. In Table 1, the shear strength refers to the gross shear failure of the CLT panel. All the strength values of the CLT panels were calculated based on the corresponding gross section of the CLT panel. Young's moduli in the major and minor directions of the CLT panel were calculated from the compression tests, and the results are shown in Table 1.

It should be noted that for CLT panels, there are three possible shear failure modes (gross, net, and torsional shear failure), as identified by the Japanese CLT Guidebook [10] as well as other studies such as [27] and [28]. Based on the material test results, the observed failure was gross shear for all specimens used in the shear strength tests, which was also the dominant failure mode as expected by the calculations mentioned in the Japanese CLT Guidebook [10] for CLT panels (Mx-60-5-5) that was used in this study.

2.2. Test matrix

In this experimental programme, eight 1200 mm by 1200 mm CLT panels were tested using the diagonal compression test configuration shown in Fig. 2a and b. Three replicates of each specimen type were tested in a total of 24 CLT panels. The details of the specimen types are shown in Table 2. In order to get representative average results, and as CLT exhibits quite variable material characteristics, and since there are no standards for testing CLT panels by diagonal compression test, the number of the replicates tested for each specimen type was decided to be three replicates. For the tested replicates, the variation in ultimate strength between the replicates was within 5% on average (with reference to Table 3), and therefore testing three replicates of each specimen type was thought to give representative results. The height (H) and length (L) of the wall specimens and height (h_o) and length (l_o) of the openings are also summarized in Table 2. For the eight specimen types, one panel was a solid panel without openings, while the rest seven panels had openings with different sizes and layouts. Only one of the specimen's configurations (A2-2) is considered a structural element according to the Japanese CLT Guidebook regulations [10]. Whilst other specimens would be considered non-structural elements in [10], as mentioned earlier.

In this study, the terms shear major direction, and shear minor direction of the CLT panel is introduced. The panel's major shear strength direction is the direction in which three of the wood layers are perpendicularly oriented (horizontal direction in Table 2), and the panel's minor shear direction is the direction in which two wood layers are perpendicularly oriented (vertical direction in Table 2), as shown in Fig. 3.

Table 1
Results of the CLT material tests.

	Loading direction	MPa
Compression strength	Major	19.6
	Minor	15.1
Young's modulus	Major	4810
	Minor	3460
Bearing strength	Major	23.8
	Minor	19.2
Shear strength	Major	5.02
	Minor	4.71

2.3. Loading set-up

The loading frame, jack, steel shoes, and CLT panel are shown in Fig. 4a and b. Each panel was installed vertically between two steel 'shoe' caps, which were designed to distribute the load such that local bearing failure of the CLT panel does not occur (i.e., the contact area between the steel shoe and the CLT panel was large enough to prevent local bearing failure under compression force). A single 2000 kN jack was used to apply a monotonic vertical downwards force on the CLT panel through the upper steel shoe, and the loading rate was in the range of 0.15–0.2 mm/s. The loading was stopped at the point where the specimen reached 80% of its maximum strength as prescribed in the Japanese CLT Guidebook [10]. No out-of-plane restraints were used; however, the out-of-plane rotation of the jack was monitored to verify that no out-of-plane deformation occurred.

Table 2
Test matrix of the CLT panels.

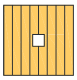
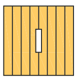
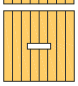
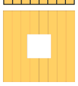
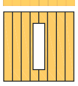
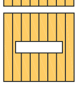
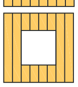
Panel	name	L (mm)	H (mm)	l_o (mm)	h_o (mm)	Opening area ratio	No. of specimens
	A0-0	1200	1200	–	–	–	3
	A2-2	1200	1200	200	200	2.8%	3
	A4-1	1200	1200	100	400	2.8%	3
	A1-4	1200	1200	400	100	2.8%	3
	A4-4	1200	1200	400	400	11.1%	3
	A8-2	1200	1200	200	800	11.1%	3
	A2-8	1200	1200	800	200	11.1%	3
	A6-6	1200	1200	600	600	25%	3

Table 3
Key values and information about the tested panels.

