MODELLING THE BEHAVIOUR OF WOOD DURING THE CRASH OF A CASK IMPACT LIMITER

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SUMMARY

We present experimental results and their analytical modelling for wood under static and dynamic compression which involves large deformations. We also present a numerical constitutive relation for the compression of wood under large deformations. This "wood model" is based on the experimental results mentioned before. It is used in a finite element explicit non-linear dynamic code. By this way, we can compare this model with other models used to characterize wood when it's used in cask impact limiters. Finally, we compare test results of a container model using wood as impact limiter crashed at 52 m/s with numerical results made with two numerical material types used to model the behaviour of wood under compression with large deformations (elastoplastic model and wood model).

INTRODUCTION

Wood is a material used as energy absorbing device in type B packaging for example. This is because it exhibits a smooth behaviour in terms of load-deflection until more than 50% strain. In recent years, cask design has changed. In the past, only tests on models or full scale containers were performed after the preliminary concept defined by hand calculations. But now we also use computer models (with dynamic code using Finite Element Method). Yet, in order to reproduce numerically the behaviour of a cask impact limiter during a crash, we have to understand the mechanical behaviour of each material involved in the device. In this context, we have tried to create a constitutive law for wood under dynamic multiaxial compression and under large deformations : the wood model (Adalian 1998).

At first, we present experimental results on wood characterisation under static and dynamic compressive loads. These tests are essentially longitudinal compression tests on slender specimen in order to get large deformations (more than 60 % crush) and large strain-rates (more than 1000 s^{-1}).

Then, we present the wood model which is based on analytical modelling of the experimental results mentioned before. This model has the same skeleton as the metallic honeycomb model available in the standard LS-DYNA3D code. We have implemented our model in this dynamic code in order to compare it with the other material types used to model wood under large dynamic compressive loads.

Finally, we compare test results of a reduced scale container using wood as impact limiter crashed at 52 m/s with numerical results made with several numerical material types used to model the behaviour of wood under compression (elastic-plastic model and wood model).

THE EXPERIMENTAL BEHAVIOUR OF WOOD UNDER LARGE STATIC AND DYNAMIC COMPRESSIVE LOADS

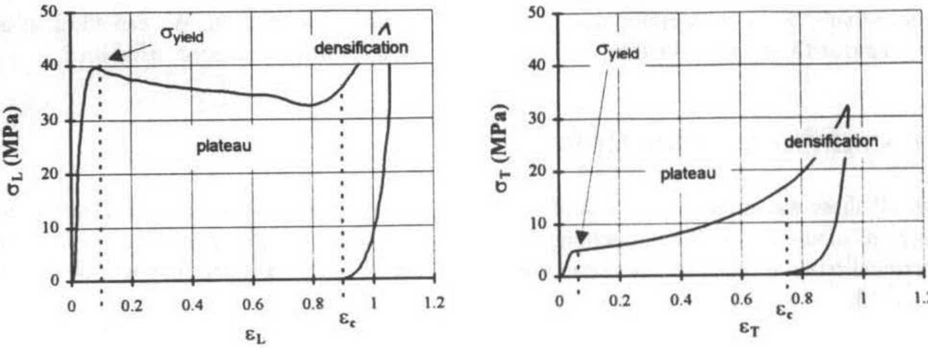
The first approach is to consider a sample of wood as a homogeneous elastic orthotropic material. Its three orthogonal axes of symmetry are the axial or longitudinal (L) axis, the radial (R) and the tangential (T) one. The stiffness and strength are greatest in the axial direction. Moreover, the mechanical properties in the two other directions of orthotropy are nearly equal. At a scale of some millimetres, wood is a cellular solid : cell walls often with the shape of hexagonal prisms enclose pore space. The relative density (d_0/d_s) where d_s is the density of the cell wall material can be as low as 0.05 for balsa and this can explain the fact that wood can sustain very large deformations. These characteristics allow us to liken the behaviour of wood to the behaviour of other cellular material such as foam or honeycomb.

