Behaviour of Mechanically Laminated CLT Members

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Abstract. Cross laminated timber (CLT) is one of the structural building systems based on the lamination of multiple layers, where each layer is oriented perpendicularly to each other. Recent requirements are placed to develop an alternative process based on the mechanical lamination of the layers, which is of particular interest to our research group at the University Centre for Energy Efficient Buildings. The goal is to develop and verify the behaviour of mechanically laminated CLT wall panels exposed to shear stresses in the plane. The shear resistance of mechanically jointed CLT is ensured by connecting the layers by screws. The paper deals with the experimental analysis focused on the determination of the torsional stiffness and the slip modulus of crossing areas for different numbers of orthogonally connected layers. The results of the experiments were compared with the current analytical model.

1. Introduction
Cross laminated timber (CLT) is one of the structural building systems based on the lamination of multiple layers, where each layer is oriented perpendicularly to each other. CLT is a plate element that consists of several board layers oriented in an angle of 90° to each other. The most mature method of connecting the layers is by sticking them with glue. Recent requirements are fully addressed to develop an alternative process based on the mechanical lamination of the layers omitting the glue. This technology could be cheaper and more accessible for producers. Currently, no detailed procedure for determining the buckling resistance and shear resistance of mechanically jointed CLT panels is described in the codes. Modifications of the procedure [1], [2] were used to simplify an analytical approach. Whereas buckling resistance of CLT wall panels loaded in the plane only depends on the effective bending stiffness $EI_{eff}$ for the interaction of the layers oriented in the direction of loading, their shear resistance depends on the torsional stiffness of the connections between the boards. The connections of wooden structures are usually considered as articulated because fasteners in the joints

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are distributed on a small area and the possibility of the torsional moment distribution to the fasteners is limited. Rigid joints are, therefore, used more as corner joints for three articulated frames or cantilevered timber columns. Mechanically jointed CLT shear walls use a large number of locally rigid connections. The orthogonal orientation of the layers and their connection with screws causes the behaviour different from the current design approach that determines the shear resistance of wood-based walls. The shear deformation of a CLT wall panel is caused by shear deformation of the boards as well as shear deformation of the crossing areas. Whereas shear deformation of the boards depends on the shear modulus of used wood, shear deformation of the crossing areas depends on the stiffness of the connection by mechanical fasteners that can be described by the slip modulus of fasteners $K_{ser}$ and torsional stiffness of joints $K_{r,ser}$. The boards have significantly greater shear stiffness than their connection by fasteners. The rotation of the joints and shear deformation of the entire panel are, therefore, formed mainly by torsional displacement of fasteners, see figure 1.

Figure 1. Torsion shear in the joint of boards (left) and in the entire panel (right).

The aim of this paper is to determine slip modulus $K_{ser}$ and torsional stiffness $K_{r,ser}$ for different numbers of orthogonally connected layers and to compare experimental results with the current analytical model.

2. Previous research on mechanically jointed CLT structures

Wall panels with mechanically jointed layers were tested to determine the characteristic values of buckling resistance and shear wall resistance.

2.1. Evaluation of buckling resistance

The test set-up for the evaluation of buckling resistance is shown in figure 2. Two series of wall panels were tested: one series for a 3-layered panel (3x27 mm) and one series for a 5-layered panel (5x27 mm). Each series consisted of three specimens with dimensions of 2200x1000 mm. The load-time diagram of a 5-layered panel is shown in figure 3.
2.2. Evaluation of shear wall resistance
The test set-up for the evaluation of shear wall resistance is shown in figure 4. Horizontal displacements were measured to evaluate the load-displacement diagrams. Both tested series for a 3-layered panel and for a 5-layered panel consisted of 5 identical specimens with dimensions of 3000x2500 mm. Horizontal deformation to the horizontal force diagram for a 5-layered panel is shown in figure 5.

3. Tested specimens
Three series of specimens were tested; the series of 2, 3, and 5-layered specimens (series A, B, and C, respectively). Series A consists of 3 identical specimens, series B and C consist of 2 identical specimens. All layers of the specimens were made of spruce boards, strength class of C24 with dimensions of 170 x 27 x 500 mm, connected together with threaded galvanized screws 5/80 mm. Two
screws were used in each board’s crossing for connection of the layer. 5-layered specimens in series C were created from 3-layered ones, where additional 2 layers were connected with the same screws, but in the diagonal position. This means that no screw goes through all layers in those specimens. A scheme of the samples used in the experiments is shown in figure 6.

