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# A GENERAL BEHAVIOUR LAW IN ORDER TO MODEL THERMOSET AND THERMOPLASTIC COMPOSITE MATERIALS SUBJECTED TO DYNAMIC LOADS

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## ABSTRACT

The economic and ecological constraints impose that the composites materials are more than an important issue in all areas of transportation. In order to increase the ability to react of the industrials, especially in the automotive domain, and to allow them to optimize the structure design, numerical simulation is proving to be a major asset. Therefore, it is important to be able to represent in finite element software, the behaviour of these materials from the quasi-static to rapid dynamic loadings. Since many years, several models have been suggested (mainly for quasi-static loadings) for different types of composites: unidirectional, woven, laminate, 3D... Most of these behaviour laws are usually adapted to the specificities of composite of interest. In this paper, we will present a unique model that can suit to different types of composite materials regardless of the fibres architecture and types of fibres/matrix. First, we sum up some key points about the experimental characterisation of different types of composite materials. The observations and the conclusion will lead us to present the theoretical background for the unified behaviour law. It takes into account elastic and inelastic deformations, damages and sensitivity to the strain rate, whatever the orthotropic directions of the material. The evolutions of each quantity are described through adapted functions face to the experimental data. The law also possesses coupling parameters between orthotropic directions that can take into account a better representation in case of non-standard fibre orientations. Even if numerous material parameters are driving the law, the experimental methodology of characterization is quite simple, clear and can be automated. This last point is important because the law must be available to any engineers. Some numerical validations about different types of composite materials will also be shown and will allow us to conclude about the good agreement with the experiment.

## 1 INTRODUCTION

Nowadays, composite materials are used in many aeronautical structures (for structural parts which can be critical or not), they are also everywhere in the boats (floats, masts...) and will be increasingly used in many components of motor vehicles. These materials have many advantages from a mechanical point of view: they have a low weight compared to equivalent structures in metal, the loadings that they can withstand are high, they have good fatigue properties (in the fibres direction)... However, the regulation constraints about the development of structures call for satisfying to many certification procedures. They impose, for example, in the crash and impact studies, to master the behaviour of these materials for a wide range of strain rates.

Contrary to metals, the understanding and the modelling of the behaviour of composite materials, whatever they are, is not easy: they naturally are non-isotropic materials and due to the assembly of their components, they induce a multitude of complex physical phenomena. It should be noted that for laminates, the physical phenomena lie not only in the mesoscopic ply but also in the interfaces between the plies. At least, the modelling of composites behaviour for quasi-static or dynamic loadings, involves mastering the macroscopic behaviour for some composite and for laminates, the behaviour at the mesoscopic scale as well as the behaviour of the interfaces between plies (this last point will not be addressed in this paper).

Regarding the quasi-static models, there are many works concerning the unidirectional and fabric thermoset composites [1-12]. These laws include damages, mainly in the shear and transverse directions. They manage also the inelastic deformations in these two directions. For these same composite materials, it can be found principally in [12-16], the taking into account of the strain rate sensitivity for unidirectional and/or fabric thermoset composites.

To sum up, there are different types of models dedicated to one specific type of composite. These models mainly have been developed and used for thermoset composite materials. It could be problematic because the thermoplastic composites nowadays become materials of interest in many transportation fields. The literature review effectively shows a lack of information about the modelling of such composites, especially in rapid dynamic loadings.

Since few years, our different and various experiences about composite materials (unidirectional, fabric, 2.5/3D...) with both thermoset and thermoplastic matrices drive us to consider the question of one unique model whatever the type of composite. Moreover, the discussions we had with many industrial partners lead to comfort this idea: to possess a unique model for thermoset/thermoplastic composites, able to catch different phenomena in each orthotropic direction, responsive to strain rate effects and for which the experimental identification is accessible, clear and simple to realise.

This paper deals with the model that we have mainly developed for numerical simulations involving shell finite element type. It takes into account elastic and inelastic strains as well as damages whatever the orthotropic direction of the composite material. It includes also the strain rate effects in order to satisfy the constraints of the rapid dynamic loadings. In a first part, we suggest a brief description of the different types of behaviour by discussing about the results and the observations issued of quasi-static and dynamic experimental characterisation. In a second part, we present the theoretical framework that describes the material behaviour law, on one hand in quasi-static and on the other hand in dynamic. Finally, we expose some basic numerical validation about different types of composite material and we conclude by the future prospects to our work.