Panel name	Maximum force (kN)		Average shear stress (MPa)		Stiffness (kN/mm)		Ultimate load deformation (mm)		Failure direction
	Avg.	CV (%)	Avg.	CV (%)	Avg.	CV (%)	Avg.	CV (%)	
A0-0	731.6	3.2	4.06	3.2	106.3	13.8	7.2	8.2	Minor
A2-2	539.8	4.6	3.6	4.6	74.9	16.0	8.5	18.8	Minor
A4-1	475.2	8.5	3.96	8.5	74.0	24.4	8.1	13.6	Minor
A1-4	493.8	2.9	4.12	2.9	57.8	10.7	10.3	15.4	Major
A4-4	431.6	6.7	3.60	6.7	40.9	7.9	16.0	1.8	Minor
A8-2	186.4	4.2	3.11	4.2	25.8	22.2	8.5	10.0	Minor
A2-8	220.1	4.4	3.67	4.4	26.5	20.6	11.0	15.4	Major
A6-6	171.8	6.0	1.91	6.0	9.9	14.9	24.4	17.9	(Flexural)

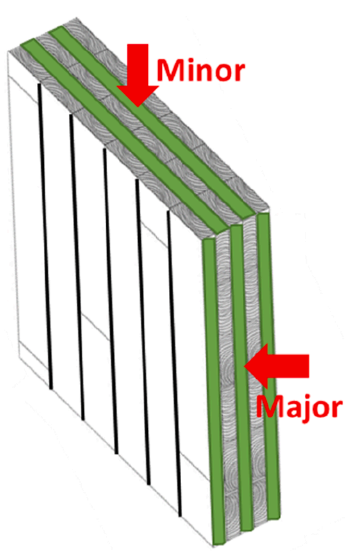


Fig. 3. Panel's shear major and minor direction.

2.4. Instrumentation

For all the CLT panels, on the front side of the panel, classical instrumentation (LVDTs) was attached, while on the backside, the deformation was measured using the digital image correlation (DIC) set-up. A typical instrumentation layout for the panels with openings is shown in Fig. 4c and d (A4-4 panel). Two LVDTs were set diagonally to capture the overall deformation of the panel along the two diagonal directions. These two LVDTs were used to calculate the total shear strain of the CLT panel. Furthermore, for all the CLT panels with openings, the response of the panel related to a combination of internal shear and flexural deformation was assumed to be symmetrical about the vertical axis of the panel in the testing position. Therefore, a set of LVDTs was attached on one side of the panel to measure the flexural deformation, while on the other side of the panel, another set of LVDTs was attached to measure the shear deformation. Positions of LVDTs for each CLT panel slightly changed based on the opening size. The panel with no openings has only two overall diagonal LVDTs. The CLT panel zones immediately below/above the loading shoes were assumed rigid, and so no measurements were made in these areas.

The overall shear strain angle and shear deformation were calculated by Eq. (2) and Eq. (3), respectively, with reference to Fig. 5a, using measurements of the overall diagonal LVDTs (Fig. 4c). The deformation of the area measured by the overall LVDTs is illustrated in Fig. 5a, and 900 mm in Eq. (2) is the distance measured along the diagonal LVDTs. In

