Fracture Behavior in Timber Element Under Climatic Variations

Frédéric Lamy [1], Frédéric Dubois [1,*], Octavian Pop [1], Mokhfi Takarli [1], Nicolas Angellier [1], Nicolas Larcher [1]

[1] Heterogeneous Material Research Group, Civil Engineering and Durability department, University of Limoges, Egletons, 19300, France
* Corresponding author: frédéric.dubois@unilim.fr

Abstract Timber elements placed in outdoor conditions are solicited by mechanical loadings and climatic variations. Joints or notched beams are subjected to stress concentrations which can cause a crack growth process due to drying phases. This paper deals with the experimental and analytical approaches about the fracture process in timber element subjected to different moisture content conditions. Two lots of SEN specimens are conditioned in different air conditions and tested in opening mode. A quasi-brittle fracture behavior is studied using a thermodynamic approach taking into account the dissipation based on the crack surface separation and the development of a process zone around the crack tip. The model includes the fracture and damage energy release rate concepts. Based on fracture and damage approaches, the dissipation separation is realized using the coupling of a finite element approach and image analysis tracking the visible crack tip during the experimental test. Experimental results and numerical treatments allow highlighting the moisture content effect on damage and crack growth with an increase of the ductility for high moisture content levels caused by the increase of the process zone size. This work allows envisaging the comprehension of the crack growth process under climatic variations introducing mechano-sorptive aspects.

Keywords Fracture mechanic, Viscoelastic behavior, Mechano-sorptive effects

1. Introduction

Timber elements placed in outdoor conditions are solicited by mechanical loadings and climatic variations. Around knots and joints, stress concentrations can induce crack growth initiation until fracture. Around these singularities, moisture content can be concentrated accentuated with climatic variations, .This coupling is usually treated by a mechano-sorptive approach coupling mechanical fields and moisture content gradients. In the past, a lot of works has been developed in order to understand this interaction at a material scale and for bending behavior. If we take the example of timber joints, the toughness can be accelerate by moisture content variations by provoking a crack initiation and the crack propagation until a partial collapse [1]. The one difficulty meet by the scientist community is the illustration of the mechano-sorptive effects in the fracture mechanic kinetic. Several scientific explorations have shown that coupling between moisture content variations and mechanical loading is subject to shrinkage-swelling effects and a modification of elastic or viscoelastic properties. In terms of thermodynamic visions, the last phenomenon is traduced, for constant mechanical loadings, by an increase of compliance properties during moistening phases and a blocking of strains during drying process corresponding to a partial storage of the free energy. These last observations request to put in evidence the local fracture behavior in moistening and drying phases. However, before to highlight the mechano-sorptive effects during wetting and drying phases, it is necessary to characterize the mechanical properties for dry and wet conditions.

The first section deals with the experimental setup based on a double cantilever beam specimen in Douglas fire using a electromechanical testing machine associated with a regulated environment chamber. These tests allow the determination of the specimen compliance and the critical energy release rate versus the crack tip position for dry and wet conditions.

Moisture content variations are stud in the second session. This part allows showing effects of a drying phase on the crack growth initiation under a creep loading.

2. Experimental setup

2.1. Material and methods

Experimental tests are based on the use of a double cantilever beam in Douglas fire submitted at a displacement control loading. Two sample groups are conditioned in dry and wet environments, respectively. In the other hand, for initial moistened specimens, a ramp of drying is imposed. All tests are filmed by CCD camera in order to record the crack tip advance. The Douglas fire specimen is a Double Cantilever Beam. Dimensions are fixed in Figure 1. The initial crack is oriented in the longitudinal axis with an initial length of 50mm. Its thickness is 20mm. The loading axes have a diameter of 10mm. The crack propagation is assumed to be in the Radial Longitudinal plane.

