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Cross laminated timber at in-plane beam loading – Prediction of shear stresses in crossing areas

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ABSTRACT

Cross Laminated Timber (CLT) at in-plane beam loading conditions present a very complex stress state and many failure modes need to be considered in design. The work presented here aims at finding improvements of a specific analytical model for stress analysis and strength verification that has been suggested in literature and which is also suggested as a basis for design equations for the next version of Eurocode 5. Although the model has appealing properties it suffers from some drawbacks related to the assumed distributions of internal forces which, based on comparison to finite element analysis, appear to be inaccurate. The main focus in this paper is on model predictions regarding the distribution and magnitude of internal forces acting in the crossing areas between longitudinal and transversal laminations. The proposed modified model assumptions regarding the distribution of lamination shear forces, which in turn influence the forces acting in the crossing areas, are suggested to be taken into account in design of CLT beams.

1. Introduction

Using Cross Laminated Timber (CLT) at in-plane beam loading conditions is very relevant from a practical engineering point of view, since the transversal layers have a reinforcing effect with respect to stress perpendicular to the beam axis. The stress state is however very complex and many failure modes and geometry parameters need to be considered in design. A particularly challenging task is strength verification with respect to in-plane shear where three failure modes need to be considered: gross shear failure (mode I), net shear failure (mode II) and shear failure in the crossing areas between adjacent longitudinal and transversal laminations (mode III).

Experimental tests on CLT beams are for example reported by Joebstl et al. [1], Bejtka [2], Andreolli et al. [3], Flaig [4], Flaig & Blass [5] and Danielsson et al. [6]. A comprehensive experimental investigation and design concepts of CLT diaphragms at shear loading are further presented by Brandner et al. [7]. The stress state differs however partly between in-plane loading of CLT diaphragms and CLT beams, for example regarding the stresses relevant for shear failure mode III.

An analytical model for stress analysis and strength verification of CLT beams has been presented by Flaig [4,8–10] and by Flaig & Blass [5], including proposals for stress based failure criteria for relevant failure modes. This model has also been used as a basis for design equations in the ongoing revision work of Eurocode 5 (EC5). The shear stresses acting in the crossing areas between longitudinal and transversal laminations (relevant for shear failure mode III) can according to Flaig and Flaig & Blass, with sufficient accuracy, be assumed to be uniformly distributed in the beam width direction, irrespective of the element lay-up. The torsional moments acting in the crossing areas are furthermore assumed to be uniformly distributed over all crossing areas in the beam height direction. Based on comparison to 3D FE-analyses as presented in [11], both these assumptions seem to be inaccurate.

The aim of this paper is to give a brief review of the analytical model presented by Flaig and Flaig & Blass and, in addition, also to present improvements of that model. The improvements relate to the magnitude and distribution of internal forces and stresses relevant for determination of load bearing capacity with respect to shear force. The main focus is here placed on the magnitude and distribution, in both the beam width and the height directions, of the forces and stresses acting in the crossing areas and how these are influenced by the beam geometry.

2. Analytical model

A brief review of the model presented by Flaig [4,8–10] and by Flaig & Blass [5] for calculation of internal forces and stresses relating to relevant failure modes for CLT beams is presented below. More detailed reviews of the considered model are presented in [6,11], where also

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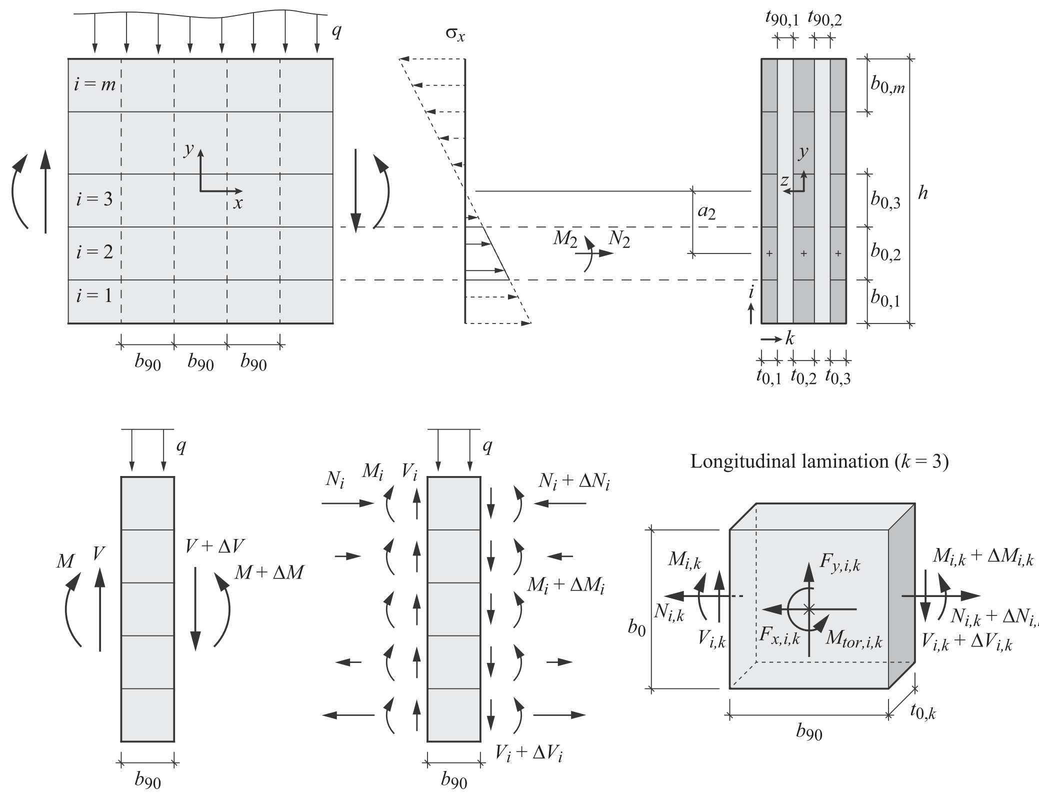

