COMPOSITE DAMAGE MODEL FOR DYNAMIC FRACTURE PREDICTION : IDENTIFICATION ISSUES

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ABSTRACT

This paper deals with the modeling of damage in laminates under dynamic loading. In the first part, the basic aspects of the model, which were developed in previous studies, are described. In the second part, we focus on current developments concerning the identification of the dynamic part of the model. Two points are detailed, the effect of delay parameters with respect to dynamic rupture and some specific difficulties regarding interface identification.

1 INTRODUCTION

The design of composite crash absorbers is still a challenging task. In order to avoid numerous and costly experimentations, *EADS Suresnes* wishes to develop a reliable numerical tool. Such a tool must include properly identified material models capable of capturing the physics of the deterioration and dissipation phenomena which take place during a crash.

The model is based on the extension to the dynamics of the damage mesomodels of laminates [1, 2]. For such a model, an identification process is established for the static behavior but the question that is addressed here deals with the identification of the dynamic effects, that are induced by the dynamic nature of the loading. In a first part, the identification of the delay effect is discussed, then, in a second part, some remarks on the rate effects on delamination, due to the loading, are presented.

2 MESOMODELING OF LAMINATES

The mesomodelisation of laminates has been developed at *LMT Cachan* and is able to take into account the static behavior of composites, by choosing an intermediary scale between the micro one of the fibers and the macro one of the structure [1, 2, 3, 4].

2.1 Static mesomodel of laminates

The material is described by means of two basic mesoconstituants: the single layer, that is supposed to be homogeneous and orthotropic, and the interface, that allows the description of delamination (Fig. 1).

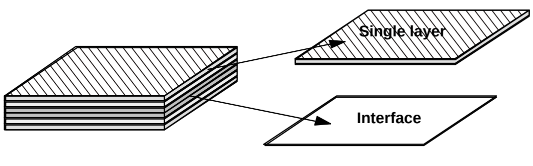


Figure 1: Mesomodel of laminate

Damage mechanisms are taken into account through internal variables, both for the single layer and the interface. Moreover, these variables are supposed to be constant throughout the thickness of each ply. As a consequence the model only allows the description of cracks linked to delamination or orthogonal to the plies.

A detailed description of both the model of the ply and of the interface can be found in [1, 2, 3]. Its ability to described the phenomena under complex loading has been illustrated in [5], in the case of low-velocity impact.

In the case of dynamic loading, the idea developed in [4] is to introduce a delay effect, that is related to the fact that the microcracks have a bounded propagation speed, in the damage evolution laws at the mesoscale.

2.2 Damage with delay effect

The model is presented and illustrated here for a unidimensional behavior, with only one damage variable, that is governed by the following state laws:

$$\sigma = E^0 (1-d) \langle \varepsilon \rangle_+ - E^0 \langle -\varepsilon \rangle_+ \quad \text{and} \quad Y = \frac{\langle \sigma \rangle_+^2}{2E^0 (1-d)^2} = \frac{E^0 \langle \varepsilon \rangle_+^2}{2} \tag{1}$$

For a large family of laminates with continuous fi bers, in the case of static loading ([2, 6]), the evolution law is given by:

$$\begin{cases} d = \left\langle f(\sqrt{\underline{Y}}) \right\rangle_+ & \text{if } d < 1 \\ d = 1 & \text{otherwise} \end{cases} \quad \text{with} \quad \begin{cases} \underline{Y} = \sup_{\tau \le t} Y|_\tau \\ f(\sqrt{Y}) = \dfrac{\sqrt{Y} - \sqrt{Y_0}}{\sqrt{Y_c} - \sqrt{Y_0}} \end{cases} \tag{2}$$

In the following, the threshold Y_0 will be taken null and we will note: $Y_c = \frac{E^0 \varepsilon_c^2}{2}$

Let us introduce the delay effect that leads to the following evolution law :

$$\dot{d} = \frac{1}{\tau_c} . \left\{ 1 - exp - a \left[\left\langle f(\sqrt{Y}) - d \right\rangle_+ \right] \right\} \text{ if } d < 1, \qquad d = 1 \text{ otherwise} \tag{3}$$

This law is such that for quasi-static loadings, ones recovers the previous static evolution law. Otherwise, especially when dealing with localization, the damage is not instantaneous, and its rate is bounded by $1/\tau_c$. Furthermore the more or less brittle character of the evolution law is governed by a. Previous works have shown the numerical consistency of the model, [4] and the question addressed here deals with its identifi cation.

3 IDENTIFICATION OF THE DYNAMIC EFFECTS

3.1 Delay effect: feasibility

In laminates, the delay effects mainly occur when localization appears. Since these phenomena only occur in a restricted part of the loaded structure, the question is addressed to know if, in a test, they can be identifi ed. This point will be considered through two approaches, by estimating the different energies involved and by studying the sensibility of the measurements to the delay parameters.

