COST E55 "Modelling the Performance of Timber Structures"
Eindhoven – Octobre 2007

Modelling load duration of timber beams under various relative humidity conditions

Dr. Myriam CHAPLAIN
Unité Sciences du Bois et des Biopolymères (US2B)
Université Bordeaux 1 – CNRS - INRA
69 route d'Arcachon
33612 Cestas Cedex - France
Tel: + 33 5 57 12 28 20 -- Fax: +33 5 56 68 07 13
m.chaplain@us2b.u-bordeaux1.fr

Abstract
Under various mechanical and climatic conditions, timber elements display evolutions which can drive to failure. The duration of load is an important problem in timber engineering especially for beams containing stress concentrations (as notches or tapered end-notches). The failure of this kind of beams is generally due to the creation and the propagation of a crack. Moreover, to model delayed rupture due to crack evolution, it is necessary to model firstly duration before the apparition of the crack (incubation time) and secondly duration of crack growth until a critical length. The presented model predicts the incubation time using a damage approach. The time of crack propagation until failure is obtained using a viscoelastic crack model. As all other mechanical properties of wood, the delayed fracture depends on the stress level but also on moisture content and so on air relative humidity. The performed model is able to take into account these effects.
For several moisture contents, the initiation and propagation time predictions of the proposed model are compared to experiments realized on Laminated Veneer Lumber (LVL) notched beams under constant or step by step bending loading. Correct trend of the experimental results is obtained.

1. INTRODUCTION

Wood is a damaged visco-elastic material, under constant or various loading and climatic conditions, timber can be damaged and this damage generally leads to an early or later failure. This paper deals with the determination of the time-to-failure of timber elements whose rupture is due to the creation and the propagation of a crack (as notched beams, beams with a hole etc...). A damage model is applied to predict initiation (incubation) time: time to create a damage area which leads to the creation of a macro-crack (Fig. 1). The propagation of the crack is modelled by a fracture mechanics model considering that the crack grows in an orthotropic viscoelastic medium and a damage area exists at the crack tip (Fig 1).

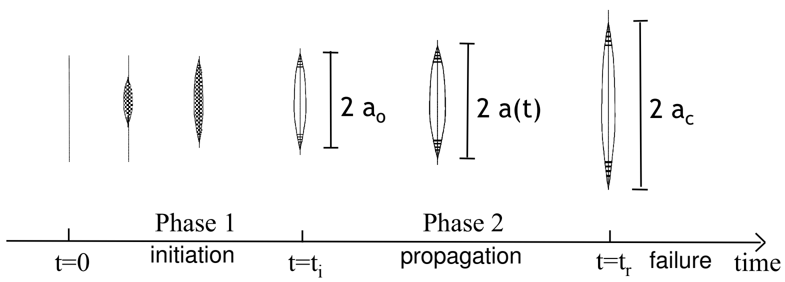

Figure 1 - Crack initiation and crack growth in an infinite medium

This model needs the elastic but also the viscous behaviour of the considered material. Experiments [4, 5, 7] showed that, for a given load, the more viscous the material is, the shorter the time to failure is. Reduced creep compliance is calculated using the orthotropic creep compliances of the tested wood. The expression of the stress intensity factor in opening mode I (K_I) expression must also be known. K_I can be expressed by mean of a calibration function g computed by finite element calculations. This function mainly depends on the crack length *a*, on geometry, type of loading (bending, tension…) and on elastic characteristics of the specimen: it also depends on moisture content (*MC*).
Duration of load predictions given by the models are compared to experimental results obtained on LVL (Kerto S – Finnforest) notched beams. These experiments were realized in bending; the loading was kept constant or by stepwise increased load.

2. EXPERIMENTAL OBSERVATIONS

The experimental results presented in the following are based on new experiments completing early ones obtained in the context of an European programme (Air project CT94-1057 [7, 8]). Bending tests were carried out on LVL notched beams, without initial crack (Fig. 2b).

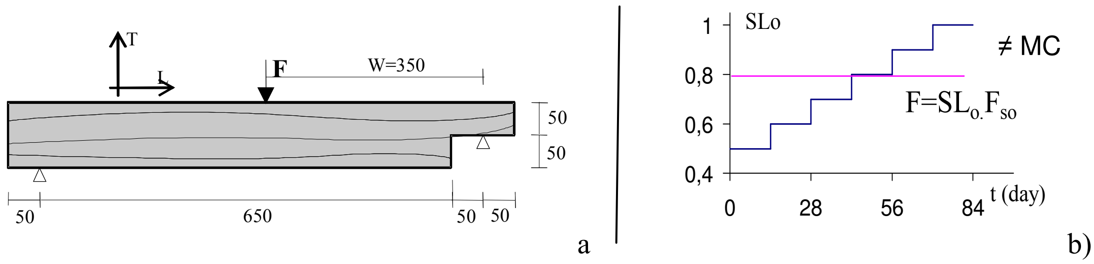

Figure 2 - a) Shoulder (notched) beam geometry in mm (thickness b =45 mm) without initial crack
b) shape of the loading (F_{so} = 8500 N, average strength at *MC*=20%)

The duration of load (*DOL*) tests include several test series, each series comprising simultaneous testing of 18 beams. Six series correspond to one season of the year. The two first series involve a stepwise increased load in autumn and winter. Four other ones involve constant loading. These six series were realized under natural climatic conditions (outside) after being conditioned outside during 3 months just before the loading. The other series have been tested under constant climatic conditions (*MC*=9% or 20%).
Figure 2b presents the two kinds of loading. The constant load tests are realized under an "average" stress level $SL_o=F(t)/F_{so}$=0,8; F_{so} is the average strength of notched beams of the same group tested under short term bending test at *MC*=20%. The stepwise load history started at a reference stress level of 50% and continued with increments of 10% of the mean short-term strength F_{so}. The step duration is 14 days (336 h).

The duration between the loading instant and the instant where a crack length (about 5 mm) is visible on both sides of the beam is called initiation time. The choice of the initial crack length equal to 5 mm appears as an acceptable value compared to the length of the beams shoulder (100 mm) and it is the minimum crack length needed for finite elements calculation of the stress intensity factor. Propagation time is the difference between the failure time and the crack initiation time.

Crack initiation:
The conditioning period is important: conditioning during a dry or getting dry season, the initiation of the failure is quicker than during wet season. A beam drained with a notch and a beam drained and notched after the conditioning has not the same duration of load, more precisely not the same initiation time. During the drying period, a stress concentration can create micro deformations at the tip of the notch. The creep tests realized in spring and summer emphasize this phenomenon: the crack appears at the beginning of the creep loading. For step by step loading, the initiation appears generally when the load increases or a few hours after. The observed initiation crack length can then be longer than 5mm and thus it has an influence on the propagation time.

Crack propagation:
Generally, under the same load, longest propagation times are found for dry and getting dry seasons. If the beam is conditioned during a dry period, the moisture content at the notch tip is low. Then, if a crack appears during a wet period, a massive water transfer appears through the crack tip. These water transfers should cause the acceleration of the crack growth. Water transfer kinetics on the crack tip appears as an important parameter for the crack propagation speed and therefore the duration of load of cracked beams. However, higher temperature can also have influence on the crack speed. Complementary tests on opening specimens (mTDCB) are carried out at the US2B to study the effect of *MC* or temperature change on crack evolution.

Duration of load (DOL):
Under the same load, duration of load is shorter for *MC*=20% than for *MC*=9% (Fig. 7). Under various climates, the experimental times to failure are scattered and found quite similar whatever the season. This can be explained maybe by the moisture content *MC* gradient created at the crack tip: the induced water movements drastically increases the crack speed.

3. VISCO-ELASTIC CRACK MODEL : VCM

3.1 Incubation time : damage model

In this approach, damage appears as a characteristic parameter D ranging from 0 at the beginning of loading to D_i at the crack initiation. The second model of Barrett and Foschi [1], with a non-linear damage evolution and a non-linear cumulative damage, has been chosen:

$$\begin{cases} \dfrac{dD}{dt} = A \cdot \left(\dfrac{F(t) - F_o}{F_s} \right)^B + C.D(t) & \text{if} \quad F(t) > F_o \\ \dfrac{dD}{dt} = 0 & \text{if} \quad F(t) < F_o \end{cases} \tag{1}$$

where $F(t)$ is the applied load, F_s the static strength of the element at a reference moisture content hereafter MC_{ref}= 20%, and F_o a threshold load. *A, B* and *C* are parameters.

Generally, damage models do not take into account the influence of moisture content. Fridley [6] or Toratti [10] proposed modifications to introduce moisture content or/and *MC* change velocity. The problem of these models is the great number of parameters (5 to 6 parameters). We tried to find a compromise between the number of parameters and the simplest modeling of the *MC* effect. As climatic conditions can vary during a DOL test, in this analysis, F_o is taken as a function of *MC*. The threshold stress level $SL_o=F_o/F_s$ is taken equal to 0,60 for *MC*=20% and SL_o=0,55 at *MC*=9%. These values are in accordance with the experimental DOL observations. These two values are also in agreement with the short term test observations; the crack initiation time is shorter in dry beams than in wet beams.
The deflection of notched beams is calculated by finite element method with or without a small crack (5 mm longer). Considering that this displacement is proportional to the compliance of the beam, a difference between the displacement with or without a crack can be representative of the damage of the beam. We found D_i=0,01 for a beam with a crack length equal to 5 mm. The other parameters are fitted on the experimental results obtained on LVL specimens (Table 1).

3.2 Propagation time: fracture mechanics model

The present viscoelactic model is based on the Shapery studies [2, 11] and on the Barenblatt's crack model. In the neighbourhood of the crack, the material is divided into two regions (Fig. 3): a process zone (length α) (1) which can be highly damaged, nonlinear and viscoelastic and a region surrounding the process zone (2) where the material is considered as linear viscoelastic. The equivalent (cohesive) crack length integrates the length of the process zone α.

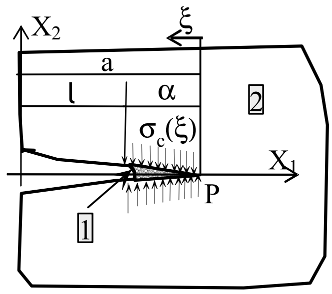

Figure 3 - Barrenblatt crack model

The distribution of the cohesive stress (σ_c) along the failure zone is not necessary uniform (no assumption on the behavior of the material). The requirement of the finite stress (Barenblatt hypothesis) at the crack tips yields to the following relations in opening mode [2,3]:

$$K_I = \left(\frac{2}{\pi}\right)^{1/2} \int_0^{\alpha} \frac{\sigma_f(\xi)}{\sqrt{\xi}} d\xi \tag{2}$$

with $I_1 = \int_0^{\alpha} \left[\frac{\sigma_c(\xi)}{\sigma_m} \frac{1}{\sqrt{\alpha.\xi}}\right] d\xi$ and $\sigma_m = \underset{0<\xi<\alpha}{\mathrm{Max}}(\sigma_c(x))$

For orthotropic viscoelastic medium containing a crack along a material axis (longitudinal direction hereafter), a relation between stress intensity factor K_I and the fracture energy G_I has been established:

$$2G_I = \kappa_{22}^{v}\left(\frac{\lambda_n{}^{1/n}\alpha}{\dot{a}}\right).K_I^2 \tag{3}$$

where $\dot{a}$ is the crack velocity; $\kappa_{22}^{v}(t)$ is a reduced creep compliance in mode I along natural axis X_2 (Fig. 3). The physical signification of $\kappa_{22}^{v}(t)$ can be related to elastic compliance in an isotropic material in plane stress state: $\kappa_{22}^{v}(t) = 2/E$ (E is the Young modulus). The parameter λ_n is depending on n [3].
The reduced creep compliance in mode I, $\kappa_{22}^{v}(t)$ can be assumed to be represented by a power law:

$$\kappa_{22}^{v}(t) = C_o \cdot (1 + C_2 t^n) \tag{4}$$

C_o, C_2 and n are material parameters.

The creep compliance (10), with the equation (9), gives a useful form of the crack velocity:

$$\frac{da}{dt} = \frac{\pi}{2}\left[\frac{C_2\lambda_n}{(K_{Ic}^2 - K_I^2)}\right]^{1/n} \frac{K_I^{2(1+1/n)}}{(\sigma_m I_1)^2} \tag{5}$$

with $K_{Ic} = \sqrt{2G_I/C_o}$ is the critical stress intensity factor

Equation (5) clearly shows that the velocity becomes unbounded when K_I approaches K_{Ic} from below; failure is obtained when K_I=K_{Ic}.

Expression of the stress intensity factor K_I

Because of the orthotropy of wood, the mode of failure of notched beam is not pure mode I but a mixture of mode I and II. However, as the failure is produced by the predominant mode which is mode I, only the opening mode is considered here.

The presented crack models need to know the relationship between the stress intensity factor K_I and the crack length. In mode I, the usual relationship between the stress intensity factor K_I, the applied load and the crack length involve the knowledge of a calibration function *g*. The calibration function generally depends on the mode of failure, on the elastic properties of the material and on the crack length *a*. It also depends on the specimen geometry on the type of loading too (traction, bending…). K_I must be expressed by equation (6).

$$K_I = \frac{F}{b\sqrt{w}} g(a/w) = SL.\frac{F_s}{b\sqrt{w}} g(a/w) \qquad (6)$$

where
F : applied load
F_s : strength of the element (hereafter at $MC=MC_{ref}=20\%$)
$SL = F/F_s$: stress level
b : the thickness of the specimen
w : a characteristic length of the specimen (Fig. 2)

The elastic behaviour of LVL used to obtain the calibration function by finite elements calculation has been obtained from tensile and bending tests. Figure 4 presents the evolution of the calibration function for this LVL notched beams for two moisture contents.

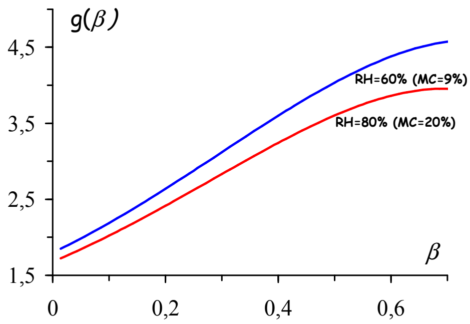

Figure 4 - Calibration function g versus the reduced crack length β=a/w (w=350 mm)

4. PREDICTIONS OF THE MODEL

For the moment, the model VCM is only applied to predict times to failure under constant moisture content (9% and 20%). When moisture content changes, we need to know how the model parameters move with *MC* and with *MC* gradiant. We made some hypothesis [5] not presented here; we still working to answer to this unknown.

Table 1 presents the experimental values obtained for LVL material and used VCM for two *MC*. The moisture contents 9% and 20% are nearly the extremes values obtained on LVL beams during the outside tests. The cohesive distribution within failure zone σ_c is assumed to be linearly distributed, thus $I_I=4/3$, maximum at the cohesive crack tip P (Fig. 3). The damage model parameters (*A, B* and *C*) are fitted on the results of beams under constant loading for high moisture content (for $MC=MC_{ref}=20\%$). The fracture mechanics parameters have been obtained from creep tests and/or fracture tests [4, 9].

MC (%)	**A [h^{-1}]**	B	**C [h^{-1}]**	SL_o	C_2 [h^{-n}]	n	λ_n	$\sigma_m I_1$ [MPa]	K_{Ic} [MPa√mm]
9	2,11.**10**^{14}	30	0,075	0,55	3,31.10^{-4}	0,41	0,63	67	23
20	2,11.**10**^{14}	30	0,075	0,60	6,28 10^{-4}	0,38	0,64	60	19

Table 1 - Parameters used in the VCM model

In this analysis, as *MC* can change during the long term test, the stress level *SL* is defined as the ratio between the applied load F and the ranked reference strength F_s of the specimens at $MC=MC_{ref}=20\%$.

During the creep tests under constants *MC*, the crack evolution was not measured, also only their times to failure are presented hereafter. In summer and spring, initial crack appears at the beginning of the constant loading. As the crack length may been long, simulations realized with an initiation crack length equal to 5 mm cannot be applied to these seasons, so we do not present the experiments obtained during these two seasons.

4.1 **Initiation time**

Figure 5 presents the experimental results obtained on notched beams under several climatic conditions and loadings. For step by step loading, the duration of load can not be represented against stress level but against the ratio between the ranked strength and the mean strength. The loading was in force but not in stress level, thus each beam has a different stress level history: $SL= F/F_s=SL_o.F_{so}/F_s$ (Fig. 2b). In this study, the ratio F_{so}/F_s varies between 0,8 and 1,2.
Despite the incertitude on estimation of F_S, VCM predictions at *MC*=20% are close to experimental results obtained during the wet seasons. At the *MC*= 9%, the "step by step" predicted initiation times are also in good agreement with experimental results as shown in figure 5b.

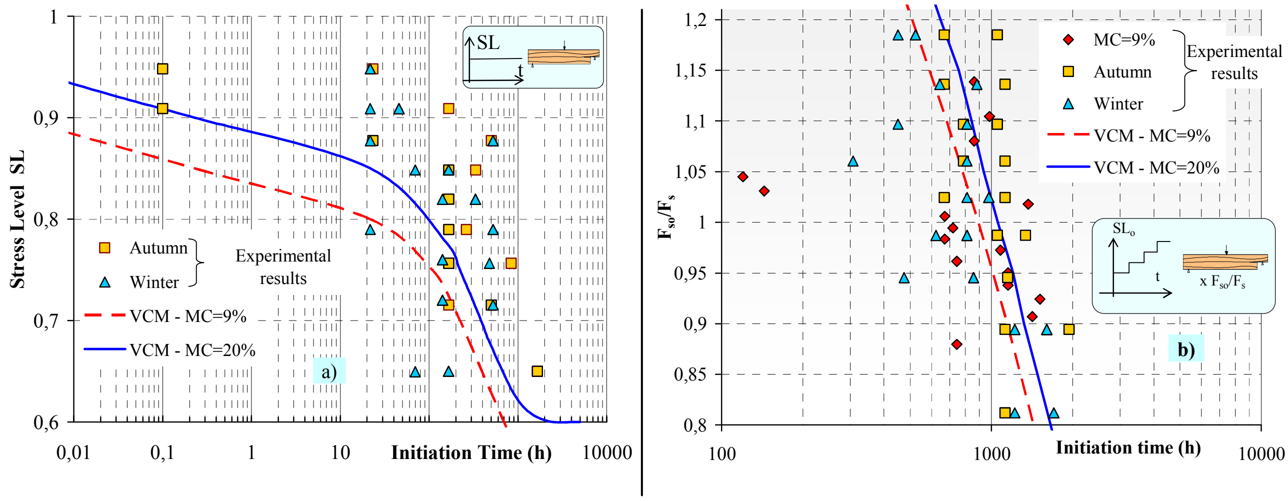

Figure 5 - Comparison between VCM initiation times predictions and experiments:
a) constant load, b) step by step load – MC: moisture content

4.2 **Propagation time**

The experimental propagation times are compared on figure 6 with VCM predictions at MC=9% and 20%. For constant loading or step by step loading, VCM is nearly close to experimental results. For step by step loading, the initiation usually appears when the load increases. The initiation crack length observed can then be longer than 5mm. These phenomena can explain the breaking up of the experimental results (Fig. 6b).

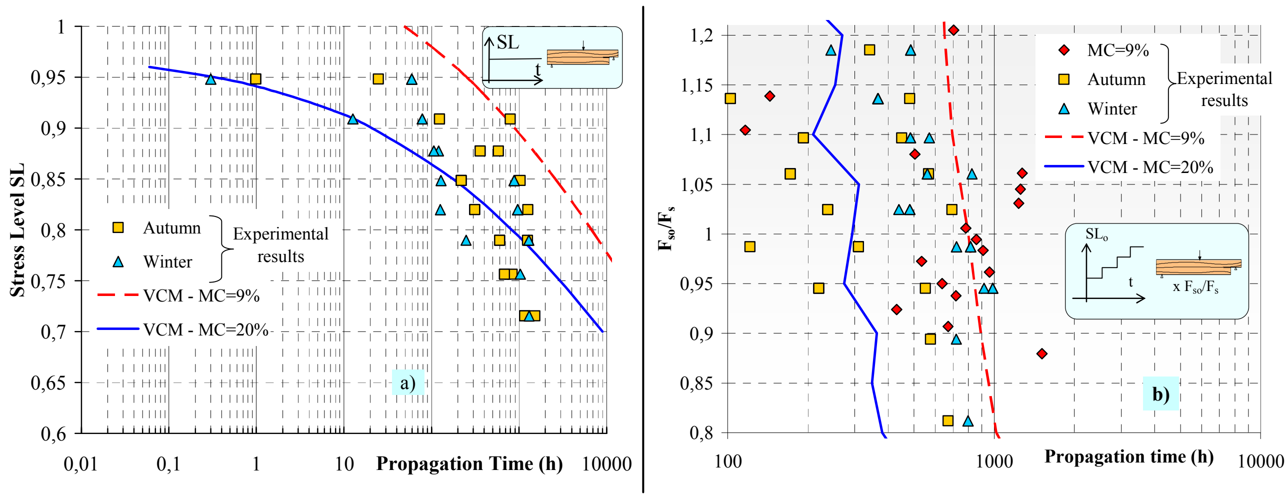

Figure 6 - Comparison between VCM propagation time predictions and experiments
a) constant load, b) step by step load – MC : moisture content

4.3 **Time to failure**

The figure 7 represents the experimental time to failure and the VCM predictions. The predictions of the model are in good agreements with the experiments obtained under constant *MC.*

Globally, the time to failure predictions are not far away from the experiments by considering the stress level dispersions.

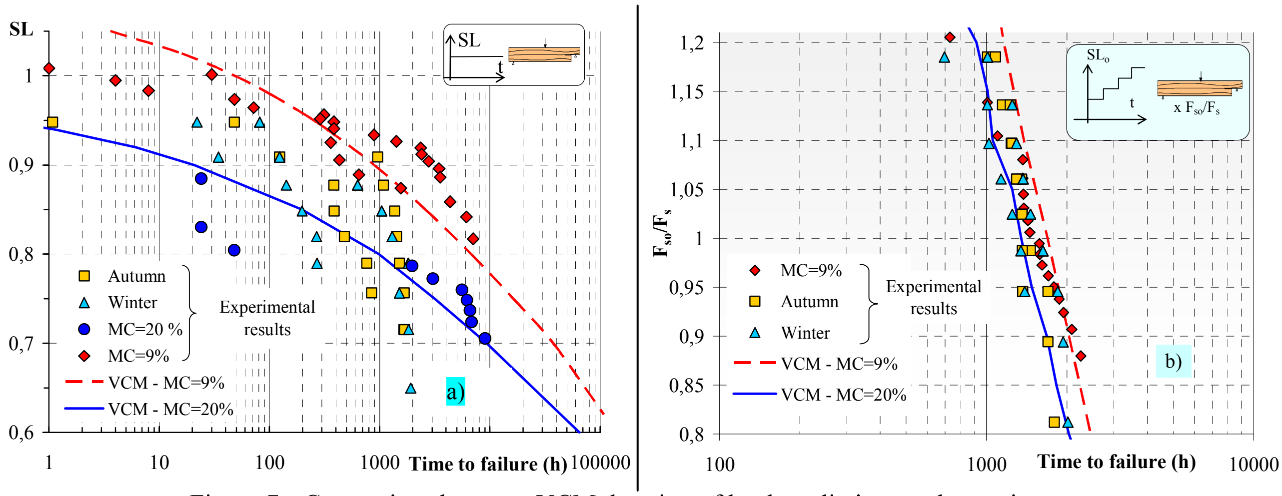

Figure 7 - Comparison between VCM duration of load predictions and experiments:
a) constant load, b) step by step load – MC: moisture content

5. CONCLUSION

The initiation times of notched beams are influenced by moisture content during loading but also between the conditioning periods. The initiation times are smaller when tests are realized during dry conditions and they are smaller anymore when the notched beams were dried before the test. The propagation time is also influenced by MC but in another way: the higher the MC is, the smaller is the propagation time. The viscoelastic crack model coupled with a damage model describes more correctly these phenomena. Good agreement with the experimental results is obtained with this model for two moisture contents (MC=9% and 20%). The VCM predictions are in agreement with the experiments considering that the dispersions on the value of the stress level SL and on the characteristics (visco elastic, fracture…) of the material.
To perform the VCM model, we must now introduce the effect of moisture content change through the damage parameters.

References

[1] Barrett J.D., Foschi R.O., (1978): Duration of load probability of failure in wood. Part I. Modelling creep rupture, Can. J. Eng. 5: 505-514.

[2] Brockway, G.S. and Schapery, R.A. (1978): Some viscoelastic crack growth relations for orthotropic and prestrained media. Engineering Fracture Mechanics: 10: 453-468.

[3] Chaplain M. , Valentin G. (2007): Fracture mechanics models applied to LVL beams delayed failure, Holz als Roh- und Werkstoff, Volume 65 (1), pp. 7-16.

[4] Chaplain M., G. Valentin G. (2006): Modelization of slow crack growth in wood considered as a damage viscoelastic material, 16th European Conference of Fracture ”Failure Analysis of Nano and Engineering Materials and Structures” Alexandroupolis, Greece, July 3-7, 8p (cd.Rom).

[5] Chaplain M., Dethan T., Castera P. (2006): Effects of climatic conditions changes on crack growth, 9th World Conference on Timber Engineering, WCTE, Portland, USA, 8p (Cd. Rom).

[6] Fridley, K.J., Tang, R.C. and Soltis, L.A. (1992): Load-duration effects in structural lumber: strain energy approach. J Struct. Eng., ASCE. 118 (4) : 2351-2369.

[7] Gustafsson, P.J., Hoffmeyer, P. and Valentin, G. (1998): DOL behaviour of end-notched beams. Holz als Roh - und Werkstoff, 56: 307-317.

[8] Jourdain, C. and Valentin, G. (1997): Duration of load effect on different sized timber beams, Final report of tasks B1.1 B1.2 B1.3, Projet Air 2. CT94-1057, 27 p.

[9] Larricq P. (1992): Une méthode d'estimation des caractéristiques de rupture différée d'un matériau viscoélastique orthotrope. Application au bois, Thèse n°738, Bordeaux University.

[10] Toratti, T. (1992): Creep of timber beams in a variable environment. Doctoral dissertation. Helsinski University of Technology, Finland.

[11] Schapery, R. A. (1975): A theory of crack initiation and growth in viscoelastic media: I. Theoritical development, International Journal of Fracture, 11: 141-159.