Shear strength of in-plane loaded cross laminated timber beam elements – experimental and theoretical investigation

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Abstract. Cross laminated timber (CLT), as a versatile engineered timber product, has in recent years become well-known and of global interests. The orthogonal laminar structure allows for application as beams, walls or panels for both out-of-plane and in-plane loading conditions. The work presented here concerns experimental investigations of in-plane loaded CLT beams, as very relevant from a practical engineering point of view due to reinforcing effect of transversal layers with respect to stress perpendicular to the beam axis. Experimental results are used for comparison and validation of design proposals from the literature, with the main focus on the shear failure mode III in crossing areas between orthogonally bonded longitudinal and transversal lamination. By using the assumed shear strength values from the literature, analytically predicted shear carrying capacities show good agreement with the experimentally obtained. Although further experimental validation is needed, obtained results indicate that suggested design proposals should be considered in ongoing revision work of Eurocode 5.

1. Introduction
Within the last decade, engineered wood product as cross laminated timber (CLT), has become a very well-known and of global interest. The orthogonal laminar structure allows its application for out-of-plane and in-plane loading conditions, for floor panels, walls, beams etc. Beams made of CLT offer several advantages over solid or glued laminated beams. The transversal layers of orthogonal structure have a reinforcing effect with respect to the stress perpendicular to the beam axis which results in however complex stress state where several failure modes need to be considered in design [1].

For verification of beam shear strength, according to figure 1., three different failure modes (FM) in general need to be considered [2]: gross shear failure (FM I), net shear failure (FM II) and shear failure in the crossing areas between adjacent longitudinal and transversal laminations (FM III).

Experimental verifications of CLT beam shear strength are for example reported by Bejtka [3], Flaig [4], Danielsson et al [5] and Jelec et al [6], where in most cases bending and shear mode III were identified as the critical failure modes. An analytical model for relevant shear failure modes of CLT beams has been presented in [2, 7]. Proposed model has been included in a current working draft of cross laminated timber for future revised Eurocode 5 [8]. This model does, however, suffer from some drawbacks as has been discussed in [9, 10], where alternative improvements were presented in [11]. Comprehensive FE-analyses and comparisons with analytical models have been shown in [12]. Based on these results, an improved model and design proposals were presented in [6, 13].
The aim of this paper is to present experimental results of in-plane loaded CLT beams for comparison and validation of design proposals [6, 13], with the main focus on shear failure mode III.

![Illustration of geometry and shear failure modes of CLT beams.](image)

**Figure 1.** Illustration of geometry and shear failure modes of CLT beams.

2. **Analytical model and design proposal**

2.1. **General assumptions**

A brief review of two design proposals [6, 13] is presented below. Both proposals are generally based on conventional beam theory taking into account the orthogonally layered composition of prismatic CLT beams without edge bonding and composed of longitudinal and transversal laminations of width $b_{0}$ and $b_{90}$, respectively. Both proposals are based on assuming equal width $b_{0}$ of all longitudinal laminations in the beam height direction and are valid for 3 and 5-layer CLT elements, with the restriction of the 5-layer element lay-up $t_{0,2}/t_{0,1} = t_{0,2}/t_{0,3} \leq 2.0$.

2.2. **Shear stress analysis**

Based on the model and design proposals (DP 1 & 2), the shear stress acting in crossing areas between longitudinal and transversal laminations can be decomposed into (1) unidirectional shear stress parallel to the beam axis $\tau_{zx}$ and (2) torsional shear stresses $\tau_{tor,z}$. Design relevant stresses are calculated for the critical crossing area, which relates to the outermost crossing area in the beam width direction and close to the centre-line with respect to the beam height direction, as follows

$$
\tau_{zx} = \frac{6V}{b_{0}} \frac{t_{0,1}}{t_{net,0}} \frac{1}{m^{3}} \text{ for DP 1 & 2}
$$