## 2 EXPERIMENTAL CHARACTERIZATIONS AND OBSERVATIONS

### 2.1 About the quasi-static characterization

The main aim of this experimental characterisation is to highlight the orthotropic behaviour of the composite using tensile and compression tests on different types of specimens. The dimensions of the test pieces must respect as much as possible the standards found in the literature (ASTM D3039, D5083, D5766, EN 2561, EN 2597, EN 6035, ISO 527-4, ISO 527-5 and AITM 1-0007): at least, it must slightly contain more than one Representative Elementary Volume (REV) of the composite of interest. The strains in each orthotropic direction (local directions) must be measured using gauges (in accordance with the REV) or with a Digital Image Correlation system. The local stresses are computed using the frame matrix and the force coming from the machine test. For the experimental data reduction, one reminds that according to the laminate theory, the plies are considered to have an isotropic transverse behaviour at the mesoscopic level. Moreover, due to the small thickness of composite, the assumption of stress plane is used.

For the unidirectional laminates, some previous experimental campaigns [4, 7-8] recommend the four following stacking:

- Stacking plies at  $0^\circ$ :  $[0]_8$ ,
- Alternate stacking plies at  $+45^\circ$  and  $-45^\circ$ :  $[\pm 45]_{2S}$ ,
- Stacking plies at  $+45^\circ$ :  $[+45]_8$ ,
- Alternate stacking plies at  $+67.5^\circ$  and  $-67.5^\circ$ :  $[\pm 67.5]_{2S}$ ,

The composite stacking  $[0]_8$  allows reaching the longitudinal behaviour of the elementary ply. The shear behaviour comes from the stacking  $[\pm 45]_{2S}$ . For the transverse behaviour of the composite ply, the stacking  $[+45]_8$  allows on one hand to identify this behaviour and the stacking  $[\pm 67.5]_{2S}$  allows on the other hand to have a better description of the coupling phenomena between shear and transverse directions.

Concerning the fabric composite laminates [9-10], it is recommended to carry out stacking in the warp direction (longitudinal), weft direction (transverse) and bias direction (shear). In the case of

balanced composites, the warp and weft directions are equivalent: just one configuration for the experimental testing is required.

To sum up, the experimental characterisation of any composite material requires at least three tests (in longitudinal, transverse and shear directions). However, two more tests can be carry out in order to better identify the coupling phenomena between both the longitudinal and shear directions (angle of 22.5°) and the transverse and shear directions (angle of 67.5°).

To highlight the variety of the behaviours and of the phenomena to be observed and to be taken into account for modelling, we suggest some results for different types of composite. The first one is related to a glass/epoxy fabric laminate in shear direction (Fig. 1): during the loading, the shear inelastic strain is considerably increasing while the damage implies a higher loss of stiffness.

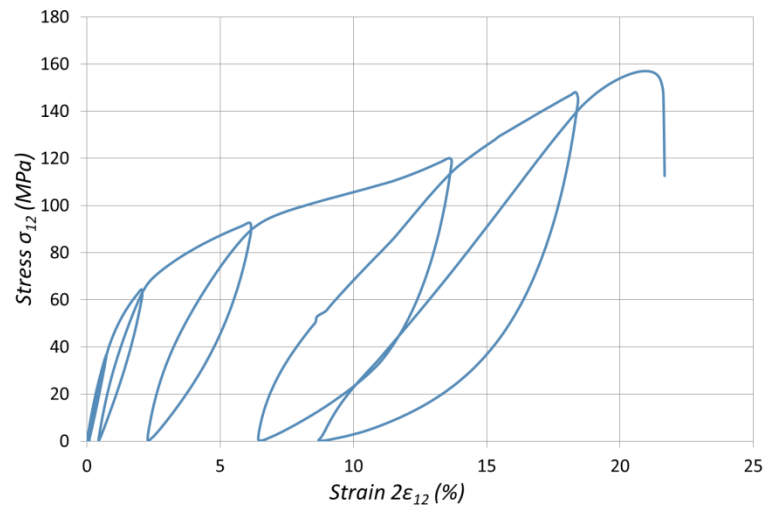


Figure 1: Medium results in tension for a fabric glass/epoxy in shear direction.

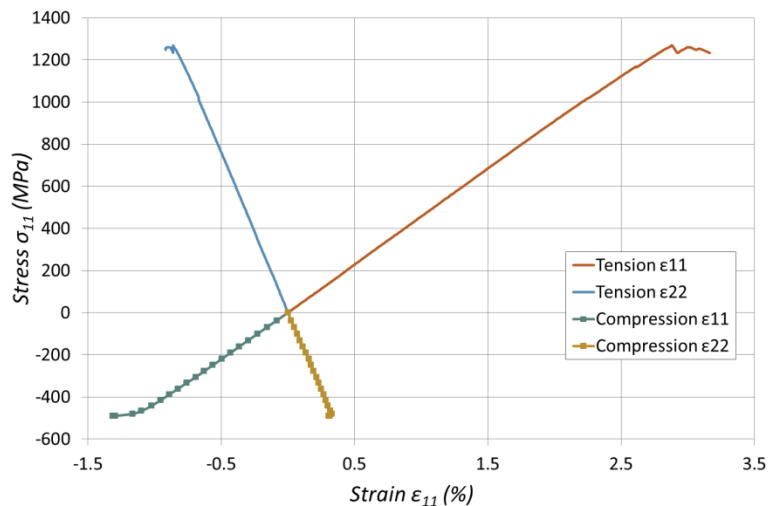


Figure 2: Medium results in tension and compression for a UD glass/epoxy in longitudinal direction.