![Diagram of samples](image)

**Figure 6.** Scheme of the samples used.

4. **Experimental setup**

The specimens were inserted into a steel device during the test. This device consisted of two arms which were connected by a pin, and thus they could mutually rotate. Sufficient rigidity of the steel device causes uniform loading for fasteners in the timber joint. Therefore, there was only stress due to the torsional moment at the joint, not due to shear forces. Torsional moments which caused the rotation of joints were determined from loading forces at a distance of 250 mm from the centre of the joint. Vertical shifts of horizontal layers at both sides of the joint were measured by two inductive sensors mounted on the front surface of the specimens. Rotations of the joint were calculated from the average values of these shifts. The joints were loaded at a rate of 0.1 mm/s and the loading was continued until the joint failure. The slip modulus and torsional stiffness of the joints were determined by conducting a test setup according to figure 7 using the requirements and assumptions of [3]. The test device was based on a configuration that uses the Flaig and Meyer approach to determine the slip modulus of connections between crosswise bonded boards [4].
5. Results
Torsional shear tests of CLT joints have been performed to evaluate the rotation of joints in torsional moment diagrams. The evaluated characteristics with average values for each series of specimens are shown in figure 8. As one can see, the differences in the connection rigidity between the boards correspond to the differences in the number of shear planes in the joints. The increase in initial stiffness was the largest in series 5L and the smallest in series 2L, as expected. After this initial steep increase in stiffness, the curves begin to be flatter, due to the embedment of wood grain by the screw, see figure 9.

The orthotropic properties of wood and the comparison of strength in compression perpendicular and parallel to grain indicate a significant influence of the angle between the direction of fasteners’ loading and the direction of wood fibres on the resistance in the connection of two perpendicular layers. From this assumption, different values of the slip modulus for orthogonal boards may be obtained, as presented by Ohashi and Sakamoto [5]. The analytical model referred to in [1] contemplated the same value of the slip modulus for screws in both fibre directions, as one can see in
equation 1. Slip modulus $K_{ser,cal}$ is dependent on the diameter of fasteners $d$ and on the density of wood material $\rho_m$.

$$K_{ser,cal} = \rho_m^{1.5} \cdot \frac{d}{23}$$  \hspace{1cm} (1)

Torsional stiffness $K_{r,ser,cal}$ can be determined from equation 2 using the slip modulus values.

$$K_{r,ser,cal} = K_{ser,cal} \cdot r_1^2 \cdot n \cdot m$$  \hspace{1cm} (2)

where $r_i$ is the distance of fasteners from the centre of rotation, $n$ is the number of fasteners and $m$ is the number of shear planes in joints. Torsional moments $M_{max,cal}$ were calculated from the characteristic load-carrying capacity for the used screws. Slip modulus $K_{ser,exp}$ was determined based on experiments for one shear plane of the fasteners according to equation 3, considering the condition of linear behaviour of the fasteners in the joint.

$$K_{ser,exp} = \frac{M_{04}}{\frac{4}{3} \cdot \phi_{04-01} \cdot r_1^2 \cdot n \cdot m}$$  \hspace{1cm} (3)

where $M_{04}$ is the torsional moment at 40% of the ultimate load, $\phi_{04-01}$ is the mutual rotation between orthogonal layers that was determined from the values, related to the difference between 10% and 40% of the ultimate load. Torsional stiffness was determined according to equation 4 from the ratio of torsional moment and the appropriate rotation of the joint.

$$K_{r,ser,exp} = \frac{M_{04}}{\frac{4}{3} \cdot \phi_{04-01}}$$  \hspace{1cm} (4)

Experimental results and their comparison with the analytical model are given in table 1.

| Specimen | Calculation | Experiment |
|----------|-------------|------------|
|          | $M_{max,cal}$ | $K_{ser,cal}$ | $K_{r,ser,cal}$ | $M_{max,exp}$ | $K_{ser,exp}$ | $K_{r,ser,exp}$ |
| 2L - I   | 0.52        | 27.03      | 0.42          | 1431.81       | 20.69        |
| 2L - II  | 0.47        | 719.18     |              | 591.97        | 8.55         |
| 2L - III | 0.47        | 591.97     |              | 1297.33       | 37.49        |
| 3L - I   | 0.62        | 54.07      | 1297.33      | 2152.84       | 124.43       |
| 3L - II  | 0.64        | 1444.48    |              | 2152.84       | 124.43       |
| 5L - I   | 1.38        | 108.14     |              | 1652.00       | 95.49        |
| 5L - II  | 1.42        | 1652.00    |              | 1652.00       | 95.49        |

Table 1. Comparison between the analytical model and experiments.
6. Conclusion
Mechanically jointed CLT panels have a potential to be widely used for multi-storey buildings. Tests of the buckling resistance and shear wall resistance for wall structures were performed. Currently, no detailed analytical procedure for determining shear resistance is described in the codes; therefore, the mechanical behaviour of layers’ connections in shear walls is investigated and described in this paper. Ongoing research is focused on an experimental program comprising different variations of mechanical layer connections.

The comparison of experimental results within each series of samples indicates a large dependence of the fasteners’ slip modulus and torsional stiffness of joints on the material properties of wood. The data obtained from the experiments show about 29.1% less value of the fasteners’ slip modulus $K_{ser,i}$ and about 51.1% (2L series), respectively 26.7% (3L series) smaller torsional stiffness of joints $K_{ser}$, than the values determined by calculation. The average measured values of torsional stiffness in the joints of 5L series are about 1.7% greater, than the value determined by calculation.

By comparing the obtained values, it is obvious that the current analytical procedure may be used for the calculation of the bearing capacity of mechanically connected CLT elements, but it does not provide a sufficient level of accuracy for the calculation of stiffness in torsional displacement of boards.

Further sets of displacement tests are being prepared. On the basis of this experimental program, suitable possibilities will be considered for further research into shear wall structures.

7. References
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