The choice of the geometry of the specimen we have used for our static and dynamic tests has been guided by a paper of François and Morlier (1993) where they recommended to use slender specimen in order to get large deformation without any shear deformation.

That is the reason why we have usually tested specimen with 5 or 10 mm height and 25, 40 or 60 mm squared section. François (1992) has also established an experimental plasticity law for wood under compression : the box-like criterion. This criterion represents the fact that the allowable value of stress in one of the three directions of orthotropy is not affected by the stresses that may be applied in the two other directions. Thus we have only made compression in anyone of the directions of orthotropy. Finally, we had to use the definition of the true strain (logarithmic strain : $\varepsilon(t) = \mathrm{Ln}\left(h(t)/h_0\right)$) for the experimental results we present in the following pages because the specimen encountered very large deformations.

Static tests have been performed in an Instron testing machine. Dynamic tests were based on the drop hammer principle where a mass impacts the wood specimen with an initial velocity V_0. During the test, the velocity of the impacting mass is decreasing whereas the specimen is crushed. Thus strain-rate inside the material is decreasing during the test. This phenomenon is important to notice and it will allow us to make an assumption on the dynamic behaviour of wood as we will see later.

The experimental behaviour of wood under large compressive loads in the three orthotropic directions is described in figure 1. We like to specify that we have considered that the behaviour of wood is the same for radial and tangential directions. We use the name transverse to characterize these directions.

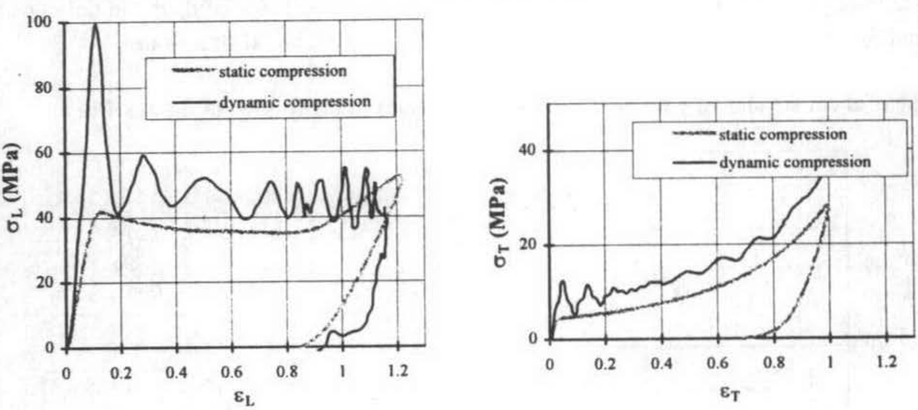


(a) (b)

Figure 1 - The main phases of the mechanical behaviour of wood under static longitudinal (a) and transverse (b) compression

For any direction we can see 3 phases. First of all, an elastic phase where the behaviour is reversible and where stresses are proportional to strains. Hooke's law characterizes this first phase and we can write : $\sigma = C\varepsilon$. For computation, in the case of compression of wood we make the assumption that the constitutive matrix C is diagonal. That means that all the Poisson's ratios are equal to zero. When the stress reaches the yield limit the behaviour becomes irreversible. Large deformations occur during this phase named "plateau". The stress level is roughly constant for the longitudinal direction and it is rising gently for the transverse directions. At the end of the plateau, when the strain reaches a critical strain ε_c, the stress rises steeply. This phenomenon is the consequence of the cell walls compression. This phase is named densification and the behaviour is the behaviour of the cell walls material. Obviously, the critical strain ε_c is strongly dependent on the material porosity.

The influence of the strain-rate on the mechanical behaviour is illustrated by the figure 2.



(a) (b)

Figure 2 - Comparison of the mechanical behaviour under static and dynamic compression in the longitudinal (a) direction or in the transverse plane (b).

