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EXPERIMENTAL ANALYSIS OF THE INFLUENCE OF OPENINGS IN THE DEFLECTION OF CROSS-LAMINATED TIMBER PLATES LOADED OUT OF PLANE

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ABSTRACT:

This paper presents a series of experimental tests that were conducted to investigate the effect of openings on the deformation of cross laminated timber (CLT) floor panels. A comparison is made between the tests results and different FE shell models and simplified beam models developed for prediction. The research aims to provide new design criteria and user-friendly models to enhance the predictability of CLT structures and increase its versatility as a building material.

KEYWORDS: CLT, cross-laminated timber, mass timber, floors, openings, experimental investigation, modelling

1 INTRODUCTION

Cross Laminated Timber (CLT) is increasingly gaining recognition and popularity in the construction industry. This technological timber product combines crosswise oriented layers of timber bonded together by adhesives, resulting in large panels (of maximum sizes around 3m wide and 15 m long) that allow to develop mass prefabricated structures based on timber wall and floor panels. The combination of prefabricated walls and floors enables to a fast erection of many types of constructions, from small structures such as dwellings to very tall buildings. Full size wall and floor panels can be manufactured on demand, and easily installed on site. This includes the possibility to include cut-outs in the panels, such as windows or doors in wall elements. In the case of floors, these openings can be part of staircases, service conduit shafts or skylights.

Knowing the influence of such openings in the mechanical behavior and distribution of forces within the panels is key to seize the capabilities of the material, and design rules and verification methods are in demand among practitioners [1].

1.1 MODELS

Different studies have investigated the influence of openings on CLT shear walls, such as Shanewaz et al. [2], Casagrande et al. [3] and Awad et al. [4]. Stress concentrations around openings on CLT column-slab connections have been studied by Muster [5]. However, there is limited research on the influence of openings on CLT slabs under bending, which is the most usual demand/case.

A simplified approach to predict the behaviour of and verify openings on CLT slabs are grillage models. In this method, the slab geometry is divided into a system of longitudinal and transversal beams that can be analysed independently to determine forces and displacements around holes in the two main directions of the panel. Wallner-Novak et al. [7] describe the application of this method to centered openings in simply-supported longitudinal slabs with uniform distributed load. In this model, a beam width equal to one tenth of the span length is assumed.

Hast and Fatemi [6] compared the results of the grillage model from [7] with finite element models and found that the grillage model provided very conservative results in all cases, and required further adjustments. The possible influence of stress concentrations around the perimeter of the holes was not addressed in the study.

In practice, the most common approach to model CLT are finite element models (FEM) with two-dimensional shell components. This type of model combines Mindlin-Reissner thick plate theory and membrane theory [8], allowing to render axial, bending and shear stiffness, as well as the in-plane and twisting stiffness of panels. All these stiffness components are described by the material stiffness matrix, which can be derived from the orthotropic properties of the different timber layers, through the application of the laminate theory.

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1.2 AIM AND OBJECTIVES

The presented research aims at bringing new insights into the influence of openings in CLT slabs on both ultimate limit state (ULS) and serviceability limit state (SLS), with the goal of making the use of CLT more efficient and user-friendly [9].

This paper, presented in companion with [10], describes a portion of the results obtained from the conducted test campaign, along with a description of the various analytical models utilized to predict the elastic behaviour of the panels. The experimental outcomes are presented and compared with the predictions made by the different models.

2 EXPERIMENTAL TESTS

2.1 TEST CONFIGURATION AND MATERIAL

To study the influence of openings in the behaviour of the panels, two series of panels were tested, one for analyzing the behaviour of the opening under bending and the second under shear, as depicted in Figure 1.

All specimens were made with a similar layup, a 5-layer composition with outers and mid layer in the parallel direction and odd layers crosswise bonded (0º-90º-0º-90º-0º) and a total panel height of 100 mm. Lamellas were made of European spruce (*Picea Abies*) graded as C24 (strength grade according to EN 338 [11], which corresponds to a bending strength of 24 MPa). Lamellas were 20mm thick, 230mm width, and non-edge glued. Individual lamellas with finger joints were fabricated according to EN 14080 [12].