The second result concerns the tension and compression tests of a glass/epoxy unidirectional composite (Fig. 2): the material possesses a quasi-elastic brittle behaviour both in tension and compression cases. However, in the case of a 2.5D interlock composite, it appears some non-negligible strains in the longitudinal direction, as shown on figure (Fig. 3).

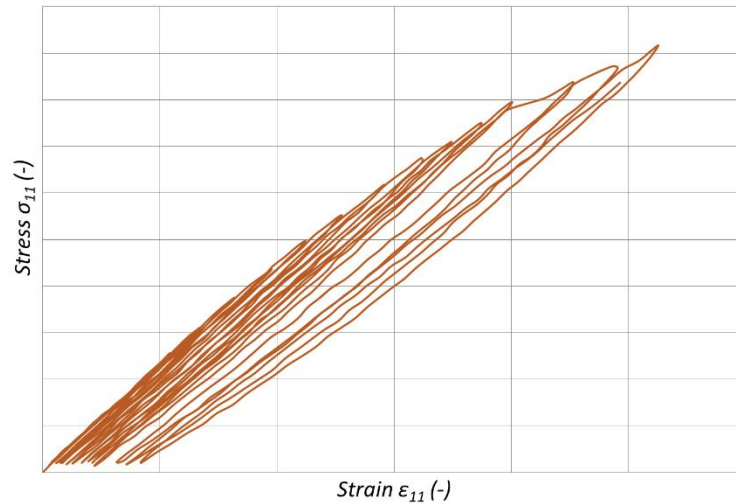


Figure 3: Medium results in tension for a 2.5D interlock composite in the warp direction.

Through these few examples of behaviour, a composite material sustains some degradations, which are different in respect of its composition and its loading. Nevertheless, in a general point of view, all of these phenomena can be taken into account similarly within a behaviour law model.

## 2.2 About the dynamic characterization

Many materials are responsive to the strain rate: this is the case of the epoxy resin. In some previous works [17], the experiments using Hopkinson bars (Fig. 4) have highlighted a great evolution of the resin characteristics due to the strain rate. As the epoxy resin is one of the main components of the composite materials, it is possible to think that they also will be influenced by the strain rate. This is the case for unidirectional glass/epoxy composite (Fig. 5 and 6) and for fabric glass/epoxy composite (Fig. 7).

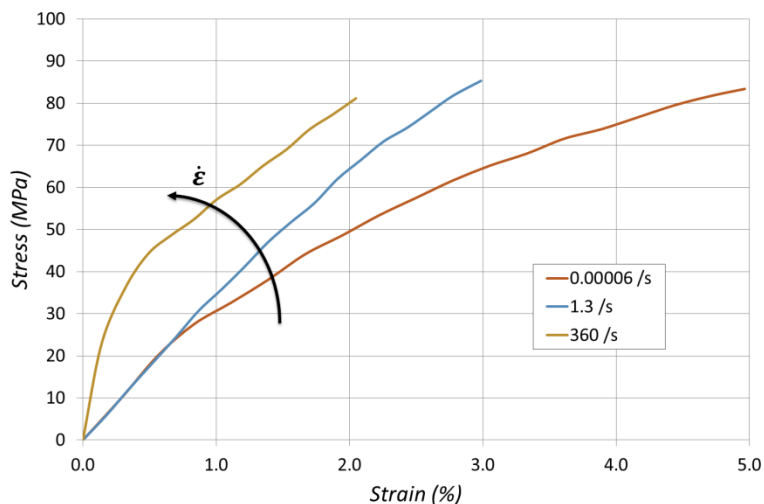


Figure 4: Strain rate sensitivity for an epoxy resin [17].

The strain rate strongly affects the elastic moduli, the yield stresses and the strains and stresses at failure. It is then important to take into account these specificities within the model of behaviour law. It should be noted that, even if no results are shown in this paper, the strain rate also strongly acts on the thermoplastic composite behaviours.

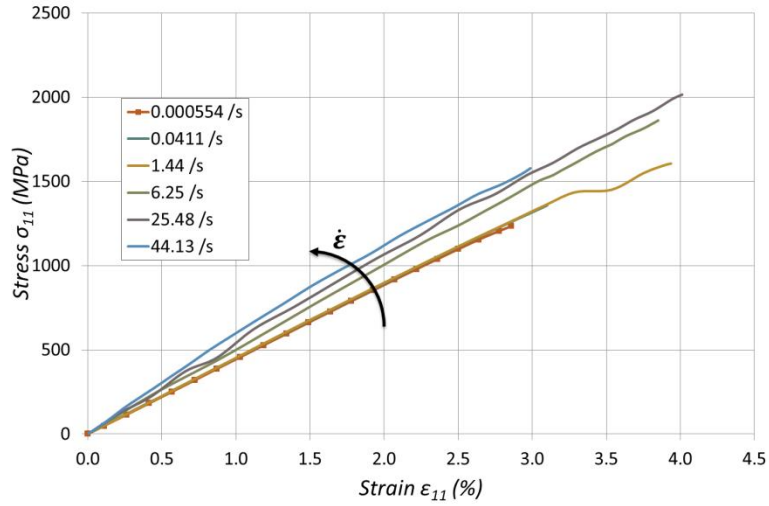


Figure 5: Medium results in tension for a UD glass/epoxy at different strain rates.

