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Evaluation of the mechanical properties of cross laminated timber with elementary beam theories

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HIGHLIGHTS

- Presents well-established theories for identification of mechanical properties.
- Covers identification procedures for loads perpendicular and parallel to plane.
- Bending response is well represented in terms of elastic and strength properties.
- Rolling shear strength demonstrates a significant variability.
- Consistency identified for a combined shear failure criterion for loads in plane.

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ABSTRACT

This paper presents a study on the assessment of the mechanical properties of cross laminated timber (CLT) panels based on four-point bending tests. The most recent or well-established analytical theories have been implemented to estimate stiffness and strength properties under loads perpendicular or parallel to the principal plane of CLT panels from laboratory tests. The main objectives were to evaluate each proposed theory in predicting the associated deformation and failure mechanisms and to assess the reliability of the estimated properties with respect to the expected values and in terms of consistency among specimens with different layer configurations. The results indicate that the bending response is on average well represented in the implemented theories for the two cases of loading and in terms of both elastic and strength properties. For loads perpendicular to plane the characteristic rolling shear strength appears to have a significant variability among the different layups for all three applied methods, while for loads in plane the consideration of a combined rolling and torsional shear failure criterion provides more consistent results with respect to a less rigorous approach.

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1. Introduction

Cross laminated timber (CLT) is a relatively new engineered wood product that is steadily increasing its share in the building market for a number of advantages over traditional wood products and over the main construction materials such as reinforced concrete and steel. In fact, Brandner [1] reports a 15–20% annual increase in CLT production capacity with an estimate of 500,000 m^3 overall production volume for 2012. CLT panels are constructed from layers of structural boards that are glued orthogonally to each other as shown in Fig. 1, forming bidirectional elements that can be used as wall diaphragms, floor plates or even beam and column elements.

The mechanical behavior of CLT panels is complex, mainly due to the orthogonality in the grain direction of successive layers and the inherent anisotropy of timber. In general, the structural response of CLT panels has been systematically studied for the case of loads perpendicular to plane (vertical or wind forces for floor or wall panels respectively) or for loads in plane (forces on vertically oriented CLT beams or shear and vertical forces on wall panels).

Most of the testing and certification procedures of CLT panels in Europe, nowadays, are based on four-point bending tests of strip-shaped CLT specimens, according to EN 408 [2] or based on the recently published EN 16351 [3], with uniform boundary supports and applied forces along the width. The mechanical properties that

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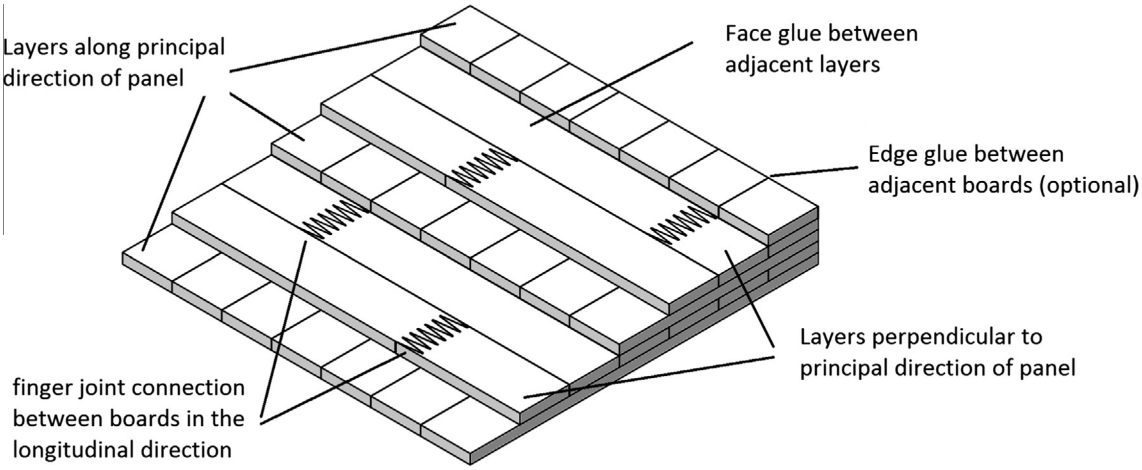

Fig. 1. Construction detail of CLT panels.

are of primary interest when conducting four-point bending tests of CLT panels are the mean values of the section bending and shear stiffness (elastic properties) and the characteristic values of bending and shear strength properties. These properties have then to be used with an applicable analytical theory to yield representative material properties of the boards of the CLT panels such as the mean modulus of elasticity parallel to grain and the characteristic values of bending strength and shear strength.

