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Simulation of crack propagation in mode I of wood by integrating the rapid variation of moisture content into a new cohesive zone model

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Résumé — In this research, a new model, introducing the influence of the moisture content on the cohesive zone, is proposed and implanted in source code ESOPE of Cast3m. Under the external loading, the crack growth simulation is carried out using joint element which represents the cohesive interface. The separation in the cohesive interface is specified in terms of the cohesive traction-separation laws. At the beginning of a current time step, the moisture diffusion with the update crack length (precedent step) is estimated; and, mechanical properties in the whole specimen are then updated. Consequently, the moisture variation introduces an additional stress.

Mots clés — Cohesive zone model, Crack length, Moisture content, Wood.

1 Introduction

The fracture mechanic approach is more and more performed to estimate time to failure of timber structures. Recently, cohesive zone models (CZM) have also been successfully employed to simulate the crack initiation and the crack growth in quasi-brittle materials such as wood. Advantages of the CZM are : i) it does not require the existence of a pre-crack, ii) the crack and the crack propagation is described without remeshing to avoid the cumbersome due to the mesh updating to match the geometry discontinuity. Moreover, wood mechanical properties depend on the temperature and on the moisture content (MC) [1]. Varying MC induces internal stresses which may cause the crack propagation because Fracture Process Zone (FPZ), at the crack tip, is directly submitted to air humidity variations [2].

In this study, a new methodology, introducing the rapid variation of MC in the cohesive zone model, is proposed.

2 Resistance curve and Cohesive Zone Model

The fracture tests in mode I on Maritime pine are performed on a modified Tapered Double Cantilever Beam specimen (mTDCB) under three constant moisture contents (8%, 12%, 30%) to determine parameters of the cohesive zone model. The crack length monitoring during its growth is very difficult to be accurately performed on wood. Due to the presence of FPZ at the crack tip, LEFM cannot be directly applied to estimate the fracture energy. Hence, an approach of the equivalent LEFM is applied on the quasi-brittle fracture and provides useful approximations [3, 4].

Resistance curve (R-curve), material resistance to the crack propagation, is estimated on the basis of the equivalent LEFM by a compliance method. The compliance function is obtained by finite element analysis. In order to describe the quasi-brittle fracture of wood, the CZM represented by a bi-linear approximation function, is used. The direction of the crack propagation is assumed to be in the middle plane of the specimen, the joint element is used to represent the cohesive interface. The parameters required to define interracial elements in the bi-linear function (Fig. 1a) are : the cohesive fracture energy G_f , the energy distribution between the two cohesive energies $G_{f\mu}$ and G_{fb} , the critical opening w_c and the tensile strength f_t .

In the theory of CZM (Fig. 1b), firstly the material follows a linear elastic law, secondly the crack initiates at the joint points (released node) occurring when the stress σ reaches the tensile strength f_t and thirdly the crack opens while stress transfers from one face to another in the cohesive zone elements. The

stress is perpendicular to the crack face and a function of the crack opening w ($\sigma = f(w)$). A damage parameter d , which evolves from 0 to 1, is written as in Eq. (1) to describe the interface state (joints).