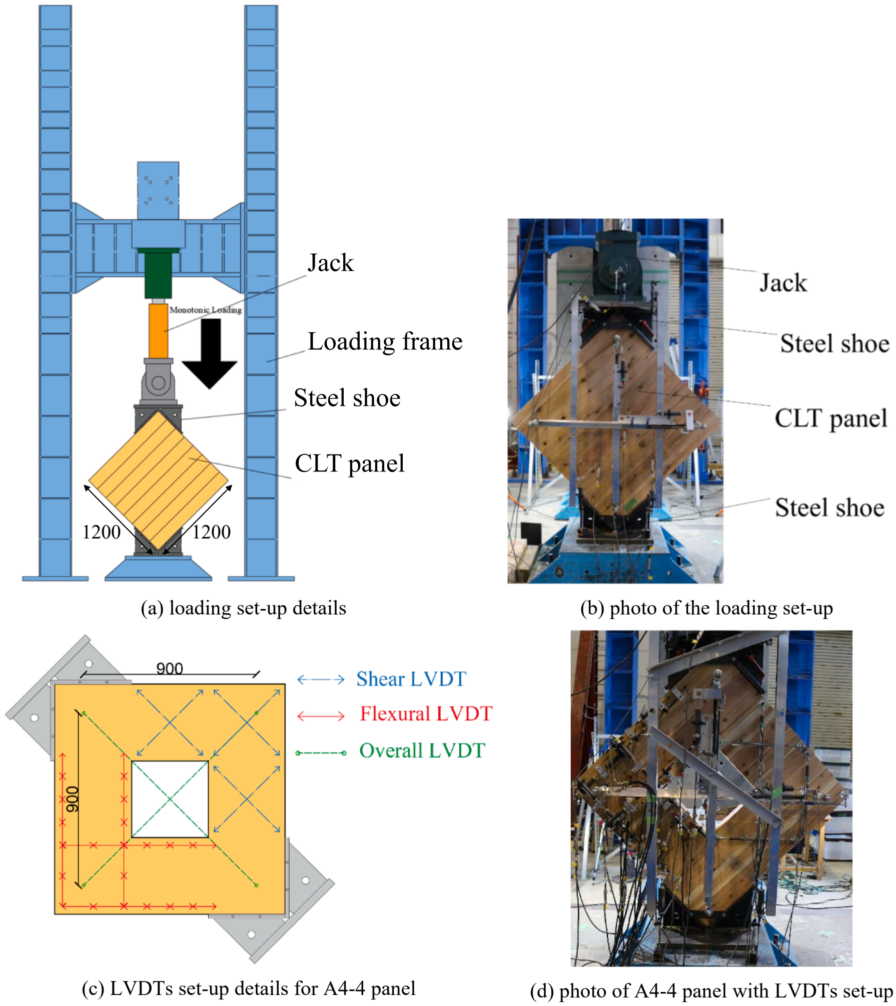


Fig. 4. Loading set-up and instrumentation.

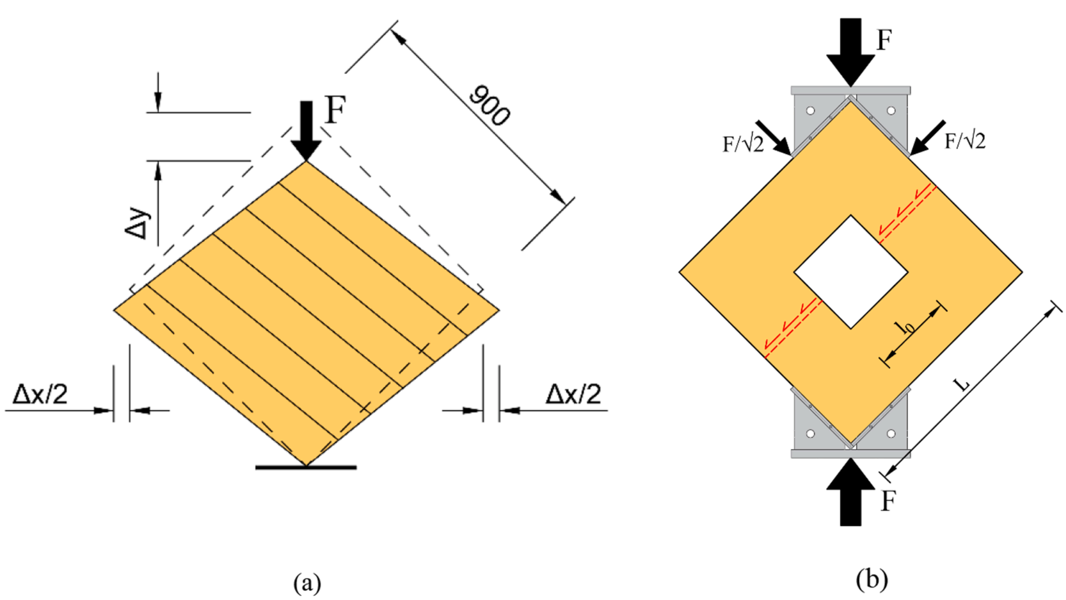


Fig. 5. (a) Deformation of the measured section by overall LVDTs; (b) panel average shear stress calculation plane.

