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INFLUENCE OF OPENINGS ON THE SHEAR STRENGTH AND STIFFNESS OF CROSS LAMINATED TIMBER (CLT) PANELS

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Abstract

In the last decade, cross laminated timber (CLT) has been receiving increasing attention as a promising construction material for multi-storey structures in areas of high seismicity. In Japan, application of CLT in building construction is still relatively new; however, there is increasing interest in CLT from researchers as well as construction companies. Furthermore, the Japanese government is providing construction cost subsidies for new CLT structures as it is a carbon neutral and sustainable material. The high shear and compressive strength of CLT makes it a good candidate for use as shear walls in mid-rise buildings. One important aspect of CLT walls, and one that is presently poorly understood, is the influence of openings on the shear carrying capacity. Openings are often necessary in CLT panels either in form of windows, doors, lift shaft openings or installation of building services. Concerning this aspect, the code regulations in Japan are relatively strict, such that if openings exceeded certain prescribed limits, the entire CLT panel is considered as a non-structural element, and its contribution to lateral strength is totally ignored. Furthermore, as the maximum opening size is usually governed by edge distance constraints, the size of openings that designers can use is inevitably limited by the standard sizes supplied by the manufacturers. As a result, designers are obligated to adopt very small opening size. This is thought to be a very conservative approach. The main purpose of this paper is to experimentally evaluate the influence of openings on seismic capacity; strength and stiffness reduction, as well as failure mode with changing opening size and opening aspect ratio. In addition, check the validity of the Japanese code regulations with regards to openings in CLT panels.

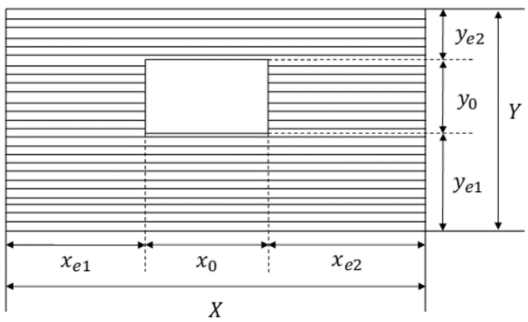
In this study, six 5-layer CLT panels containing different openings were tested. The parameters considered include the size and layout of the opening. The panels were specifically designed with openings that would render them ineffective in resisting lateral loads according to the Japanese standard. However, in addition to the six panels, one panel without openings and one panel with openings that meet the Japanese standard was designed. All the CLT panels were tested in uniaxial diagonal compression in order to simulate pure shear loading. The CLT panels and the loading setup were designed such that the resulting failure mode will be governed by a shear mechanism. The main focus of the experiment was to relate the deterioration of the lateral strength and stiffness of the panels to the size and layout of the opening.

The results showed that the panels with openings with the same area have relatively different failure direction and reduction factors for panel shear strength and stiffness, and that is due to the shear weak and strong direction that CLT panels have. Also, the effect of openings on the reduction of stiffness for CLT panels was found to be greater than their effect on the reduction of shear strength. The prescribed equation in the Japanese CLT Guidebook underpredicts stiffness reduction, and has discrepancies with regard to strength as the difference of panel strengths in weak and strong directions are not considered.

Keywords: Cross laminated timber; diagonal compression test; openings; lateral strength; in-plane shear stiffness.

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 on all sides ability which makes it a potential replacement for concrete, masonry or steel in some mid-rise and high-rise building. In Japan, the use of CLT as a building material is recent compared to Europe; however, the CLT industry in Japan is growing and gaining more attention due to the fact that CLT is a natural and carbon storage product, takes less construction time compared to reinforced concrete buildings (due to prefabrication of components) and produces little waste during the assembly process. CLT panels have a relatively high shear strength and are therefore becoming a good alternative for use as shear walls in timber structures to maximise shear resistance of the structure. Openings in CLT shear walls are very common either as windows or doors or as openings for installation of building services. However, the effect of these openings on shear strength and stiffness of CLT shear walls are still not well understood. Fig. 1 indicates the limitations of opening size in structural CLT elements as described in the Japanese CLT Guidebook [1]. These regulations are relatively strict and if the opening dimensions exceeded these described limits the entire wall must be considered as a non-structural component.



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 Japanese CLT Guidelines [1].

One way of testing CLT shear walls to get their shear strength and stiffness is by using cantilevered walls configuration, where steel connections are provided at the base. Several researches have used this testing configuration to conduct experimental and analytical studies to evaluate the influence of openings on the strength and stiffness of CLT walls [2-4]. In all of these studies, CLT walls had base-to-wall connections that influenced the maximum strength and stiffness of these walls. Thus, the effect of openings on the strength and stiffness characteristics of only the CLT panels (without other influences of connections) cannot be obtained from these tests.

An alternative method to testing cantilevered walls to assess CLT performance is to perform a component diagonal compression test. Using this test configuration, shear load can be induced in the CLT walls without the need for base-to-wall connections. Several researches have performed this test on CLT panels with a primary objective of determining the CLT shear modulus (G) [2,5-8]. None of these previous diagonal compression tests have considered the effect of openings on the CLT panel performance.