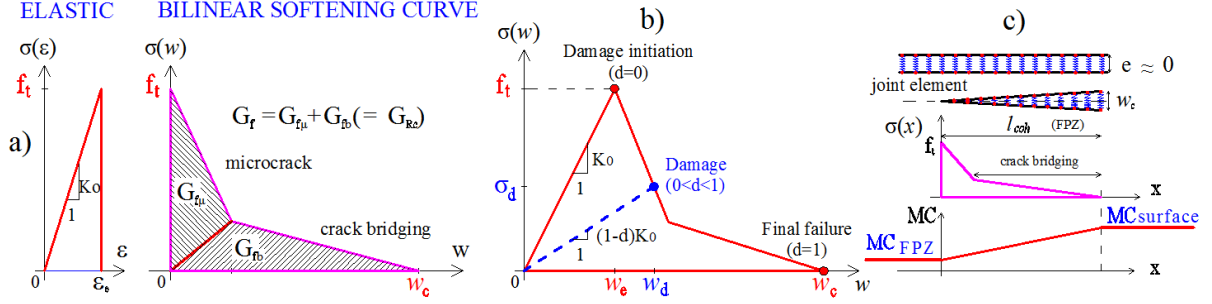


FIGURE 1 – Illustration of the bi-linear traction-separation law (TSL) in CZM

$$d = \frac{w_d f_t - w_e \sigma_d}{w_d f_t} \quad (1)$$

where w_d is the maximum separation for the interface element over the entire loading history ; w_e is the critical separation for damage initiation on the interface element.

The opening stress related to the opening displacement w is written :

$$\sigma = \begin{cases} K_o w & \text{if } w \leq w_e \\ (1-d)K_o w & \text{if } w_e < w < w_c \\ 0 & \text{if } w \geq w_c \end{cases} \quad (2)$$

Our results show that the critical fracture energy, the characteristic length of the cohesive zone increase with the increasing of the moisture content.

3 Integration of the rapid variation of the moisture content in a CZM

In this work, we change the value of $MC_{surface}$ to simulate the variation of relative humidity (RH). Due to the rapid variation of RH, this variation only has a direct impact on fibers in the FPZ ; this impact is assumed to be linear (Fig. 1c).

The second Ficks law (Eq. (3)) is used for the moisture content diffusion in wood [5, 6]. For the Maritime pine, all values of diffusion coefficients in Eq. (3,4) have been experimentally measured [7].

$$\frac{\partial MC}{\partial t} = \frac{\partial}{\partial x} \left(D_{MC}(MC) \frac{\partial MC}{\partial x} \right) \quad (3)$$

$$D_{MC}^\alpha(MC) = D_0^\alpha e^{\kappa_0 MC} \quad \text{where} \quad \alpha = (L, R, T) \quad (4)$$

where D_0^α is the anhydrous transverse wood moisture diffusion coefficient in the α direction. κ_0 characterizes the non linear behavior of the moisture diffusion coefficient.

In the finite element code, during the time increment Δt_n , the crack opening w is considered constant, fictive stress σ_{n+1}^f can be written as Eq. (5) :

$$\begin{cases} \sigma_n & = K_n w & = K_0 f(MC_n, w) (1-d) w \\ \sigma_{n+1}^f & = K_{n+1} w & = K_0 f(MC_{n+1}, w) (1-d) w \\ \rightarrow \Delta \sigma_n & = \sigma_{n+1}^f & - \sigma_{n+1}^f \end{cases} \quad \text{if } w_e \leq w \leq w_c \quad (5)$$

The value $\Delta \sigma_n$ will be converted into the external mechanical nodal force increment inducing on the cohesive zone during the time increment Δt_n which allows incorporating the mechanical response history and the moisture content. Displacement and stress fields at the time t_{n+1} will be calculated by solving the nonlinear mechanic problem. These calculations have been implemented in source code ESOPE of Cast3m (Fig. 2).