CLT walls with openings, there is stress concentration around the openings. However, for the sake of the comparison between the results of all the specimens, an average shear stress was calculated for each panel using Eq. (4), with reference to Fig. 5b. Finally, the shear modulus and stiffness of each CLT panel were determined based on the standard EN 408 [29] by considering the linear part of the stress–strain curve between the values that are corresponding to 0.1 and $0.4F_{max}$.

$$\gamma = \frac{\Delta x + \Delta y}{900 \times \sqrt{2}} \tag{2}$$

$$\delta = \gamma \times 1200 \tag{3}$$

where Δx and Δy are the values obtained from horizontal and vertical overall LVDTs, respectively.

$$\tau = \frac{F}{\sqrt{2}\bullet(L - l_o)\bullet} t \tag{4}$$

where F is the vertical force, L is the panel length, l_o is the opening dimension in the direction of failure, and t is the panel thickness.

3. Results and discussion

3.1. Damage and failure characteristics

The cracks observed on the surface layer at the final failure for all the tested CLT panels are illustrated in Fig. 6. The red lines indicate the paths of the observed cracks on the outer layer after failure; yellow lines indicate the failure direction in the panel's shear major direction (panels A1-4 and A2-8). In all the tested panels with openings, except A4-4 panel (shown in Fig. 6e), the failure plane was from corner to corner of the opening. A4-4 panel showed slightly different failure characteristics with a failure line in the middle of the opening, although a small crack at the top corner was observed, as shown in Fig. 6e. For all the specimens, all the observed cracks on the outer layer of the CLT panel were only parallel to the fiber direction of this layer. In panels with a square opening (A2-2, A4-4, and A6-6), the failure plane was always parallel to the shear minor direction (i.e., parallel to grain for three wood layers and perpendicular to the grain for two wood layers). In panels with a rectangular opening (A4-1, A1-4, A8-2, and A2-8), the failure plane was parallel to the larger dimension side of the opening irrespective of the outer layer grain direction. In the case where the larger dimension of the opening is perpendicular to the CLT outer layer fiber direction (A1-4 and