(1)

$$
\tau_{tor,z} = \frac{3V}{b_{0}} \left( \frac{\alpha \beta}{t_{net,0}} \frac{1}{m^{3}} \right) k_{b} \text{ with } k_{b} = \frac{2h_{max}b_{0}}{b_{0}^{2} + b_{90}^{2}} \text{ for DP 1}
$$

(2)

where $m$ is the number of longitudinal laminations in beam height direction and $\alpha$ and $\beta$ are weighting factors for shear stress distribution in beam height and width direction, as follows

$$
\alpha = \frac{3m^{2} - 4}{2m^{3}}
$$

(3)
\[ \beta = \begin{cases} \frac{t_{0,1}}{t_{net,0}} & \text{for 3-layer CLT beams} \\ \frac{1}{8} \left( 1 + 4 \frac{t_{0,1}}{t_{net,0}} \right) & \text{for 5-layer CLT beams} \end{cases} \]  

(4)

A further simplification is introduced in DP 2 by replacing two weighting factors (\( \alpha \) and \( \beta \)) with a single factor \( \gamma \), as follows

\[ \tau_{\text{tor},z} \leq \frac{3V}{h^2} \left( \frac{1}{m^2} \right) \left( \frac{1}{m^2} \right) k_b \gamma \quad \text{with} \quad k_b = \frac{2b_{\text{max}}b_0}{b_0^2 + b_{90}^2} \quad \text{for DP 2} \]  

(5)

where

\[ \gamma = \begin{cases} 1.5 & \text{for 3-layer CLT beams} \\ 0.2 \frac{t_{0,2}}{t_{0,1}} + 1.1 & \text{for 5-layer CLT beams} \end{cases} \]  

(6)

2.3. Shear strength verification

For verification of shear failure mode III, due to stress components in two directions, \( \tau_{z} \) and \( \tau_{\text{tor},z} \), a stress interaction criteria may be needed. According to the original model [2], a linear stress interaction criterion is proposed

\[ \frac{\tau_{\text{tor},z}}{f_{v,\text{tor}}} + \frac{\tau_{z}}{f_R} \leq 1.0 \]  

(7)

where \( f_{v,\text{tor}} \) is a torsional shear strength and \( f_R \) is the rolling shear strength. Test results found in literature [1, 7] indicate a mean value of the torsional strength of about \( f_{v,\text{tor}} = 3.5 \) MPa and a mean value of the rolling shear strength of about \( f_R = 1.5 \) MPa. The corresponding characteristic values are \( f_{v,\text{tor}} = 2.75 \) MPa and \( f_R = 1.1 \) MPa.

3. Experimental study

3.1. Test series and materials

Experimental tests of in-plane loaded CLT beams have been carried out at Lund University and at the Faculty of Civil Engineering at University of Zagreb and a detailed description of the tests and results are presented in [5, 6]. One test series from each testing place is presented below where each consisted of four nominally equal tests resulting a total of 8 individual tests. The main geometry and lay-up parameters are presented in table 1 and shown in figure 2.

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**Table 1. Geometry parameters of tested CLT beams.**

| Test series | \( n \) [\text{-}] | \( L \) [\text{mm}] | \( h \) [\text{mm}] | \( \text{t}_{\text{gross}} \) [\text{mm}] | \( b_0 \) [\text{mm}] | \( b_{90} \) [\text{mm}] | lay-up [\text{mm}] |
|-------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| CLT 5s      | 4              | 2400           | 600            | 160            | 150            | 146            | 40-20-40-20-40 |
| CLT 3s      | 4              | 2400           | 600            | 100            | 150            | 198            | 40-20-40       |