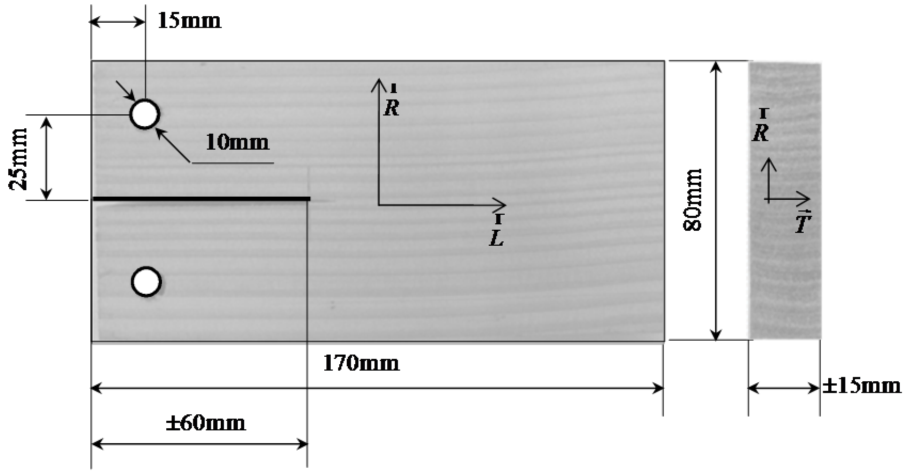


Figure 1. Double Cantilever Beam geometry

Two families of four specimens are placed in a dry (20°C, 40%HR) and wet (20°C, 85%HR) climate corresponding to moisture contents of approximately 9% and 19%, respectively. These specimens are acclimated during several weeks in order to obtain a moisture content homogeneity. The testing machine is a Zwick electromechanic incorporating an environmental chamber allowing the time synchronization between force-displacement and temperature/humidity histories, Figure 2.

Figure 2. Zwick electromechanic machine and CCD camera

The experimental device is completed by the crack tip advance monitoring using a CCD camera. The synchronization between images and mechanical data (force and displacement of the machine crossbar) is permitted by using a tracking marker technique of the point of force application, Figure 3.

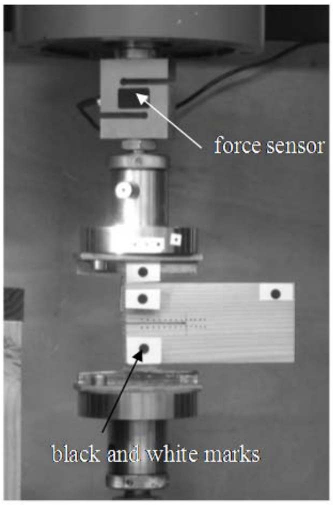


Figure 3. Synchronization with marker tracking method

During tests, the environment chamber is regulated in order to impose the equivalent moisture content conditioning. In order to limit creep effects, we impose a high constant displacement speed of 0,5mm/min until the total specimen collapse. In these conditions, the total test time does not exceed 4 minutes. Viscoelastic effects can be neglected in the following of this study.

2.2. Experimental results

Experimental results are composed of the force evolutions and the crack tip advance versus displacements. The force displacement curves are posted in Figure 4. First results highlight a decrease of the initial sample stiffness and the strength with eth moisture content increasing. In the other hand, wet samples seem to be characterized by a higher ductility.