In the Japanese CLT Guidebook [1], Eq. (1-4) are used to calculate a single reduction factor to reduce both the shear strength and stiffness of CLT shear walls with openings. The use of this equation is limited to the opening dimensions shown in Fig. 1. Otherwise, the CLT walls with opening is considered non-structural.

$$R_0 = \frac{\gamma}{8 - 7\gamma} \tag{1}$$

Where, R_0 is the reduction factor, and γ is the opening coefficient and it is calculated as in Eq. (2-4):

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$$\gamma = \frac{1}{1 + {}^{\alpha}/_{\beta}} \tag{2}$$

$$\alpha = \frac{x_0 \cdot y_0}{X \cdot Y} \tag{3}$$

$$\beta = \frac{y_{e1} + y_{e2}}{Y} \tag{4}$$

Where x_0, y_0, y_{e1}, y_{e2}, X and Y are as defined in Fig. 1.

Okabe et al. [9] and Araki et al. [10] tested several CLT shear walls with openings of different sizes in a cantilever wall configuration. The base-to-wall connections used in these tests were strong enough to ensure the failure in the CLT panels. In both of these studies the reference CLT walls without opening did not fail due to insufficient loading jack capacity. As a result, and in order to calculate the estimated maximum strength of the panel without opening, a shear stress capacity of 2.7 MPa in the weak direction was assumed (as provided in the Japanese CLT Guidebook [1]). Fig. 2.a and Fig. 2.b give a comparison between maximum strength and initial stiffness reduction factors obtained from [1] and experimental reduction factors from [9] and [10], respectively. The results from these two studies were compatible with the values calculated from the Japanese CLT guidebook [1] for both strength and stiffness. However, because the strength of the CLT panels without an opening was assumed based on the CLT Guidebook, the strength reduction evaluation may not be valid. In addition, in these tests base-to-wall connections were also used which will affect the overall stiffness of the CLT shear wall.

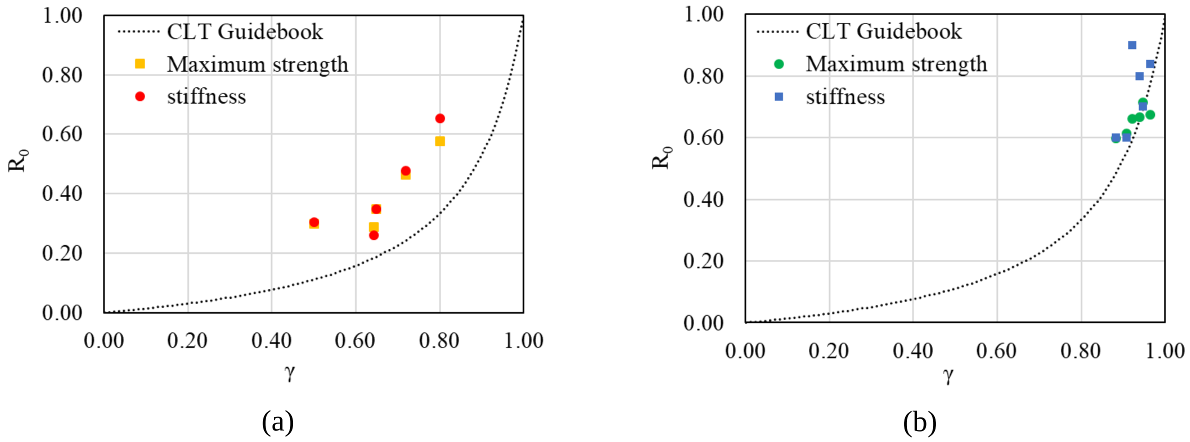

Fig. 2 – Comparison between code reduction factor and (a) [9] reduction factor; (b) [10] reduction factor.

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

2. Experimental program

2.1 Test matrix

In this experimental program eight 1200 mm by 1200 mm CLT panels shown in Table 1 were tested using the diagonal compression test configuration shown in Fig. 3.b. 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 1. One panel was a solid panel without openings while the rest of the panels had openings with different sizes and layouts. Only one of these configurations (A2-2) is considered a structural element according to the Japanese CLT Guidebook regulations [1]. It was assumed that the panel's 'strong' shear strength direction is the direction in which three of the wood layers are perpendicularly oriented (horizontal direction in Table 1), and the panel's 'weak' shear direction is

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the direction in which two wood layers are perpendicularly oriented (vertical direction in Table 1), as shown in Fig. 3.a.

2.2 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 Young's modulus of one board in the strong direction (6 GPa). The CLT density was 400 kg/m^3 and moisture was around 14.9%. Table 2 shows compression, bearing and shear strength of the CLT as obtained from material test.

2.3 Loading set-up

The loading frame, jack, steel shoes and CLT panel are shown in Fig. 3.b and 3.c Each panel was installed vertically between two steel 'shoe' caps, which were designed to distributed the load such that failure of the CLT panel in bearing did not occur. A single 2000 kN jack was used to apply a monotonic vertical downwards force on the CLT panel through the upper steel shoe. No out-of-plane restraints was used; however, the out of plane rotation of the jack was monitored to ensure that no out-of-plane deformation occurred.

Table 1 – Test matrix of the CLT panels.

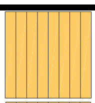
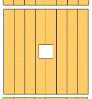
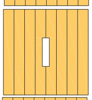
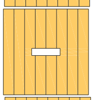
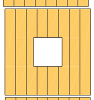
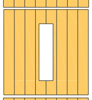
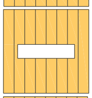
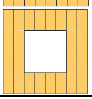
Wall	name	L (mm)	H (mm)	l_o (mm)	h_o (mm)	Opening area ratio
	A0-0	1200	1200	-	-	-
	A2-2	1200	1200	200	200	2.8%
	A4-1	1200	1200	100	400	2.8%
	A1-4	1200	1200	400	100	2.8%
	A4-4	1200	1200	400	400	11.1%
	A8-2	1200	1200	200	800	11.1%
	A2-8	1200	1200	800	200	11.1%
	A6-6	1200	1200	600	600	25%

Table 2 – Results of CLT material test.