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**Figure 2.** Test setups for CLT 5s (left) and CLT 3s (right), dimensions in mm.
Beams from CLT 5s were produced by Cross Timber Systems LTD according to ETA-15/0906 and beams from CLT 3s by Hasslacher Norica Timber according to ETA-12/0281. The wood species are stated as being European Spruce or equivalent softwood. The mean density of the CLT 5s was 452 kg/m$^3$ with the moisture content at the time of testing about 10-11%, while the mean density of the CLT 3s was 458 kg/m$^3$ with the moisture content at the time of testing about 11-12%. At the time of testing, there were no visible gaps between the laminations belonging to the same layer, which is in line with both ETA-s. All beams were cut from larger CLT panels without consideration of the position of the longitudinal lamination in relation to the beam elements edges, with the width of the upper- and lowermost longitudinal laminations in the range 5 < $b_0$ < 172 mm with $b_{0,\text{max}}$ = 172 mm for CLT 5s, and 54 < $b_0$ < 149 mm for CLT 3s with $b_{0,\text{max}}$ = 198 mm, respectively. The laminations widths $b_0$, as shown in table 1, are thus approximated mean values.

3.2. Test results
The results of all test specimens in terms of maximum loads and graphs of applied loads vs. global deflection are shown in figure 3. All tests were run by deformation controlled testing machine, with the test duration of approximately 15-20 min which allowed careful observations of critical locations where the failure was expected.

![](image1.png)

**Figure 3.** Applied load $F$ vs. global deflection.

In CLT 5s the load bearing capacity in terms of maximum load is related to bending failure of lowermost longitudinal laminations. Before reaching the maximum loads, a gradual decrease in stiffness can however be noted from figure 3. Also, significant sliding between longitudinal laminations in the exterior layer was observed (figure 4), indicating thus partial failure in crossing areas (FM III).

![](image2.png)

**Figure 4.** Photos of fractured specimens for CLT 5s (left) and CLT 3s (right).
In CLT 3s the failure modes are related to a combination of shear failures in crossing areas (FM III) and failures due to bending. The initial failure started at 85% of the maximum loads approximately, as shown in figure 3, after which decreasing in stiffness and obvious sliding between laminations was observed, indicating shear damage/failure in crossing areas, as shown in figure 4.

4. Comparisons and discussion
The results for both test series are given in figures 5 and 6 in terms of shear stress components and stress interaction criteria at maximum load for shear failure mode III. The stress values are calculated according to both design proposals from Section 2, based on assumption of equal widths of the longitudinal and transversal laminations, i.e. \( b_0 = b_{90} = 150 \text{ mm} \). The stress interaction criteria according to equation 7 is calculated based on the assumed value of torsional shear strength of \( f_{v,\text{tor}} = 3.5 \text{ MPa} \) and the rolling shear strength of \( f_R = 1.5 \text{ MPa} \).

For test series CLT 5s, stress interaction ratios according to both design proposals (DP 1 & 2) are all above 1.0, as shown in figure 6, indicating that shear failure mode III would be expected. These results are in-line with observations during testing where obvious sliding between longitudinal laminations and cracking sounds were noticed before reaching maximum load. Based on assumed shear strength values, \( f_{v,\text{tor}} \) and \( f_R \), both design proposals are conservative and underestimates the shear capacity compared to test results. Design proposal 2 seems, however, slightly conservative compared to design proposal 1. For three specimens of test series CLT 3s, stress interaction ratios according to both design proposals (DP 1 & 2) are below 1.0, as shown in figure 6, indicating that shear failure mode III would not be expected. This is however not in-line with observations during testing where obvious sliding and cracking sounds were noticed before reaching maximum load. Based on assumed shear strength values, \( f_{v,\text{tor}} \) and \( f_R \), both design proposals slightly overestimates the shear capacity compared to test results. This overestimation is, however, relatively small compared to the mean value of test results, where the main reason could be on assumed shear strength values. For test series 3, a slightly lower values of shear strength components, \( f_{v,\text{tor}} \) and \( f_R \), would be thus expected.

![Figure 5](image-url)
**Figure 5.** Calculated stress component values at maximum load for CLT 5s (left) and CLT 3s (right).