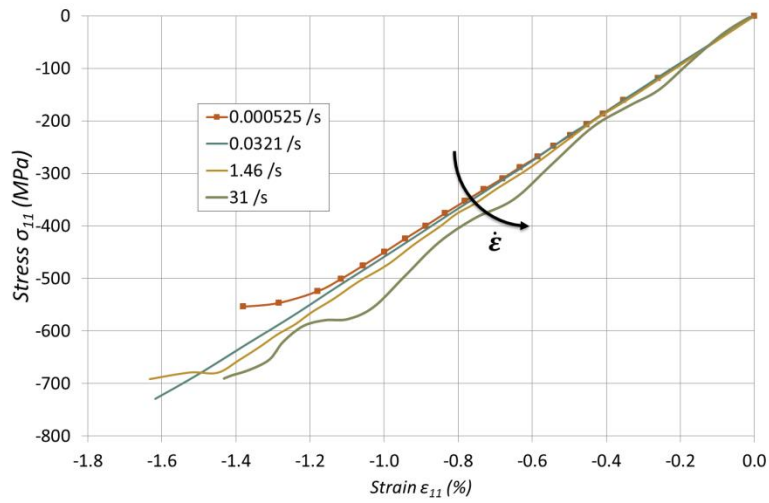


Figure 6: Medium results in compression for a UD glass/epoxy at different strain rates.

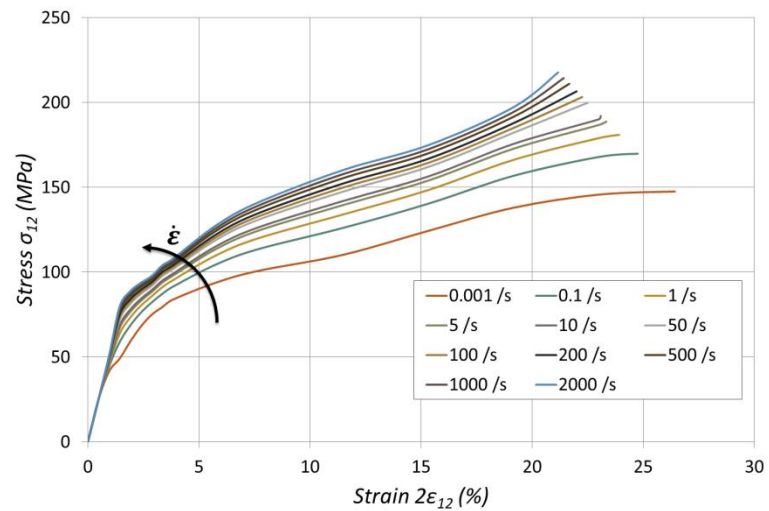


Figure 7: Medium results of the strain rate sensitivity for a fabric Glass/epoxy.

### 3 UNIFIED BEHAVIOUR LAW FOR COMPOSITE MATERIALS

#### 3.1 Elasto-plastic damage model

The formulation is done under the thermodynamic framework of the irreversible process [18]. The density of Helmholtz free energy  $\rho\psi$  is selected as thermodynamic potential:

$$\rho\psi(\boldsymbol{\varepsilon}^e, d_i, p, \beta_i) \quad (1)$$

The choice of this potential is not identical to the one that is commonly proposed in the different works from the literature [4-6,8-10]. For a formulation adapted to the algorithms of explicit dynamic software, it is better to introduce the potential based on the strain tensor [7,19]. Indeed, the associated thermodynamical forces can be expressed only with strains and will be then independent from the damage variables [20].

$$\tilde{\sigma}_{ij} = \frac{\sigma_{ij}}{1 - d_{ij}} \quad (2)$$

Thanks to the effective stresses definition (2) and the principle of equivalence in strains [18], we suggest to introduce five scalar damage variables (3) which will act on the diagonal components of the stiffness matrix ( $C$ ). Their evolutions and their “existences” will be different in tensile and compression cases in order to satisfy to the experimental observations.

$$C_{ij} = C_{ij}^0(1 - d_{ij}) \text{ where } i, j \in [1,3] \text{ except the case } i = j = 3 \quad (3)$$