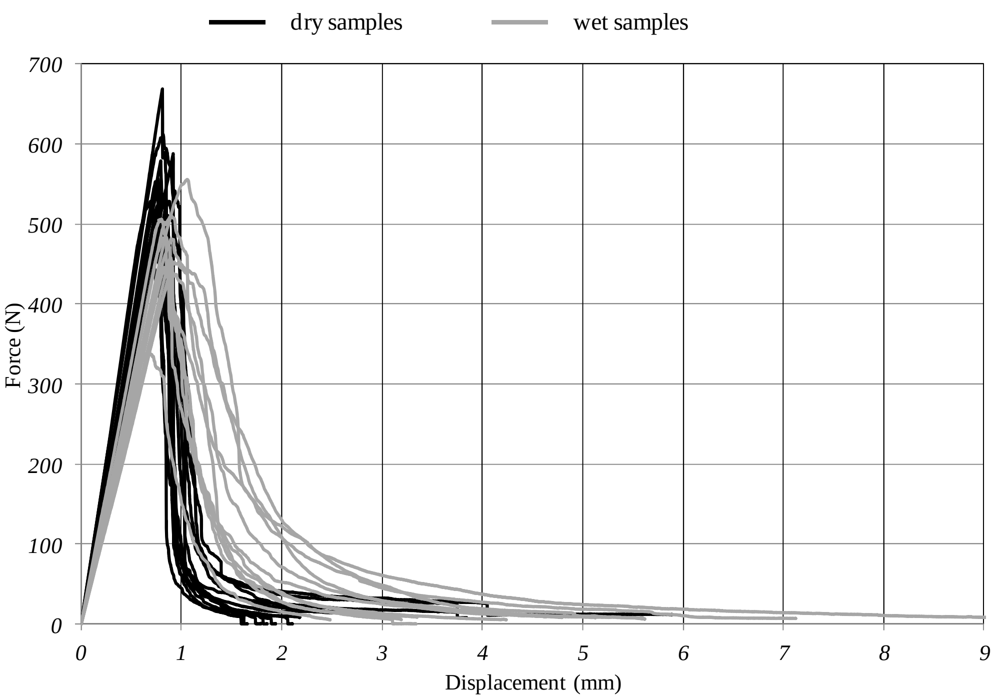


Figure 4. Force displacement curves under dry and wet conditions

All tests being filmed, the visible crack tip position can be noted versus displacements. In Figure 5, they are plotted crack length versus critical displacement corresponding to the crack tip advance. The graph highlights moisture content effect with an increase of sample compliance at a given crack length at high moisture content level (grey marks).

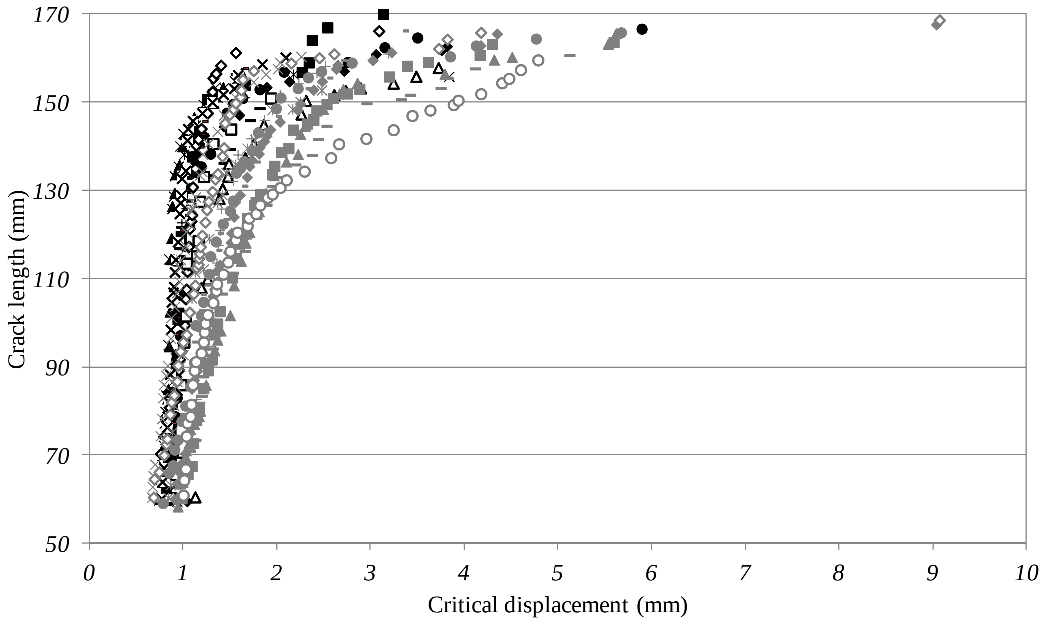


Figure 5. Visible crack length vs critical displacement

These observations prompt us to understand the cracking process by an energy approach. This one will clearly identify the effects of moisture content on the crack growth process by identifying energetic dissipation in terms of crack surface formations and process zone development.

3. Global thermodynamic approach

3.1. Thermodynamic formalism

Experimental results, shown in Figure 4 and 5, enables us to describe, at a global scale, energetic balance by introducing the global Helmholtz free energy $\psi\left[J\right]$ defined by observable variables represented by the total displacement d and an internal variable inducing softening of the sample stiffness [2]. By analogy with a damage theory, we introduce a virtual damage variable D and the effective stiffness $\tilde{k}\left(D\right)$. D represents the effects of the crack growth surface and the damage evolution in the process zone. Its form can be calculated from the non damage stiffness k such as :

$$D = 1 - \frac{\tilde{k}}{k} \quad \text{or} \quad \tilde{k} = \left(1 - D\right) \cdot k \tag{1}$$

Considering $F\left[N\right]$ as the reaction force, the global sample behavior can be defined as the relationship between this force and the global displacement u such as:

$$F = \tilde{k}\left(D\right) \cdot u \tag{2}$$

According to the thermodynamic approaches introduced by Lemaître, let us introduce the global thermodynamic potential in the form of the Helmholtz free energy variation is defined as:

$$\dot{\psi} = \frac{\partial \psi}{\partial u} \cdot \dot{u} + \frac{\partial \psi}{\partial D} \cdot \dot{D} \tag{3}$$