![Figure 6](image-url)
**Figure 6.** Calculated failure interaction criterion for CLT 5s (left) and CLT 3s (right).
5. Conclusions
Two design proposals, as presented in [6, 13], are reviewed and beam strength predictions are compared to the experimental result. Based on the assumed values of torsional $f_{\text{v,tor}}$ and rolling shear strength $f_R$, as proposed in the literature, in general good agreement between test results and design proposals was obtained. Both design proposals seem suitable for use in practical design situation for CLT beams composed of 3 or 5 layers with the surface layers oriented in the beam length ($x$) direction. Further studies of CLT beams with inverted layer orientation or studies of 7-layer elements should preferably be carried out.

The proposals are based on assuming equal longitudinal lamination width $b_0$ for all $m$ laminations in beam height direction. Dimensions and placement of laminations are however in general not known in actual design situation since the CLT beams in general are cut from larger CLT elements, irrespective of their location in relation to the edges of element. The reduced lamination widths close to the beam edges have a small influence on the beam strength, as it is shown in [6]. The lamination widths $b_0$ and $b_{90}$ to be used in calculation can then be based on values as specified by producer or slightly lower values for conservative design. Following the recommendation in the draft version of new Eurocode 5 [8], in cases where the lamination width is not known, it should be assumed as $b_0 = b_{90} = 80$ mm.

6. References
[1] Jeleč M, Varevac D and Rajčić V 2018 Cross laminated timber (CLT) – a state of the art report Građevinar 70 75-95
[2] Blaß H J and Flaig M 2012 Stabförmige Bauteile aus Brettsperrholz (Karlsruhe: KIT)
[3] Bejtka I 2011 Cross (CLT) and Diagonal (DLT) Laminated Timber as Innovative Material for Beam Elements (Karlsruhe: KIT)
[4] Flaig M 2013 Biegeträger aus Brettsperrholz bei Beanspruchung in Plattenebene PhD Thesis (Karlsruhe: KIT)
[5] Danielsson H, Jeleč M and Serrano E 2017 Strength and stiffness of cross laminated timber at inplane beam loading Report TVSM-7164 (Lund: Div of Structural Mechanics, Lund University)
[6] Jeleč M, Danielsson H, Rajčić V and Serrano E 2019 Experimental and numerical investigations of cross-laminated timber elements at in-plane beam loading conditions Construction and building materials 206 329-346
[7] Flaig M and Blaß H J 2013 Shear strength and shear stiffness of CLT-beams loaded in plane Proc. Int. Conf. CIB-W18/46-2-3 (Vancouver, Canada)
[8] European Committee for Standardization (CEN/TC 250/SC5) Working draft of design of cross laminated timber in a revised Eurocode 5-1-1, Version 2018-04-13, part of N892
[9] Jeleč M, Strukar K and Rajčić V 2017 Structural analysis of in-plane loaded CLT beams Electronic Journal of the Faculty of Civil Engineering Osijek e-GFOS 8 20-30
[10] Danielsson H, Serrano E, Jeleč M and Rajčić V 2017 In-plane loaded CLT beams - Tests and analysis of element lay-up. Proc. Int. Conf. INTER/50-12-2 (Kyoto, Japan)
[11] Danielsson H and Serrano E 2018 Cross laminated timber at in-plane beam loading – Prediction of shear stresses in crossing areas Engineering Structures 171 921-927
[12] Danielsson H, Jeleč M, Serrano E and Rajčić V 2019 Cross laminated timber at in-plane beam loading – Comparison of model predictions and FE-analyses Engineering Structures 179 246254
[13] Jeleč M, Danielsson H, Serrano E and Rajčić V 2018 Cross laminated timber at in-plane beam loading - New analytical model predictions and relation to EC5 Proc. Int. Conf. INTER/51-J25 (Tallin, Estonia)