The expression of the elastic strain energy of the damaged material can be then written as:

$$2W_e^d = C_{11}^0(1 - d_{11})(\varepsilon_{11}^e)^2 + C_{22}^0(1 - d_{22})(\varepsilon_{22}^e)^2 + 2\nu_{21}^0 C_{11}^0 \varepsilon_{11}^e \varepsilon_{22}^e + C_{12}^0(1 - d_{12})(2\varepsilon_{12}^e)^2 + C_{13}^0(1 - d_{13})(2\varepsilon_{13}^e)^2 + C_{23}^0(1 - d_{23})(2\varepsilon_{23}^e)^2 \quad (4)$$

One can express now the behavior law:

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \end{Bmatrix} = \begin{bmatrix} C_{11} & \nu_{21}^0 C_{11}^0 \\ \nu_{12}^0 C_{22}^0 & C_{22} \end{bmatrix} \begin{Bmatrix} \varepsilon_{11}^e \\ \varepsilon_{22}^e \end{Bmatrix} \text{ and } \sigma_{ij} = C_{ij} 2\varepsilon_{ij}^e \text{ for } i \neq j \quad (5)$$

The expression of the associated thermodynamical variables to the five scalar damage variables is consequently given by:

$$Y_{11} = \frac{1}{2} C_{11}^0 (\varepsilon_{11}^e)^2; Y_{22} = \frac{1}{2} C_{22}^0 (\varepsilon_{22}^e)^2; Y_{ij} = \frac{1}{2} C_{ij}^0 (2\varepsilon_{ij}^e)^2 \text{ for } i \neq j \quad (6)$$

For most composite materials or laminates, the shear behavior in the plane (12) induces some strains higher than in the longitudinal and transverse directions, due to their small thickness. Due to this fact, we decided to take the following norm in order to describe the undamaged state:

$$\bar{Y}^2 = Y_{12} + \frac{G_{13}^0}{G_{12}^0} Y_{13} + \frac{G_{23}^0}{G_{12}^0} Y_{23} + \frac{E_{22}^0}{G_{12}^0} Y_{22} + \frac{E_{11}^0}{G_{12}^0} Y_{11} \quad (7)$$

The evolutions of damages are under their integrated forms (8). The consequence of this choice is that the model is non-standard: it is then compulsory to check the positivity of the dissipation potential.

$$d_{ii} = \frac{E_{ii}^0}{G_{12}^0} f_D(\bar{Y}) = b_{ii} f_D(\bar{Y}); d_{ij} = \frac{G_{ij}^0}{G_{12}^0} f_D(\bar{Y}) = b_{ij} f_D(\bar{Y}) \text{ with } \bar{Y}(t) = \sup_{\tau \leq t} (\bar{Y}(\tau)) \quad (8)$$

An approximate law describes the damage variables evolution (8) according to the function of undamaged domain (7). This law, which can be linear, logarithmic, power, polynomial as for (9), is chosen to satisfy as much as possible the experimental data. Its constants can be considered as material constants.

$$d_{ij} = \sum_{k=1}^n \alpha_{ij}^k (\bar{Y} - Y_{ij}^0)^k \quad (9)$$

To the previous theoretical description, some functions  $\bar{Y}_{ij}$  for  $ij \neq 12$  are added to better drive the evolutions of the damages (except the shear damage). From the experiment, the shear critical rate (7) proves to be sometimes not enough rich to represent the longitudinal and transverse maximum damages. The form of these functions is similar to (7):

$$\bar{Y}_{ij}(t) = \sup_{\tau \leq t} \left( \sqrt{Y_{ij}(\tau)} \right) \text{ for } ij \neq 12 \quad (10)$$

The evolution of damages will then as:

$$d_{ij} = b_{ij} f_D(\bar{Y}) \text{ for } d_{ij} \leq d_{ij}^{max} \text{ and } \bar{Y}_{ij} \leq \bar{Y}_{ij}^{failure} \text{ (with } b_{12} = 1) \quad (11)$$

Regarding the coupling between the inelastic strains with the damages, it can be done using effective strains and stresses (2). The stresses are therefore substitute by the effective stresses in the yield criteria function, which is:

$$f_P(\tilde{\sigma}, R) = \sqrt{\tilde{\sigma}_{12}^2 + a_{11}^2 \tilde{\sigma}_{11}^2 + a_{22}^2 \tilde{\sigma}_{22}^2 + a_{13}^2 \tilde{\sigma}_{13}^2 + a_{23}^2 \tilde{\sigma}_{23}^2} - R(p) - R_0 \quad (12)$$