3.1.1 Dissipated energy in a quasi-static test

Let us consider a bar submitted to a quasi-static loading up to rupture and let us estimate the different energies involved.

The first question is to estimate the size of the localization zone. A first study, based on the linearized equations about a homogeneous state denoted $(\underline{\varepsilon}, \underline{d})$ before localization, [7]. This leads to the following expression for the localization length :

$$L_{loc} = \frac{2\,c_0\,(1-\underline{d})^{\frac{3}{2}}}{\underline{d}}.\frac{\tau_c}{a} \tag{4}$$

This first estimation gives an order of magnitude of the size, as shown figure 2, but is based on strong simplifications linked to the linearization. In the case of dynamic loadings, [8] proposed an estimation of the localization size in the case of the propagation of a shock wave. This study is based on the evolution equation of the damage on the wave front and gives an estimation of the localization length linked to the magnitude of the loading $\Delta\sigma$:

$$L_{loc} = c_0\,\tau_c\,\log(\frac{\Delta\sigma}{\sigma^{lim}}) \tag{5}$$

where σ^{lim} is the stress that corresponds to $\dot{d} = \tau_c^{-1}$, in the simplified model.

These two approaches propose an estimation of the localization length that needs to be completed. Nevertheless, one can combine them with the estimated dissipation density in the localization zone, in order to compare it to the other energies involved in the bar up to rupture. Outside the localization zone, the strain rate is governed by the external loading and the damage follows the static evolution law. In the localization zone, the strain rate will reach much higher values.

By considering the case of a loading at constant strain rate $Y(t) = \frac{E^0.\dot{\varepsilon}^2 t^2}{2}$, it is possible to have a first order estimation of the dissipation in the localization zone, [7] :

$$\begin{aligned} \omega_d = \int_0^{t_r} Y.\dot{d}\,\delta t \quad & \simeq \frac{E^0.(\tau_c\dot{\varepsilon})^2}{6}\left[1+\frac{3\,\varepsilon_c}{a\,\tau_c\dot{\varepsilon}}\right] \\ & \simeq \frac{E^0}{6}\varepsilon_c^2\left(1+\frac{7}{a}\right)^2 \end{aligned} \tag{6}$$

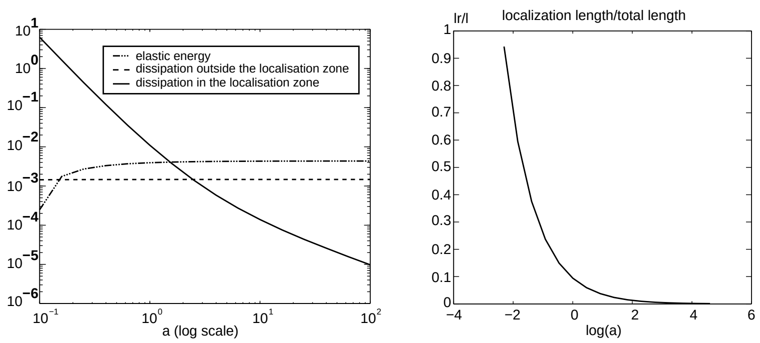


Figure 2: Estimation of the energies in the bar

From eqn(4) and eqn (6), figure 2 presents the energies involved in the bar up to rupture as a function of a, for standard material parameters. One can conclude that within a range of reasonable values, the delay parameters could be identified from a dissipation point of view.

3.1.2 *Sensibility of the measurements to the parameters*

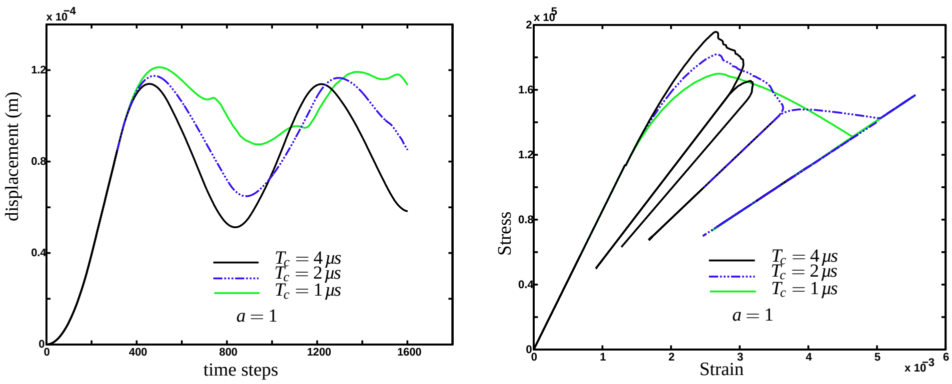
In the case of the identification from *SHPB* tests, the identification is based on the measurements of the boundary conditions. This section studies the influence of the delay parameters on the boundary conditions in order to estimate the possibility of inverse identification from the boundary conditions.