We can see that strain-rate is mainly important for the yield stress area. On the other hand, during the plateau, stress level is roughly constant whereas strain-rate is evolving. So we can suppose that strain-rate does not affect the behaviour during the plateau. We can add that the peak in stress for dynamic loading is a consequence of a strain-rate induced instability.

THE ANALYTICAL WOOD MODEL

With all these assumptions we have defined 7 parameters that can be used to describe the behaviour in any of the three directions for wood under static and dynamic compression until the critical strain is reached. These parameters are defined in figure 3 and they will be used to estimate the stress-strain behaviour in the numerical wood model.

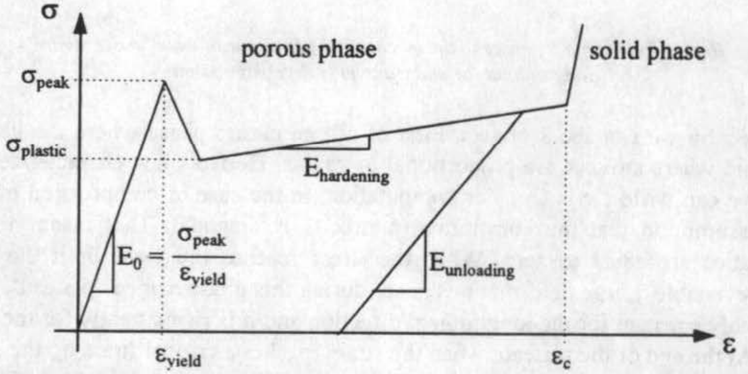
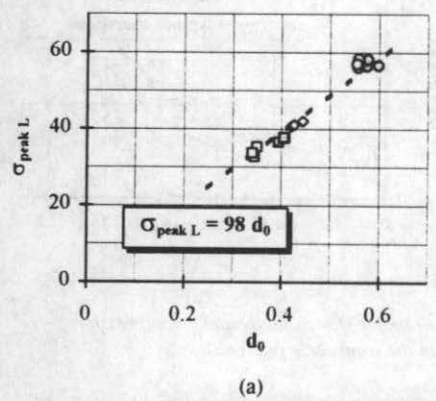


Figure 3 - Definition of the seven parameters that are used to describe the behaviour of wood under static and dynamic compression in the porous domain

In order to get the value of these parameters without doing any experiment, we have determined empirical laws for each of the seven parameters in each direction of orthotropy. These laws give the value of the parameter with the only knowledge of d_0 the initial density, h_0 and S_0 the initial geometry, $\varepsilon(t)$ the actual strain and $\dot{\varepsilon}_0$ the initial strain-rate.

Some of them are shown with their experimental values in the following figures 4 to 6.



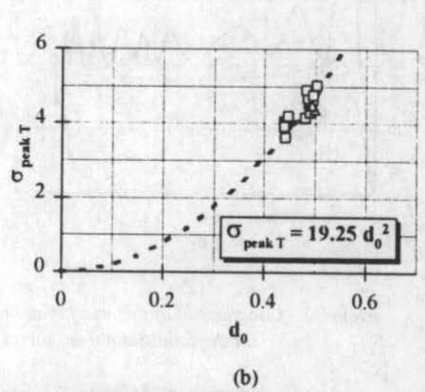


Figure 4 - Peak stress related to initial density for static compression in the longitudinal direction (a) and in the transverse direction (b)