The coefficients  $a_{ij}^2$  that are introduced in the expression of the criteria function, play the role of weighting coefficients: they allow to estimate the importance of the shear stress in regard of the other stresses, and particularly the longitudinal and transverse stresses. The expression of the threshold function  $R(p)$  is commonly such as:

$$R(p) = \beta p^m \quad (13)$$

It should be noted that the form of the law (13) can be adapted to experimental observations like the ones dedicated to the damages evolutions (8), (9). From a practical point of view, a general form such as a polynomial law of order  $n \geq 1$  and defined with material constants  $\beta_k$  allow to satisfy numerous cases:

$$R(p) = \sum_{k=1}^n \beta_k p^k \quad (14)$$

### 3.2 Integration of the strain rate sensitivity

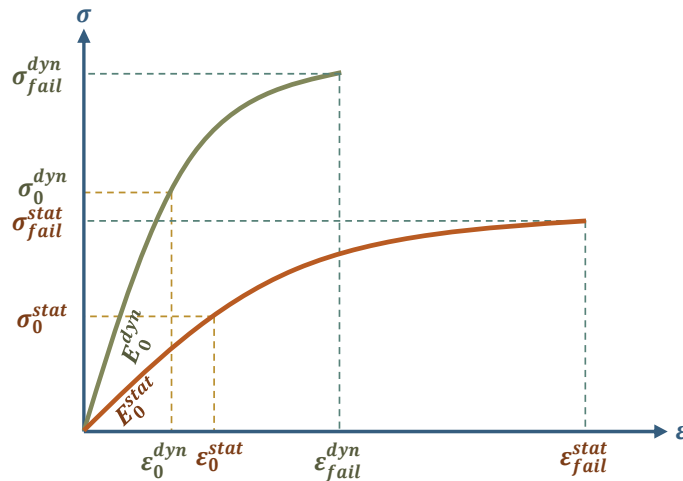


Figure 8: Schematic description of static and dynamic behaviours.



From the dynamic experimental tests, the effects of the strain rate on the material behavior (Fig. 5, Fig. 6 and Fig. 7) result in a non-negligible increasing of the elastic moduli, of the yield stresses and of the failure strains/stresses. This can be schematized as on the figure (Fig. 8).

It is also possible to assert that the strain rate effects affect the inelastic strains and the damages sustained by the material, even if it is problematic to demonstrate experimentally this fact. We try to develop some “stopped” tests in order to confirm this assumption. Owing to these few last reasons, one of the way that we chose for the model, is based on the viscous fluids definition proposed by [18]. The “pseudo-viscoelasticity” of the matrix (and then of the composite) is taken into account with a viscous stress that is added to the elastic stress (Kelvin-Voigt solid model):

$$\sigma = \sigma^e + \sigma^v \quad (15)$$

Using this definition for the unidimensional case and knowing that the time of dynamic loadings (crash, impact...) are very small, it is possible with a first order development to express the stress as:

$$\sigma_{11} \overset{o(1)}{\approx} C_{11}^0 \varepsilon_{11}^e (1 + F_{11}) \quad (16)$$

The relation (16) show that it is possible to consider the evolution of the elastic modulus using a function  $F_{11}$ . In our study case, this function will be dependent of strain rate. If we apply this idea to each directions of the stress tensor [12-16], one can determine each viscosity function  $F_{ij}$  which will describe the evolution of elastic moduli in regard of the strain rate. Two possibilities are offered concerning the strain rate definition: the first one is naturally to consider each function  $F_{ij}$  depending on each strain rate  $\dot{\varepsilon}_{ij}$ . However, one can also introduce the mean strain rate value defined by (17): this choice allows not only decreasing the number of material parameters but also to suit to most of behaviours that are responsive to strain rate. In this case, the reader can replace in each following relations the value of  $\dot{\varepsilon}_{ij}$  by  $\dot{\varepsilon}$ .

$$\dot{\varepsilon} = \sqrt{\frac{2}{3} \dot{\varepsilon}_{ij}^e \dot{\varepsilon}_{ij}^e} \quad (17)$$

The elastic relation can be summarized by:

$$(\sigma) = (C_0) \left[ (I) + \left( F(\dot{\varepsilon}_{ij}, \dot{\varepsilon}_{ij}^0) \right) \right] (\varepsilon^e) = \Lambda_0(\dot{\varepsilon}_{ij}, \dot{\varepsilon}_{ij}^0)(\varepsilon^e) \Leftrightarrow \Lambda_{ij}^0 = C_{ij}^0 \left( 1 + F_{ij}(\dot{\varepsilon}_{ij}, \dot{\varepsilon}_{ij}^0) \right) \quad (18)$$

It is quite obvious that the viscosity functions  $F_{ij}$  depend on the current strain rate  $\dot{\varepsilon}_{ij}$  but also on a threshold strain rate  $\dot{\varepsilon}_{ij}^0$  from which the strain rate has an important role on the composite behaviour. In other words, if the threshold strain rate is not reached, the elastic constants correspond to the ones from quasi-static case:

$$F_{ij}(\dot{\varepsilon}_{ij}, \dot{\varepsilon}_{ij}^0) = 0 \text{ si } \dot{\varepsilon}_{ij} \leq \dot{\varepsilon}_{ij}^0 \quad (19)$$

At the moment, the model is only an elastic behaviour model depending on the strain rate: it is necessary to complete this model by adding the damages and the inelastic strains. Experimentally, the main difficulty during the dynamic testing is the impossibility to directly access to the damages by loading/unloading due to speed of loadings. Nevertheless, the tests until complete failure offer an access to some important information at the level of elasticity domains (ie undamaged domains and non-inelastic domains) as well as at the failure level (ie rate of energy required to break the composite).