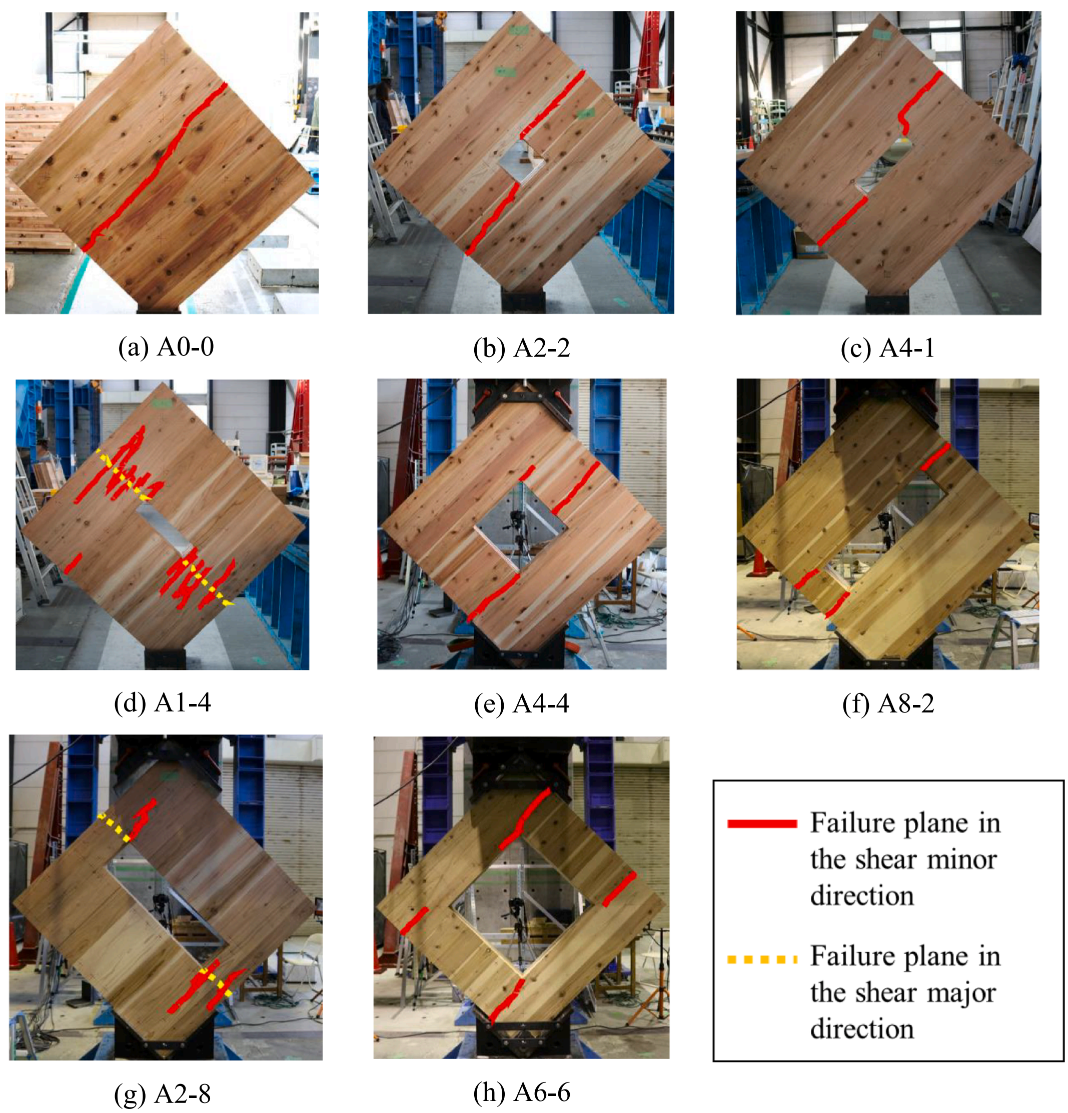


Fig. 6. Cracks observed on the surface layer for all the tested CLT panels (red line); the yellow line indicates the failure plane in the panel's shear major direction (panels A1-4 and A2-8). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A2-8 panels), the second and fourth layer failed by shear (yellow lines in Fig. 6d and g), and on the outer layer several parallel to the grain cracks were observed (red lines in Fig. 6d and g). In other words, the cracks seen on the outer layer of the CLT panel were parallel to the failure plane in the case of A4-1 and A8-2 panels and perpendicular to the failure plane in the case of A1-4 and A2-8 panels. For all the specimens that failed in shear (all the specimens except A6-6), the failure mode observed was gross shear failure (failure parallel to the grain). The average shear stresses of the CLT panels were calculated using the gross section of the CLT panel as shown in Eq. (4). A6-6 panel showed flexural failure characteristics. All the replicates for the same specimen had similar failure characteristics.