Test	Loading direction	Strength (MPa)
Compression	Strong	19.6
	Weak	15.1
Bearing	Strong	23.8
	Weak	19.2
Shear	Strong	5.02
	Weak	4.71

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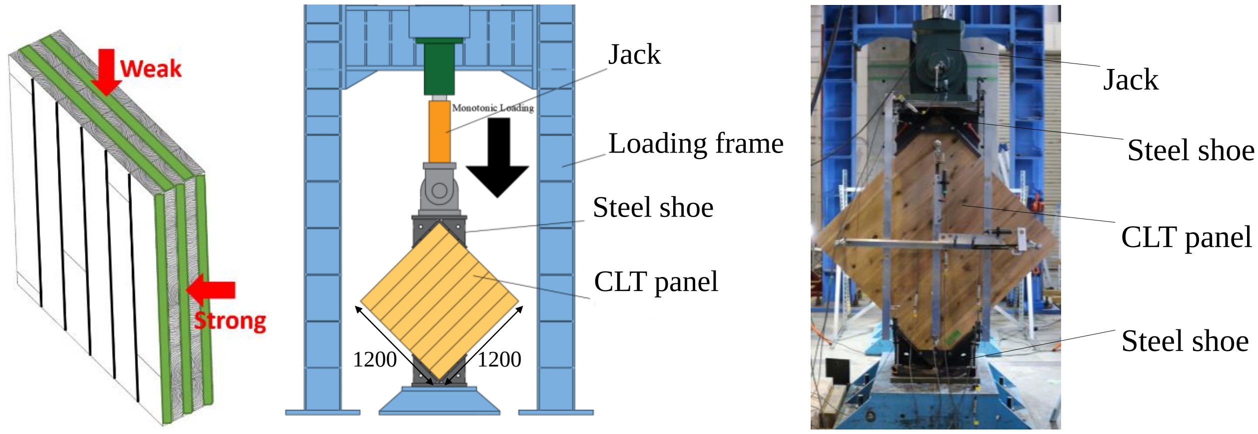
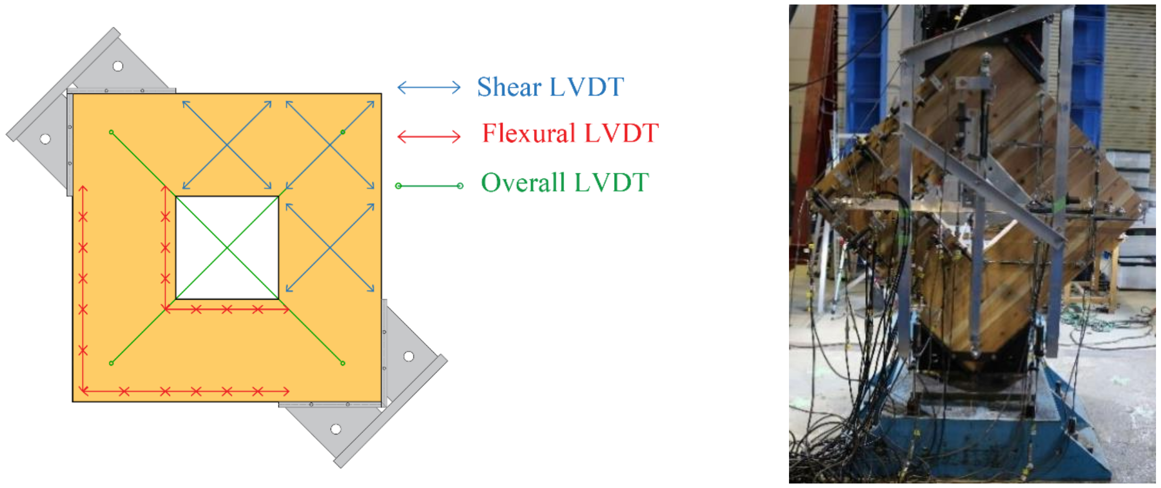


(a) (b) (c)

Fig. 3 – (a) Shear strong and weak direction; (b) loading set up details; (c) photo of the loading set up.

2.4 Instrumentation

A typical instrumentation layout for the panels with openings is shown in Fig. 4. For all the CLT panels with openings, the response of the panel related to a combination of internal shear and flexural deformation 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. Furthermore, another two LVDTs was set diagonally to capture the overall deformation of the panel along the two diagonal direction. Positions of LVDTs for each CLT panel slightly changed based on opening size. The panel with no openings has only two overall diagonal LVDTs. The CLT panel zones immediately below/above the loading shoes was assumed rigid and so no measurements were made in this area.



(a) (b)

Fig. 4 – (a) LVDT set up details for A4-4 panel; (b) photo of A4-4 panel with LVDTs set up.

The shear strain angle was calculated by Eq. (5) with reference to Fig. 5.a, using measurements of the overall diagonal LVDTs (Fig. 4.a). Fig. 5.a illustrate the deformation of the area measured by overall LVDTs. The shear stress deformation is assumed to be uniform, hence shear stress of each panel was calculated using Eq. (6) with reference to Fig. 5.b. Finally, shear modulus and stiffness of each CLT panel was determined based on the standard EN 408 [11] by means of a regression analysis on the linear part of the stress-strain curve between the values that are corresponding to 0.1 and $0.4F_{max}$.

