Shear Capacity of Cross-Laminated Wooden Walls

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Summary
The new structural systems consisted of solid cross-laminated wooden slabs are becoming more popular as effective technology for construction of prefabricated medium-rise buildings. Austrian company KLH Massivholz GmbH produces large-sized cross-laminated wooden slabs in different number of layers and thickness which are used for all construction and non-construction building elements. As special attention is paid to buildings located in earthquake prone areas comprehensive research was done at University of Ljubljana FGG to set appropriate guidelines for design horizontal stability of KLH system.

Shear walls are structural elements that are used to resist seismic and wind loads. In design of wood structures, the contribution of fenestrated wall segments usually is not taken into account when calculating the wall shear capacity. The load-bearing capacity and stiffness of fenestrated wood walls are influenced mostly by the size and layout of the openings. To evaluate the shear strength and stiffness reduction for different size and placement of openings in the wall, development of a mathematical model verified against experimental tests, is of paramount importance.

The main goals of the experimental research and parametric study presented in this paper are to provide information on how to estimate the racking strength and stiffness of cross-laminated solid wood walls with openings, and to recognize how the shape and the area of the openings influence the shear capacity and stiffness of cross-laminated wood walls. Results form the preformed parametric study are summarized in diagrams that could serve as a practical tool for estimating the influence of fenestration on the stiffness and load-bearing capacity of cross-laminated solid wood walls.

1. Introduction
Shear walls are structural elements that are frequently used to resist seismic and wind loads in timber structures. Currently, wood-frame buildings are designed for earthquake and wind loads by taking into account shear resistance of full wall segments only. Parts of wall above and bellow the openings are excluded from the calculation method (Fig.1). Although this approach may be valid for light-frame buildings, it can lead to under-estimation of shear resistance of a building with cross-laminated walls. For more accurate and economic design, parts of wall above and below the openings have to be taken into account as they transfer the loads between full wall segments and influence their boundary conditions [1]. Therefore entire wall assembly with different openings could be determined as one structural element of full length with reduced shear strength and stiffness [2]. To evaluate the shear strength and stiffness reduction for different fenestrations,
development of a verified and validated mathematical model is needed to reduce number of experimental tests. A series of racking tests on fenestrated cross-laminated (X-lam) solid wood panels were carried out at University of Ljubljana. The main objective of the testing was to understand the global response of fenestrated panels and to obtain data for verification and validation of response of the panel predicted by a numerical model [3]. The model was developed and the parametric study carried out using the commercial software SAP2000. Main parameters of interest were related to nonlinear behaviour of anchors and elastic behaviour of X-lam wall segments around openings and were determined through additional testing. The numerical model of experimentally tested panels was used for parametric study on panels with different patterns of fenestrations. The parametric study resulted in diagrams, which show the relation between panel area ratio and ratio of racking load and stiffness of fenestrated X-lam walls against non-fenestrated one. Study of fenestrated X-lam wood walls followed the concept of previous research on light-frame walls presented in Section 2.

2. Definition of fenestrated wall panel

As there are no published research results concerning behaviour of X-lam fenestrated panels, we followed published research results on fenestrated light-frame walls [4] [5] [6]. They defined the sheathing area ratio, \( r \) (eq.1), in order to classify walls based on the amount of openings in the wall (Fig.2). The sheathing area ratio was determined by: a) the ratio of the area of openings to the area of wall and b) the length of wall with full height sheathing to the total length of wall. Two empirical equations were put forward [4] [5], which make it possible to estimate the shear strength and stiffness of any fenestrated timber frame wall if shear characteristics of a fully-sheathed wall of the same size is known. The ratios between shear strength \( F \) and shear stiffness \( K \) of fenestrated light-frame wall and non-fenestrated one, as obtained from tests, are presented in Fig.16, respectively.

Using the same definition, the parameter \( r \) is proposed here to be named “panel area ratio” of fenestrated X-lam wooden wall (Fig.2). The proposed panel area ratio \( r \) takes into account both size and shape of openings. Regarding the size aspect, the value of \( r \) is inversely proportional to the opening area. Regarding the shape of the opening, a higher value of \( r \) is associated with vertically oriented fenestration. In the case of non-fenestrated wall the value of \( r \) is equal to 1.0.