Figure 3: Composite bar and its loading

A numerical approach is led by proceeding to several calculations under the same loading with various parameters. Let us consider a unidimensional bar with a section $S = 1\,mm^2$, and a length $L = 100\,mm$, made of two materials in parallel, figure 3. One of the materials has a delay damage constitutive law. Let us note: $T_c = \frac{\tau_c}{a}$.

The other one is purely linear elastic with a Young's modulus, $E^1 = E^0/2$. The ratio between the sections of the two materials is equal to 1.

The bar is loaded at both ends by a traction, made of a linear increase and then a constant value. The increase time is equal to $10\,\mu s$ and the constant value is chosen so that rupture occurs in the middle of the bar, $F_{max} = 1.3\,(E^0 + E^1)\,S\,10^{-3}\,N$. The total time is equal to $80\,\mu s$ and the meshing of the bar is made of 100 two nodes linear elements of constant size. The simulation is carried out using an explicit time scheme for the displacements and a theta-method, with $\theta = 0,5$, for the delay damage evolution law.



(a) Boundary condition at $x = 0$

(b) Stress-strain curve in the middle of the bar

Figure 4: Influence of T_c on the response of the bar

The figure 4 shows the effect of the delay parameter T_c on the boundary fields. The displacement are represented only at $x = 0$, the ones at $x = L$ being similar. Furthermore, the figure 4(b) represents the stress-strain curve at $x = \frac{L}{2}$, that is where central ply breaks.

This part points out the sensibility of the boundary fields to the delay parameters, leading to the conclusion that, from a model point of view, these parameters could be identified from such a test.

3.2 Delamination dynamic effects

The aim of this part is to show on the basis of an analytical analysis of a unidimensional example, that, when dealing with an interface, some rate effects appear linked to the dynamic character of the loading. Let us consider a $1D$ bar of infinite length L, with E its Young's modulus and h its height, linked by an interface of length $L-a$ to a rigid base, as shown figure 5. The bar is clamped at the end $x=L$. The interface is solicited in shear, the corresponding stress being noted τ and its constitutive relation is given by : $\tau = k(1-d)\,u$, where u is the displacement of the bar and d is a damage variable that follows the evolution law :

$$d(t) = \sup_{t_1<t} \frac{u(t_1)}{u_c} \quad \text{if}\, d<1 \quad d=1\,\text{otherwise} \tag{7}$$

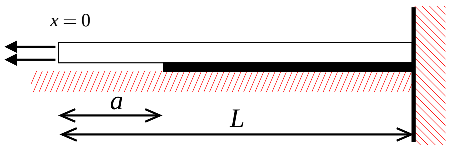


Figure 5: Bar linked to a rigid base by an interface

Let us consider the steady state propagation of the delamination, that is to say $\dot{a}$ is constant.

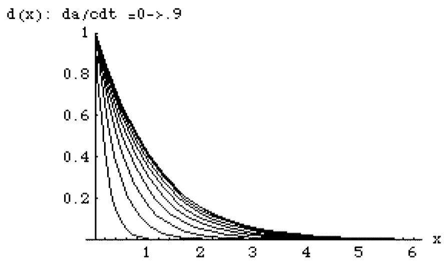


Figure 6: Damage evolution at the crack tip as a function of $\dot{a}$

It is then possible to express the equations verified by the solution to this problem in the referential of the crack tip, the space variable being noted x_1 :

$$\frac{d}{dx_1}\left(\left(\frac{dv}{dx_1}\right)^2 - \frac{v^2}{l^2}\left(1-\frac{1}{3}v\right)\right) = 0, \quad x_1 > 0 \tag{8}$$

where

$$v = \frac{u}{u_c} \quad ,\text{and} \quad l = \sqrt{\frac{Eh(1-(\frac{\dot{a}}{c})^2)}{k}} \quad ,\text{with} \quad c = \sqrt{\frac{E}{\rho}} \tag{9}$$

Then one can deduce from 8 an analytical expression of the solution fields. Thanks to this solution, one can estimate the influence of the loading rate on the damage field. The figure 6 represents the damage field in front of the crack tip, as a function of $\frac{\dot{a}}{c}$, which the adimensionned crack-opening rate. It can be seen that the size of the process zone, and as a consequence the behavior of the interface, depends on the loading rate. This has to be taken into account in order to identify the material rate effect for the interface.

4 CONCLUSION

The mesomodelisation of laminates allows a good description of complex phenomena in statics [5]. Its extension to the case of dynamic loadings leads to the question of the identification of the dynamic material effects. The first effect considered here is the delay effect, which is linked to rupture. A study based on a model point of view pointed out that its identification should be possible from dynamic tests by an inverse approach [7]. The second part of this paper aimed at showing that rate effects appear in the case of interface model, even if the model of the interface has no rate dependency.

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