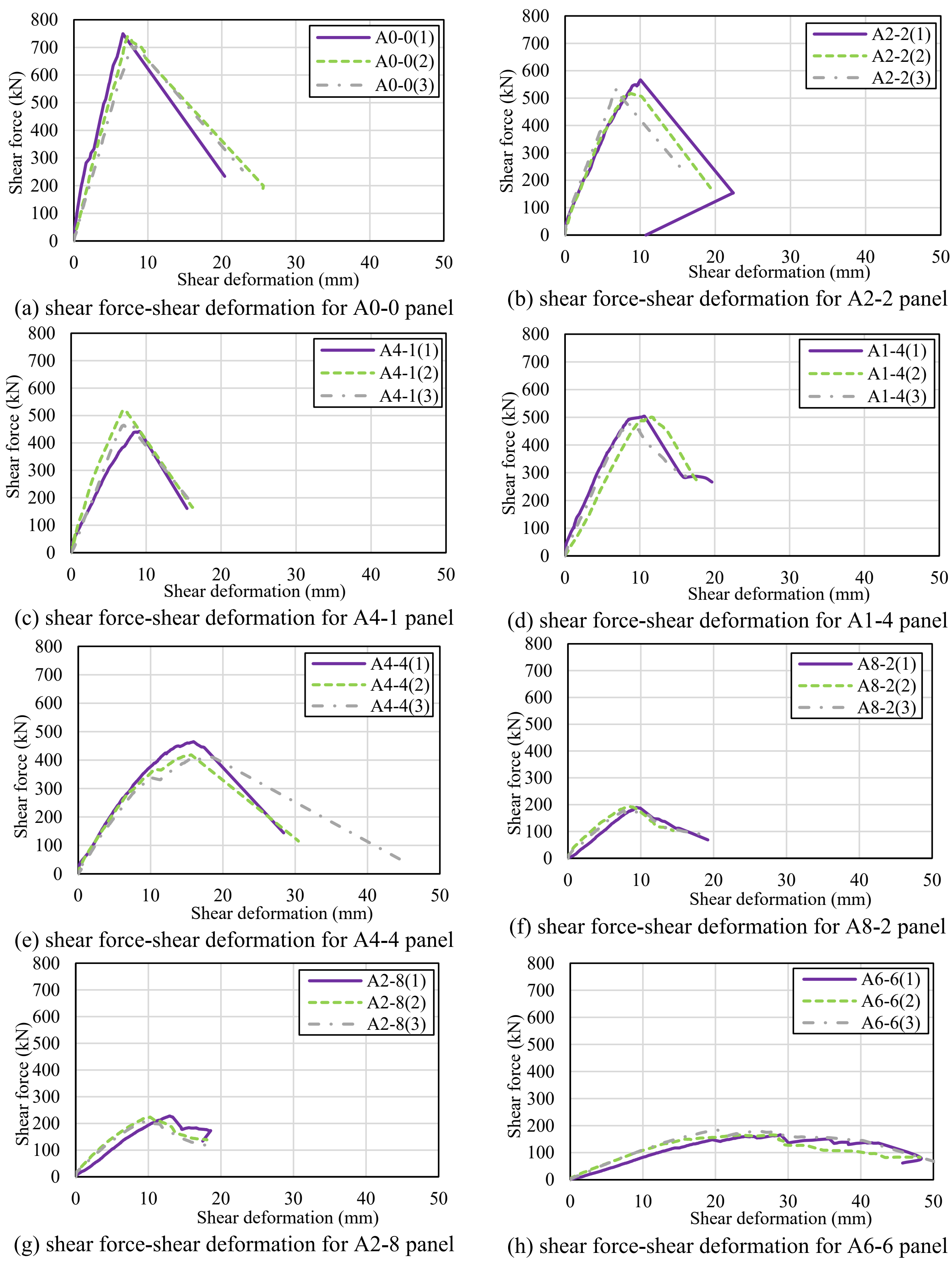


Fig. 7. Shear force-shear deformation curves for all the replicates of all the specimen types.

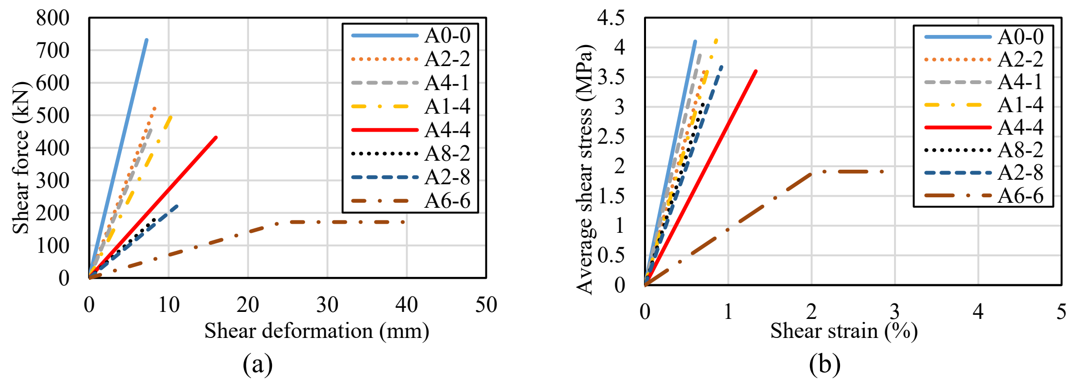


Fig. 8. (a) Shear force-shear deformation curves of the tested panels (average values of three replicates); (b) average shear stress-shear strain of all the tested panels (average values of three replicates).