By assuming a total crack closure after unloading, the global elastic behavior (2) provides the first state equation:

$$F = \frac{\partial \psi}{\partial u} \tag{4}$$

Crossing expressions (2) and (4), the Helmholtz free energy can take the following form:

$$\psi = \frac{1}{2}\tilde{k}\left(D\right)\cdot u^2 \tag{5}$$

The energy release rate Y_D (associated to damage variable) can be defined as follow:

$$Y_D = \frac{\partial \psi}{\partial D} \tag{6}$$

Introducing equation (5) in (6), its definition becomes:

$$Y_D = \frac{u^2}{2}\cdot\frac{\partial \tilde{k}}{\partial D} \tag{7}$$

Considering the damage definition in expression (1), the energy release rate (7) can be rewritten by:

$$Y_D = -\frac{1}{2}\cdot k\cdot u^2 \tag{8}$$

By considering the Clausius-Duhem relationship, the dissipation, induced by the crack growth process φ can be defined by, Figure 6:

$$\dot{\varphi} = -Y_D \cdot \dot{D} \tag{9}$$

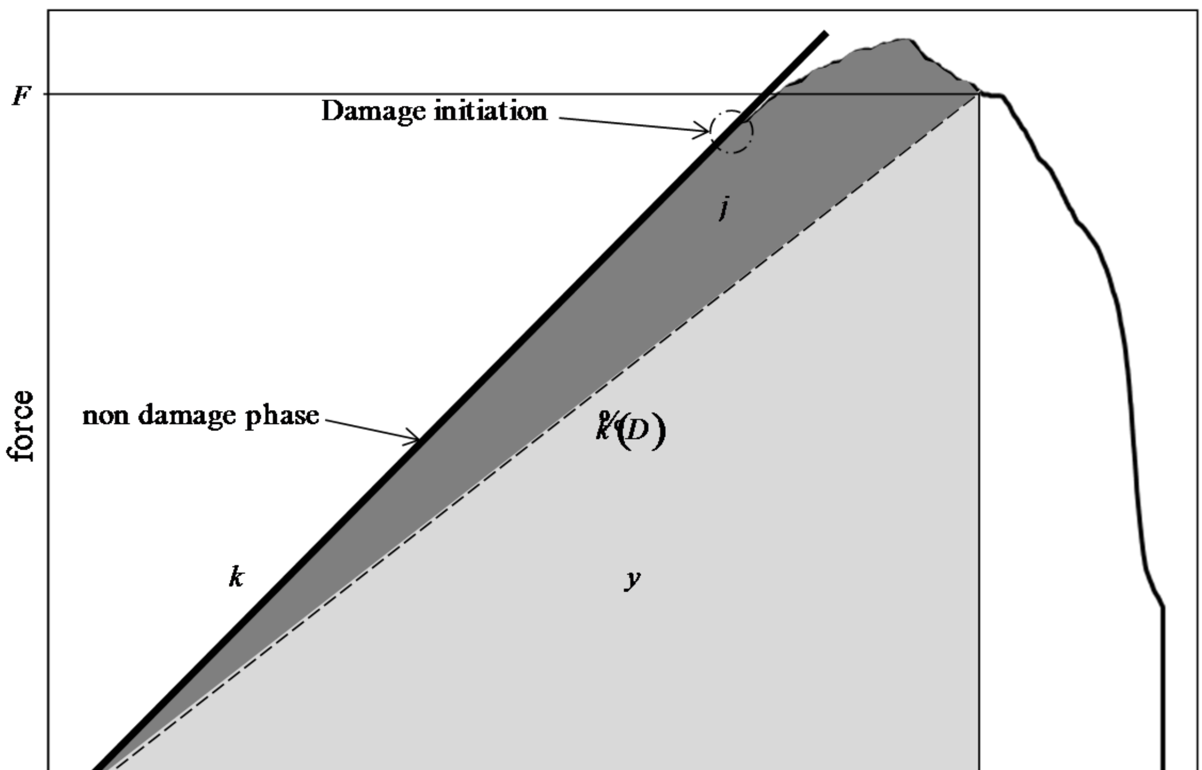


Figure 6. Experimental force-displacement he curve and thermodynamic description

3.2. Thermodynamic formalism

In the thermodynamic approach, an additional behavior law consists on the relationship between energy release rate and the global damage variable. Experimentally crossing expressions (1) and (8), we can easily plot the energy release rate – damage curve as shown in Figure 1. We can clearly note a behavior difference between dry and wet samples with a higher ductility at high moisture content levels. The behavior law can be separated into two regions. The first concerns the damage growth initiation which can be described by the following criterion:

$$D = 0 \quad \text{and} \quad \dot{D} = 0 \quad \text{if} \quad |Y_D| < Y_c \tag{10}$$