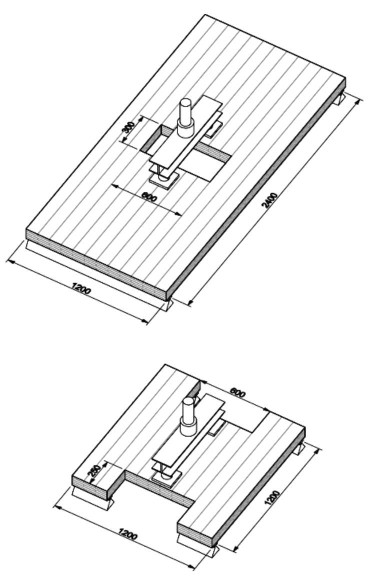

Figure 1: Bending and shear test series.

Test configurations were designed based on EN 16351 and EN 408 normalized tests [13]. Panel length, distance between supports and load application distance were set as a proportion of the panel height. Panel width was set to 1200 mm, so that openings of different widths could be tested, and bending in the secondary direction could be activated. Load was applied on two points, to induce bending in the two main directions. Square-shaped pinned pressure plates of 200 mm width were used.

The conducted experimental campaign involved testing full panels (without holes) within the elastic range, followed by testing the same panels with a 300 mm wide opening, also within the elastic range, and finally testing the panels with a 600 mm wide opening until failure. This paper presents the result of the non-destructive tests, which were conducted to evaluate the displacement predictions of different models.

2.1.1 Preliminary tests and material properties

Different material properties were evaluated experimentally before doing the cut-outs on the panels. Density of the panels was measured following the standard EN 408 [13]. The density was corrected to a reference moisture content of 12%, following the procedure of EN 384 [14]. Modulus of elasticity was determined on bending tests on panels without openings, following the test configuration from EN 16351 Annex C [15]. For these tests, a panel width of 1200mm was used. After testing all panels, rolling shear tests were conducted, according to EN 16351 [15] and EN 789 [16]. Rolling shear test specimens, as the one shown in Figure 2, were obtained from the opening cut-outs. Table 1 presents a summary of the obtained results.

Table 1: *Material properties obtained during the preliminary tests.*

Preliminary tests		
Property	Mean value	COV [%]
Density ρ [kg/m^3]	438,40	1,78
Full Cross-Section MOE $E_{CL,net}$ [N/mm^2]	13.578,59	5,53
Effective Shear Modulus G_{eff} [N/mm^2]	554,00	22,62
Longitudinal Shear Modulus G_0 [N/mm^2]	895	-
Rolling Shear Modulus G_R [N/mm^2]	41	19

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Figure 2: *Rolling shear test.*

2.1.2 Bending series

Bending series was designed according to the configuration described in the bending test with load perpendicular to the plane from EN 16351 [15]. Distance between supports was set to 2400 mm, and the load application points were separated 600 mm. The overall size of the panels was 2500 x 1200 mm.

Figure 3: *Bending test.*

Openings were cut in the centre of the panel, following a symmetric configuration in the two main directions. Panels were tested within the elastic range. First, without any opening, then with an opening of 300 x 300 mm and lastly with an opening of 300 x 600 mm. Table 2 presents the various opening geometries that were tested on each specimen.

Table 2: *Test iterations on bending series.*

Bending series		
Test iteration	Opening width w_h (mm)	Opening length l_h (mm)
1	0	0
2	300	300
3	600	300

During the three tests, vertical displacement was measured around the opening, under the load application point and at the center of the panel edges, following the pattern illustrated in Figure 4.

