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A simple strategy for constitutive modelling of timber

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HIGHLIGHTS

- Development of an orthotropic constitutive law for timber.
- Nonlinear finite element analysis of timber and engineered wood products.
- Capturing failure mode of timber using isotropic material models.
- Application of theory of composites for modelling timber behaviour.

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ABSTRACT

This paper focuses on development of a simple technique for modelling anisotropic behaviour of timber and engineered wood products. In the proposed approach, timber is treated as a composite material comprising a matrix with smeared fictitious reinforcing fibres in the principal directions. The matrix is assumed to be isotropic with a piecewise continuous failure envelop in the bi-axial stress space and the reinforcements follow uni-axial stress–strain relationships with different strengths under tension and compression. The stress–strain relationship of timber is obtained by superimposing the constitutive law of matrix and the fictitious reinforcements based on the principles of compatibility and equilibrium. Such a modelling strategy provides a simple platform for calibration of the constitutive law against available mechanical properties of the timber in different directions (i.e. parallel or perpendicular to the grain). The proposed modelling technique is implemented in a finite element code and the developed analytical tool is verified by examples taken from the literature including bending tests on timber beams with notches and web openings, embedding tests on timber and push-out tests on TCC joints. It is shown that the proposed modelling strategy can adequately capture the mode of failure as well as the nonlinear behaviour of timber at local and global level.

1. Introduction

In the last decade, timber and timber–concrete composite (TCC) structures have found extensive structural applications because of the lower cost of construction and maintenance, as well as better sustainability compared with reinforced concrete and steel. In particular the new engineered wood products (i.e. laminated veneer lumber (LVL), glued-laminated timber (glulam), cross-laminated timber (CLT) and oriented strand boards (OSB)) with improved structural characteristics have made it possible for structural engineers to design and construct large buildings that are as robust as steel and reinforced concrete but more sustainable. Accordingly, there is a need for development of simple yet accurate modelling strategies that can adequately capture the failure modes and load–deflection response of timber and engineered wood products.

Sawn and engineered timber such as LVL, glulam, CLT and OSB are anisotropic (orthotropic or two-dimensionally isotropic) materials with different strengths in tension and compression [1]. Also, behaviour of timber is strongly direction-dependent with large ratios of mechanical properties such as modulus of elasticity or strength between the respective values parallel and perpendicular to the grain directions. In tension, timber exhibits a nearly linear elastic–brittle failure behaviour and under compression the hardening part of the stress–strain diagram is nonlinear with limited ductility up to ultimate stress which is followed by a mild softening part [2,3]. In addition, compression perpendicular to the grain direction can lead to wood densification and subsequent increase of yield (ultimate) strength.

Apart from anisotropy, wood is an inhomogeneous material owing to presence of knots and defects. These defects/imperfections can locally affect the grain deviation and subsequently influence

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the mechanism and mode of failure. Over the last decade, different experimental and numerical studies have been conducted to address the localised behaviour of knots and its influence on the response of the timber beams [4–6]. Also, different methods for modelling knots have been developed and it has been concluded that modelling a knot as a hole can be a reasonable assumption, provided the knot is located within the tensile zone of flexural members [5]. In such situations, the failure is triggered by combination of shear and tensile stresses parallel and perpendicular to the grain. Accordingly, the local effects of knots should be taken into account when accurate analysis of timber beams is required, however, modelling the knots is beyond the scope of this paper.

The short- and long-term response of the timber and TCC structures depend strongly on the behaviour of timber. Accordingly, accurate analysis of timber structures requires constitutive laws which can adequately capture the stress–strain relationship and modes of failure under multi-axial stress states [7]. In a general classification the available constitutive laws of timber can be categorised as 1D, 2D and 3D. The 1D (uniaxial) stress–strain relationships are typically empirical models which are solely established on fitting curves against the experimental data without a rigorous mechanical/mathematical postulate used [2,8]. The uniaxial stress–strain relationships in conjunction with frame fibre element models have been successfully used for capturing the flexural response of timber and TCC beams at global level [9–11]. In 2D and 3D constitutive laws a mechanical/mathematical postulate is usually adopted to capture the onset of yielding/failure and determine the evolution of damage or plastic flow under multi-axial stress states. In FE modelling of timber and TCC systems, the 2D and 3D constitutive laws are normally used for capturing the detailed local behaviour of connections/joints [1,7,12–18] and for capturing the global response of timber and TCC beams the 1D models are considered to be adequate [9–11].