Variables in equation 1 are as follows:

\[
r = \frac{1}{1 + \frac{\alpha}{\beta}} = \frac{H \sum L_i}{H \sum L_i + \sum A_i}
\]

\( r \) panel area ratio

\( H \) height of the wall element

\( L \) length of the wall element

\( \sum L_i \) length of full height wall segments

\( \sum A_i \) sum area of openings

\( \alpha = \frac{\sum A_i}{HL} \) ratio of openings in wall element

\( \beta = \frac{\sum L_i}{L} \) ratio of full wall segments.

Fig.2 Definition of panel area ratio

3. Experimental research on X-lam walls

3.1 Racking tests on X-lam walls with and without openings

Two configurations of walls of equal dimensions (320x272x9.4cm) represented by two specimens each have been tested under the same boundary conditions. Specimens of Wall 13 had a door and a window openings while the specimens of Wall 14 were without openings (Fig.3). The tests have
been preformed at the Laboratory of the Faculty of Civil and Geodetic Engineering in Ljubljana, Slovenia using the test set-up specially designed and constructed for testing of panels under different boundary conditions and constant vertical loading [1] [2].

The specimens were produced by the Austrian company KLH Massivholz GmbH as solid elements composed of three layers of cross glued laminated (X-lam) timber. Four BMF corner connectors with ribs with a height of 105mm were installed as shown in Fig.3. Corner connectors were placed 10cm from the edge of the wall and attached with ten 4.0/40mm nails with annular threads to the KLH plate and with two steel bolts M12 to reinforced concrete foundation.

A total of four cyclic tests were performed to obtain the hysteretic response of fenestrated and non-fenestrated X-lam walls (Fig.4 and Fig.5). EN 12512 standard was used for determination of the cyclic loading protocol. The hysteretic wall response showed two significant differences in stiffness and in thickness of the hysteretic loops. These differences were more visible in response of non-fenestrated wall relative to the fenestrated one. The first stage was characterized by more stiff response with tight hysteretic loops and represented shear wall response where mainly shear deformations of X-lam wood material occurred along with some initial contact slip between assembled elements. The vertical load prevented tension deformations of anchors. The second stage was characterized by lower stiffness and much wider hysteretic loops. Higher level of horizontal load caused tension forces in anchors and therefore uplift of the wall.
3.2 Accompanying tests for determination of mechanical properties of constituent elements

The response of the tested wood walls depends on the boundary conditions and the magnitude of vertical load and also on the configuration and mechanical properties of the constituent elements and the assembly as a whole. Therefore, some accompanying tests were done on constituent elements of the wall to obtain their mechanical properties, which were used in the model.

3.2.1 Mechanical properties of X-lam wall segments

The main load-bearing direction of 3-layer X-lam wooden plate is defined by direction of wood fibres in outer layers. Therefore the E-modulus in load-bearing direction was signed as \( E_{p,0} \), while E-modulus in the perpendicular direction was signed as \( E_{p,90} \). Moduli of elasticity in both orthogonal directions were determined using wall segments of 30x30x9.4cm in size. X-lam timber plate consisted of strips of spruce stacked on top of each other and glued together forming large-size solid X-lam plates. The thickness of the strips wall was 30mm in the main load-bearing direction and 34mm in perpendicular direction (Fig.7). E-moduli in plane of 3-layer X-lam timber plate were determined on three specimens for each orthogonal direction according to EN 789. Because two layers of wood strips were oriented in the main load-bearing direction with the cross section almost double that of the perpendicular one, the ratio of E-moduli in the orthogonal directions was expected to be of the same magnitude.

The mean value of E-modulus in load-bearing direction \( (E_{p,0}) \) was determined as a value of 898 kN/cm² and in the perpendicular direction \( (E_{p,90}) \) as a value of 443 kN/cm².