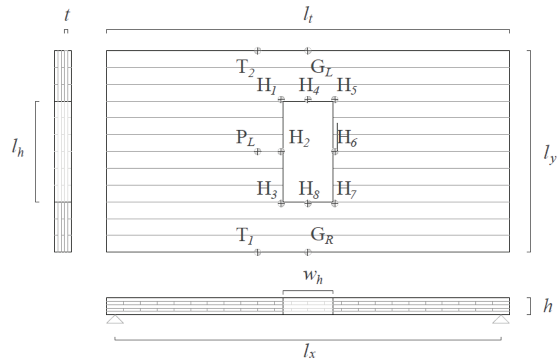

Figure 4: *Measuring points for vertical displacement in bending test series.*

2.1.3 Shear series

Shear series was designed according to the configuration of the bending test for determination of shear strength and stiffness from EN 16351 [15]. The overall size of the panels was 1300 mm long and 1200 mm wide. The distance between supports was set to 1200 mm, and the two load application points were separated 600 mm, the same as in the bending series.

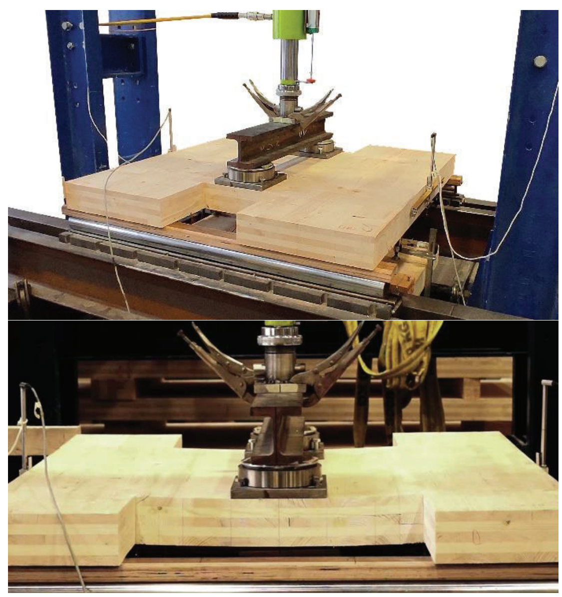

Figure 5: *Shear tests.*

Openings were cut at the supported edges of the panels, following a symmetric configuration in the two main directions. Panels were tested without any opening, then with two openings of 250 x 300 mm and lastly with an opening of 300 x 600 mm.

Table 3: *Test iterations on shear series.*

Shear series		
Test iteration	Opening width w_h (mm)	Opening length l_h (mm)
1	0	0
2	300	250
3	600	250

Vertical displacements were measured around one of the openings, in the central point of the panel, and at the center of the panel edges.

3 MODELS

3.1 ANALYTICAL MODELS

Beam grillage models [7] simplify the analysis by decomposing the floor slab with an opening into a grillage system composed of six beams. Each beam can be analysed independently and later combined with the rest to determine the deflection of the slab. Wallner-Novak et al. [7] describe this system for a rectangular slab with supports in two sides with a central rectangular opening. This method assumes a minimum strip width between the opening and the slab edge of one tenth of the span length l_x must remain.

Since the beam model proposed by Wallner-Novak [7] is for distributed load, a direct comparison with the test results, where point loads were applied, is not possible. Thus, two alternative assumptions have been considered for the validation.

In the first beam model (BM 1) the force is applied as a point load on both transverse beams 3 and 4. The second beam model (BM 2) considers an equivalent uniform distributed load obtained by redistributing the force around the panel surface. The equivalent distributed load is obtained by dividing the reference force F by the surface area of the slab A, as follows:

$$q = \frac{F}{A} = \frac{F}{(l_x l_y) - (l_h w_h)}$$

In both cases, an extra load equal to the self-weight of the panel is considered, obtained from the thickness of the slab h and the density of the panel ρ. The bending stiffness of the beams was assessed with the Modified Gamma Method [17], an adaptation to CLT of the method for composite structural elements included in the Eurocode 5 Annex B [18], originally proposed by Blass and Görlacher [19]. In the herein case of a CLT panel, the rolling shear stiffness of the transverse layers is considered, instead of the stiffness of the connectors. By including the shear influence, the corresponding deformation is increased.

$$(EI)_{ef} = E_{0,mean} \cdot I_{ef,net}$$

$$I_{ef,net} = \sum_{i=1}^{n} (I_i + \gamma_i \cdot A_i \cdot a_i^2)$$

The scheme of the load application and distribution in the two models is given in Figure 6.