The 2D and 3D phenomenological constitutive laws of timber can be classified as elasticity-based models (e.g. equivalent uniaxial and invariant-based models) [7], plasticity-based models including classical plasticity, bounding surface plasticity and multi-surface plasticity [1,13,17,19–22], models based on progressive damage and fracture mechanics [23,24], continuum damage models and combination of plasticity with damage and fracture models [25]. Most of the existing anisotropic constitutive laws, however, are not applicable for practical engineering design of timber mainly because such models need too many input parameters to be properly calibrated [20,21,26] and require advanced integration schemes [27,28]. Also, some of these models do not allow unequal tensile and compressive strengths for materials which is not consistent with the real behaviour of timber [21]. In addition, the anisotropic plasticity-based constitutive laws typically tend to overestimate the loading capacity and stiffness of timber because they do not allow for progressive damage and softening of material [12,26,29].

In this paper a simple strategy for modelling anisotropic behaviour of timber is proposed that can adequately capture the global as well as the localised failure modes associated with stress concentrations. In the proposed technique, timber is treated as a composite material comprising a matrix with smeared reinforcing fibres. The failure of this matrix under bi-axial stress states is captured by an isotropic piecewise continuous failure surface that allows different strength in tension and compression and constitutive law of the matrix is formulated within the framework of equivalent uniaxial strain. For the reinforcing fibres, a uni-axial stress–strain relationship with different strengths under tension and compression is adopted. The stress–strain relationship of the timber is obtained by superimposing the constitutive law of the matrix and the reinforcements based on principles of compatibility and equilibrium. This approach provides a flexible platform for calibrating the constitutive law of timber against commonly available mechanical properties, i.e. tensile and compressive strengths as well as moduli of elasticity parallel or perpendicular to the grain. In addition, the proposed strategy is more robust and stable compared with similar techniques such as the layered approach [7] in which the orthotropic behaviour of timber is captured by introducing contact elements between different layers. The knots and grain deviations in timber are not modelled in this study; however, the proposed modelling strategy can be used in conjunction with methods such as the ones developed by Baño et al. [5] (e.g. knot is modelled as a hole) to capture the influence of knots/defects on the behaviour of timber elements. It is shown that the proposed modelling strategy can adequately capture the nonlinear behaviour and the failure modes of timber at local and global level.

2. Constitutive law of timber

2.1. Piecewise continuous orthotropic failure envelop

The failure points under different biaxial stress states for a spruce wood specie [30] are given in Fig. 1 and it is seen that an ellipse can adequately represent the failure envelop. Accordingly, some researchers such as Tsai and Wu [19] have proposed a fit with a second-order tensor polynomial (an ellipse in bi-axial stress state) as a first approximation of the actual behaviour of orthotropic composites (see Fig. 1). The elliptical envelops have shown merits to capture the failure of timber and engineered wood products under biaxial stress states [1]; however, they typically overestimate the strength of timber for stress states shown in the shaded domain of Fig. 1.

With regard to the experimental results shown in Fig. 1, a piecewise continuous failure envelop can be adopted that allows for accurate calibration of the constitutive law under different stress state regimes. The schematic outline of the piecewise continuous failure envelop inspired by failure surface of quasi-brittle materials is shown in Fig. 2.

The failure envelop in the tension–tension region is based on Rankine criterion [31] (see Fig. 2).

$$\begin{cases} \sigma_1/X^T - 1 = 0 & : \text{Tensile failure parallel to grains} \\ \sigma_2/Y^T - 1 = 0 & : \text{Tensile failure perpendicular to grains} \end{cases} \quad (1)$$

where σ_1 and σ_2 denote the maximum tensile strength parallel and perpendicular to the grain and X^T and Y^T are tensile strength of timber parallel and perpendicular to the grain, respectively.

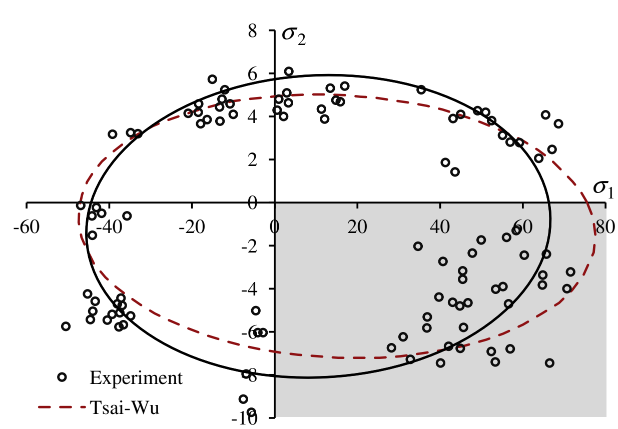

Fig. 1. Failure points obtained from bi-axial strength tests undertaken by Eberhardsteiner et al. [30] for a spruce wood specie, and the outline of an elliptical fit according to Tsai and Wu [19] failure criteria.