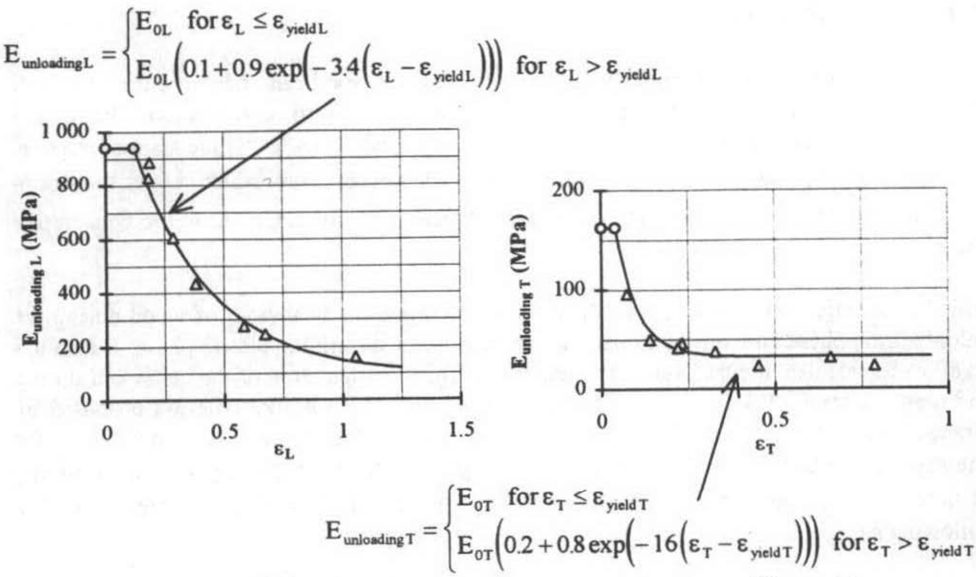


Figure 5 - Unloading static modulus related to the deformation reached at the beginning of unloading for longitudinal (a) and transverse (b) compression

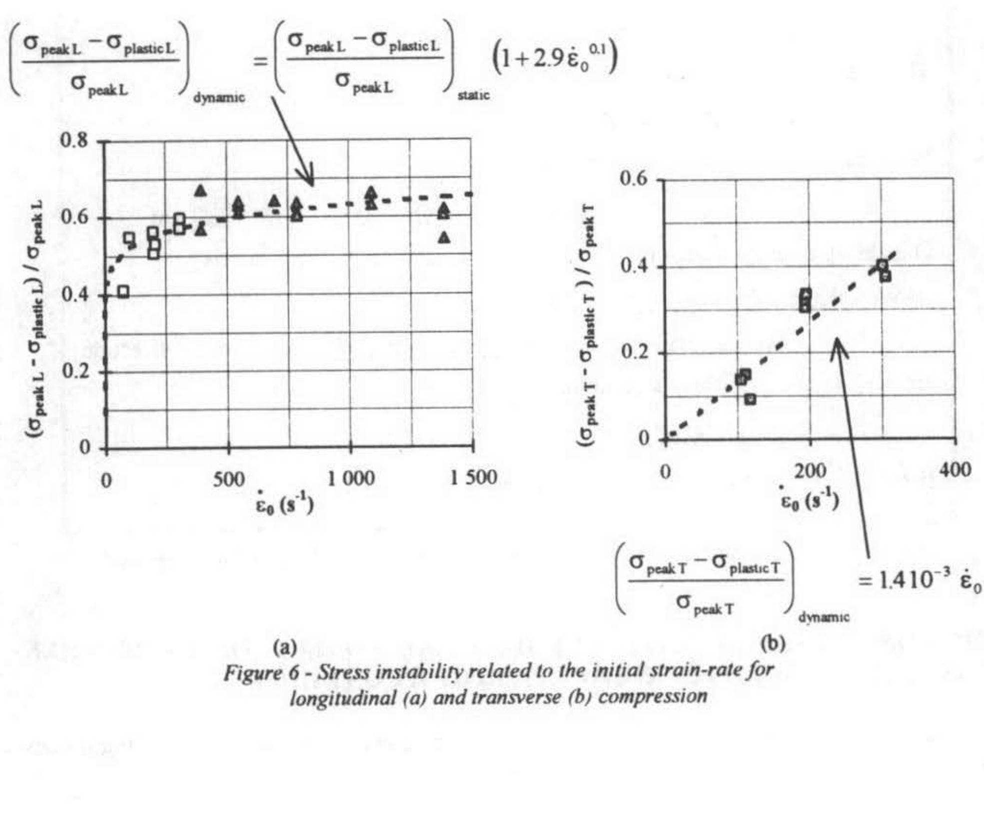


Figure 6 - Stress instability related to the initial strain-rate for longitudinal (a) and transverse (b) compression

