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Analysis of the behavior of multiple dowel timber connections in fire

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ABSTRACT

Being a combustible material, timber has not benefited from recent advances in fire research and associated computational work. However, as the design of timber structures is moving from prescriptive to performance based, there is a need for the development of material models that can be used in numerical simulations to predict fire resistance. A model based on continuum mechanics is therefore presented for the determination of the load bearing capacity of multi-dowel timber connections under fire. The model applies the classical flow theory of plasticity. It takes into account the orthotropic elastic behavior, the plastic anisotropic hardening, the large plastic deformations, and the effect of heat. Qualitatively, the predicted results agree with the experimental ones. The model can be easily implemented as a subroutine in existing finite element software.

1. Introduction

Timber consists mainly of cellulose and lignin which are formed of carbon, oxygen, and hydrogen, and therefore combustible. As a result prescriptive codes of practice have greatly restricted its use in buildings. Unlike steel and concrete for which there is a large body of literature under fire [1–5] just to cite a few, timber has not benefited from recent advances in fire research, in particular the associated computational work. However, with the move of fire safety engineering from a prescriptive to a performance base in the last two decades, there is currently renewed interest in the use of timber in the construction industry. Indeed, performance based regulations are not biased against any material [6]; all that is required is that the building achieves the goals it is designed for. One of such goals is structural adequacy. It is a functional requirement that the structure remains stable to allow adequate time for safe evacuation and rescue [7]. One of the key features however for implementing the performance-based fire design codes is the assessment of the fire resistance of the structure as a whole, hence the need to study the thermo-mechanical behavior of timber at elevated temperatures and develop material models suitable for numerical implementation.

Timber is a consumable material. Total combustibility of structural elements is however very rare. The development of a growing layer of charcoal acts as an insulator and protects the inner core but, at the same time, it does reduce the effectiveness of the cross-area to carry loads as shown in Fig. 1.

In addition, the existence of a temperature gradient in the inner core beneath the charred layers directly affects the mechanical properties of the wood as reported in [8–13]. The coupling of these physical and mechanical phenomena could led to the modification of the initial load bearing capacity of the structure, which in turn could eventually lead to total collapse. Another aspect of timber design is the role of connections in the stability of the structure. Their design is critical since they provide continuity to the members, strength and stability to the system. Of the all the aspects of timber design, they are the least understood. This is even more so in a fire situation because they are characterised by sharp corners and large surface-to-volume ratios, which results in less favorable fire behavior.

Connections used in timber structures are categorised according to different criteria. The first criterion is the type of the connection: mechanical, adhesive or combined. As a consequence therefore of the different fastening methods, and the complexity of the failure modes of timber, Eurocode 5 [14] does not allow currently a complete modelling of the variety of connections used in timber structures. Numerical simulations remain therefore the only reliable method of predicting the complex behavior of these connections. Numerical simulation not only allows a better

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0379-7112/

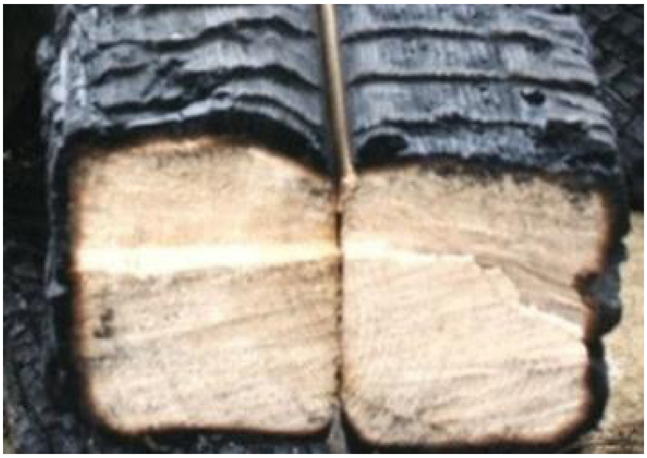

Fig. 1. Charcoal protective layer.

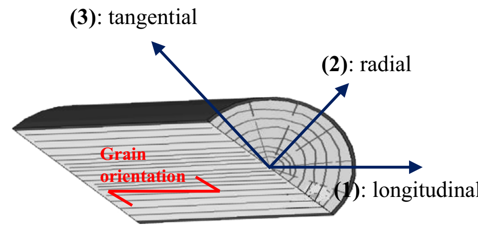

Fig. 2. Coordinate system for timber.

understanding of the failure mechanisms but also a mean of optimising the parameters governing the behavior of the connections. Yet, there are very few publications on the three-dimensional modelling and practical applications. This area of research remains significant and the use of numerical simulations is essential if we are to understand the failure mechanisms of connections, and thus improve the reliability of the existing calculation models.