Where Y_c is a critical energy release rate value corresponding to a damage growth initiation. The second is the damage evolution function versus energy release rate. According to the global form, we propose an evolution under a Prony's serie form such as:

$$D = \chi_1 \cdot \left(1 - \exp\left(\frac{Y_D + Y_c}{Y_1}\right)\right) + \chi_2 \cdot \left(1 - \exp\left(\frac{Y_D + Y_c}{Y_2}\right)\right) \tag{11}$$

For dry and wet samples, **Error! Reference source not found.** and **Error! Reference source not found.** fixe thermodynamic parameters, respectively.

Table 1. Thermodynamic parameters for dry samples

	$Y_c\ (mJ)$	$Y_1\ (mJ)$	$Y_2\ (mJ)$	χ_1	χ_2	$k\ (N/mm)$
Average	207	88	794	0.94	0.06	709
Standard Variation	57	28	26	0.05	0.05	79

Table 2. Thermodynamic parameters for wet samples

	$Y_c\ (mJ)$	$Y_1\ (mJ)$	$Y_2\ (mJ)$	χ_1	χ_2	$k\ (N/mm)$
Average	169	183	787	0.81	0.19	571
Standard Variation	41	67	19	0.15	0.15	50

3.3. Average global behavior

The average behavior for dry and wet samples can be built by the following algorithm. Firstly, a global displacement history $u(t)$ is fixed. The energy release rate Y_D is calculated according to expression (8). The equation (11) allows defining the damage evolution. In a last time, the global sample behavior (2) after updating the effective stiffness (1). Results can be shown in Figures 7 and 8. The model can represent the differences in terms of ductility behavior between average dry and wet tests. The main criticism that we could do on this approach and the non decoupling process of crack propagation and the process zone. If our approach allows reproducing experimental test, it cannot be generalized for other geometry and doesn't take into account a scale effect induced by the process zone existence.