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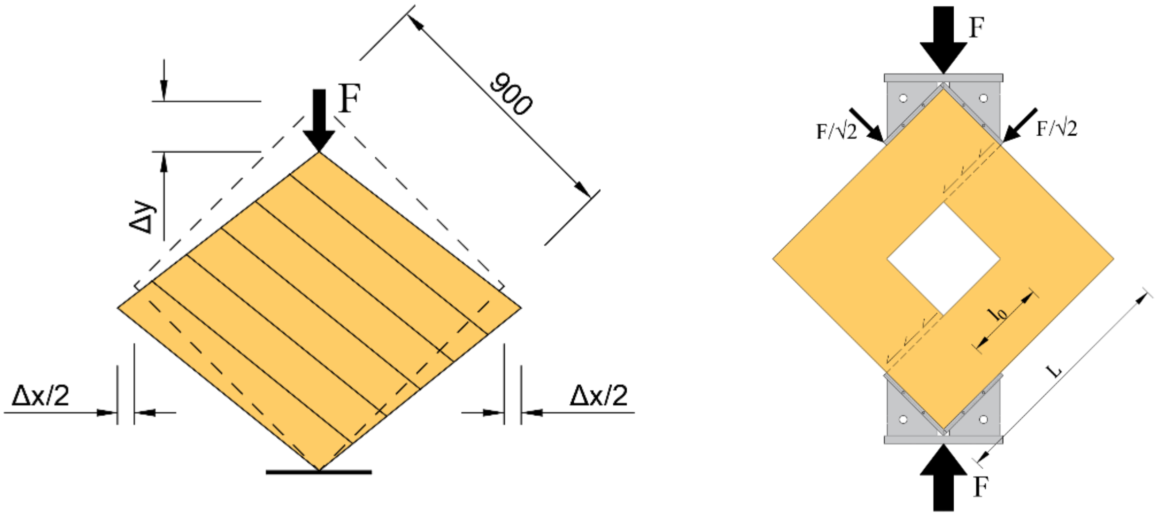
$$\gamma = \frac{\Delta x + \Delta y}{900 \times \sqrt{2}} \tag{5}$$

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

$$\tau = \frac{F}{\sqrt{2} \cdot (L - l_o) \cdot t} \tag{6}$$

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.



(a) (b)

Fig. 5 – (a) Deformation of measured section by overall LVDTs; (b) shear stress distribution for CLT panel.

3. Results

3.1 Damage and failure characteristics

The specimens were not approached during loading, but from distance no visible cracks were observed for panels A0-0 to A4-4; however, some minor cracking sounds was heard throughout the loading. For panels A8-2 and A2-8 some cracking sounds was heard during loading and visible cracks were observed from a distance. The cracks seen on the outer layer of CLT panel were parallel to the failure plane in case of A8-2 panel and perpendicular to the failure plane in case of A2-8 panel. For panel A6-6 a lot of cracking sounds were heard and cracks was observed. A brittle shear failure mechanisms was observed for all the CLT panels with the exception of panel A6-6.

The cracks observed on the surface layer for all the tested CLT panels are illustrated in Fig. 6. The red line indicates the path of the observed cracks after failure; yellow lines indicates the failure direction in the panel strong direction (panels A1-4 and A2-8). In all the tested panels with openings, except A4-4 panel (shown in Fig. 6.e), the failure plane was from corner to corner of the opening. For all the specimens, all the observed cracks on the outer layer of 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 weak direction (i.e., parallel to grain for three wood layers and perpendicular to 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 A2-8 panels), second and fourth layer failed by shear parallel to the grain and on the outer layer many cracks parallel to grain was observed as shown in Fig. 6.d and Fig. 6.g.