Shear modulus of 0.5 GPa was obtained by experimental tests on X-lam wall segments, where three specimens were loaded by compressive force in diagonal direction through rigid shoes with concrete pads of 150mm length (Fig.8). The average moisture content of wood specimens was 12±2%. Dimensions and mass of each specimen were measured prior to destructive testing. Determined mean density was 418 kg/m³ with standard deviation of 11 kg/m³.

3.2.2 Tension and shear behaviour of anchors

The main purpose of tension and shear tests of anchors was to determine the global response of this constituent part of the shear wall, which significantly influences its racking behaviour.
X-lam wall segments were attached to a steel plate using 105mm BMF corner connectors with ribs. The corner connector was fastened to the X-lam wall segment with 10 annularly threaded 4.0/40mm nails and with two M12 bolts to the steel plate.

Shear wall anchors are subject to a combination of tension and shear forces. Therefore the segments of X-lam wall were tested in two perpendicular directions. In the “up-lift tests” (Fig.9), tension load on anchor was applied, and in the “slide tests” (Fig.10), shear load was applied. Monotonic and cyclic tests were performed according to EN 26891 and EN 12512 standards, respectively. Total of four tests in each direction were carried out, one with monotonic and three with cyclic loading. From cyclic tests the envelopes of the hysteretic responses were obtained and basic mechanical characteristics were defined for use in the numerical model (Fig.11).

4. Numerical analysis

Prediction of racking behaviour of X-lam walls using the commercially available finite-element program SAP2000 is presented in this section. An attempt was made to develop as much as possible exact mathematical model of X-lam wall (Fig.11) taking into account realistic mechanical properties of all constituent elements. Experimental results of racking tests as presented above served for the model verification (Fig.6). The model is composed of orthotropic membrane elements and longitudinal sprigs which simulate anchors. Three cross-laminated glued layers of KLH walls were taken into account as homogeneous orthotropic material. Material characteristics for the membrane elements of thickness of 9.4cm have been defined according to the results of tests on wall segments. Contact between wall elements and RC foundation is represented by set of springs which are absolutely stiff in the direction of foundation and allow free movement away from foundation. Friction between foundation and wall element is modelled using bi-linear link elements placed in horizontal direction along the whole length of the lower edge of the panel. The value of friction coefficient between the rough concrete and X-lam wooden surface was estimated at 0.7. Springs are absolutely stiff until the shear flow in the contact zone does not attain the estimated friction force. After this, friction springs have constant load-bearing capacity and resist sliding of the panel in combination with the RC foundation.
with non-linear springs, which represent shear behaviour of the corner connectors as determined from tests (Fig.9 and 10). Experimentally obtained envelopes were incorporated in the model as multi linear springs. In the numerical model, vertical load of 15kN/m² was imposed on the top of the wall. Horizontal load was applied once in positive and once in negative direction as the response of the wooden panel is not equal in two different directions as a result of asymmetrical placement of the anchors and openings. Non-linear static pushover analysis using SAP2000 was executed and the obtained results were presented in a form of horizontal force-displacement diagram (Fig.12 and 13).

Fig.12: Comparison of experimental and calculated response of fenestrated wall with panel area ratio r of 0.41

Comparison of the calculated and experimentally obtained envelopes shows reasonably good agreement between the results. In case of Wall 13, the resistance in the negative direction is over predicted because P-∆ effect due to out-of-plane movement of the narrow segment of the wall was not accounted for in the model.

5. Parametric study of influence of openings

The presented numerical model was used in a parametric study to determine the influence of the size and layout of openings on the load-bearing capacity and stiffness of fenestrated X-lam timber walls. Total of 36 configurations of fenestrated walls of three different lengths, 240cm, 320cm and 400cm, were modelled and analysed. For each length an additional non-fenestrated wall was modelled to obtain the shear capacity ratios. All fenestrated models had a symmetrical openings, which varied in length and height according to the matrix by one quarter of wall dimension. In Table 1 the matrix of fenestrated models having wall length of 320cm is presented. The openings in walls of other lengths were configured in a similar fashion.