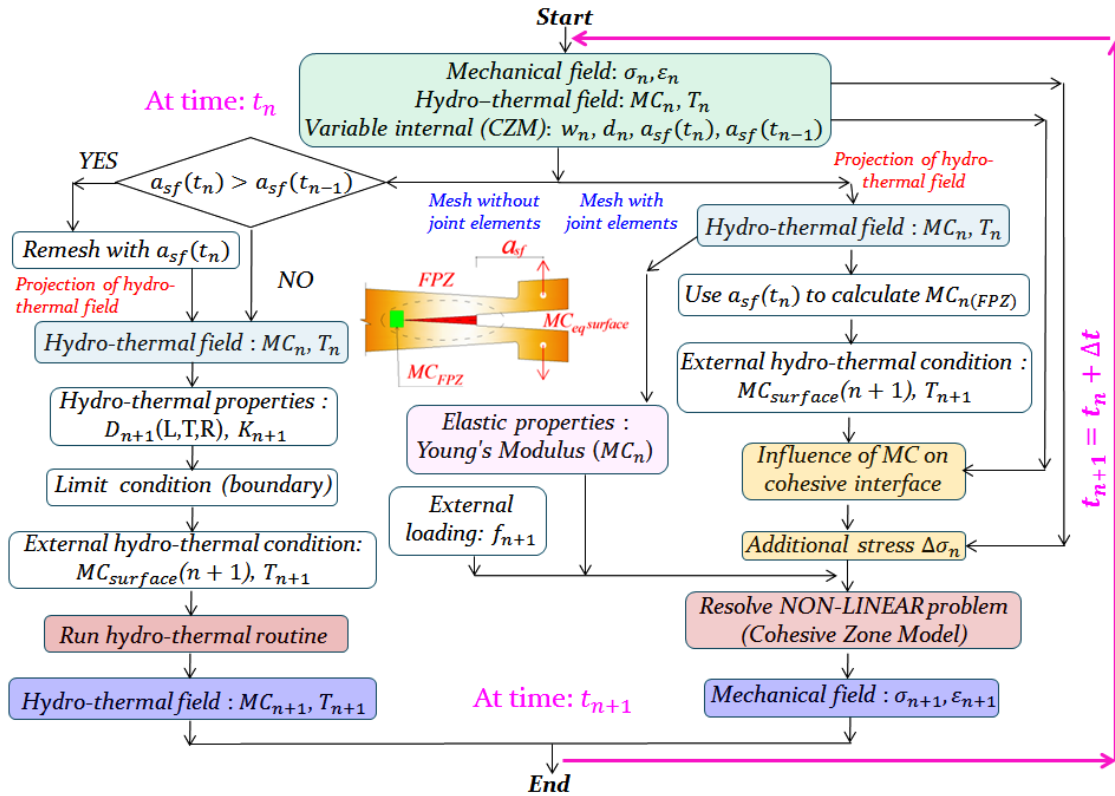


FIGURE 2 – Finite element algorithm for the crack growth under the moisture content variation

4 Simulation of crack propagation in wood under the humidity variation

A simulation of the specimen subjected to the imposed displacement under the moisture content variation between 6% and 18% is performed. The initial moisture of the specimen is 12%. The mechanical response obtained through our model can be expressed through four phases as shown in Fig. 3 and Fig. 4. In the 1st phase and the 3rd phase, the imposed displacement is increased while the moisture is constant; inversely for the case of the 2nd phase and the 4th phase. Fig. 3 shows an example of the moisture content distribution and of the stress obtained by the finite element simulation in the middle section of the mTDCB specimen.