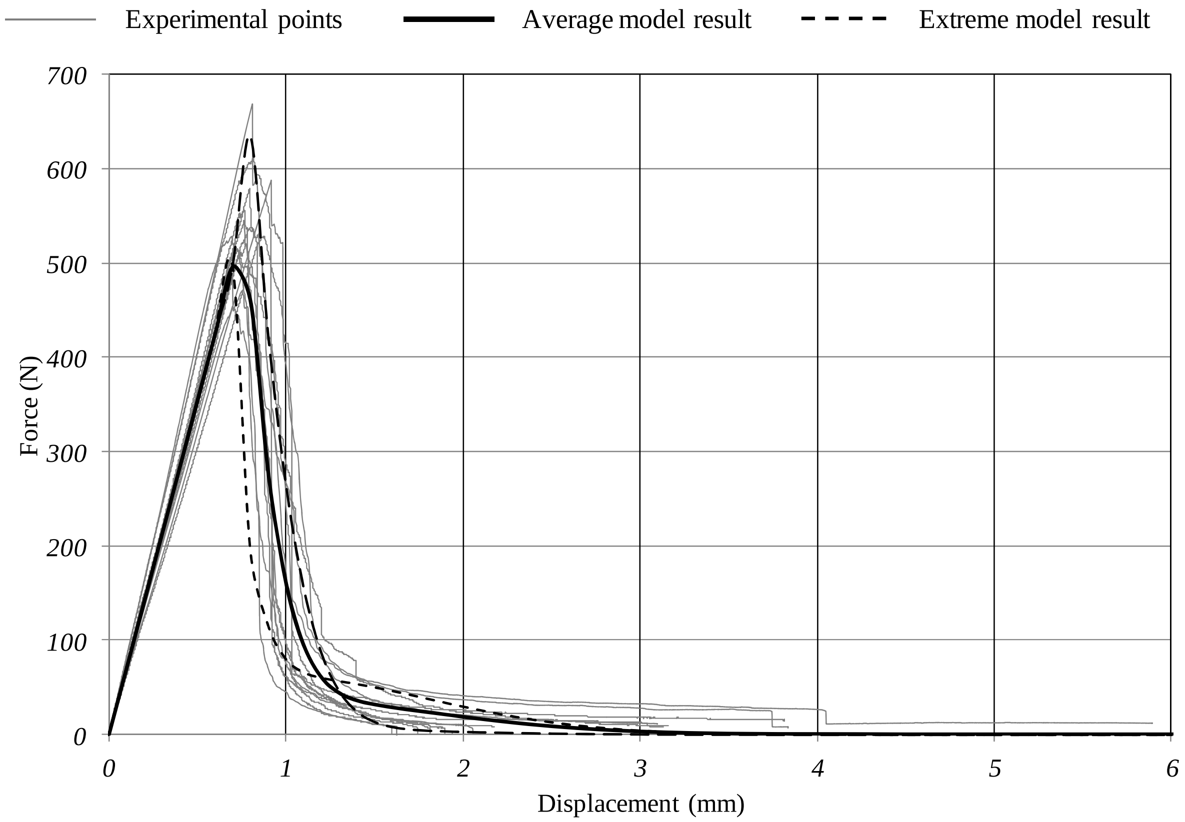


Figure 7. Modeling of fracture process for dry samples

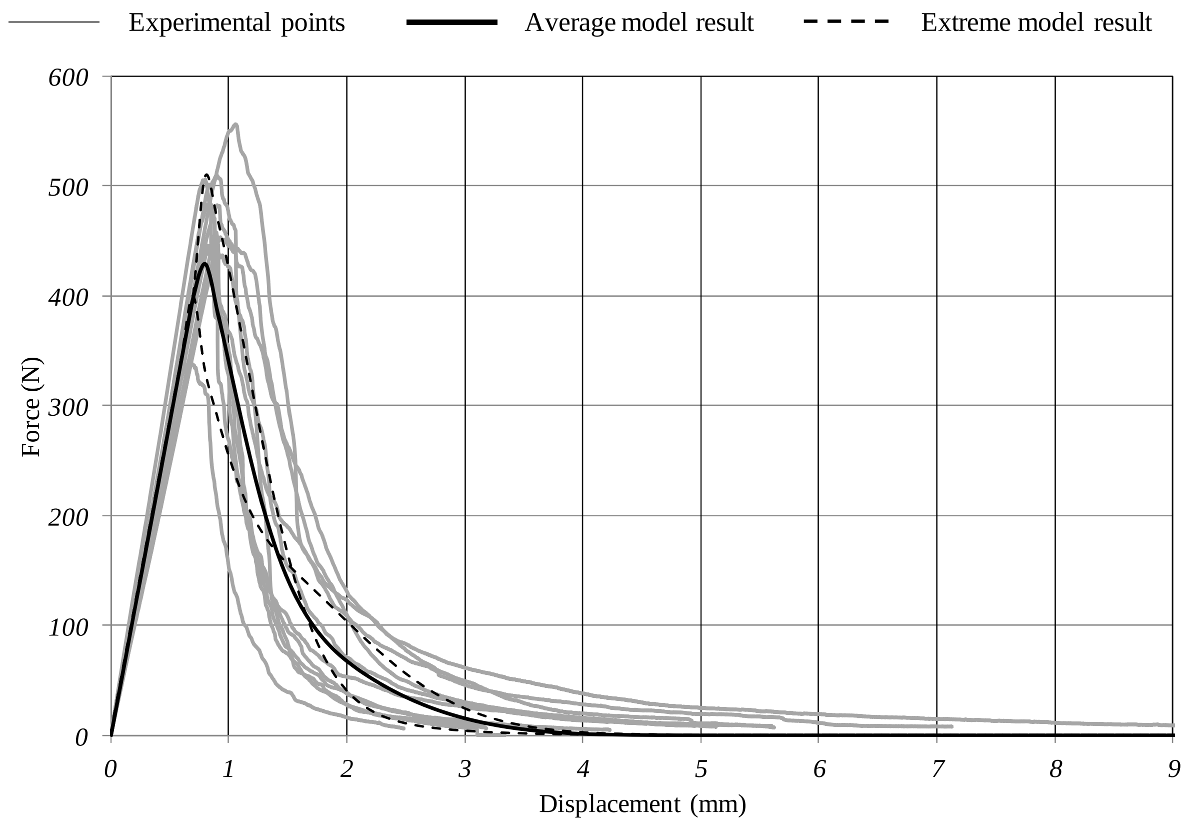


Figure 8. Modeling of fracture process for wet samples

4. Mechanical tests under variable climate

The mechanical test under variable climate conditions is based on a creep loading accompanied by relative humidity changes. This test allows the introduction, in the fracture behavior, effects of the viscoelasticity, the shrinkage or swelling and mechano-sorptive process. In this paper, we focus our investigation of drying process.

