Timber fracture behavior during drying phase

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Résumé :

Ce papier présente une approche expérimentale permettant de mettre en évidence l’initiation de propagation de fissure dans une éprouvette Double Cantilever Beam sollicitée en fluage dans un environnement simulant un séchage sévère. Les essais sont complétés, d’une part, par un protocole expérimental caractérisant des échantillons humides et secs à la fissuration et, d’autre part, par une simulation éléments finis de la phase d’initiation intégrant le retrait hydrique et la mécano-sorption orthotrope.

Abstract :

This paper deals with an experimental approach which highlights the crack growth initiation in a Double Cantilever Beam specimen under creep loading and placed in an environment reproducing a severe drying. These tests are supplemented, in a first time, by an experimental protocol which allow to characterizing dry and wet samples and, in a second time, by a finite element simulation which integrates the orthotropic shrinkage and a mechano-sorptive behavior.

Keywords: fracture mechanic, mechano-sorptive behavior, climatic variations

1 Introduction

Timber structures are subject to problems related to the presence of cracks. In a life duration context, the crack growth process is directly impacted by climate variations in terms of moisture content gradients. The drying steps are quite critical toward this cracking. More specifically, the air-conditioned and heated buildings are subject to very dried air conditions thus inducing the development of a crack that could affect locally the stability of the structure. Before proposing solutions preventive and / or strengthening of these structures, it is necessary to understand the phenomenon of cracking under severe drying to develop in order to design tools for predicting the risk of cracking, the crack initiation zone and the strength loss of singular sections or timber joints. This work deals with the study of the cracking of wood material in the drying phase. An experimental protocol is presented to highlight the crack initiation acceleration during the drying phase. In order to control the crack initiation, we opt for a double cantilever beam geometry (DCB) inducing an unstable crack growth.

The first part describes the mechanical test under variable climate. The experimental configuration is based on a creep test in which moisture content \( w \) varies between a wet state \( (w > 22\%) \) to a dry state \( (w < 9\%) \). The crack growth initiation is visualized by recording the test with CCD cameras. After two stabilization hours at high humidity (20% mc) in a climatic chamber, it is observed the brittle rupture of the sample. The second part deals with a finite element approach allowing the understanding of the coupled effects of shrinkage and mechano-sorptive effects in the crack growth initiation process.

2 Mechanical tests under variable climate

Experimental tests are based on the use of a double cantilever beam in Douglas fir submitted to a creep loading, figure 1. With an initial length of 60mm, the pre-crack is oriented in the grain direction. Its thickness is 15mm. The loading axes have a diameter of 10mm. The crack propagation is in the Radial Longitudinal plane. Samples are conditioned in a wet environment \( (T = 20\degree C, RH = 85\%) \) corresponding to an average moisture content around 20%. The mechanical test under variable climate conditions is based on a creep loading at constant temperature accompanied by a relative humidity decreasing until 30%.
2.1 Experimental setup

The fracture behavior study is performed employing a Zwick electromechanic machine incorporating an environmental chamber allowing a time synchronization between the force-displacement control and the climatic environment histories, figure 2.

The experimental device is completed by the recording of the crack growth using a CCD camera through the climatic chamber window. The synchronization between images and mechanical data is allowed using a tracking marker technique of the loading application point.

FIG. 2 – Experimental devices
The figure 3 shows the synchronization between the mechanical loading and climatic variations. A first phase concerns the mechanical loading controlled in displacement (0.5mm/min) until 1mm. The force is maintained constant for 10 min in order to observe creep response in constant wet climate. The next step is characterized by a drying phase by changing climate conditions at a dry state (20°C, 30%HR). The experimenters expect now the complete collapse of the sample and, more precisely, the crack growth initiation.

### 2.2 Experimental observations

The force-displacement curve is posted in figure 4. The graph can be separated in four specific zones.

![Graph showing force-displacement curve](image)

**FIG. 4 – Force and displacement evolutions versus time**

The first zone corresponds to the loading of the wet sample with a displacement speed of 0.5mm/min. The overall stiffness is equal to 360N/mm. According to a finale displacement of 1mm, the corresponding force is 360N.

In this second zone, the force is kept constant for ten minutes. The sample mechanical state is in a creep configuration. We can observe the displacement evolution versus time. The relative humidity is always maintained at 85%.

In the third step, the drying phase starts with a relative humidity fixed at 30%. According to the diffusion process, the specimen begins to dry from the outside surface. The mechanical response puts in evidence the combination of mechano-sorptive and shrinkage effects with a total displacement blocking.

The last phase is characterized by a continuous increase of displacements. According to a non linear behavior, this phase can be assimilated at a secondary creep state accentuated by the 3D diffusion process with, by way of an example, a time development of a process zone. The total sample fracture is observed after 2h40.