It is only very recently that some notable efforts were made to model the behavior of timber connections in a fire environment [15–20]. These models require the use the embedment strength of the fastener. They assume that each material composing the assembly has a perfect rigid-plastic behavior which is not the case in practice. The procedure and definition of the embedment strength are detailed in EN 383–1993 [21]. This test provides load–displacement curves that express the mechanical performance of the connection in the form of variable strength, stiffness and static ductility. Unfortunately little information is available on the effect of temperature on the embedment strength as reported in [10,11]. Little work has been done in this area, and the current regulations are not the most appropriate. The European standards EC5 [14] do certainly offer simplified methods for the determination of the fire resistance of timber structures but these methods are not sufficient to describe the complex thermo-mechanical behavior of timber.

Predicting the strength of a timber structure in fire requires a deeper understanding of all the processes involved. To date, there are few readily available computer codes able to predict the behavior of timber connections in fire. In the present work, a material model which can be easily implemented in existing FE software is presented. The proposed model is capable of describing the complex behavior of timber. It is formulated within the framework of plasticity. It takes into account the orthotropic elastic behavior, the plastic anisotropic isotropic hardening, the large plastic deformations, and the effects of temperature. The wood material is considered as a continuous medium.

2. Mathematical model for thermo-mechanical behavior of timber

2.1. Mechanical aspects

The generalised Hooke's law is written as

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

where $\underline{\sigma}$ is the Cauchy stress tensor, $\underline{\varepsilon}^{e}$ the elastic strain tensor, $\underline{\varepsilon}$ the total strain tensor, $\underline{\varepsilon}^{p}$ the plastic strain tensor, $\underline{\varepsilon}^{th}$ the thermal strain tensor, $\underline{\underline{\Lambda}}$ is the fourth-order operator of elastic properties, and is a function of the Young moduli E_1, E_2, E_3, shear moduli G_{12}, G_{23}, G_{13}, and Poisson's ratios ν_{12}, ν_{23} and ν_{13} as shown in directions (1), (2) and (3) given in Fig. 2. The operator $\underline{\underline{\Lambda}}$ is the inverse of the elastic compliance operator $\underline{\underline{C}}$:

$$\underline{\underline{\Lambda}} = \underline{\underline{C}}^{-1} \tag{2}$$

with

$$\begin{aligned} &C_{1111} = 1/E_1; \quad C_{2222} = 1/E_2; \quad C_{3333} = 1/E_3; \\ &C_{1212} = 1/G_{12}; \quad C_{2323} = 1/G_{23}; \quad C_{1313} = 1/G_{13}; \\ &C_{1122} = -\nu_{12}/E_2; \quad C_{2233} = -\nu_{23}/E_3; \quad C_{1133} = -\nu_{13}/E_3 \end{aligned} \tag{3}$$

The plastic flow f_p is described by the quadratic criterion of Hill [22–28] as

$$f_p = \sqrt{\underline{\sigma} : \underline{\underline{H}} : \underline{\sigma}} - Q \times r - \sigma_{yield} = 0 \tag{4}$$

where σ_{yield} represents the yield strength, r is the scalar variable of isotropic hardening, Q is the isotropic hardening modulus, and $\underline{\underline{H}}$ is the fourth order operator reflecting Hill anisotropy, function of six parameters F, G, H, L, M and N, which are given as follows:

$$\begin{aligned} &H_{1111} = G + H; \quad H_{2222} = F + H; \quad H_{3333} = G + F; \\ &H_{1212} = 2N; \quad H_{2323} = 2M; \quad H_{1313} = 2L; \\ &H_{1122} = -H; \quad H_{2233} = -F; \quad H_{1133} = -G \end{aligned} \tag{5}$$

The mechanical dissipation is described using the theory, which considers only one potential of dissipation F_p

$$F_p = f_p + \frac{Q}{2b} \times R^2 = \sqrt{\underline{\sigma} : \underline{\underline{H}} : \underline{\sigma}} - Q \times r - \sigma_{yield} + \frac{Q}{2b} \times R^2 \tag{6}$$

with

$$R = Q \times r \tag{7}$$

b represents the isotropic hardening parameter and R the isotropic hardening modulus.

The complementary relations are derived as follows:

$$\underline{\dot{\varepsilon}}^{p} = \dot{\lambda}\frac{\partial F_p}{\partial \underline{\sigma}} = \dot{\lambda}\frac{\partial f_p}{\partial \underline{\sigma}} = \dot{\lambda}\frac{\underline{\underline{H}} : \underline{\sigma}}{\|\underline{\sigma}\|} = \dot{\lambda}\underline{n} \tag{8}$$

$$\dot{r} = -\dot{\lambda}\frac{\partial F_p}{\partial R} = -\dot{\lambda}[1 - br] \tag{9}$$

where $\underline{n}$ is the normal to f_p the loading surface, $\dot{\lambda}$ is the plastic multiplier and b is the parameter of isotropic hardening.

An elasto-plastic behavior is also assumed for steel. Contact with friction is used to model the interaction between the timber, the steel plate and the dowels. Generally, friction models are defined through a relation between the normal stress, the tangential stress and the relative tangential velocity at the contact point between different parts of the connection (timber, steel plate and dowels, all supposed deforming plastically). Here we limit ourselves to the isotropic friction models, and particularly to the well-known Coulomb friction model characterised by the friction parameter μ and available in the Abaqus/Explicit [29] library.