THE NUMERICAL WOOD MODEL

This model has to represent large strain that a specimen of wood can undergo during static or dynamic compression. For this reason, it is based on a hypoelastic formulation. That means that the constitutive law used is an incremental law that calculates σ_{n+1}, the state of stress at time t_{n+1} from σ_n, the state of stress at time t_n and a hypoelastic law which relates the strain-rate tensor $\dot{\varepsilon}$ to the Jaumann stress rate (corotational) σ^J : $\sigma^J = C\dot{\varepsilon}$. C is the constitutive matrix.

This hypoelastic formulation has to allow us to determine the behaviour of wood during the initial elastic phase and during unloading that may occur during the plastic phase. It also has to allow to calculate the trial state of stress needed for the calculation of the behaviour during the plastic plateau. This trial state of stress is used with the box-like criterion proposed by François and Morlier (1993). We also use the analytical models we have presented before for the stress-strain behaviour of wood in the porous phase. Therefore, for any state of stress σ_n at time t_n in the porous phase, we can calculate the state of stress σ_{n+1} at time t_{n+1} by the following steps.

We have to be in the orthotropic coordinate system.

I/ <u>We calculate the trial state of stress</u> :

a/ <u>hypoelastic law</u> : $\sigma^J = C\left(\varepsilon^{n+1}\right)\dot{\varepsilon}^{n+1/2}$

This is a non-linear relation

b/ <u>integration of the hypoelastic law</u> :

We get the trial state of stress : $\left(\sigma^{n+1}\right)^*$

$$\left(\sigma^{n+1}\right)^* = \sigma^n + \left(\Omega^{n+1/2}\sigma^n - \sigma^n\Omega^{n+1/2}\right)\Delta t + C\left(\varepsilon^{n+1}\right)\dot{\varepsilon}^{n+1/2}\Delta t$$

Ω is the spin tensor (antisymmetric part of the velocity gradient matrix).

II/ <u>We calculate the state of stress at time n+1</u> :

a/ we calculate the <u>admissible value of the stress</u> in each direction $\sigma_{ij}^y = f\left(d_0, \varepsilon_{ij}, \dot{\varepsilon}_{ij}\right)$ thanks to our analytical laws

b/ <u>radial return</u> :

If $\left(\sigma_{ij}^{\ n+1}\right)^* > \sigma_{ij}^y$ then $\sigma_{ij}^{\ n+1} = \sigma_{ij}^y$ else $\sigma_{ij}^{\ n+1} = \left(\sigma_{ij}^{\ n+1}\right)^*$.

Figure 7 - The main steps of the calculation of the state of stress at time t_{n+1} for the wood model

THE COMPARISON OF DIFFERENT MATERIAL MODELS FOR WOOD WHEN IT IS USED FOR MODELLING THE CRASH OF A CONTAINER

Our reduced scale container is a cylindrical one made of two steel liners surrounding blocks of wood. Figure 8 shows the geometry of the model.

The axial direction of wood is symbolized by arrows. In the corners we have used a new material named IWOC (Isotropic Wood Composite). This material made of wood has the particularity to be isotropic (Roussel 1997, Roussel and Morlier 1998).

A lot of calculations have been made with the classic elastic-plastic type of material in order to represent wood. So we have to compare this model with our wood model.

The main drawbacks of the elastic-plastic model when it is used to represent wood is that it is an isotropic material model that does not take into account the possible porosity of the material. This implies that the plastic volume is constant. That means that when the material is crushed over the yield stress in one direction of orthotropy, its section is increasing in order that the volume remains the same as at the beginning of the plastic phase. Moreover there is no distinction in this model between the porous phase and the solid one.