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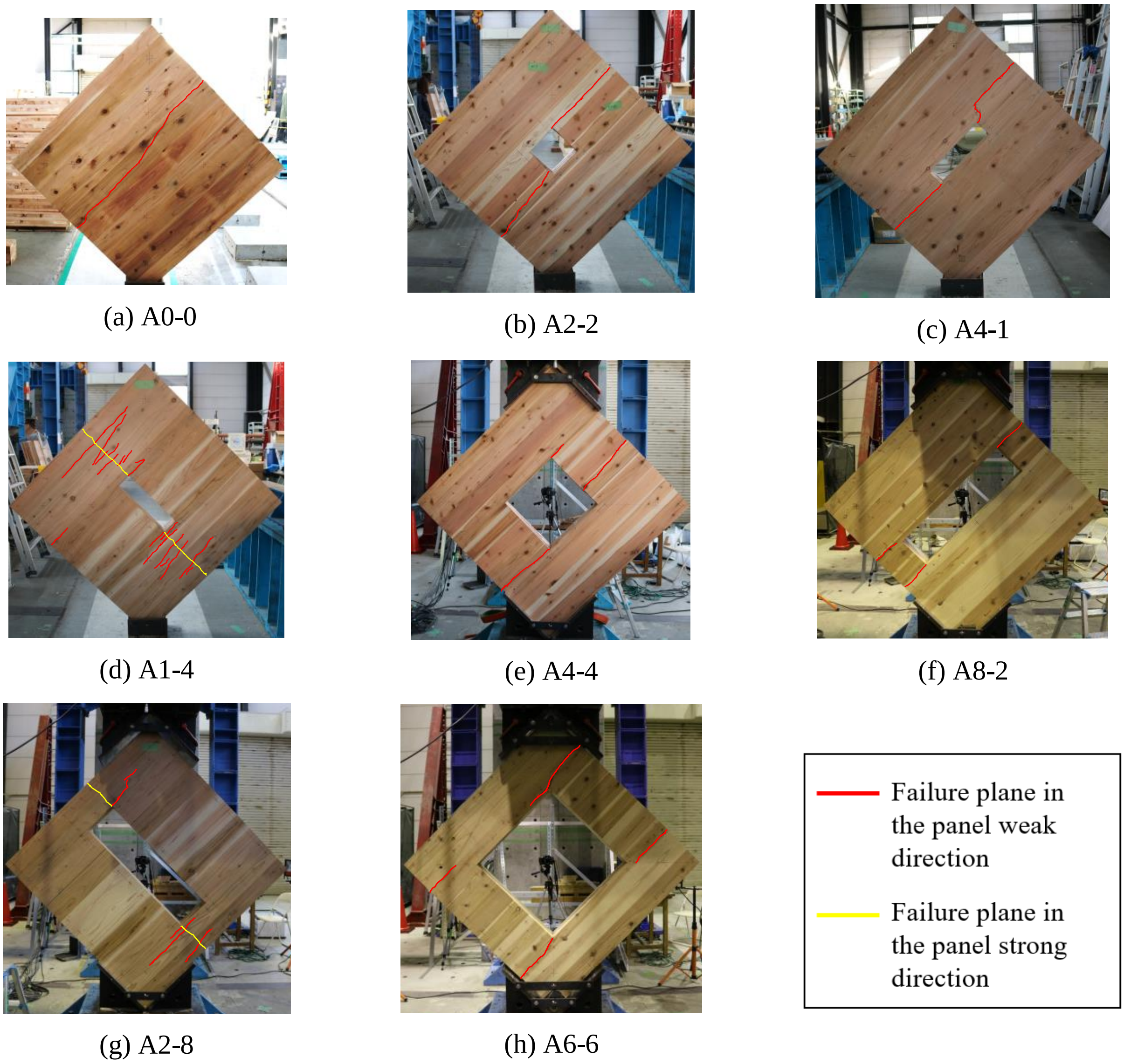

Fig. 6 – Cracks observed on the surface layer for all the tested CLT panels (red line); yellow line indicates the failure plane in the panel strong direction (panels A1-4 and A2-8).

3.2 Force deformation response

Force-shear deformation curves and stress-strain curves for all the tested CLT panels are illustrated in Fig. 7.a and 7.b, respectively. It can be observed that except panel A6-6, all panels experienced sudden loss of load carrying capacity after the maximum load carrying capacity was reached. For CLT panel A0-0 (no opening) the maximum force reached was 1060 kN, and the shear modulus (G) was found to be 795 MPa, Also the maximum shear stress for this solid panel (τ_{max}) was 4.2 MPa. τ_{max} is the value corresponding to the maximum load observed and was calculated as given in Eq. (6). The maximum forces, shear stress, stiffness, ultimate deformation (corresponding to maximum force) and failure direction for all panels are summarised in Table 3. Strong and weak directions for the panels were defined in section 2.1. With the exception of panel A1-4, the maximum shear stress for all the specimens with opening was lower than that for the solid panel (A0-0). Panel A6-6 sustained about half the shear stress compared to the solid panel (1.84 MPa), because the failure mode was not pure shear. For all the other specimens the range of the shear stress was between 92% and 75% of the shear stress for the solid panel.

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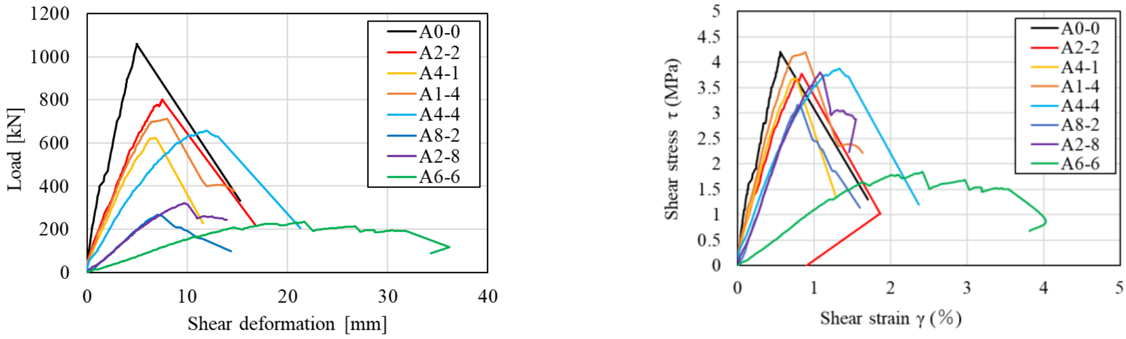

(a) (b)

Fig. 7 – (a) Load-shear deformation curves for all panels; (b) shear stress-strain curves for all the panels.

Table 3 – Key values and information about tested panels.

