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New design approach for controlling brittle failure modes of small-dowel-type connections in Cross-laminated Timber (CLT)

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HIGHLIGHTS

- New design approach is proposed for controlling brittle failure modes of CLT connections.
- Effect of cross layers is included in a model already validated in LVL and glulam.
- Cross layers in CLT contribute in such a way providing a wider and deeper connection.
- Verification is performed using timber rivet joints loaded parallel to grain.
- Proposed design approach can be extended to other fasteners such as nails and screws.

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ABSTRACT

The introduction of Cross-laminated Timber (CLT) as an engineered timber product has played a significant role in considerable progress of timber construction in recent years. Extensive research has been conducted in Europe and more recently in Canada to evaluate the fastening capacity of different types of fasteners in CLT. While ductile capacities calculated using the yield limit equations are quite reliable for fastener resistance in connections, however, they do not take into account the possible brittle failure mode of the connection which could be the governing failure mode in multi-fastener joints. Therefore, a stiffness-based design approach which has already been developed by the authors and verified in LVL, glulam and lumber has been adapted to determine the block-tear out resistance of connections in CLT by considering the effect of perpendicular layers. The comparison between the test results on riveted connections conducted at the University of Auckland (UoA) and the Karlsruhe Institute of Technology (KIT) and the predictions using the new model and the one developed for uniformly layered timber products show that the proposed model provides higher predictive accuracy and can be used as a design provision to control the brittle failure of wood in CLT connections.

1. Introduction

Timber construction has experienced considerable progress in recent years. The implementation of new engineered timber products such as Cross-laminated Timber (CLT) has played a significant role in such progress. CLT is made up of dimensional lumber glued together with structural adhesive and stacked in sheets with perpendicular orientation. It is most commonly utilized as floor and wall components across a wide range of residential and commercial building types. Due to its prefabricated elements and ease of installation, its application in mass timber multi-storey construction is growing rapidly [1]. Through the emergence of such advanced engineered timber products, international building standards are revising their codes to accept high-rise timber buildings. In these types of structures, the joints need to transfer large loads and these become more critical for designers. Extensive research has been conducted in Europe and more recently in Canada to evaluate the fastening capacity of different types of fasteners in CLT [2–4]. While ductile capacities calculated using yield limit equations based on the European Yield Model (EYM) are quite reliable for fastener resistance in connections, however, they do not take into account the possible brittle failure mode of the CLT connection which could be the governing failure mode in multi-fastener joints [4–8]. This is the reason why the wood engineering community has dedicated a significant amount of effort over the last decades to establish a reliable predictive model to determine

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the capacity of timber connections under wood failure mechanisms. In recognition of this fact, a stiffness-based design approach which has already been developed by the authors and verified in Laminated Veneer Lumber (LVL), glulam and lumber (with uniform layers) is adjusted to determine the connection brittle block-tear out resistance in CLT by considering the contribution of perpendicular layers.

2. Proposed design approach

The different orientation of the layers in a CLT member in comparison to glulam and LVL in which all the layers are laid in a similar direction makes it a specific timber product. This is more important from the design perspectives as the CLT member is loaded through a joint and the stresses are distributed among the outer and inner layers. Initially, a numerical study has been conducted in order to have a better understanding of the stress distribution and the load path among layers in CLT connections. Observations were then used to develop a closed-form analytical model.

2.1. Stress distribution in CLT

Through a simple numerical model, the parallel and perpendicular layers in a CLT member were simulated to investigate the effect of their orientation on transferring the joint load (Fig. 1). Based on potential CLT member configurations, it was assumed that the planks in a given plane are not connected on edges and there is only full contact between planks of different plane as a result of gluing. To model the elastic behavior of wood, the orthotropic stiffness properties in longitudinal, radial, and tangential axes were considered. The moduli of elasticity and rigidity and the relation among them were assumed as $E_R = E_T = E_L/30$; $G_{LR} = G_{LT} = 10G_{RT}$; and $G_{LR} = E_L/15$. Also, the Poisson's ratios were set to $\mu_{LR} = \mu_{LT} = \mu_{RT} = \mu_{TR} = 0.35$; and $\mu_{RL} = \mu_{TL} = 0.03$.