This study aims to present the most recent or well-established analytical theories, as applied within a numerical framework that implements the Euler-Bernoulli and the exact Timoshenko beam element [4], for the assessment of the mechanical properties of CLT panels from laboratory tests. The main objectives are to investigate the level of accuracy of each proposed theory in predicting the associated deformation and failure mechanisms of a CLT panel and to evaluate the reliability of the estimated properties with respect to the expected values and in terms of consistency among specimens with different layer configurations.

1.1. Loads perpendicular to plane (out of plane)

The mechanical response of CLT panels under loads perpendicular to plane is, nowadays, fairly well understood as it has been the primary field of study for the qualification of CLT elements as structural components of floor systems. Although CLT panels are bi-dimensional elements that can resist bending around both orthogonal in plane axes, it is common practice to analyze and design them as beam elements when used as floor or roof plates because they typically have a maximum width of 2.5 m, for ease of transportation, and the connection of two adjacent panels does not transfer bending moments.

Various theories have been proposed, mainly in Germany and Austria, for the analysis of CLT panels under loads perpendicular to plane and the majority focuses on the calculation of the effective bending and shear stiffness based on the layer characteristics (thickness and grain direction). In chronological order, according to the references provided by Thiel and Schickhofer [5] for publications in the German language, Kreuzinger in 1999 presented the *Shear Analogy* method and Blass and Gorlacher in 2003 suggested the *Modified Gamma* method, which stems from the *Mechanically Jointed Beams Theory* or *Gamma* method, available in Annex B of Part 1-1 of Eurocode 5 [6]. Finally, Schickhofer et al. proposed the *Timoshenko* beam theory in 2009 as a simplified alternative.

The *Modified Gamma* method is probably the most common approach in Europe. It can be implemented with the Euler-Bernoulli beam element as no shear deformations are considered, but accounts indirectly for them by calculating the effective bending stiffness based on the efficiency of the connection between the longitudinal layers (those with grain parallel to the beam length). This connection is provided by the shear stiffness of the internal transverse layers (those perpendicularly oriented to the beam length). The method is applicable to a 3- or 5-layer CLT panel but can be extended to 7- and 9-layer panels, as well. The effective bending stiffness $EI_{eff,Gamma}$ is calculated as:

$$EI_{eff,Gamma} = \sum_i \left(E_i \cdot b_i \cdot h_i^3/12\right) + \sum_i \left(\gamma_i \cdot E_i \cdot b_i \cdot h_i \cdot z_i^2\right) \tag{1}$$

where E_i is equal to the modulus of elasticity parallel to grain E_0 for longitudinal layers while for transverse layers E_i is considered in this method equal to zero; b_i is the width, h_i the thickness and z_i the distance from the centroid of the ith layer to the centroid of the cross section; γ_i is the connection efficiency factor that is non-zero only for longitudinal layers and equal to unity for the middle layer. The latter is computed as:

$$\gamma_i = \left(1 + \frac{\pi^2 \cdot E_i \cdot b_i \cdot h_i}{L_{eff}^2 \cdot (G_{90,j} \cdot b_j)/h_j}\right)^{-1} \tag{2}$$

where L_{eff} is the effective length of the beam; j refers to the transverse layer connecting the ith layer with the central layer and G_{90} is the shear modulus in the plain perpendicular to grain or rolling shear modulus. As it can be observed from Eq. (2), the connection efficiency factor depends on the effective length of the beam, that is the length of the beam between the two zero-moment points (inflection points). Fig. 2 illustrates qualitatively the normal and shear stress diagrams in a CLT section for various values of the connection efficiency factor γ. As γ approaches unity, the longitudinal layers work as part of the whole cross section, while, as it approaches zero, they work as independent layers under bending.

As for the *Timoshenko* beam theory, the bending stiffness is calculated as shown in Eq. (1) considering, though, γ_i equal to unity for all layers and E_i equal to E_{90} for transverse layers, where E_{90} is the elastic modulus perpendicular to grain. Thus, the stress profiles are similar to those shown in Fig. 2a. The effective shear stiffness $GA_{eff,Timo}$ is calculated as:

$$GA_{eff,Timo} = \kappa \cdot GA = \kappa \cdot \sum_i (G_i \cdot b_i \cdot h_i) \tag{3}$$

where G_i is equal to the shear modulus in planes parallel to grain G_0 for longitudinal layers and to the rolling shear modulus G_{90} for transverse layers; κ is the shear correction factor that, for most

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