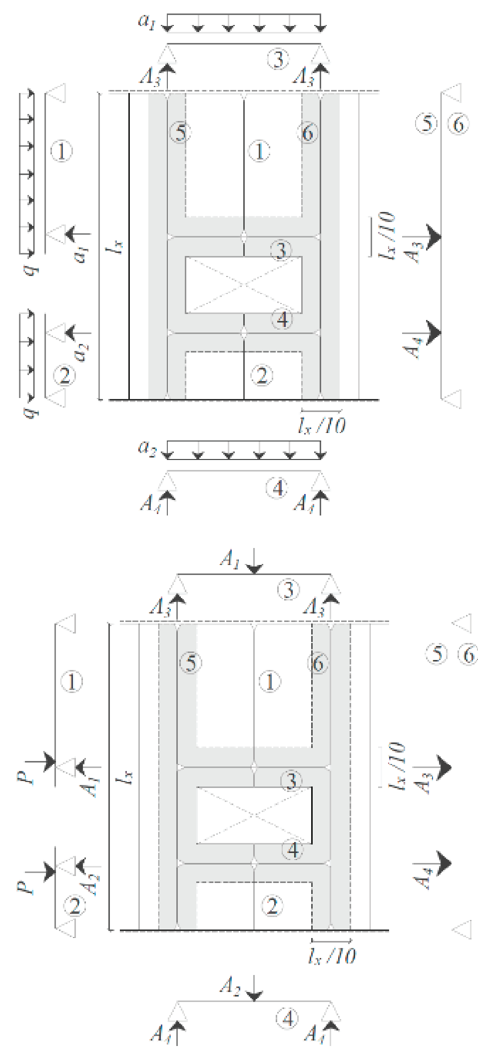

Figure 6: *Load application in beam model with distributed load (top) and beam model with punctual load (bottom).*

In the beam models with distributed load (BM 2), the force was applied to the transverse beams 3 and 4 as a distributed load equal to the reaction force of beams 1 and 2. Longitudinal beams 5 and 6 included both a distributed load and the reaction forces of the transverse beams. In the models with punctual load (BM 1), beams 1 and 2 were neglected, and the load was directly applied to the transverse beams 3 and 4 as punctual forces at their centers, and transferred to beams 5 and 6 as reaction forces. Both models assumed pinned beams. Additionally, to adapt the model with distributed load to the shear series, beams 1 and 2 were replaced by a single loaded beam connecting the center of beams 3 and 4.

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3.2 FINITE ELEMENT MODELS

Linear finite element (FE) analyses have been performed using the software RFEM DLUBAL [20]. A parametric study has been carried, analyzing configurations with different opening widths, from 0 to 900 mm with steps of 100 mm.

The FE models were made with 2D shell elements, with stiffness matrix components derived from the individual layer properties according to the lamination theory [8]. Layers were modelled as non-edge glued by neglecting the stiffness in the transverse direction (E_y=0). Correction factors were applied to the torsional and membrane stiffness of the shell elements, according to Austrian National Annex of the Eurocode 5 [21]. The reduction factors for torsional stiffness D_{33} and membrane stiffness D_{88} were set to 0,59 and 0,68 respectively.

A quadrangular mesh with a density of 50 mm was implemented, so that there were always at least 4 elements within the width of the edge of the opening. Displacements were measured at the same points as the recorded displacement in the experimental tests and correspond also to the calculated points in the beam grillage model .

A first set of models (FE 1) was created using the mechanical properties declared in the ETA-06/0138 [22]. In the second set (FE 2) the material model was defined from the properties obtained experimentally in the peliminary tests. The FE models are shown in Figure 7.

