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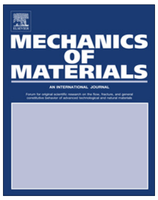

Numerical modelling of ductile damage evolution in tensile and bending tests of timber structures

A. Khennane [a], M. Khelifa [b,*], L. Bleron [b], J. Viguier [b]

[a] *School of Engineering and Information Technology, UNSW Canberra, Northcott Drive, ACT 2600 Canberra, Australia*
[b] *University of Lorraine, ENSTIB/LERMAB, 27 rue du Philippe Séguin, Epinal, France*

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ABSTRACT

The characteristic values for strength and stiffness of all sorts of timber products are based on the assumption of a linear relation between stress and strain prior to failure and consequently verification of the load-bearing capacity of individual members in a construction is also based on a similar linear relation. Such an approach is very conservative and ill suited for performance-based design, which requires a full analysis of the structure with the possibility of moment and/or stress redistribution within parts of the structure. The development of material models that encompass the complex behaviour of wood is therefore necessary. The present work presents a model formulated within the frameworks of plasticity and continuum damage mechanics (CDM). It applies the classical flow theory of plasticity to formulate ductile failure of wood in compression and damage mechanics for the brittle failure modes. It takes into account the orthotropic elastic behaviour, the plastic anisotropic isotropic hardening, the isotropic ductile damage, and the large plastic deformations. The model was used to predict the initiation and growth of ductile damage in tensile and bending tests on different timbers types. Good agreement was found between the predictions of the model and the experimental results.

1. Introduction

Finite element analysis of timber structures has acquired great importance in recent years due to the short supply of wood and increasing environmental awareness among users and manufacturers. Nowadays most of timber used in the construction industry comes from sustainable softwood plantations. This type of timber has lower elastic and strength properties than its hardwood counterpart. As a result, new designs of timber structures need to be optimised not only for stiffness and strength but also for cost. The best way to achieve such outcomes is through the use of numerical simulation. Successful numerical simulations however require realistic constitutive models that encompass the complexities of wood as a material. Its anisotropic nature limits the applicability of analytical models. It is highly orthotropic with large ratios of mechanical properties and strength between the respective values parallel and transverse to the grain direction. Its failure in compression in the direction parallel to the grain is very different from that perpendicular to the grain. At angles to the grain between 10° and 45°, the failure modes are brittle due to the activated transverse tension and shear. However, as the angle increases, the failure modes shift from brittle to ductile with large deformations leading to the onset of micro-defects as voids and micro cracks as supported by experimental evidence on different wood species as reported in Poulsen (1998), Reiterer and Stanzl-Tschegg (2001), Sandhaas (2012). When these micro-defects initiate and grow inside the plastically deformed wood, the stress and strain fields are deeply modified, leading to significant modifications in the deformation process itself. The coalescence of these defects can lead to the initiation of macro cracks or damaged zones, inducing an irreversible damage.

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[*] Corresponding author. Tel.: +33 (0) 3 29 29 61 18.
E-mail address: mourad.khelifa@univ-lorraine.fr (M. Khelifa).

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Yet this complex behaviour is seldom taken into account in standards of practice. For instance, in Eurocode 5 (1995) the characteristic values for strength and stiffness of all sorts of timber products are based on the assumption of a linear relation between stress and strain prior to failure and consequently verification of the load-bearing capacity of individual members in a construction is also based on a similar linear relation except for members subjected to compression loading, for which a nonlinear elastic-plastic computation may be used. The maximum stress a timber member can resist is a function of the deformation modes and takes the form of a relationship between the low and large strains. Hence, it is necessary that load levels everywhere remain within the limit strengths fixed by EC5 in order to avoid damage occurrence. Such an approach is very conservative and ill suited for performance-based design, which requires a full analysis of the structure with the possibility of moment and/or stress redistribution within parts of the structure. A material model capable of being used in performance-based design must encompass the complex behaviour of timber. The latter can only be captured through the use of multidimensional failure criteria. Because of the interactions between brittle and ductile failure modes, it is crucial to use coupled constitutive equations accounting for both non-linear isotropic hardening and isotropic ductile damage.