### 2.3 Additional experimental tests

In the goal to understanding the mechano-sorptive effects on the crack growth initiation, we propose to develop an energetic approach based on wet and dry behaviors of the samples. In this context, several additional fracture tests have been realized in wet (mc = 22%) and dry conditions (mc = 9%) with acclimated samples. 15 samples have been tested for the two climatic conditions. Average results are presented in figure 5 in terms of force F displacement U curves. These additional results allow defining the initial sample stiffness $k_{ini}$ and the average critical energy release rate $G_c$ defined by, see table 1:

$$k_{ini} = \lim_{U \to 0} \frac{dF}{dU} \quad \text{and} \quad G_c = \frac{1}{b \cdot \Delta a} \cdot \int F \cdot dU$$ (1)
\( \Delta a \) designates the total crack way. In our case, its value is 110mm. \( b \) is the thickness sample (+/- 15mm).

\[
\text{FIG. 5} – \text{Average force-displacement curves for dry and wet samples}
\]

<table>
<thead>
<tr>
<th>w</th>
<th>( k_{\text{ini}} ) (N/m)</th>
<th>Standard deviation</th>
<th>( G_c ) (J/m²)</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>9%</td>
<td>556</td>
<td>51</td>
<td>183</td>
<td>44</td>
</tr>
<tr>
<td>22%</td>
<td>425</td>
<td>34</td>
<td>244</td>
<td>50</td>
</tr>
</tbody>
</table>

**TABLE 1** – Average fracture parameters for wet and dry samples

3 **Numerical interpretation**

A good understanding of the fracture process, during drying phase, requests to develop a numerical model allowing separate mechano-sorptive and shrinkage effects. So, we propose a finite element modeling taking into account the mechanical properties dependence with moisture content. We limit our investigations at an elastic response. Taking into account geometry and loading symmetries, only the half finite element mesh is discretized according to boundary conditions as represented in figure 6.

**FIG. 6** – Finite element mesh and boundary condition
3.1 Mechano-sorptive model

The coupling between moisture content variations and mechanical behavior is based on the addition of shrinkage-swelling response and mechano-sorptive behavior. During the drying process, Gril et al. [1] and Husson et al. [2] have brought to light a hygro-lock effect affecting elastic and viscoelastic responses. By limiting our investigation to elastic behavior, the mechanical model can be likened to a Bazant model [3] with respect to hardening behavior during the drying phases. The mechanical behavior is written in terms of strain rate $\dot{\varepsilon}$ as follow:

$$\dot{\varepsilon}(t) = C(t) \cdot \dot{\varepsilon}(t) + \alpha \cdot \dot{w}(t)$$

(2)

The total stress rate tensor is called $\dot{\sigma}$. $C(t)$ is the four-order compliance tensor adapted for orthotropic properties. $\alpha$ is the shrinkage-swelling expansion tensor. In the orthotropic reference frame, this tensor is diagonal. In this study, we assume a constant tensor in the hygroscopic domain. $\dot{w}(t)$ is the moisture content rate. Implemented as an incremental formulation in the software Castem, at the time $t_n$, the expression (2) becomes:

$$\Delta \varepsilon(t_n) = \Delta C(t_n) + C(t_{n-1}) \cdot \Delta \sigma(t_n) + \alpha \cdot \Delta w(t_n)$$

(3)

Between two calculus step, the compliance and stress tensors and moisture content are assumed as linear functions. They are identified by their value at the time $t_{n-1}$ and their increment during the time increment $\Delta t_n$.

3.2 Elastic properties versus moisture content

According to a stress plane vision, $C(w)$ can be defined according longitudinal, radial and shear modulus $E_L(w)$, $E_R(w)$ and $G_{LR}(w)$, respectively. For Douglas fir, Guitard [4] gives a linear dependence of elastic properties versus moisture content. The Poisson’s ratio $\nu_{LR}$ is assumed to having a constant value of 0.39. For the shrinkage-swelling coefficient, we chose the values given by Guitard ($\alpha_L = 0.01\%/\%$ and $\alpha_R = 0.08\%/\%$). Table 2 gives elastic properties for 9% and 22% of moisture content.

<table>
<thead>
<tr>
<th>$w$</th>
<th>$E_L$ (MPa)</th>
<th>$E_R$ (MPa)</th>
<th>$G_{LR}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9%</td>
<td>17000</td>
<td>1400</td>
<td>1000</td>
</tr>
<tr>
<td>22%</td>
<td>14025</td>
<td>900</td>
<td>677</td>
</tr>
</tbody>
</table>

TABLE 2 – Elastic properties versus moisture content

3.3 Numerical analysis

In accord with a moisture content decrease between 22% and 9% and a constant force loading, the numerical algorithm allows tracing the total displacement variations of application force point versus moisture content, figure 7. The displacement evolution puts in evidence a small increase corresponding to the combined effects of shrinkage deformations and deformation blockings characterizing the mechano-sorptive behaviour. As shown in precedent paper [5], the crack growth initiation is induced by a concentration of the energy, accumulated during loading in wet conditions, and its increasing during drying process.
As shown in figure 8, the concentration of radial tensile stresses increases during drying process until causing the crack propagation.

4 Conclusion and outlooks

This paper has presented a first approach about the crack growth initiation due to a severe drying process. This study confirms the fracture risk met in timber structures placed in dry environments. This approach needs to be complemented by more global experimental tests integrating cyclic climatic variations with wetting and drying phases under loading. The finite element model should integrate an energetic approach based, for example, on the concept of the energy release rate by generalizing the idea of the invariant integrals. More stable geometries can be employed in order to understand the crack growth process versus moisture content variations. In a second step, real cracked timber elements could be tested like knocked beams or timber joints in which steel elements could block strain variations. For applied research, this work can be employed in the reinforcement fracture techniques in order to arrest the crack tip advance and to limit the crack initiation risks. In the live duration study of timber structures, the model should be generalized by considering a viscoelastic behaviour integrating a mechano-sorptive character. Finally, the 2D approach must be reconsidered by introducing three-dimensional effects by introducing mass transfer effect in the sample thickness which can induce additional torsion effects in the crack tip vicinity.

References