4.1. Loading history

The association of the mechanical loading with the decrease of the relative humidity requests to introduce the time as synchronization variable. In your case, we choose to load the specimen conditioned in a wet environment (20°C, 85%HR). The loading value is chosen according to a static displacement of 1mm with a displacement speed of 0,5mm/min. At this time, the force is fixed as constant during 10 minutes 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. The Figure 8 summarizes the hygro-mechanical loading.

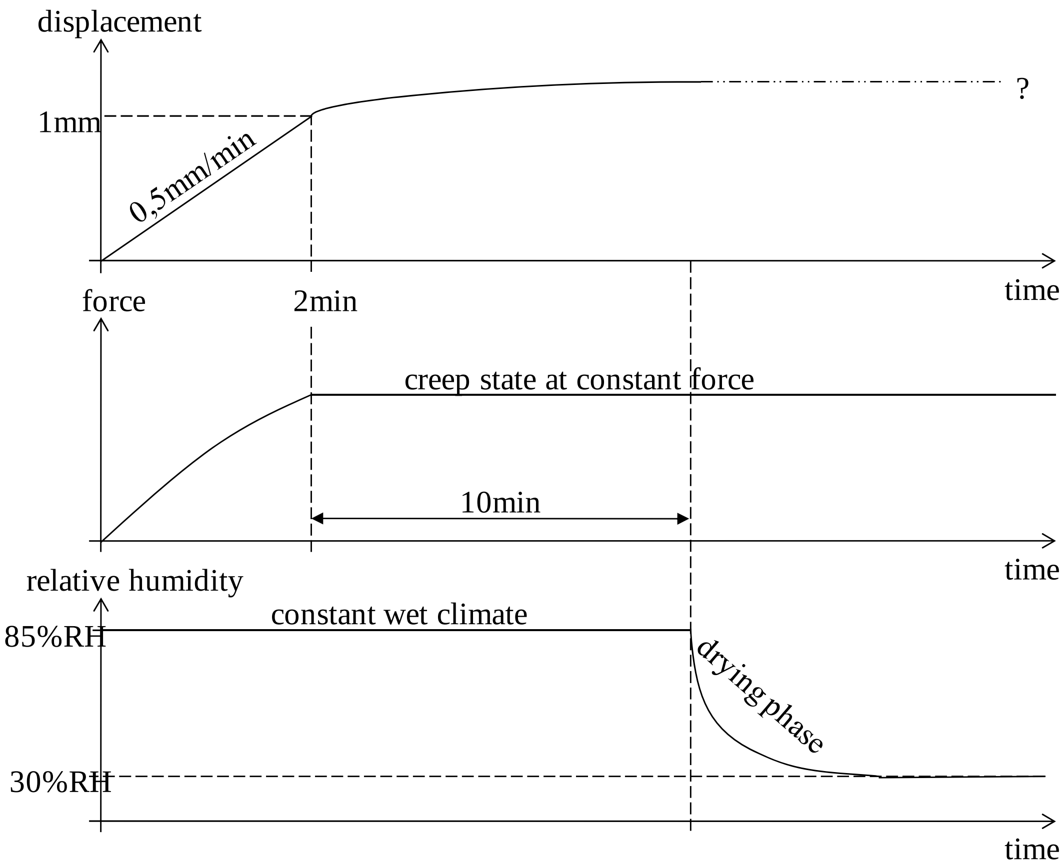


Figure 9. Hygro-mechanic loading history

4.2. Experimental results

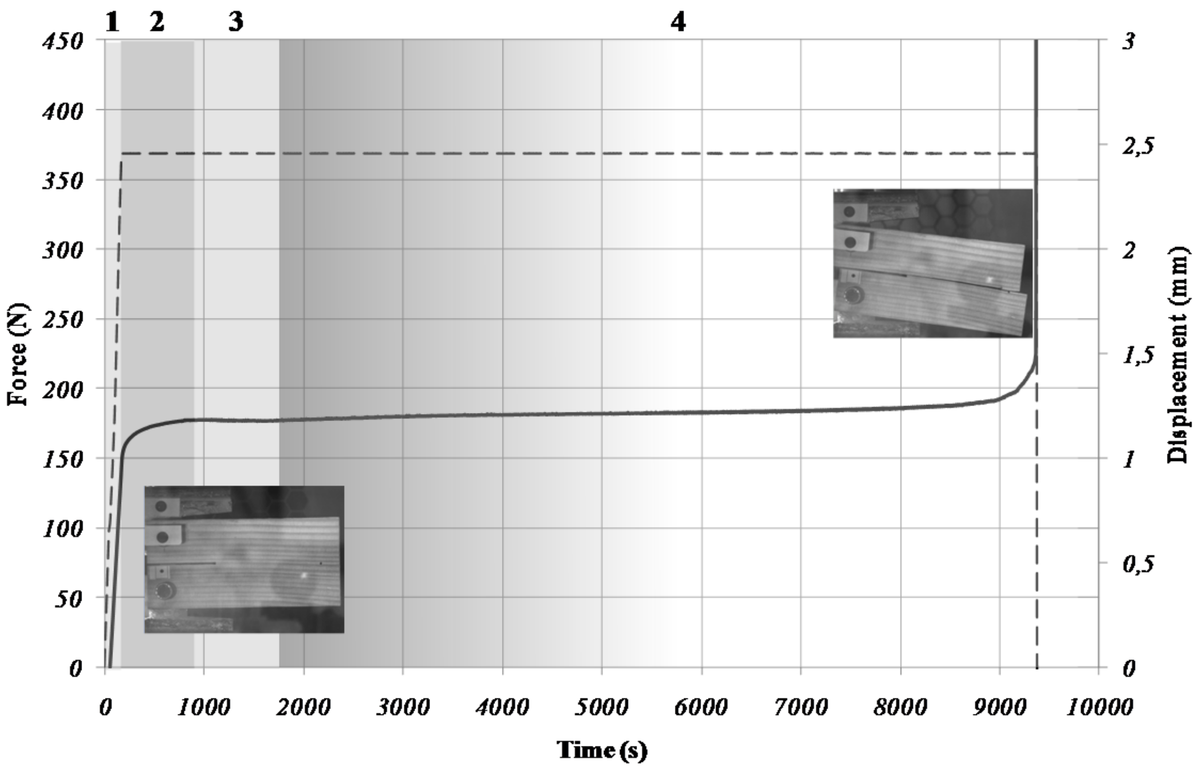
The force-displacement curve vs time is posted in Figure 10. The graph can be separated in four specific zones.

1- This zone corresponds to the loading of the wet sample with a displacement speed of 0,5mm/min. The overall stiffness is equal to 260N/mm. According to a finale displacement of 1mm, the corresponding force is 355N.

2- During ten minutes, the force is kept constant. The sample mechanical state is in a creep configuration. We can observe the displacement evolution versus time. At this state, the relative humidity is maintained at 85%.

3- At this time, the phase of drying starts. According to diffusion process, the specimen begins to dry from the outside surface. The creep response results on the combination of mechano-sorptive and shrinkage effects. We can observe a displacement blocking characterizing of mechano-sorptive effects and, more particularly, its hygro-lock properties [3], [4], [5].