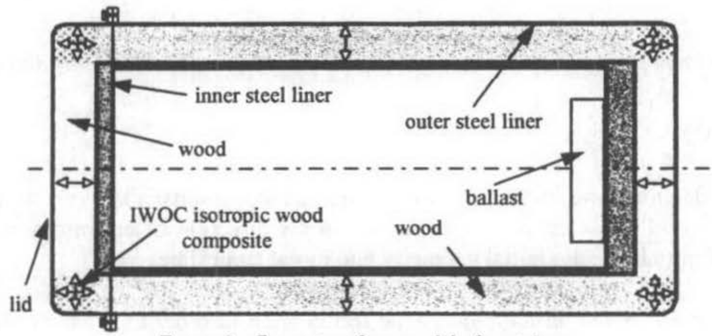
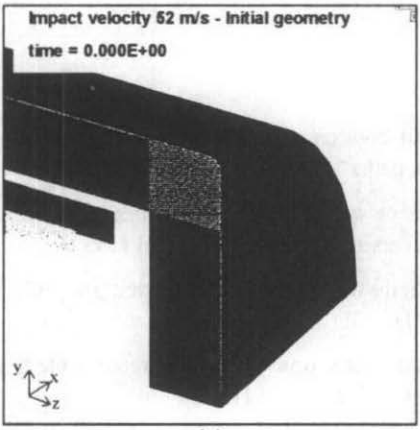
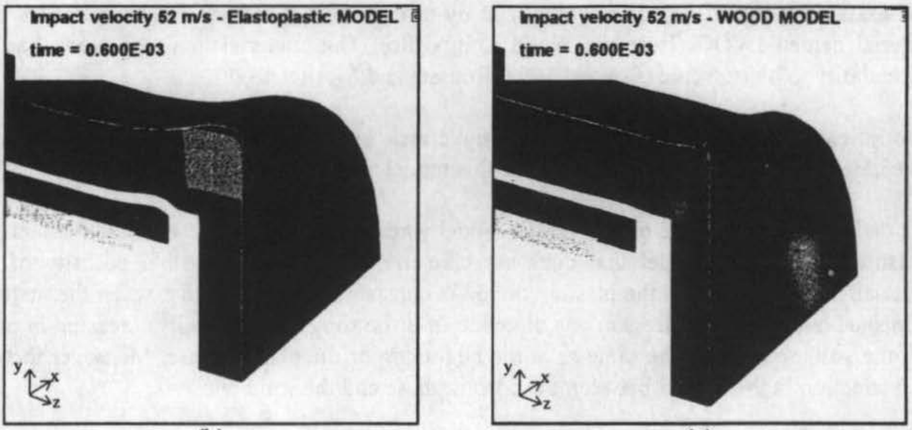


Figure 8 - Geometry of our model of container

Thus we have compared the calculations made with this elastoplastic model with the calculations made with the wood model for a container crashed at 52 m/s. And we can see that the elastic-plastic model gives a non-realistic increase of the section of the container near the impact face even at the beginning of the impact (at time t=0.6 ms as shown in figure 9).



(a)



(b) (c)

Figure 9 - Modelling of a crash of a container
initial geometry (a), geometry at time t=0.6 ms with the elastic-plastic model (b) and with the wood model (c)

CONCLUSION

Analytical modellings we have got from experimental results allow us to estimate the behaviour of wood under uniaxial compression in the direction of orthotropy with the only knowledge of initial density, initial geometry and initial strain-rate.

Our wood model is based on the hypoelastic formulation in order to calculate the behaviour of wood in dynamic compression. That is the reason why it has to evaluate the yield surface for any state of strain. This evaluation is made with our analytical modellings.

The results we got with the wood model are closer to the experimental behaviour of wood than when we used the elastoplastic model. Yet, this latter model is the one that has been widely used to represent wood in impact limiters. In order to represent the porous characteristic of wood when it undergoes large deformations we recommend to use the presented wood model.

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