Panel name	Maximum force (kN)	Shear stress (MPa)	Stiffness (kN/mm)	Ultimate deformation (mm)	Failure direction
A0-0	1060	4.2	218.4	4.97	Weak
A2-2	801	3.78	114.6	7.51	Weak
A4-1	625	3.68	101.1	6.84	Weak
A1-4	712	4.2	111.5	7.98	Strong
A4-4	657	3.87	74.1	11.97	Weak
A8-2	268	3.16	41.5	7.04	Weak
A2-8	322	3.8	38.6	9.7	Strong
A6-6	234	1.84	15.6	21.74	-

3.3 CLT shear strength and stiffness reduction due to opening

The effect of area of opening on the reduction in strength and stiffness for CLT walls with openings with the same aspect ratio is shown in Fig. 8.a. 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 and A4-4 panel with 11.1% area ratio was 18%, while the reduction between A4-4 panel and A6-6 panel with 25% area ratio was three and half times more with 64% reduction. The effect of aspect ratio of the opening on the reduction in strength and stiffness for CLT walls with openings with the same opening area ratio of 11.1% is illustrated in Fig. 8.b. It can be seen that the reduction between A4-4 panel with 1:1 opening aspect ratio and A8-2 panel with 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 weak or strong 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 weak direction) was 17% less than the A2-8 panel (opening's longest dimension is in the shear strong direction) Internal deformation components for panels with different square openings of different area ratio are shown in Fig. 8.c. It can be seen that flexural deformations increase as the opening area ratio increases. For walls with small area openings the shear deformation is dominant while flexural deformation is dominant in specimen A6-6.

A comparison between the reduction factor calculated using the Japanese CLT Guidebook [1] and the experimental reduction factors for strength and stiffness for all the specimens is shown in Fig. 9. CLT panel A2-2 with an opening size that is compliant with the Japanese CLT Guidebook [1] for a structural wall (2.8% opening to wall area ratio) had an experimental reduction factor for strength less than the one described in the guidebook by 4%. However, for this panel the reduction in stiffness was around 35% higher than the value obtained from the CLT Guidebook. CLT panel A4-4 had an experimental reduction factor for strength bigger than that described in the CLT Guidebook by 45%. The CLT Guidebook estimates of strength reduction factor for A4-1 and A8-2 panels do not match the experimental values. This is partly because the CLT Guidebook

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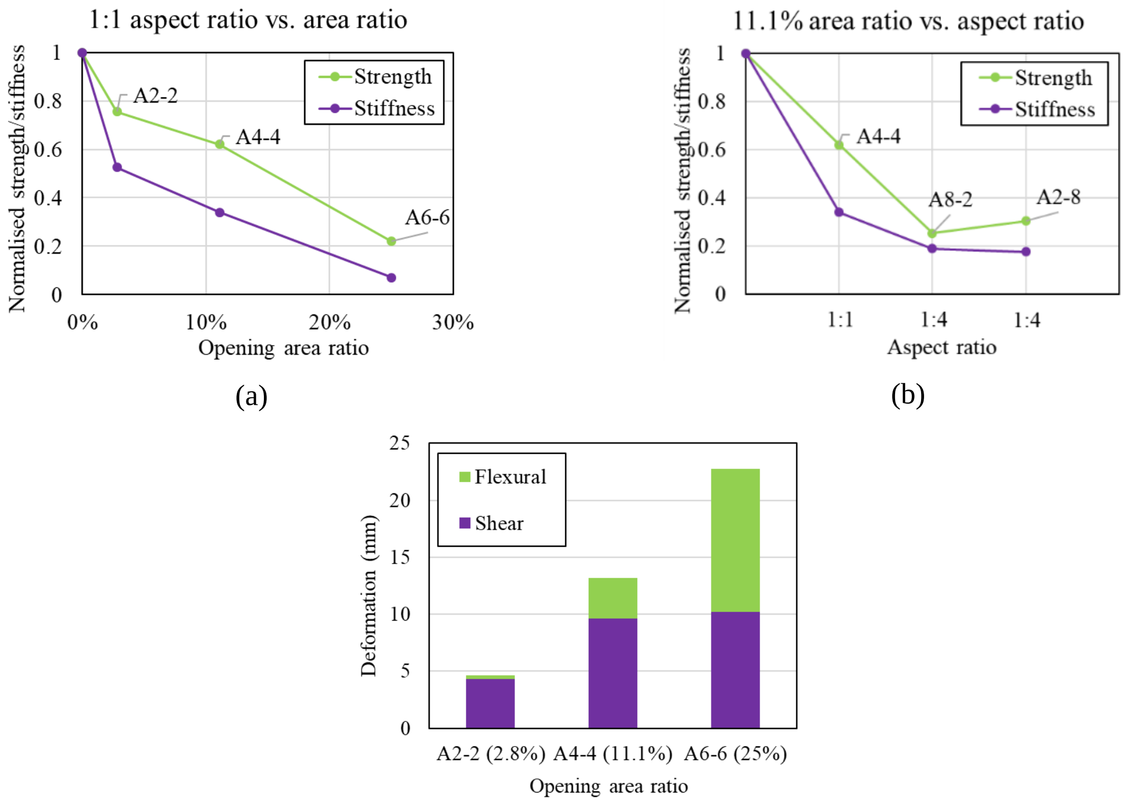
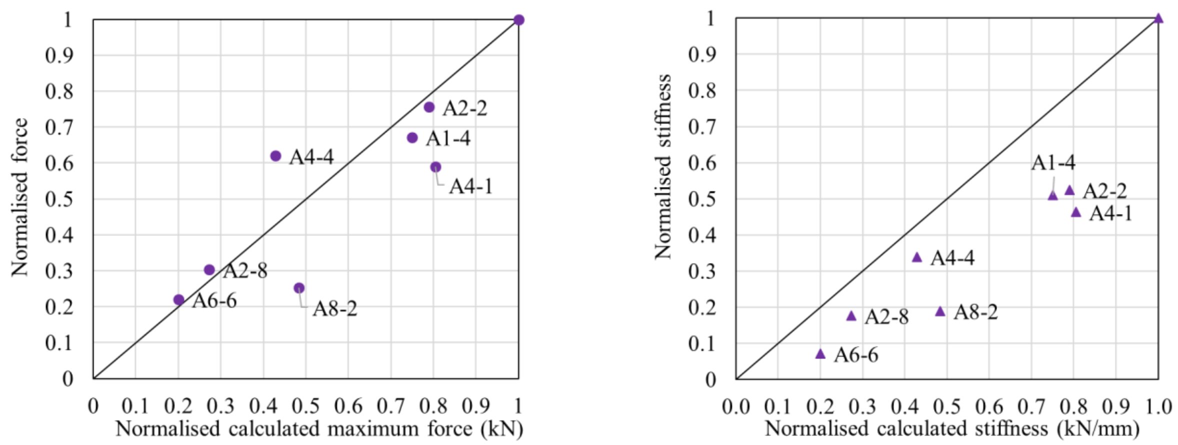
equation does not take the effect of the panel shear weak and strong direction into account. All the tested panels had a larger experimental reduction factor for stiffness than the reduction factor calculated by the CLT Guidebook. It is clear that the reduction equation described in the Japanese CLT Guidebook underestimates the reduction in stiffness compared to the experimental values by an average of 41% over the tested panels. This could lead to overestimation in the designed CLT structures stiffness and consequently lead to more flexible structures than intended.



