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An algorithm to model wood accounting for different tension and compression elastic and failure behaviors

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A B S T R A C T

Wood, as a natural heterogeneous material, is a challenging material to simulate. This work presents an algorithm to model both its elastic and post-elastic responses. It allows to model different compression and tension elastic and failure behaviors in both material directions, parallel and perpendicular to the grain. It employs two different strategies: a sequential application of different failure criteria, and the modeling of post-elastic response by means of damage and stress reduction parameters. The proposed algorithm is applied to spruce in two experimental cases with different loadings and failure modes. When reasonable mesh density and increment size are used, the obtained results are in good agreement with the experimental results. The proposed algorithm has been programmed in the commercial software ABAQUS. However, it may be easily applied to different platforms or wood species.

1. Introduction

Wood is a natural material, and therefore, a very heterogeneous material. Apart from the differences between particular species, other features, such as knots and grain direction, highly influence its properties and response [1].

The previously referred heterogeneity, its so called defects or characteristics of growth and its anisotropy make timber a challenging material to model by means of finite element analyses. It has been already outlined the need to model such properties in order to get more accurate models [1–6]. Predictive methods and models for the simulation of structural behavior are required.

Commercially available software packages do not include appropriate models for wood. Therefore, researchers have created their own material models by means of user defined subroutines [1,7–12].

The most accurate and general models to predict the onset of damage and ultimate failure of structures are based on the implementation of constitutive models developed in the context of continuum damage mechanics in finite element (FE) models [9,11,12]. Fracture mechanics has been applied as well to model wood connections [13–16]. These latter require the predefinition of the crack starting point and often the crack growth direction too.

A failure criterion is required to determine the onset of damage. Phenomenological criteria, which were originally intended for composite materials, such as Tsai-Wu [17], are mainly used. Several works have assessed the performance of the usual failure criteria for wood [18–21]. A number of numerical models for wood have incorporated these failure criteria [7,8,22–26] as a way to determine failure onset.

For a comprehensive modeling, not only an appropriate failure criterion is required, but also an adequate model of the progressive failure of the wood material is needed. As explained, some researchers [1,7–12] have dealt with the problem by means of defining a new material model. The USDFLD subroutine has been used to accomplish progressive failure based on degradation factors in composite materials [27,28]. Examples for the use of the USDFLD routine in timber are scarce. Andre et al. compared the performance of a USDFLD subroutine with a region of stiffness degradation for uniaxial compression behavior, and concluded it was an adequate modeling strategy [29].

This work proposes an algorithm to model wood behavior by means of user subroutines. Progressive failure parameters are introduced by the user-defined subroutine USDFLD integrated in ABAQUS. The USDFLD subroutine is a user subroutine to redefine field variables at a material point as functions of time or any of the available material quantities listed in the Output Variable Identifiers Table. It can be used to introduce solution-dependent material properties. This paper shows how to model progressive failure in the material and how to implement both ductile and fragile

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failure modes. It may be extended to model other materials, even with different software packages. After an introduction to the required background information on elastic and failure behavior in wood and progressive damage in Section 2, the proposed algorithm is presented in Section 3. Its application is demonstrated for two different structural cases in Section 4.

2. Background information and methods

2.1. Tension and compression elastic moduli

Wood is usually considered to be a material with equal tension and compression stiffness. However, there is a strong evidence of wood as a bimodular material, with different tension and compression elastic moduli [30]. For small clear specimens, such differences may depend only on the species [31]. For full-size spruce structural timber, it has been shown that the modulus of elasticity in bending and tension depend on the type of load as well as on timber quality (knots, grain deviation...) [32]. Such difference is quite relevant, as addressed by Shim et al. [33], who found a prediction error of about 30% for beams in bending when it was not taken into account. They consequently emphasized the need to take it into account.

The proposed algorithm allows the use of different elastic moduli for tension and compression. It redefines the material properties of the corresponding element according to the actual stress state. It provides a more realistic way to model wood, even when failure is not accounted for.