The development of such models however has been hampered by the lack of data. It was only until the mid 80's that data on the general effect of multi-axial state of stress were made available (Mackenzie-Helnwein et al., 2003). Nonetheless some notable efforts were made to model the generalised behaviour of wood; among them the use of fracture mechanics (Barrett et al., 1981; Smith et al., 2003; Vasic et al., 2005; Van der Put, 2007), plasticity (Mackenzie-Helnwein et al., 2003), and damage mechanics (Wittel et al., 2005; Qing and Mishnaevsky, 2011). However all of the approaches suffer from some drawbacks. Fracture mechanics based models are very complex and computationally very expensive because of the required model scale and mesh size. Plasticity on its own is not capable of capturing stiffness degradation. As to damage, it is not capable of capturing permanent plastic deformations. More recently (Schmidt and Kaliske, 2009) developed a material model based on a multi-surface plasticity formulation with anisotropic, moisture and temperature dependent yield surfaces and direction dependent post-failure behaviour to model the permanent deformations and cohesive elements to discretely model tension and shear cracks. This formulation however required the definition of an interface element formulation with traction separation law for wood.

In the present work, a material model which can be easily implemented in existing finite element software is presented. The model is capable of describing the complex behaviour of timber. It is formulated within the frameworks of plasticity and continuum damage mechanics (CDM). It applies classical flow theory of plasticity to formulate ductile failure of wood in compression and damage mechanics for the brittle failure modes. It takes into account the orthotropic elastic behaviour, the plastic anisotropic isotropic hardening, the isotropic ductile damage, and the large plastic deformations. The wood material is considered as a continuous medium. The macroscopic approach not only saves considerable CPU time, but most studies have shown that it can successfully estimate the states of stress and strain (Khelifa et al., 2007; Oudjene and Khelifa, 2009). Furthermore, a material model based on CDM and plasticity can be easily implemented as a subroutine in existing finite element software. The model is used to predict damage occurrences in tensile and bending tests.

2. Constitutive equations for wood including damage

Wood is a lignocellulosic material admitting cylindrical symmetry. The presence of growth rings, which are used to indicate the age, contributes to some material heterogeneity. Yet in the mechanics of continuous media, it is assumed continuous and macroscopically homogeneous. Hence based on the geometry of a log, a Cartesian coordinate system LRT is defined as shown in Fig. 1.

The material model uses the coordinate system shown on Fig 1, and is formulated within the framework of thermodynamics of irreversible processes with internal variables (Khelifa et al., 2007; Oudjene and Khelifa, 2009; Lemaitre and Chaboche, 1978; Lemaitre and Chaboche, 1985; Murakami, 1988; Saanouni et al., 1994).

The state relations are written as:

$$\underline{\sigma} = (1 - D)\underline{\underline{\Lambda}} : \underline{\varepsilon}^e \quad \text{(Cauchy stress tensor)} \tag{1}$$

$$R = (1 - D) \times Q \times r \quad \text{(Isotropic hardening stress)} \tag{2}$$

$$Y = \frac{1}{2}\underline{\varepsilon}^e : \underline{\underline{\Lambda}} : \underline{\varepsilon}^e \quad \text{(Isotropic damage driving force)} \tag{3}$$

where D represents the damage parameter, $\underline{\varepsilon}^e$ represents the elastic strain tensor, $\underline{\sigma}$ the Cauchy stress tensor; (R, r) two scalar variables representing the isotropic hardening stresses, Q the isotropic hardening modulus, and $\underline{\underline{\Lambda}} \equiv \Lambda_{\mathrm{ijkl}}$ the fourth-order operator of the elastic properties given as:

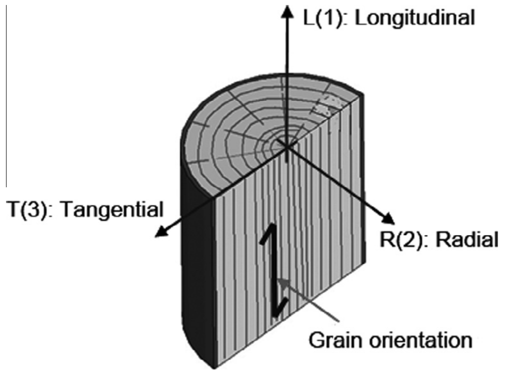

Fig. 1. LRT coordinate system for wood.