4- The last phenomenon is characterized by a continuum 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. The total collapse can be observed after a total time of 2h40.



he th

Figure 10. Experimental results

5. Conclusion and outlook

This present thermodynamic approach allows studding the crack growth process by taking into account the global dissipation process induced by the new crack surfaces formations and a process zone development. The generalization of this approach for climatic variations request introducing mechano-sorptive behavior in the energetic balance. In the same time, the global behavior needs the uncoupling of shrinkage-swelling effect. In this last case, a finite element modeling allows the prediction of the free displacement induced by moisture content level taking into account orthotropic properties in the specimen thickness and diffusion process in the transverse section.

References

[1] M. Chaplain, T. Dethan, G. Valentin, Crack propagation in wood under relative humidity variations, 12th International Conference on Fracture, Ottawa, 2009.

[2] J. Lemaitre, J.L. Chaboche, Mécanique des matériaux solides, Dunod Press, Paris, 1988.

[3] J.M. Husson, F. Dubois, N. Sauvat, Elastic response in wood under moisture content variations: analytic development, Mechanics of Time Dependent Materials, doi: 10.1007/s11043-009-9104-y, MTDM149.2, 2009.

[4] F. Dubois, J. M. Husson, N. Sauvat, N., Manfoumbi Modeling of the viscoelastic, mechano-sorptive behavior in wood, Mechanics of Time Dependent Materials, doi: 10.1007/s11043-012-9171-3, 2012.

[5] J. Gril, International COST 508 Wood mechanics Conference, 1996.