Phenomenologically, the material state can always be determined from its state in the quasi-static configuration (Fig. 8). We can assume that this state for a given strain rate corresponds to the state of other composite material for which the material characteristics are different. This allows us to extract a relation between the viscosity functions and some quantities. The undamaged domains are defined by the threshold functions  $Y_{ij}^0$  of the relation (9). As the damages are nil, we suggest that the evolution of these threshold functions follow the relation:

$$Y_{ij}^{0dyn} = \frac{1 + F_{ij}^{\sigma}(\dot{\varepsilon}_{ij}, \varepsilon_{ij}^0)}{\sqrt{1 + F_{ij}(\dot{\varepsilon}_{ij}, \varepsilon_{ij}^0)}} Y_{12}^{0stat} \quad (20)$$

As the elastic moduli, the yield stresses and the threshold of undamaged domains are strictly increasing with the strain rate, we properly postulate a progression of the damages quicker than in the quasi-static case. Therefore, the coefficients  $\alpha_{ij}^k$  from the relation (9) will be imposed to progress identically to the threshold undamaged functions:

$$\alpha_{ij}^{dyn} = \frac{1 + F_{ij}^{\sigma}(\dot{\varepsilon}_{ij}, \varepsilon_{ij}^0)}{\sqrt{1 + F_{ij}(\dot{\varepsilon}_{ij}, \varepsilon_{ij}^0)}} \alpha_{ij}^{stat} \quad (21)$$

The energy release rates  $Y_{ij}^{failure}$  can also progress (or not) regarding the experimental observations by an identical form:

$$Y_{ij}^{failure^{dyn}} = Y_{ij}^{failure^{stat}} \frac{1 + F_{ij}^{\sigma}(\dot{\varepsilon}_{ij}, \varepsilon_{ij}^0)}{\sqrt{1 + F_{ij}(\dot{\varepsilon}_{ij}, \varepsilon_{ij}^0)}} \text{ or } Y_{ij}^{failure^{dyn}} = Y_{ij}^{failure^{stat}} \quad (22)$$

Experimentally, the initial yield stresses are also varying in function the strain rate. Whatever the directions of composite (longitudinal, transversal or shear), we propose an equivalent form of evolution:

$$\sigma_{ij}^{dyn} = \sigma_{ij}^{stat} \left( 1 + F_{ij}^{\sigma}(\dot{\varepsilon}_{ij}, \varepsilon_{ij}^0) \right) \text{ and } R_0^{dyn} = R_0^{stat} \left( 1 + F_R(\dot{\varepsilon}_{ij}, \varepsilon_{ij}^0) \right) \text{ with } F_R = F_{12}^{\sigma} \quad (23)$$

#### 4 BASIC NUMERICAL VALIDATIONS

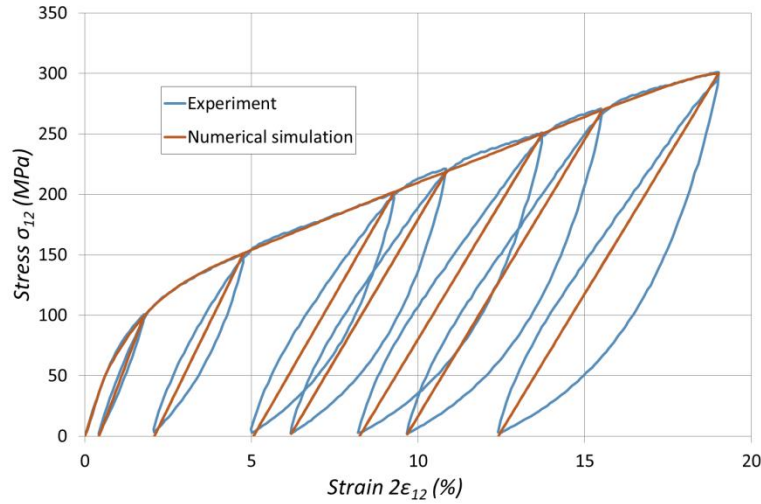


Figure 9: Schematic description of static and dynamic behaviours.