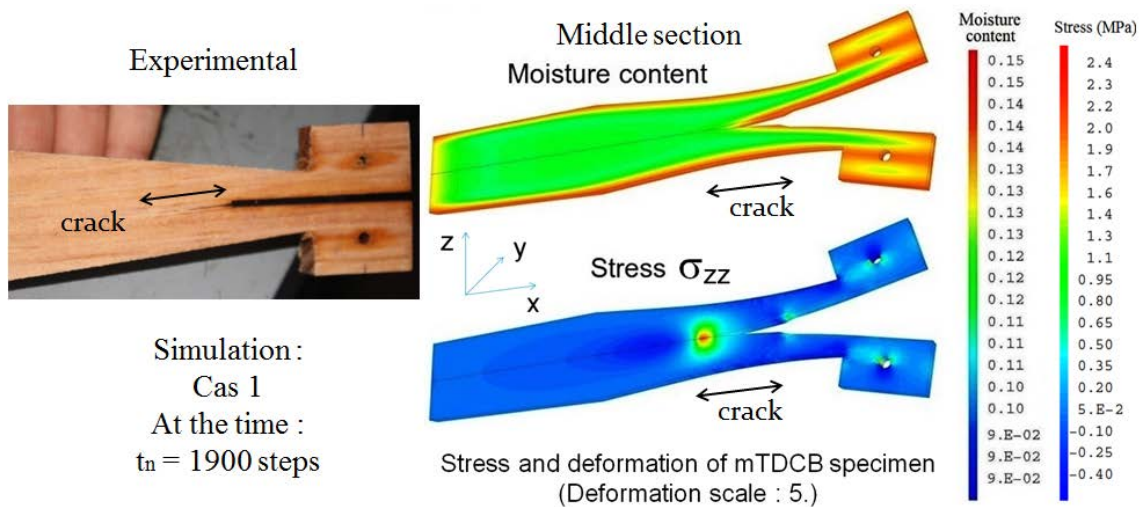


FIGURE 3 – Evolution of the moisture content and the stress of the mTDCB specimen

As shown in Fig. 4, in the wetting process while the imposed displacement is constant (phase 2), the stiffness decreases leading to reduced stress in the cohesive zone. The crack tends to close and the applied

force tends to increase (crack does not further develop). All phenomena are converse in case of the drying phases. Phase 3 is continued with the increasing the imposed displacement and the constant moisture. We observe a continuity of the mechanical response which takes into account all previous changes.

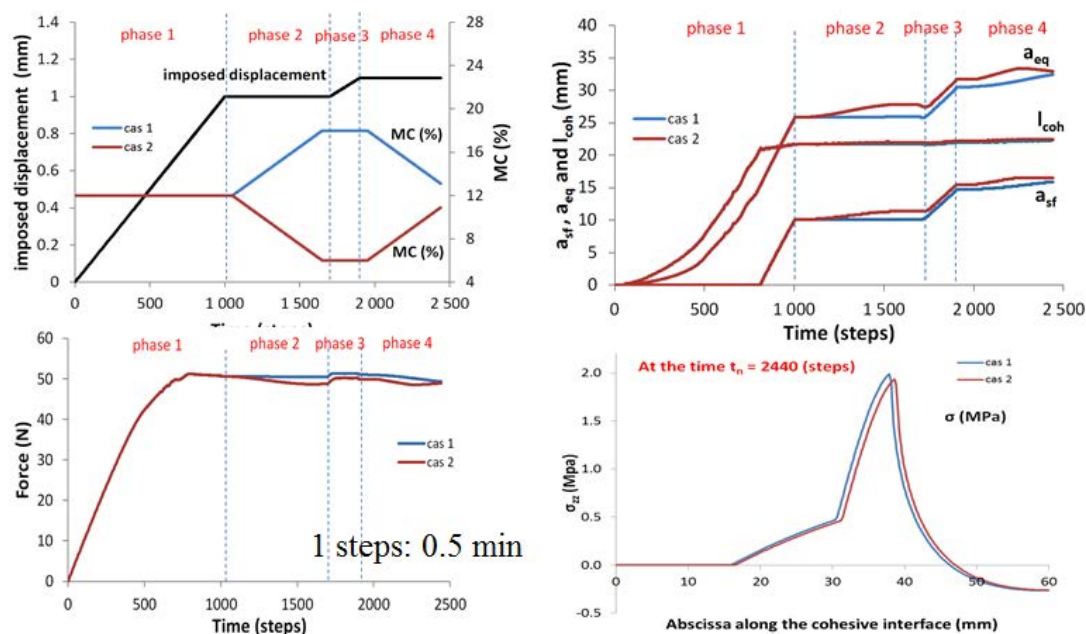


FIGURE 4 – Evolution of the load, the equivalent crack length and the stress under several displacement and moisture content variations

5 Conclusion and Perspective

In this research, the influence of moisture content on the mode I fracture behavior has been investigated on mTDCB specimens of maritime pine. Values of the critical fracture energy and the characteristic crack length also depend on the moisture. A new model introducing influence of the moisture content on the cohesive zone is proposed and implanted in Cast3m.

In further studies, this model will be analyzed with the moisture diffusion inside the whole specimen which results in viscoelasticity variation.

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