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A constitutive numerical modelling of hybrid-based timber beams with partial composite action

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HIGHLIGHTS

- A numerical methodology to simulate the flexural behaviour of the hybrid timber beams was developed.
- The model was implemented as an external subroutine in Abaqus FE software.
- Comparison between experimental and numerical results is given.

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ABSTRACT

This work focuses on the development of a three dimensional constitutive model for timber to simulate the flexural behaviour of hybrid timber-steel and timber-concrete beams. This is motivated by the lack of dedicated non linear material behaviour laws for timber in the commercial finite element software by compared to the conventional materials such as concrete and steel.

The flexural behaviour of hybrid timber beams is very complex because of the combination of the two different material behaviours and their nonlinar and partial compostion action. Numerical simulation of such behaviour requires an accurate description of the nonlinear material behaviour, in particular that of timber because of its anisotropic nature. A realistic description of the material nonlinearities and of the composite action between the different materials could aid considerably in achieving acceptable predictions. An incremental approach based on the strong coupling between orthotropic elasticity, anisotropic plasticity with mixed nonlinear isotropic hardening and an isotropic damage is used. The developed constitutive model for timber is implemented in Abaqus code using an external subroutine. The 3D FE model is calibrated and validated through comparison with experimental data reported in literature. The model is able to predict the nonlinear structural response of hybrid beams in terms of load-midspan deflection, and provides an acceptable accuracy.

1. Introduction

Timber is a structural material widely used in the engineering applications, and it is lightweight and strong. It is easier to process than steel or concrete as it requires much less energy. It is renewable, nontoxic and has a high thermal efficiency. Additionally, it is a net carbon absorber and it can be easily recycled. This environmental interest has sparked a need for a high level of knowledge of its structural behaviour, which in turn requires the characterisation of its intrinsic mechanical properties to guarantee the reliability and stability of timber structures [1].

Timber is a highly orthotropic material, and its mechanical and dimensional characteristics exhibit an exceptionally high variability with time, temperature and moisture content [2]. Tabiei and Wu [2] present a nonlinear material model with power functions to capture the stiffness change based on initial stiffness. In this work, a modified Johnson model [3] was developed to take into account the influence of strain rate on the dynamic response of timber material [2], and the parameters of the used model were adjusted to improve the fits between the predicted and the measured results.

Concerning the mechanical characterization there are a large amount of experimental studies dealing with the compressive behaviour of timber material, as reported by Reiterer and Stanzl-Tschegg [4]. These authors studied the compressive behaviour of spruce wood under uniaxial loading at different orientations with regard to the longitudinal and radial directions. The dependence of the Young modulus, Poisson ratio, crushing strength and failure mechanisms on the loading angle with respect to the grain

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orientation were also addressed using a Tsai-Hill's strength criterion. For analytical analysis, the wood material is commonly assumed to be orthotropic because it presents different mechanical properties in three directions: longitudinal, tangential and radial. Nonlinear material behaviour complicates the modelling of such material, as reported by many authors [2,4,5].

A variety of elastoplastic models for timber material have been developed for the yield surface of anisotropic compressible solids. Tagarielli et al. [6] proposed an elastic-plastic constitutive model for transversely isotropic compressible solids in which a quadratic yield surface with four parameters and one hardening function has been developed. The transversely isotropic cellular solid model [6] was used to simulate the indentation test of balsa wood. Good agreement was found between the finite element results and experimental ones. By extending the Hill [7] quadratic yield criterion for incompressible solids with orthotropic symmetry, Deshpande et al. [8] developed a yield surface for compressible solids. The authors [8] applied this criterion of plasticity to analyse the behaviour of the cubic Octet truss lattice under arbitrary states of stress. The predicted results revealed that the used compressible version of the Hill [7] model, presented in [8], is not able to predict the real plastic behaviour of the Octet truss material. Schellekens and De Borest [9] applied the Hoffman model [10] to study the behaviour of plate and shell structures. In this work [9], a simpler return mapping algorithm was developed, and the calculated results are accurate for curved parts of the yield surface. To simulate the behaviour of a double shear timber steel connection, Xu et al. [11] have proposed a plastic flow law based on the Hill criterion associated to the Hoffman criterion representing the evolution of damage in wood. The obtained results [11] showed that the modelling is adequate when calibrated by the load-slip experimental response. The use a simple elastoplastic model without damage affect, describing the material degradation, cannot lead to a quite good prediction of the global load-displacement behaviour up to failure. Moreover, none of these developments are yet used in the simulation of the behaviour of hybrid timber beams with damage effect. It was the aim therefore of the present study to simulate the damage evolution in hybrid timber structures within the framework of continuum damage mechanics and plasticity.