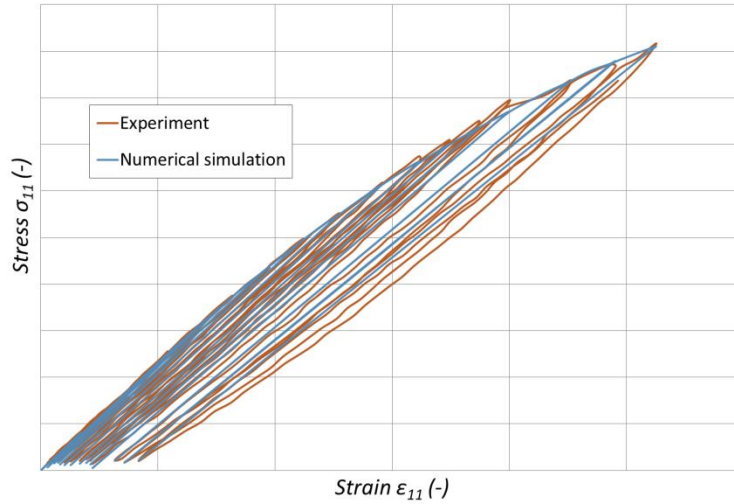


Figure 10: Comparisons for a 2.5D interlock composite in the warp direction.

In order to show the different possibilities offered by the behaviour law, we suggest in this section some numerical simulations about a Carbon/Pa66 thermoplastic composite (Fig. 9). The evolution of the shear damage in function of the associated thermodynamical variable is done with an eight order polynomial approximation. A same approximation has been used to the hardening function  $R(p)$  where  $p$  is the cumulative plastic strain. It is observed a good agreement between both numerical and experimental results. The comparison in the warp direction for a 2.5D interlock composite (Fig. 10) allow to conclude that the taking into account of the inelastic strain in the warp direction are correctly modeled. Regarding a UD glass/epoxy composite (Fig. 11), the strain rate sensibility is well described for different strain rates.

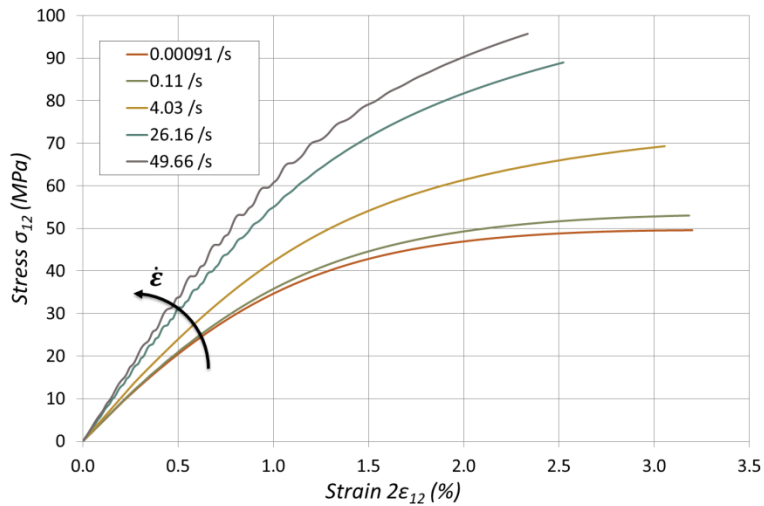


Figure 11: Numerical simulation for different strain rates for a UD glass/epoxy composite.

## 9 CONCLUSIONS AND FUTURE PROSPECTS

Instead of developing a behaviour law that is adapted to one type of composite materials, we had suggested in this paper a unified behaviour law. Indeed, even if the mechanisms of degradations, the physical phenomena and their evolution in function of time are inherent in the fibres architecture, in the nature of fibres and matrix, we show that it is possible to consider them through “common” variables belonging to the behaviour law. Their physical significations and law evolutions will automatically be adjusted. The richness of the law lies in the numerous behaviours that one can

represent: the laws allow describing the evolution of elastic and inelastic strains, the damages evolution (from brittle thanks to Heaviside functions to complex evolutions) as well as the strain rate sensitivity. In this last case, we assumed that the behaviour for a given strain rate can be always identify from the quasi-static case (ie under a threshold strain rate from which there is no noticeable modification of the behaviour). We recommended that the elastic moduli, the damage evolution constants and the yield stresses develop using suitable approximation.

Even if we do not discuss about the experimental characterisation procedure, it is important to underline that this procedure is not much depending from the user. This is a key point of this model: the main objectives of developments were to propose an accessible and usable law for the industry. Moreover, a genetic algorithm can be used in order to increase the reliability of the identified law parameters in order to reduce more the dispersions on the experiment framework.

The future prospects of the presented work are dealing now in the taken into account of the temperature and hygrometry effects. These two points are crucial points for some thermoplastic composite materials. As they are increasingly introduced in the automotive field, it is required to complete the model by implementing these two effects. Other work that we prospect, concerns the taking into account of the fibres reorientation during the loading. Indeed, the thermoplastic composite are more responsive to the temperature. Due to this, there is a slightly change of the nature of the matrix that allow more move of the fibres. It is necessary also to have a better description of the damage state to complete the behaviour law with this phenomenon. Finally, we also continue to develop the present model for the 3D cases.

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