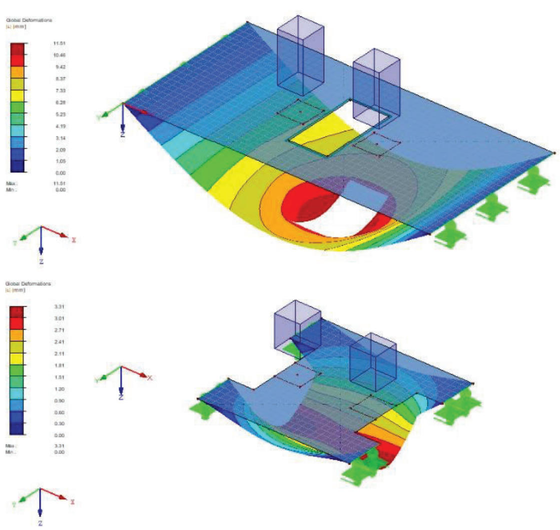

Figure 7: *FE models: bending series (top) and shear series (bottom).*

4 RESULTS AND DISCUSSION

The following graphs show a comparison of displacements from the tests, the FE models and the beam models. The displacement of three representative points is studied, whose location is based on those easily obtained from the beam models. These points are (A) the center of Beam 3, (B) center of Beam 5, and (C) the point where Beam 3 is supported by Beam 5. Points are shown in the diagrams in Figure 6. These points were directly studied on the FE models. However, in the case of the test results, some adjustments were required to do the comparison, since the measuring points were fixed for the three openings studied.

The comparison of the test results and the four cases derived from the analytical models is plotted for bending and shear specimens, respectively. The displacements for the three already described points are plotted separately: the center of Beam 3 (A) is presented in Figure 8 and Figure 11, the center of Beam 5 (B) is studied in Figure 9 and Figure 12, and the support of Beam 3 (C) is given in Figure 10 and Figure 13.

In all the graphs, the abscissas axis accounts for the width of the hole(s) of the slab, while the ordinates axis displays the displacement of the corresponding point. The results of the tests, which consider three cases of holes of widths 0, 300 and 600 mm, are plotted as single values. The behaviour of each of the four models is plotted with curves that consider an opening width range between 0 and 900 mm (when possible), and therefore allow to observe the trend in the response of each case.

The performance of the models clearly differs when considering bending or shear tests. The accuracy of the models is much higher in the bending series, while the displacements predicted for the shear cases are generally lower than the experimental results. It can also be clearly seen that, in all the graphs, the influence of the hole's width is not linear. This trend is reflected in the test results, the FE curves, and the beam models with distributed loads (BM 2). However, the beam model with point loads (BM 1) sometimes exhibits a linear behavior, as noticed for the case of support of beam 3, and in beam 5, for both bending and shear tests. This is due to the assumption of pinned beams, resulting in consistent reaction forces from beams 3 and 4 to beams 5 and 6 being in all hole width scenarios. Despite that, this model tends to predict higher deformations, leading to a more conservative model. No big difference is found between the FE models when considering different material properties.

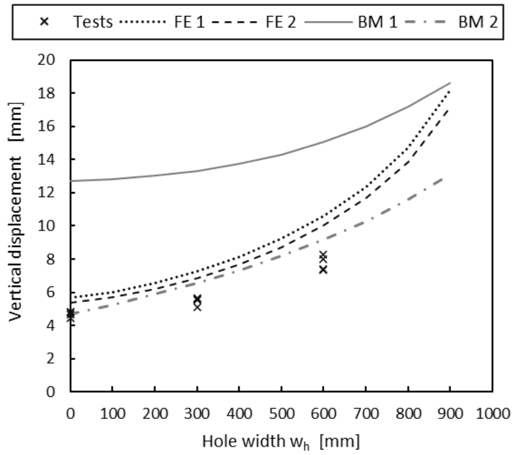

Figure 8: *Bending series. Displacements at reference point A (center of Beam 3).*