Numerical analyses were performed as non-linear static pushover analyses. In every model analysis results for each loading step were compiled and presented

Table 1 Matrix of numerical models with wall length of 320cm

<table>
<thead>
<tr>
<th>Wall dim.: l = 320 cm h = 270 cm</th>
<th>Ratio of opening length</th>
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<td></td>
<td>1/4l</td>
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in a form of response diagrams as relation between horizontal force and displacement (Fig.14). At higher loads, stress distributions around openings were verified against compression or tension failure of wood, because the model using orthotropic membrane elements is not able to recognize non-linear mechanical properties of timber cross-section. The characteristic strength of homogenised 3-layer X-lam cross section was determined by analytical approach using composition factors [7].

On Figure 14 definition of shear stiffness of calculated racking response is presented. Shear stiffness is defined as a slope of the line which goes through the yielding point determined according to CEN II. In this definition the yield limit state is set as the point of intersection between two lines. The lines are the secant of the skeleton curve defined by points at 10% and 40% of horizontal load-bearing capacity and tangent on the upper part of the envelope, which is parallel to the secant through the skeleton curve at 40% and 90% of horizontal load-bearing capacity. The shear force values at horizontal displacement of h/200 or 0.5% of story drift were set as horizontal load-bearing capacity of calculated response according to EC 8 recommendation for structures attached to brittle elements. The accuracy of calculated response of fenestrated model with large openings at higher stage of deformation is questionable as failure usually occurs by smashing or tearing wood fibres in the corners around openings. Therefore in calculated racking response shear strength was set at deformation of 0.5% of the story drift, which corresponds to the horizontal displacement of 13.5mm. As the normal stresses in analysed specimens with the largest opening attain maximum values (due to yielding of anchors) at story drift higher than 0.5%, it can be concluded that the models produce acceptable results up to this deformation level. When the stress level corresponds to wood failure in the cross-laminated panel the rest of calculated racking response is presented by dashed curve (Fig.14).

The parametric study resulted in diagrams (Fig.15a and 15b) which show the relation between panel area ratio and normalized values of shear capacities expressed as ratio of racking load and stiffness of fenestrated X-lam walls against non-fenestrated one. The diagrams in Fig.15 and Eq.2 also present simple formulas of regression lines which were fit to the results of the numerical analysis. Comparing the influence of openings on shear capacities of X-lam and light-frame walls similar trends were obtained for reduction of shear stiffness (Fig.16) while for reduction of the shear strength the trend curve with the opposite curvature was established. The experimentally obtained empirical equations (Eq.2) are expressed by panel area ratio and could be used for direct evaluation of reduced shear capacities if shear stiffness and shear strength of non-fenestrated wall are already known.

![Fig.14: Calculated responses of 3 fenestrated walls and one non-fenestrated with length of 320cm](image)

![Fig.15: Calculated shear stiffness (a) and shear strength (b) reduction regarding the panel area ratio for X-lam walls.](image)
Fig. 16: Comparison of shear stiffness (a) and shear strength (b) reduction for light-frame wall [4][5] and X-lam solid timber walls with respect to the panel area ratio, r.

6. Conclusion

Non-fenestrated cross-laminated wooden walls have relatively high stiffness and load-bearing capacity. Therefore, the critical elements that govern the X-lam timber shear wall response to earthquake excitations are anchors connecting the panels to the building foundation. X-lam panel with large openings has lower shear stiffness, but its load-bearing capacity is not reduced as much, because failures are mostly concentrated in anchoring areas and in the corners around openings with smashing and tearing of wood. To evaluate the trends of shear strength and stiffness reduction for different fenestrations a numerical model was utilised and verified with experimental tests on full-size X-lam walls. To reduce the number of tests a numerical parametric study was performed for 36 configurations of openings in the walls of three different lengths. The study resulted in diagrams that could serve for simple engineering design of X-lam timber walls with openings using a reduction factor based on the ratio of the openings similar to light-frame walls. The parametric study showed that the openings with the area up to 30% of the wall surface do not reduce the load-bearing capacity significantly, while the stiffness is reduced for about 50%.

Additional experimental tests and numerical analyses will enlarge the knowledge related to lateral stiffness and stability of X-lam wooden walls with openings. Additional tests, already finished at University in Ljubljana, Faculty of Civil and Geodetic Engineering, will serve as verification of the empirical equations presented herein.

7. References