2.2. Failure modes in wood

Wood is a highly anisotropic material, with very different failure modes. After testing clear spruce wood panels under multiaxial conditions, Mackenzie-Helnwein et al. [24] identified four failure modes:

- *Brittle tensile failure in fiber direction:* This mode shows a sudden decrease of the strength. On the macroscopic level, a crack pattern is produced.
- *Brittle tensile failure perpendicular to the grain:* This mode exhibits a crack parallel to the fiber direction.
- *Ductile compressive behavior perpendicular to the grain:* Its behavior is similar to a plastic hardening as shown in Fig. 1. Some strength degradation (noted as $\sigma_{post,i}$) of the initial failure stress, S_i, is usually observed in the post-elastic plateau. The densification that usually takes place at high deformation is dismissed in this proposal.
- *Compressive failure in fiber direction:* After initial failure, a stress degradation of about 70–80% of the initial failure stress S_i is found in the plateau.

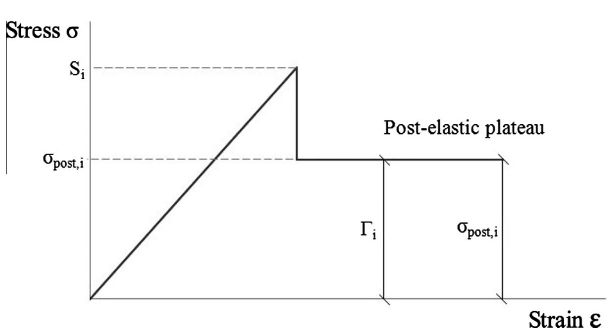

Fig. 1. Parameters to define the ductile compressive behavior.

2.3. Implementation of the failure criteria

Failure criteria which were originally developed for composite materials have been widely used for wood. The Hill failure criterion [34] is adopted in this paper for every possible stress combination. It is used as a generic quadratic failure criterion and for demostration purposes, since any other criterion could be implemented in the proposed algorithm. This criterion was based in the Von Mises yield criteria [35] and it was first developed for anisotropic metals, but now it is widely used.

The Hill criterion [34] is written as:

$$\begin{aligned} 1 = & F(\sigma_R - \sigma_T)^2 \\ & + G(\sigma_T - \sigma_L)^2 \\ & + H(\sigma_L - \sigma_R)^2 \\ & + 2L\tau_{RT}^2 + 2M\tau_{LT}^2 + 2N\tau_{LR}^2, \end{aligned} \tag{1}$$

where:

$$F = \frac{1}{2}\left[\frac{1}{S_R^2} + \frac{1}{S_T^2} - \frac{1}{S_L^2}\right], \tag{2}$$

$$G = \frac{1}{2}\left[\frac{1}{S_T^2} + \frac{1}{S_L^2} - \frac{1}{S_R^2}\right], \tag{3}$$

$$H = \frac{1}{2}\left[\frac{1}{S_L^2} + \frac{1}{S_R^2} - \frac{1}{S_T^2}\right], \tag{4}$$

$$L = \frac{1}{S_{LR}^2}, \tag{5}$$

$$M = \frac{1}{S_{LT}^2}, \tag{6}$$

$$N = \frac{1}{S_{RT}^2}, \tag{7}$$

where S represent the material strengths for each direction and type of stress. The subscripts refer to the directions of the wood, longitudinal L, radial R and tangential T, which form a cylindrical coordinate system. In this paper, as it is the usual practice, wood is analyzed in a rectangular coordinate system. The result is a simplification into an orthotropic material with geometric and orthotropic axes coincident [36]. In each stress quadrant, the corresponding material strengths for tension or compression are used [20]. As usual in many failure criteria, when the general expression of the criterion (1) is equal or higher than unity, the material is assumed to fail.

For each finite element, failure states for each material direction are individually considered. Failure is not considered to be complete until the three directions have failed.

Fig. 2 describes the employed methodology, in which the failure criterion is sequentially modified by dismissing the already failed directions. The ellipsoid A_{LRT} represents a generic three-dimensional failure criterion in the $\sigma_L - \sigma_R - \sigma_T$ stress space, which is used before any failure has been detected.

When failure is detected (point a in Fig. 2), the corresponding damage d_i and stress degradation r_i parameters are modified to reproduce the required post-failure behavior (Section 2.4). The failed material direction is dismissed for failure verification in following analysis steps. As a result, a bidimensional failure criterion (B_{ij} in Fig. 2) is used. When a second material direction is found to fail, it is dismissed as well, and failure in the remaining material direction is checked against a maximum stress criterion (C_i in Fig. 2).