3.2. *Force deformation response*

Shear force-shear deformation curves for all the tested CLT panels in the three tested replicates are illustrated in Fig. 7a to h. It can be observed that except panel A6-6, all panels experienced a sudden loss of load-carrying capacity after the maximum load-carrying capacity was reached. The average values of the results from the three replicates for each panel were calculated. Based on that, shear force-shear deformation and average shear stress-shear strain curves were drawn as shown in Fig. 8a and b, respectively. Also, the average maximum force, average shear stress, stiffness, the deformation at the ultimate load, and failure direction for all panels are summarised in Table 3. For CLT panel A0-0 (no opening) the average maximum force reached was 731.6 kN, and the average shear modulus (G) was found to be 711 MPa. Also, the average maximum shear stress for this solid panel (τ_{max}) was 4.1 MPa. τ_{max} is the value corresponding to the maximum load observed and was calculated as given in Eq. (4) as average shear stress for the CLT panel. Shear major and minor directions for the panels were defined in Section 2.2. With the exception of panel A1-4, the average shear stress for all the specimens with openings was lower than that for the solid panel (A0-0). Panel A6-6 sustained about half the average shear stress compared to the solid panel (1.84 MPa), since, as noted previously, panel A6-6 had a relatively ductile failure.

3.3. *Stiffness and strength reduction*

The effect of the area of opening on the reduction in strength and stiffness for CLT walls with openings with the same aspect ratio is shown

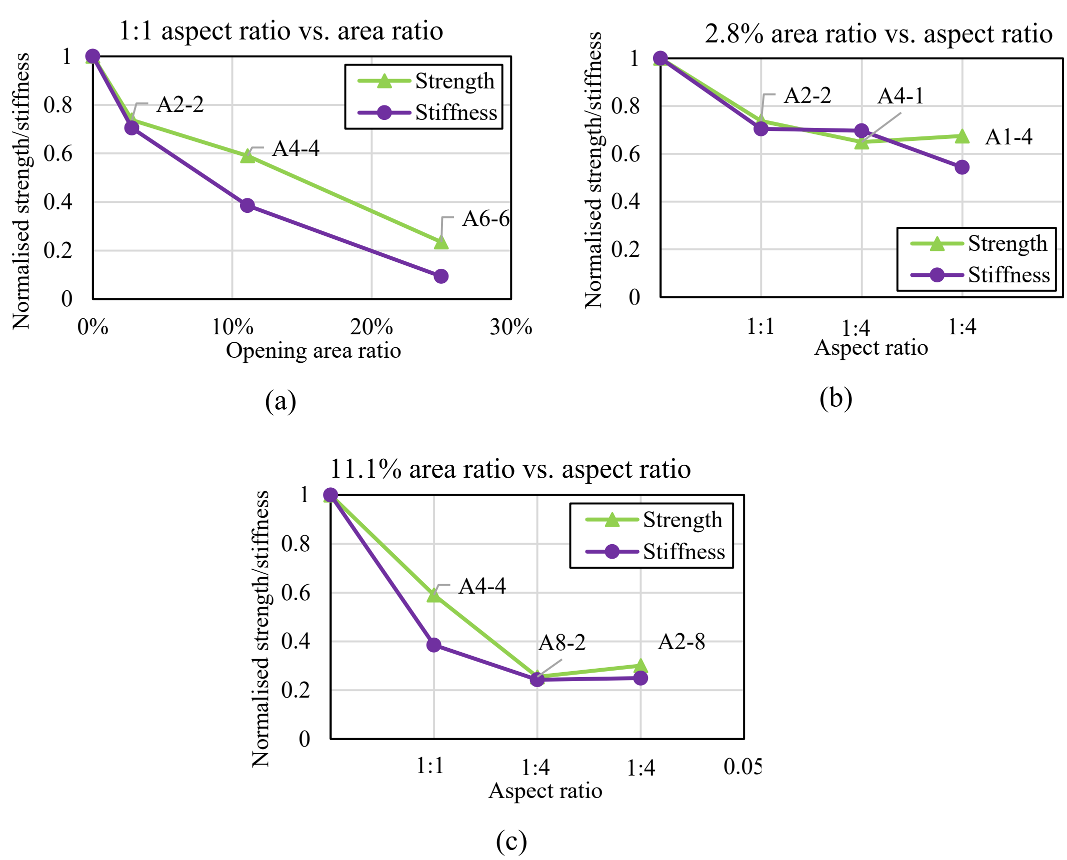


Fig. 9. (a) Reduction for walls with openings with 1:1 aspect ratio; (b) reduction for walls with openings with 2.8% area ratio; (c) reduction for walls with openings with 11.1% area ratio.

Table 4
Experimental reduction vs. Guidebook reduction for A2-2 panel.