Recent years have witnessed a renewed interest in the use of hybrid timber-steel and timber-concrete beams in high rise buildings. Indeed, the concept of combining the two materials (timber-steel and timber-concrete) has many economical and environmental advantages [12–15]. The hybrid elements can replace structural steel and concrete beams in construction, thereby allowing significant time and cost savings. The inclusion of a ductile material, in this case steel, confers to the timber-steel beam a wide range of additional advantages such as reduced creep and a high shear capacity in comparison with solid timber, which is rather poor from this point of view, and which is also prone to brittle failure. The introduction of timber material into the concrete beams reduces considerably the weight of the structures, and constitutes a major advantage where the timber is stressed by the tensile forces and the concrete by the compressive forces.

Regarding to the coupling model between orthotropic elasticity, anisotropic plasticity and an isotropic damage at different loading orientations to the grain, there is a great lack in this field. A primary motivation of this work is thus the development of a constitutive law for timber material that will allow efficient numerical solution of large structural problems subjected to various static loading conditions. The work continues the effort underway by the authors for many years to develop continuum constitutive relations to characterize a wide range of engineering applications and to validate them using the analysis of the flexural behaviour of hybrid timber beams. In the modelling, the commercial code Abaqus [16] has been used with an external subroutine, which has been implemented based on a three-dimensional constitutive model developed in this study.

2. Timber constitutive model

2.1. Theoretical aspects

The hypothesis of small deformations allows the decomposition of the total strain tensor into two additive components: elastic part $\underline{\varepsilon}^e$ and a plastic part $\underline{\varepsilon}^p$ such that:

$$\underline{\varepsilon} = \underline{\varepsilon}^e + \underline{\varepsilon}^p \tag{1}$$

The elastic strain tensor is related to the Cauchy stress tensor $\underline{\sigma}$ through elastic law [17]:

$$\underline{\sigma} = (1 - D)\underline{\underline{\Lambda}} : \underline{\varepsilon}^e \tag{2}$$

where D is the isotropic damage variable; $\underline{\underline{\Lambda}}$ is the orthotropic elastic tensor of the material. The inverse has the form:

$$\underline{\varepsilon}^e = \frac{1}{(1 - D)}\underline{\underline{S}} : \underline{\sigma} \tag{3}$$

$\underline{\underline{S}}$ is the elastic compliance tensor and is given in a matrix form as:

$$\underline{\underline{S}} = \underline{\underline{\Lambda}}^{-1} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{23}} \end{bmatrix} \tag{4}$$

E_i is the elastic modulus in the direction (i); G_{ij} and ν_{ij} are, respectively, the shear modulus and Poisson's ratio in the plane (i-j).

The dissipative plastic potential F_p and the plastic yield criterion f can be stated as:

$$F_p = f + \frac{1}{2}\frac{1}{(1 - D)}\frac{b}{Q}R^2 + \frac{S}{(1 + s)}\left[\frac{Y}{S}\right]^{s+1} \tag{5}$$

$$f = \frac{\|\underline{\sigma}\| - R}{\sqrt{1 - D}} - \sigma_e \tag{6}$$

with:

$$\|\underline{\sigma}\| = \sqrt{\underline{\sigma} : \underline{\underline{P}} : \underline{\sigma} + \underline{L} : \underline{\sigma}} \tag{7}$$

$$\underline{\underline{P}} = \begin{bmatrix} \alpha_{13} + \alpha_{12} & -\alpha_{12} & -\alpha_{13} & 0 & 0 & 0 \\ -\alpha_{12} & \alpha_{23} + \alpha_{12} & -\alpha_{23} & 0 & 0 & 0 \\ -\alpha_{13} & -\alpha_{23} & \alpha_{13} + \alpha_{23} & 0 & 0 & 0 \\ 0 & 0 & 0 & 3\alpha_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & 3\alpha_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & 3\alpha_{66} \end{bmatrix} \tag{8}$$

$$= [\alpha_{11} \;\; \alpha_{22} \;\; \alpha_{33} \;\; 0 \;\; 0 \;\; 0] \tag{9}$$

$$Y = \frac{1}{2}\underline{\varepsilon}^e : \underline{\sigma} + \frac{1}{2}\frac{R}{(1 - D)}r = \frac{1}{2}\underline{\varepsilon}^e : \underline{\sigma} + \frac{1}{2}Qr^2; \quad R = (1 - D)Qr \tag{10}$$

r represents the isotropic hardening and associated to the isotropic stress R; Q and b are the isotropic hardening parameters; σ_e is the elastic limit; Y is the force associated with the isotropic damage D; S and s are the damage parameters. $\underline{\underline{P}}$ and $\underline{L}$ are the Hoffman tensors defined in [9–11]. The constants α_{ij} are obtained using the following relationships: