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LVL BEHAVIOUR UNDER CYCLIC TORSION: DAMAGE MODELLING

Myriam Chaplain[1], Faouzi Bouras[2], Zahreddine Nafa[3]

ABSTRACT: This paper deals with the study of the LVL behaviour (Laminated Veneer Lumber) under cyclic torsion loading. This study is part of an approach to better design the wooden structures under extreme wind or earthquakes. Torsion tests were carried out on rectangular specimen, end fixed with possibility of sliding head to prevent warping. Before each cyclic test, each specimen is tested under a monotonous rotation in the elastic area: torsion angle limited to 15 °. A reference cyclic stress level is defined as the ratio of the maximum moment applied to the maximum moment reached during the initial monotonous test. The signal of cyclic loading is triangular at various levels and amplitudes; the frequency is fixed at 1 Hz. The experimental results are used to study the influence of stress level and load magnitude on the damage and on the lifetime. A Model based on the damage theory is proposed. These cyclic torsion tests performed on LVL are also compared to experiments realized on glulam.

KEYWORDS: Torsion, Fatigue, LVL, Damage, Modelling

1 INTRODUCTION

In timber constructions, structural elements are subjected to complex state stress due to combination of simple loads and also due to structure geometry. Thus, torsion stress can appear under the effect of simple torque or under the effect of a geometrical instability like lateral-torsion buckling. In addition, loading can be constant or varying (for example, loads due to wind or earthquakes). There are some papers concerning the behaviour of wood or wood-based products in torsion: for example, under short term tests, Hindman et al. [6] have studied the behaviour torsional rigidity of composited I-joists with Laminated Veneer Lumber (LVL) flanges, Khokhar et al. [7] have analysed the effect of knots on shear modulus and Francescato et al. [5] have studied the torsion modulus of LVL beams. Under fatigue tests, Ayina [1] has presented results of short and long-term tests on glulam under torsion; Chen [4] has studied the effect of grain orientation on the torsional fatigue properties of hardwoods and softwoods. The torsion fatigue behaviour of solid wood under cyclic torsion-axial combined loading has been investigated by Sasaki and Yamasi [9, 10]. They have applied pulsating torsion with a triangular waveform at 1 Hz while the specimen was also simultaneously subjected to an axial (tension or compression) load at the same phase along the longitudinal direction. They have studied the effect of the axial load on the fatigue time of Japanese cypress specimens: in conclusion, compression load increases lifetime compared to tension load.

To complete fatigue torsion results, pure cyclic torsion tests have been carried out under various amplitudes triangular loading on glulam specimens by Nafa [3, 8]. Only the speed of loading time was kept the same (110 Nm/s) (frequency depending on the amplitude and on the mean value of the load). In the present study, complementary to the previous on glulam, cyclic torsion tests are performed on LVL specimens at 1 Hz frequency. We analyse the influence of amplitude and of maximum moment on the behaviour and the lifetime of LVL beams. These torsion tests are compared with those realised on glulam specimens and a damage model is performed.

2 EXPERIMENTAL PROGRAMME

The testing specimens have a rectangular section (40x28 mm^2) end fixed with a possibility of sliding head to prevent warping, the free length is 600 mm (Figure 1). The measured rotation is a global rotation (crosshead rotation).

[1] Myriam Chaplain, Université de Bordeaux, I2M/GCE, 351 cours de la libération-33405 Talence cedex France – m.chaplain@i2m.u-bordeaux1.fr
[2] Faouzi Bouras, Université 08 mai 45, LGCH, BP 401, 24000 Guelma, Algérie
[3] Zahreddine Nafa, Université 08 mai 45, LGCH, BP 401, 24000 Guelma, Algérie
[4] Zahreddine Nafa, Université 08 mai 45, LGCH, BP 401, 24000 Guelma, Algérie

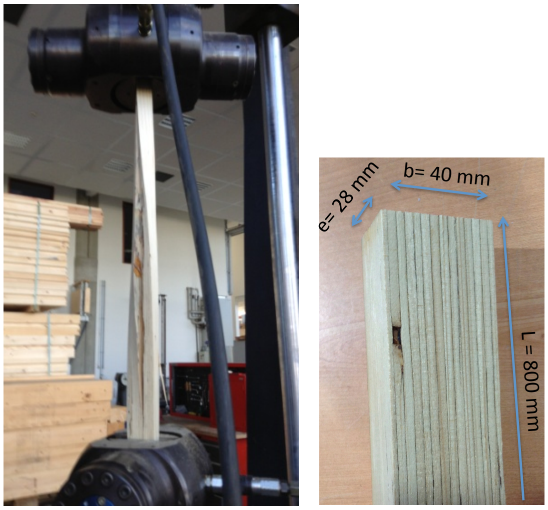


***Figure 1:** Test device and LVL specimen dimension*

Although the effects of moisture are non-negligible on viscous behaviour of wood, they are not studied hereafter; the moisture content of the specimens was around 12%.

The experimental program consists in three phases applied to each beam: firstly a monotonous rotation test is realised remaining in the elastic domain (torsion angle restricted to 15°), secondly cyclic torque under controlled moment is performed until reaching the press rotation limit 75°. Due to this limitation, specimens tested under fatigue loading are not completely damaged; also thirdly, a last monotonous rotation is realised until 75°. From these tests, the damage level of the specimens will be determinate.

2.1 MONOTONEOUS TESTS

Before each cyclic test, each specimen has been subjected to a monotonous rotation rate of 0.5 degrees per second during loading and 1 degree per second during unloading; torsion angle is limited to 15° to stay under the elastic domain. This preliminary test will help us to differentiate each beam considering the maximum torque at 15° ($C_{15°}$) and the initial shear modulus (G_{ini}) (Figure 2, Table 1).

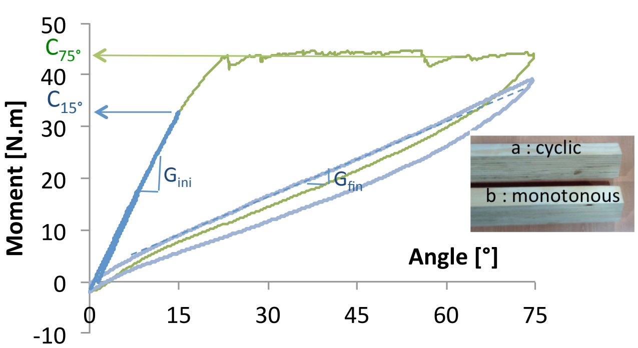


***Figure 2**: Moment - angular deformation evolution before and after fatigue testing (specimen a - blue curves) and monotonous result on specimen b (green curve)*

Generally, to study load duration, a stress level (*SL*) is defined as (Equation (1)):

$$SL = \frac{C_{max}}{C_s} \tag{1}$$

Where C_{max} is the maximum moment applied during cyclic test and C_s is the estimated strength moment of the specimen.

To obtain an estimate of the torsion strength C_s of the cyclic tested specimens, monotonic tests up to 75° have been performed on eight "twin" specimens (Figure 2). Indeed, in eight LVL beams, two specimens were cut side by side: one specimen noted *a*, is tested under the "cyclic" protocol, the second one noted *b*, is summited only to a monotonous rotation until 75° (Figure 2). Even if the specimen *b* is not completely broken, maximum moment (strength) is reached. Thus, we consider that the strength obtained on specimen *b* is the strength C_s of associated specimen *a*.

Only the strength of the specimens *a,* testing with *R*=0, are known from monotonous tests on specimens *b*. For the other specimens, C_s is unknown but, using initial monotonous tests, we have the moment reached at 15° ($C_{15°}$). The figure 3 presents the relationship between the estimated strength C_s and the torque à 15° deformation of the specimens *b*.

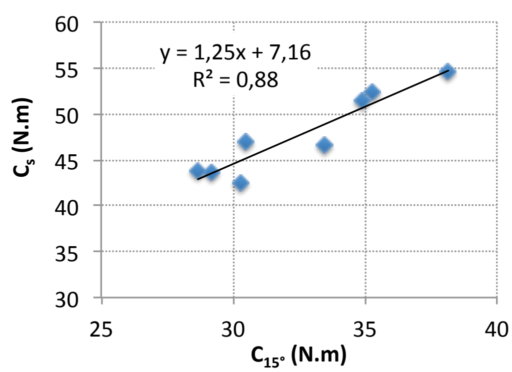


***Figure 3**: Relations between torque $C_{15°}$ versus strength torque C_s obtained on specimen b*

In view of these results, we decide to define in this study, to differentiate specimens, a reference stress level SL_r as (equation (2)):

$$SL_r = \frac{C_{max}}{C_{15°}} \tag{2}$$

Where C_{max} is the maximum torque applied and $C_{15°}$ the torque supported by the specimen for an angular deformation of 15°.

As the cyclic tests were limited to 75° rotation deformation (machine limit); thus, specimens were not completely broken and monotonous test could be performed after cyclic test. Final monotonous tests have been carrying out until the limit machine (75°) following the same instructions as in first monotonic tests. A final modulus G_{fin} can be determinate (Figure 2) for each specimen. This modulus will be used to calculate the damage to the beam (Equation 4).

2.2 CYCLIC TESTS

The cyclic torsion test is triangular; the frequency is fixed at 1 Hz. The maximum moment (C_{max}) is taken equal to 45 N.m, this value is nearly equal to 95% of the average strength value obtained on specimen *b*. The ratios *R* of minimum moment C_{min} to maximum moment C_{max} is equal to: $R = 0$, $R = 0.1$, $R = 0.25$ and $R = 0.5$. Ten specimens are testing under each *R* value (Figure 4).

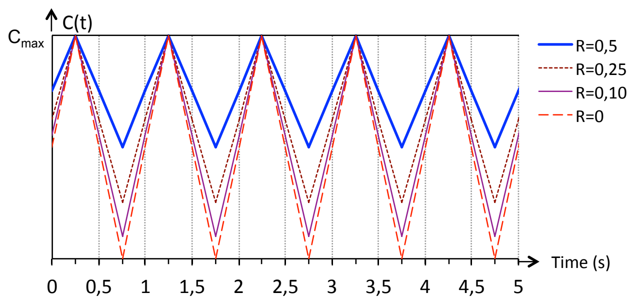


Figure 4: *Experimental cyclic loading (C_{max} : maximum torque, C_{min} : minimum torque, $R= C_{min}/C_{max}$)*

3 TESTS ANALYSIS

3.1 SHEAR MODULI

From the monotonic tests, using the relationship between the angular distortion and torque, torsion made without warping, the value of the shear modulus *G* is obtained using Equation (3):

$$\frac{d\theta}{dx} = \frac{C}{kGbe^3} \rightarrow G = \frac{l}{kbe^3}\frac{C}{\theta} \qquad (3)$$

Where *C* is the torque, *b* the width and *e* the thickness of the specimen, and *k* is a coefficient according to the ratio *b/e*. θ is the angular deformation in radian, *l* is the torsional length equal to 600 mm.

In our study, we obtain $b/e \approx 1.43$, $k \approx 0.19$ (recalculated values according to the dimensions of each specimen). The average shear moduli obtained during the initial and the final monotonous tests are presented on Table 1.

3.2 DAMAGE PARAMETER

In this study, the damage is characterized by a parameter D which varies between 0 when the material is not damaged and D_{fin} when the cyclic test is finish (angular deformation upper 75°). Analysis of the loss of rigidity between monotonous test, before and after cycle tests, allows us to determine final damage. Final damage D_{fin} is obtained through the Equation (4):

$$D_{fin} = 1 - \frac{G_{fin}}{G_{ini}} \qquad (4)$$

Where G_{ini} and G_{fin} are respectively shear moduli obtained during the initial and the final monotonous tests (Figure 2).

Table 1 summarizes the mean values of $C_{15°}$, $C_{75°}$, shear moduli G_{ini} and G_{fin}, final damage D_{fin} and density.

Table 1: *Mean values and standard deviations (sd) of torque $C_{15°}$ and $C_{75°}$, initial and final shear moduli G, final damage D_{fin} and density (43 specimens)*

$C_{15°}$ [N.m]	mean	35,76	G_{ini} [MPa]	mean	532,17
	sd	14,0%		sd	11,7%
$C_{75°}$ [N.m]	mean	39,17	G_{fin} [MPa]	mean	99,77
	sd	7,7%		sd	9,8%
Density	mean	0,521	Final damage D_{fin}	mean	0,81
	sd	1,6%		sd	1,8%

3.3 DAMAGE EVOLUTION

Figure 5 presents the angular deformation versus the applied torque when the minimum torque equal zero. We can observe the decreasing of the angular deformation and of the rigidity; we will analyse these decreasing versus time to obtain the damage parameter *D* evolution. Small hysteresis loops due to viscosity of wood can also be observed on Figure 5.

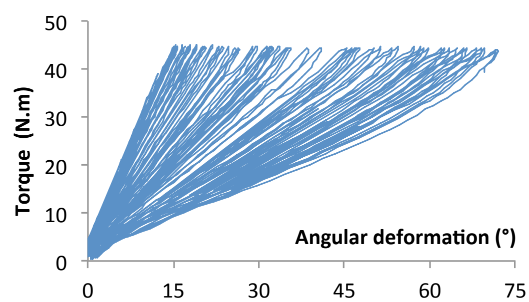


Figure 5: *Example of torque – angular deformation curves (C_{min} : minimum torque =0) (1/10 cycles represented)*

The damage during cycles can be analysed from the evolution of maximum angular deformation (Figure 6a). After a first flow (primary phase), the evolution of extreme angular deformation versus the number of cycles becomes almost linear (secondary phase). After a higher or lower number of cycles, a third exponential flow (tertiary phase) is observed due to specimen crack precursor to failure. The difference between the tertiary flow and the secondary flow is selected as damage index, this difference is normalize by D_{fin} (final damage) thereafter to obtain the damage parameter D.

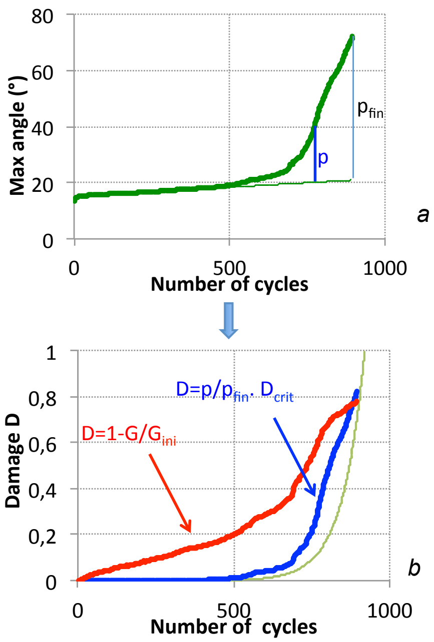


***Figure 6**: (a) Maximum angular deformation versus number of cycles: determination of the damage index p.*
(b) Damage parameter D evolution and prediction (thin line) for SL = 0.88 (R = 0); SL estimated from the monotonous test realised on the twin specimen b

The damage D can also be determined from the study of stiffness changes during each cycle compared to the initial modulus, G_{ini} obtained under the preliminary monotonous test (Figure 2). Thus the damage can be express by Equation (5):

$$D = 1 - \frac{G}{G_{ini}} \quad (5)$$

Where G is the observed shear modulus for a given cycle and G_{ini} the initial modulus.

The determination of D from the equation (5) is perturbed by the viscosity of the material, the rigidity observe during cycles does not represent only the stiffness of this material (rheological sense), it integrates the viscosity of wood. Some tests stopped at 2 000 cycles without apparent damage to the beam did not reveal a third flow: D is zero using the flow method. On the other side, during cycles, apparent stiffness has decreased: the rigidity method gives a non-zero final D value. Monotonic tests on the undamaged specimens confirm the absence of damage ($G_{ini} = G_{fin}$). The method based on the flow seems better to determine the damage D.

3.4 DURATION OF LOAD

The number of cycles to "failure" (limit 75°) is presented as a function of the stress level using a semi-logarithmic diagram (Wöhler curve). Figure 7 shows the number of cycles to failure versus the reference level SL_r and, for the specimens *a*, versus the stress level *SL*.

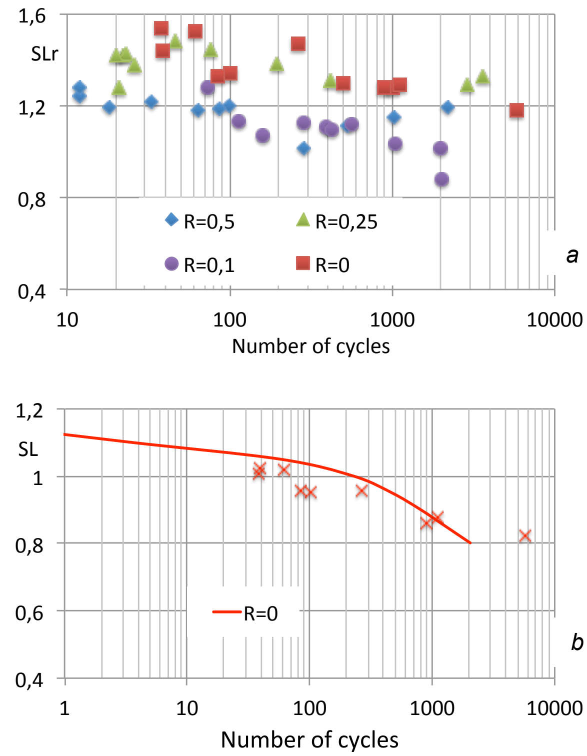


***Figure 7:** (a) Lifetimes versus the reference stress level SL_r*
(b) Lifetimes versus stress level SL predicted by the damage model and experimental results (points) at R=0 (specimen a)

The number of cycles to failure increases when SL_r decreases, the influence of R on the lifetime seems negligible. This can probably be explained by the fact that the time to failure is more conditioned by the maximum torque return (here every second) than by the speed of the triangular loading.

4 COMPARISON OF TWO CYCLIC TORSIONAL TESTS

Cyclic torsional tests performed on the LVL are compared with those realised on glulam by Nafa [8].

4.1 EXPERIMENTAL TESTS ON GLULAM

The specimens tested (were small models of beams used for construction. They were 900 mm long and were obtained by gluing six spruce lamellas of 40 mm wide and 10 mm thick (Figure 8) [3, 8]. The used adhesive was Enocol RLF 185 of the Ceca society (Paris); it is a mixture of resorcine, phenol, and formalin. All tests were performed in a room where temperature and humidity were constant or varying weekly. The moisture content of specimens is about 11%.

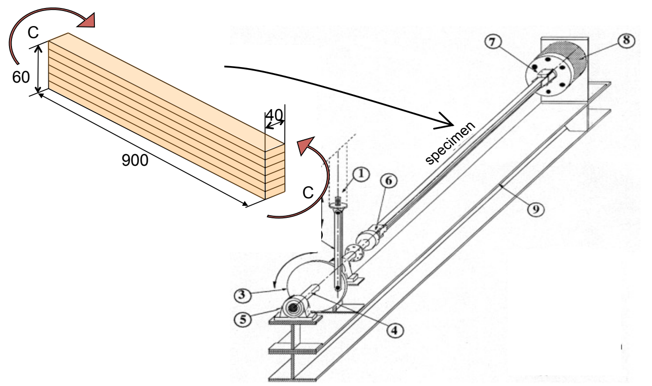


***Figure 8**: Test device and glulam specimen dimension in mm*

Short term (monotonous) tests were carried out to measure the torsion strength torque C_s. Tests were led under controlled displacement with a constant gradient of 2°/s. Long term tests were led under controlled moment with a constant speed of 110 N.m/s (and different frequencies for each amplitude). The signal was triangular (Figure 9). To emphasize the effects of the amplitude and of the maximum moment, three fatigue programs were carried out. For the first set, the middle moment was equal to zero with various maximum torque (R = -1). For the second set, the amplitude was constant and the maximum moment changed. For the third set, the maximum moment was fixed while the amplitude changed. Because of the large number of specimens and in order to limit the total time of test execution, a conventional limit of 2 000 cycles was fixed. Lifetime versus the stress level, $SL=C_{max}/C_s$, is presented on Figure 11b.

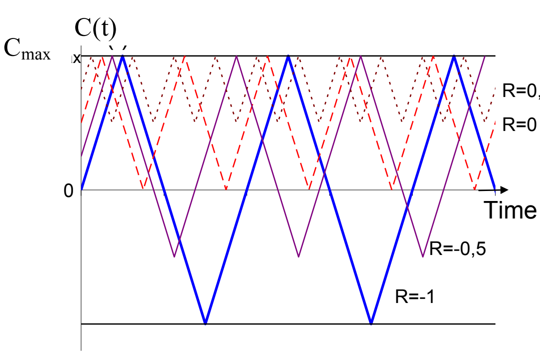


***Figure 9**: Cyclic torque signal, same torque speed: 110 N.m/s. R= C_{min}/C_{max} with C_{max} maximum torque and C_{min} minimum torque*

The damage evolution is obtained by considering the flow angular deformation evolution. Figure 12 present the damage evolution obtained for alternative torque (R = -1) and for three stress levels.

4.2 COMPARISON OF THE TWO CYCLIC TORQUE TESTS

The damage Glulam is more sudden, the tertiary stage is shorter than LVL, LVL is "softer" and deforms more.

The triangular cyclic tests on glulam were performed at constant speed, also for each ratio R and each load level SL, the frequency was different. For SL = 0.90, R = -1 for the frequency f was equal to 0.08 Hz, for R = 0.5, f = 0.10 Hz, for R = 0, f = 0.15 Hz and R = 0.5, f = 0.31 Hz

Under these conditions, as can be seen in Figure 11b, R has a significant effect on the time to failure: for the same stress level, the number of cycles to failure decreases when the amplitude increases. This is not the case of tests at constant frequency of 1 Hz on LVL, the effect of the amplitude is negligible.

5 DAMAGE MODELLING

The modelling is based on the damage theory: the time to failure of the specimens is predicted using a damage model [3] able to take into account the change in the average moment and frequency.

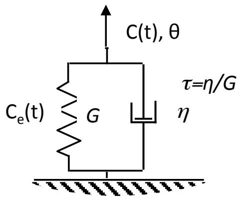
5.1 DAMAGE MODEL

A non-linear evolution and non-linear accumulation of damage model is retained. This model, as usual damage models, does not take into account the influence of the frequency or more precisely they do not include the viscoelastic behaviour of the material. To fill this gap, Chaplain [3] proposed to combine the rheological model of Kelvin-Voigt with the second model developed by Barrett and Foschi [2].

In the damage model, the viscous behaviour of wood is represented by the model of Kelvin-Voigt (Figure 10) and we consider that only the elastic part of the material is damaged. In the damage model, we integrate the elastic moment (C_e) and not the total moment applied to the element. This elastic moment depends on the state of damage D. The expression of the new model is obtained as follow (Equation (6)):

$$\begin{cases} \dfrac{dD}{dt} = a\left(\dfrac{|C_e(t)| - C_o}{C_s}\right) + \lambda D(t) & if\ |C_e(t)| > C_o \\ \dfrac{dD}{dt} = 0 & if\ |C_e(t)| \leq C_o \end{cases} \tag{6}$$

where C_s is the static strength moment and C_o the damage threshold moment. a, b et λ are fitted parameters. $||$ is absolute value.



η : viscosity
G : torque modulus : $G=G_{ini}(1-D)$
G_{ini} : initial modulus
D : damage parameter
C_e : elastic torque
$\tau=\eta/k=\tau_o/(1-D)$ with $\tau_o=\eta/G_{ini}$

***Figure 10**: Kelvin Voigt model and notation*

In expression (6), we consider that the limit damage moment C_o is not a constant but that C_o is depending on the average elastic torque $\overline{C_e}$ (Equations (7) and (8)):

$$\frac{C_o}{C_s}=SL_o=\frac{\overline{C_e}}{C_s}+\frac{C_{lo}}{C_s}.\left(1-\alpha\frac{\bar{C}}{C_s}\right) \tag{7}$$

$$\overline{C_e}=\frac{C_{emax}}{2}.(1+\mathrm{R}) \tag{8}$$

Where SL_o is the damage threshold level, $\overline{C_e}$ is the average elastic torque and C_{lo}/C_s is the damage threshold level under alternate loading. C_{emax} is the maximum elastic torque. $\bar{C}$ is the average applied torque and α is a parameter.

5.2 APPLICATION TO LVL AND GLULAM TESTS

Looking at the experimental results on glulam, the threshold level (C_{lo}/C_s) is taken equal to 0.47. It corresponds to values of damage threshold level found in literature. From the hysteresis loop observed on LVL (Figure 5) and on glulam [3, 8], the value of τ_o= 0.03 s has been determinate. The numerical values of a, b and λ have been fitting to obtain the best accuracy between predictions of time to failure and predictions of damage evolution on cyclic alternative test on glulam [3]. Their values have been obtained by successive simulations: simulations are performed for various set of parameters. The best values of a, b, and λ obtained are: a = 1E14 s^{-1}, b = 30, λ = 0.05 s^{-1}. The value of α = 1.26 is also obtained after several simulations to obtained the best times to failure for different R values compared to the experimental results on glulam. These parameters fitting on glulam tests are applied without change to predict damage of LVL specimens.

In Figure 11 presents the model predictions for the two experiments. In the case of torsion tests on glulam, Figure 11b shows the forecasts of the number of cycles to failure (D_{fin} = 1) with the experimental points. In this study the strength C_s has been estimated and therefore the stress level has been calculated [3]. Figure 11a shows the number of cycles predicted by the model with a final level of damage D_{fin}=0.81 (Table 1). In Figure 11a, the experimental points correspond to the tests carried out on twin specimen a: $SL=C_{max}/C_s$ with C_s equal to the strength of the specimen b (see chapter 2.1).

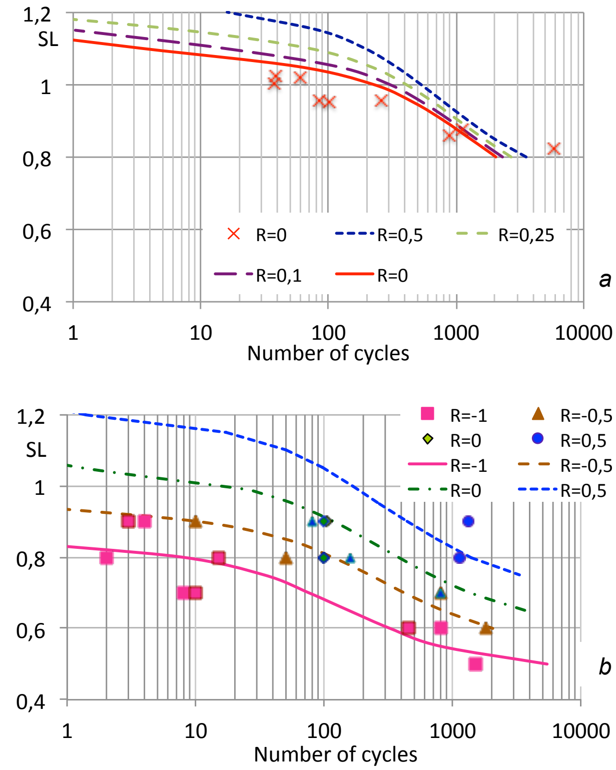


***Figure 11**: Lifetimes predicted by the damage model and experimental results (points) (a) for tests on LVL at the frequency 1 Hz, (b) for tests on glulam at constant load speed (variable frequency)*

Figures 6b and 12 (black line) show an example of number of cycles predicted for LVL test at R= 0; the experimental points correspond to the test carried out on specimens a at SL=0.88. Modelling and experimental development are close especially if we consider the flow evolution to determine the damage D.

Figures 12 shows the theoretical and experimental damage evolution under alternating cyclic loading (R = −1) for glulam specimens. Considering the uncertainties on the values of the stress level (estimation of C_s of the beam tested under cyclic loading) and despite the dispersion of results and the lack of experimental points, the model predictions are acceptable. The experimental observations are reasonably well respected.

On figure 12, we also compare the predictions of the damage model for glulam tests (constant speed and alternative loading (R = -1)) and for LVL test (constant frequency and wavy loading (R = 0)): the damage parameter evolution is very sensitive to the loading shape.

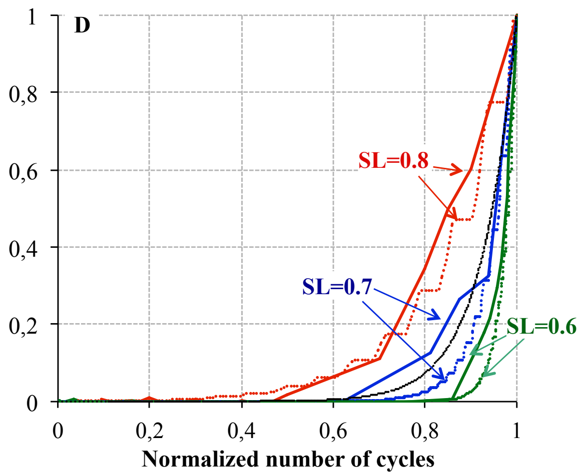


***Figure 12**: Damage evolution under alternating torque (R = -1) Glulam tests. Full line: experimental results – Dotted line: simulation. Black line damage evolution prediction for LVL test at SL = 0.88 and R = 0.*

6 CONCLUSIONS

A series of wavy torsion cyclic tests have been carrying out at constant frequency 1 Hz and variable amplitude on LVL specimens to complete a previous study on glulam. We have established a testing protocol and processing which allows us to obtain the evolution of the damage and the lifetime of the specimens.

Tests on LVL beams at constant frequency have shown the small influence of the signal amplitude on the lifetime contrary to the results obtained on torsion cyclic tests on glulam under constant speed loading (ie variable frequency).

The damage model developed gives predictions of damage evolution and of lifetime in agreement with the observations; the model takes into account the effect of frequency, amplitude and of stress level.

Tests on other LVL beam sections and or length will be carrying out in addition to this study. These dimension should be selected to obtain complete failure of the specimen before the press limit rotation 75°, while maintaining the section-length ratios observed in wood constructions.

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