(c)

Fig. 8 – (a) Reduction for walls with openings with 1:1 aspect ratio; (b) Reduction for walls with openings with 11.1% area ratio; (c) internal deformation vs. opening area ratio.



(a) Strength (b) Stiffness

Fig. 9 – CLT Guidebook calculated reduction factors vs. experimental reduction factors for (a) strength and (b) stiffness.

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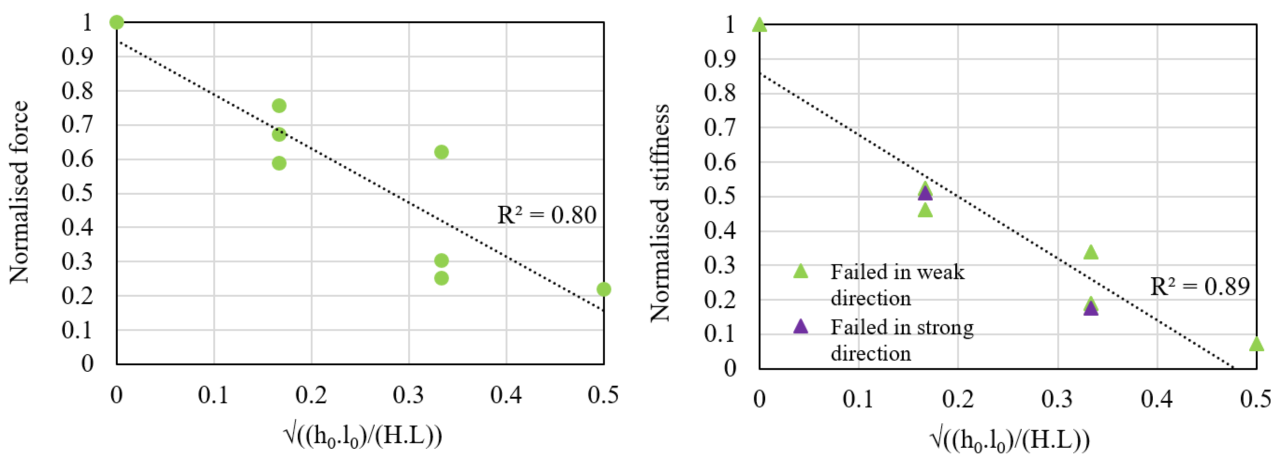
3.4 Relationship of opening characteristics and strength/stiffness reduction factors

In the pursuit of understanding the key parameters that affects the reduction in strength for CLT walls with openings, some of the basic parameters were investigated. Opening area to wall area ratio is an important parameter as it accounts for the loss of the area that deforms. Therefore, this parameter is more relevant for stiffness reduction than for strength reduction. In Fig. 10, the area ratio parameter shows good correlation for both stiffness and strength reduction (R^2 = 0.80 – 0.89), with a slightly better correlation with stiffness. On the other hand, length ratio of opening is an important factor for strength reduction as it directly reduces the material of the panel that resist the shear force in the failure plane. The CLT walls always fail in the direction of the longest dimension of the opening; hence, to calculate the length ratio of opening the maximum of l_0/L and h_0/H is taken. The effect of length ratio of opening is related more to the strength reduction (R^2 = 0.90) than stiffness (R^2 = 0.80) as can be seen in Fig. 11.