	Experiment reduction	Guidebook reduction [10]
Stiffness	0.70	0.79
Strength	0.73	0.79

in Fig. 9a. It can be observed that the reduction in stiffness is larger than the reduction in strength for all the walls. Furthermore, the reduction between A2-2 panel with 2.8% area ratio (opening area to wall area) and A4-4 panel with 11.1% area ratio was 20%, while the reduction between A4-4 panel and A6-6 panel with 25% area ratio was three times more with 60% reduction. The effect of the aspect ratio of the opening on the reduction in strength and stiffness for CLT walls with openings with the same opening area ratio of 2.8% and 11.1% is illustrated in Fig. 9b and c, respectively. It can be seen that the reduction between A4-4 panel with a 1:1 opening aspect ratio and A8-2 panel with a 1:4 opening aspect ratio was 59%. Therefore, the longest direction of opening has more influence on the reduction than the area ratio of opening. Also, the orientation of the longest dimension of the opening (with respect to the CLT minor or major shear direction) has an effect on the reduction of strength and stiffness. The maximum strength of the A8-2 panel (opening's longest dimension is in the shear minor direction) was 19% less than the A2-8 panel (opening's longest dimension is in the shear major direction). However, for panels with relatively small openings (2.8 % openings area ratio), the reduction in strength and stiffness for all the CLT panels were relatively close regardless of the opening's aspect ratio.

As mentioned in Section 2.1, all the tested CLT panels except for A2-2 panel are outside the scope of the Japanese CLT Guidebook for a structural element due to its strict limitations. However, even A2-2 that have an opening size compliant with the Japanese CLT Guidebook [10] regulations (2.8% opening to wall area ratio) had an experimental stiffness reduction less than the one described in the guidebook by 11%, and an experimental strength reduction less than the one described in the guidebook by 6.5%. A comparison between the experimental reduction and the reduction factors calculated using the Japanese CLT Guidebook [10], which was mentioned previously in Eq. (1), for the strength and stiffness of A2-2 panel is shown in Table 4.

4. Conclusion

Diagonal compression tests on three replicates of eight CLT panels (24 panels in total) with and without openings were conducted to evaluate the shear strength and shear stiffness reduction in CLT walls based on the size and shape of the openings. This paper focused on symmetrical openings in the middle of the CLT walls with no eccentricity. Relationships between the experimentally observed shear stiffness/strength reduction and various characteristics of the opening were presented. The main findings of this study are as follows:

- Experimental results showed that the probable failure direction for CLT walls with openings would be the direction of opening that is closer to the edge of the CLT panel in the case of the rectangular openings, regardless of the direction of minor shear direction. However, panels with rectangular openings with different orientations relative to the minor shear direction had relatively different strength and stiffness reduction.
- In the case of CLT panels with square openings, the failure plane direction is the shear minor direction of the CLT wall, which is the direction along the fiber direction in the CLT external layer.
- Except for A6-6 panel (the panel with 25% opening to wall area ratio), all the tested panels experienced shear failure with a sudden loss of the load-carrying capacity. A6-6 panel showed ductile behaviour with flexural failure characteristics.
- The effect of the aspect ratio of the opening was found to be almost negligible in the case of panels with 2.8% opening to wall area ratio, whereas panels with 11.1% opening to wall area ratio showed great effect for the aspect ratio of opening.
- The reduction in stiffness for CLT walls with openings is greater than that in strength (with an average ratio between stiffness reduction and strength reduction of 80.9%).

The presented study clarified the influence of openings on the shear strength and stiffness of CLT panels. The study focuses on the effect of openings on the strength and stiffness of CLT walls, excluding the effect of the steel connections. The actual reduction will be affected by the type of the connections used in the CLT panel; however, this effect is related to the size of the opening (i.e., as the opening gets larger, the failure will be more likely in the panel itself, and thus the effect of connections will be less dominant). Future research work to incorporate the effect of the steel connections into the reduction due to the opening experimentally and analytically is needed.

It should be noted that the scope of this study is within certain limits of type of CLT (Japanese Cedar), the thickness of 150 mm, and the size of the panel of 1200 m × 1200 m. Further research is needed to investigate the effect of openings on larger CLT shear walls. It also should be noted that the findings of this study are based on the results of walls with openings in the center. Other parameters such as eccentricity of the opening, door openings as well as multiple openings might influence the results and need further investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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