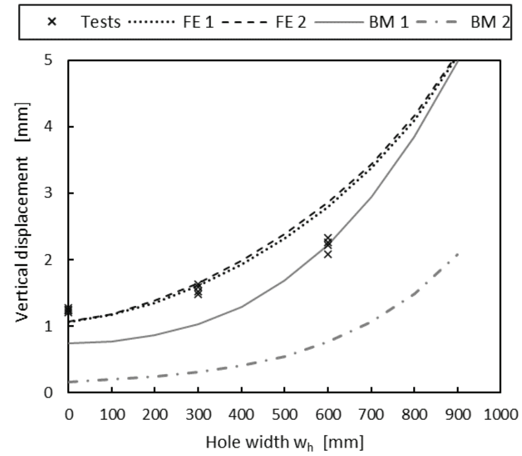

Figure 11: *Shear series. Displacement at reference point A (center of Beam 3).*

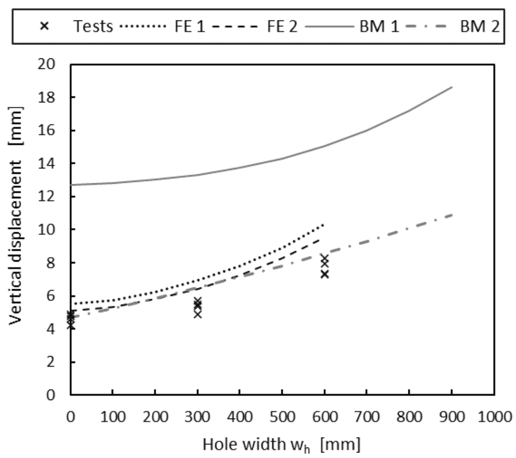

Figure 9: *Bending series. Displacement at reference point B (center of Beam 5).*

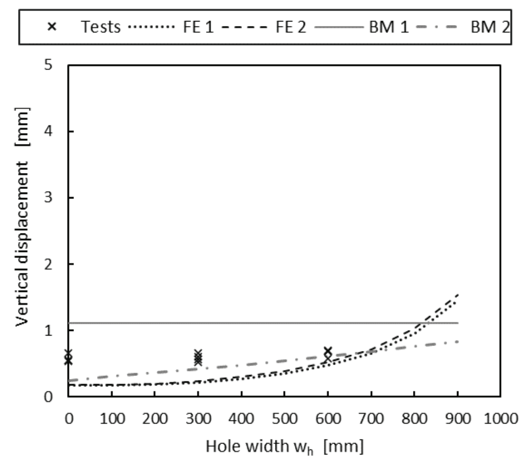

Figure 12: *Shear series. Displacement at reference point B (center of Beam 5).*

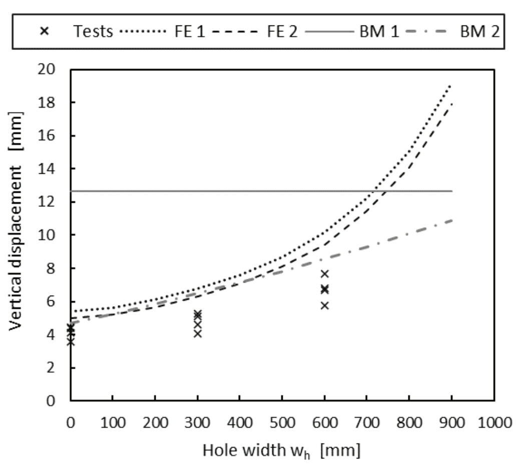

Figure 10: *Bending series. Displacement at reference point C (support of Beam 3).*

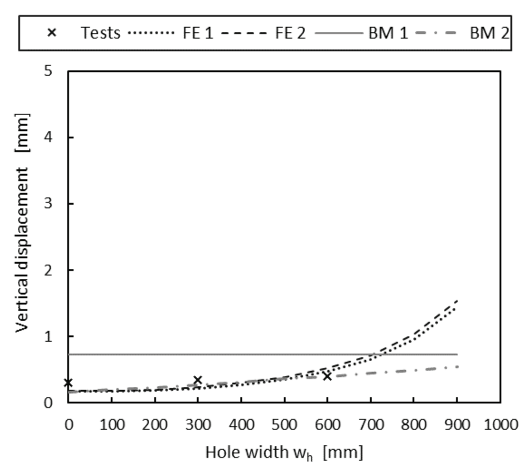

Figure 13: *Shear series. Displacement at reference point C (support of Beam 3).*

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