Fig. 1. Illustration of beam model and definition of load and geometry parameters.

experimental tests and comparison of model predictions and test results are presented.

The equations presented below are based on notation for geometry and load parameters according to Fig. 1. They further relate to prismatic CLT beams without edge-bonding and composed of longitudinal and transversal laminations having identical stiffness properties. Index i refers to the position of the longitudinal laminations in the beam height direction and index k refers to the position of the longitudinal and transversal layers in the beam width direction.

Cross section forces and bending moments are considered on three separate levels according to Fig. 1: (V,N,M) refer to the forces and the bending moment acting on the total cross section, (V_i,N_i,M_i) refer to the sum of forces and bending moments acting in all k longitudinal laminations for a certain i and $(V_{i,k},N_{i,k},M_{i,k})$ refer to the forces and the bending moment acting in an individual longitudinal lamination i,k.

2.1. Bending

The *maximum* normal stress in the longitudinal layers, due to bending, is given by

$$\sigma_x = \frac{M}{W_{net}} \quad \text{where} \quad W_{net} = \frac{t_{net,0}h^2}{6} \tag{1}$$

where M is the bending moment, $t_{net,0} = \sum t_{0,k}$ is the sum of the widths of the longitudinal layers, i.e. the longitudinal net cross section width, and h is the beam height.

2.2. Shear mode I and mode II

Schematic illustrations of the shear stress distributions in the longitudinal and transversal layers are presented in Fig. 2. The illustrations relate to beams having an integer number of longitudinal laminations, m, of identical width, b_0, in the beam height direction. Section A-A refers to a section through the centre of a transversal lamination while section B-B refers to a section in-between two adjacent transversal laminations. The shear stresses in the longitudinal and transversal layers are here denoted $\tau_{xy,0}$ and $\tau_{xy,90}$, respectively.

The *maximum* value of the gross shear stress (shear mode I) is given by

$$\tau_{xy,gross} = \frac{3}{2}\frac{V}{t_{gross}h} \tag{2}$$

where V is the shear force and $t_{gross} = \sum t_{0,k} + \sum t_{90,k}$ is the gross cross section width. For verification with respect to gross shear failure, relevant for CLT elements with edge-bonding, characteristic shear strength according to the strength class of the laminations according to EN 338 and use of $k_{cr} = 1.0$ is proposed in [9]. Brandner et al. [7] suggest to use a characteristic shear strength of 3.5 MPa for CLT composed of C24 laminations and to account for the influence of possible cracks by disregarding half of the width of the outermost layer on each side of the beam, when determining t_{gross} and $\tau_{xy,gross}$ according to Eq. (2).

The *maximum* values of the net shear stress in the longitudinal and transversal layers (shear mode II) can according to [9], with sufficient accuracy, be expressed as

$$\tau_{xy,0} = \tau_{xy,net,0} = \frac{3}{2}\frac{V}{t_{net,0}h} \tag{3}$$

$$\tau_{xy,90} = \tau_{xy,net,90} = \frac{3}{2}\frac{V}{t_{net,90}h} \tag{4}$$

where $t_{net,0} = \sum t_{0,k}$ and $t_{net,90} = \sum t_{90,k}$ refer to the net cross section widths of the longitudinal and transversal layers, respectively. Eq. (3) is based on assuming that the total shear force is uniformly distributed over the m longitudinal laminations, i.e. $V_i = V/m$. The maximum values of the shear stress distributions $\tau_{xy,90}$ and $\tau_{xy,net,90}$ are exactly equal for beams with an even number of laminations, m, in the beam height direction while they differ slightly for beams with an odd number m, see Fig. 2. For net shear failure, a characteristic shear strength of 8.0 MPa is suggested in [9]. Test results indicate an influence of the width t of the