It is important note that the solid panel failed in the weak direction, while this is not the case for all the panels with openings (panels A1-4 and A2-8 failed in strong direction). In order to evaluate the suitability of the reduction factor with respect to l_0/L or h_0/H parameters, it is necessary to make comparisons between walls with the same failure mode. Since the solid wall in this study (A0-0) failed in the weak direction, the solid panel shear strength in the strong direction was determined based on the ratio of the strong and weak direction shear stress determined from material tests as f_s/f_w = 1.06. Correcting the strength reduction factors of panels A1-4 and A2-8 based on this assumed 'solid' wall strength, the correlation between the parameter max $(l_0/L, h_0/H)$ and the strength reduction factor are shown in Fig. 12. Based on this correction the max $(l_0/L, h_0/H)$ showed better correlation with strength reduction than the correlation before the correction Fig. 11.a. These results demonstrate the importance of having an *a priori* understanding of the expected failure mode of the wall to use the reduction factors correctly. It should be noted that the strength reduction calculated for specimen A6-6 that had a ductile failure is not compatible with the other reduction factors. That is because the ductile failure mode for A6-6 is different from the shear failure for the solid panel A0-0. Since this correction is based on shear strength (f_s/f_w = 1.06), the stiffness reduction factors were not corrected using this assumption. However, the difference of the failure direction (in weak or strong direction of CLT panel) did not have a big effect on the stiffness of the CLT panels that have the same area ratio and the same aspect ratio as can be seen in Fig. 10.b.



(a) Strength (b) Stiffness

Fig. 10 – The square root of opening area to wall area ratio vs. experimental normalised (a) strength and (b) stiffness.

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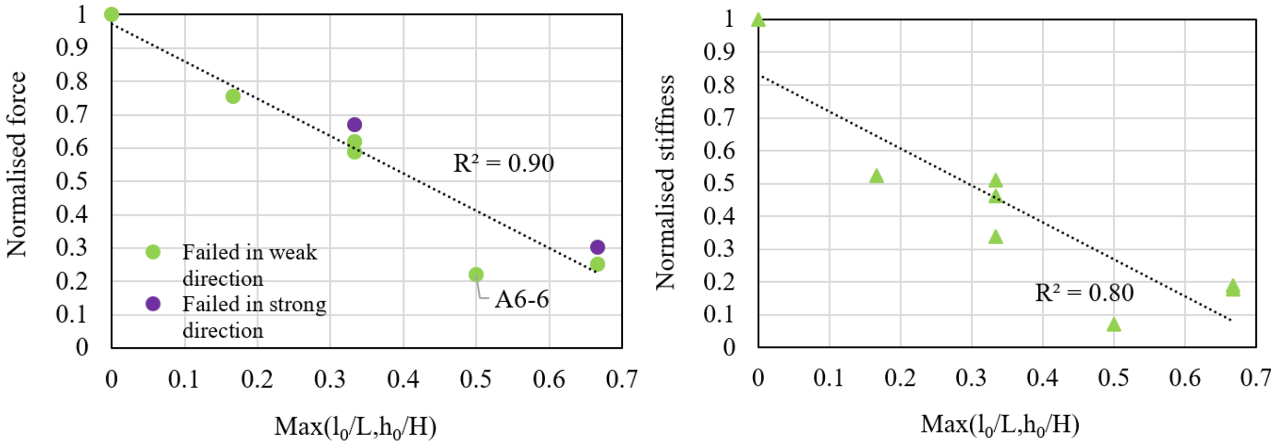

(a) Strength (b) Stiffness

Fig. 11 – Length ratio of opening vs. experimental reduction factor for (a) strength and (b) stiffness; based on the strength of solid panel in the weak direction only.

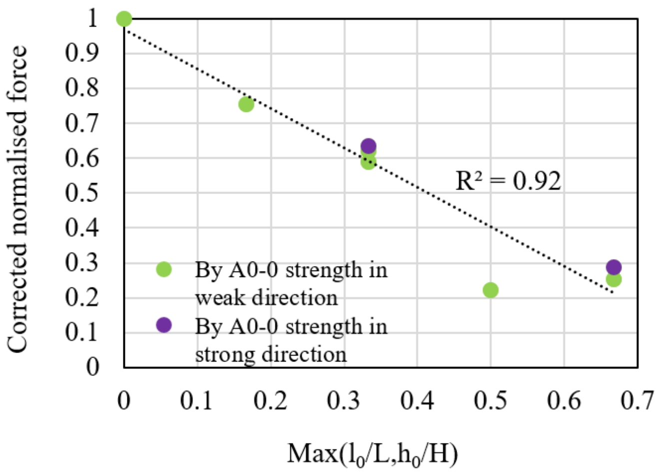

Fig. 12 – Length ratio of opening vs. corrected experimental reduction factor for strength based on the strength of the solid panel in weak and strong direction

4. Conclusion

Diagonal compression tests on eight CLT panels 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 with various characteristics of the opening were explored. The main findings of this experimental study are as follow:

- The probable failure direction for CLT walls with openings is the direction of the longest dimension of the opening in case of rectangular opening and the weak direction of the CLT wall in case of square opening
- Flexural deformation component increases as the opening size increases.
- 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 63%).

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- For walls with openings with the same area the aspect ratio of the opening affected the strength reduction factor, indicating that strength of the panel with openings is first governed by opening shape, then the opening orientation with respect to the shear strong/weak panel directions and then by opening area.
- The Japanese CLT Guidebook reduction factors underpredict the stiffness reduction due to openings. The strength reduction factor requires prior knowledge of the panel failure direction (along weak or along strong direction).
- The reduction factor for shear stiffness and shear strength of CLT panels with openings is not the same, unlike what is implied by the CLT Guideline.
- By correcting the strength reduction for CLT panels with openings that failed in the strong direction (by assuming the strength of a 'solid' wall in the strong direction) the strength reduction showed better correlation with max$(l_0/L, h_0/H)$ parameter.

For future work, more consideration on the effect of shear weak and strong direction for CLT panel is required in order to understand the effect of openings on the strength of the panel. In addition, further investigation on the effect of openings on the stiffness of the CLT panel is needed in order to estimate reduction factors accurately.

5. Acknowledgements

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