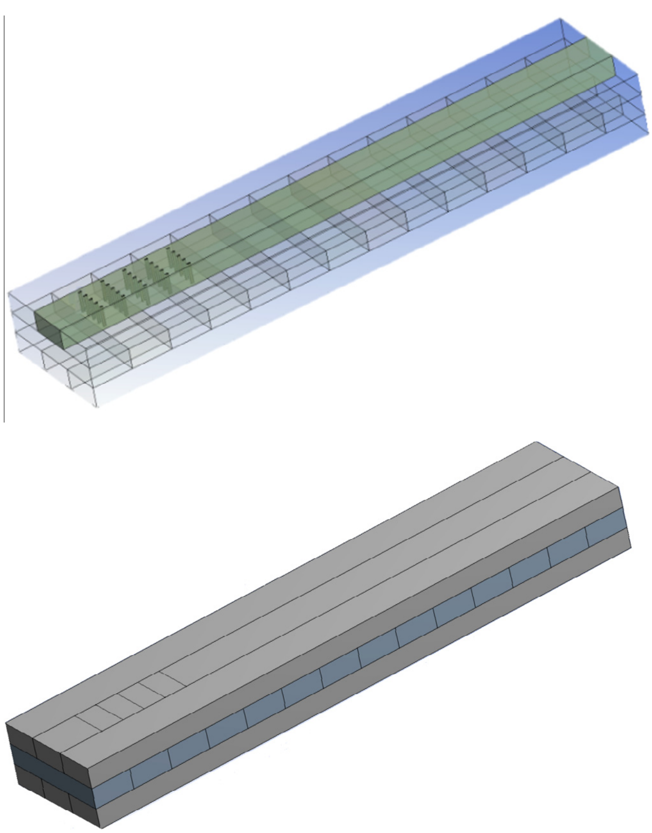

Fig. 1. Model of a CLT connection in which just the outer middle plank is loaded.

In the example shown in Fig. 1, the single shear connection consists of fasteners penetrating only the outer middle plank. In this example, the results of the FE analysis (Fig. 2a) demonstrate that about 55% of the applied load is taken by the loaded plank and the rest is distributed to the outer parallel planks adjacent to the loaded one and also to the inner parallel planks as a result of the reinforcing effect of the cross layer. In fact, the cross layer ties all adjacent parallel planks to the next layer of parallel planks (Fig. 2b). Therefore, for the joint resistance, the contribution of the other parallel planks should not be ignored even though the fasteners are not penetrating these layers.

2.2. Joint wood load-carrying capacity in CLT

The authors have already introduced a stiffness-based model (Fig. 3) for the prediction of wood block tear-out failure of connections in uniformly layered timber products such as LVL and glulam [9,10]. However, in CLT, the load transfer and stress distribution at the joint location are quite different due to the particular arrangement of the layers. Therefore, adjustments in the previously developed model are required in order to include the reinforcing effect of cross layers and determine the connection load-carrying capacity in wood brittle failure mechanisms.

In the previous model developed for LVL or glulam, the applied load is transferred from the wood member to the failure planes in conformity with the relative stiffness ratio of each resisting volume adjacent to the individual failure plane. As shown in Fig. 3, three resisting planes are involved which are the head tensile, bottom shear and lateral shear planes. However, in the case of CLT (Fig. 4), the following considerations are necessary for the determination of the load path:

I. Disregard any contribution from the lateral shear planes ($K_l = 0$) since there is no control on the positioning of the lateral planes of the joint cluster relative to the unbounded interface of the parallel planks. The worst scenario would be the matching of the lateral shear planes with the parallel planks interface which results in no load transfer between adjacent parallel planks.
II. Incorporate the reinforcing effect of the cross layers which contribute in transferring the load from the loaded planks at the connection zone to the adjacent outer and inner parallel planks. The resulting effect is that the joint can be assumed wider and deeper.

In the connection shown in Fig. 4, a block tear-out of depth t_{ef}, width w_c and length $L_c + d_a$ is assumed. The wood volume of thickness d_z adjacent to the bottom shear plane is bonded to the cross layer at the glued interface. Therefore, its deformation under the acting shear force at the bottom plane decreases due to the additional stiffness resulting from the cross layer. As shown in Fig. 5a, the cross planks are restrained entirely at their bottom interface by the inner parallel planks. Also, the outer parallel planks adjacent to the loaded planks are constraining the top ends of the cross planks (Fig. 5b). Hence, the stiffness of the cross layer can be determined from the combination of its rolling and longitudinal shear deformations. Consequently, the overall stiffness corresponding to the depth under the bottom shear plane can be determined as

$$K_d = K_b + K_r + K_a \tag{1}$$

where K_b is the bottom shear plane stiffness corresponding to d_z. The K_r and K_a are the rolling and longitudinal shear stiffnesses of