NUMERICAL AND EXPERIMENATAL CHARACTERIZATION OF THE HYGROTHERMAL AND STRAIN RATE DEPENDENT BEHAVIOR OF WOVEN GLASS FIBER REINFORCED POLYAMID

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Abstract
Nowadays, polymer matrix composites are increasingly used in the automotive industry due to their easy design, light weight and good mechanical properties. For their application in structural components, it is important to be able to well describe their behavior whatever the loading case and the hygrothermal/temperature conditions of the environment. The present work aims to study the behavior of woven glass fiber reinforced polyamid 66. An experimental campaign including quasi static and dynamic tests is performed on specimens of the material under investigation, conditioned at equilibrium at different relative humidities. The influence of the environmental conditions such as temperature and relative humidity have been studied. A numerical model dedicated to woven fabric composites has been also presented. The efficiency of this model has been analyzed by comparison with obtained experimental results.

1. Introduction

In the actual context of reduction of both CO_2 emissions and fuel consumption, imposed by European standards, and faced with today's great ecological challenges, the automotive industries are in constantly searching of new technological solutions in terms of material to lighten vehicles. Fiber reinforced thermoplastic resins are excellent composite materials which combine high levels of mechanical performance and low density. In addition, they are both less expensive and easier to process; and thus appear as an appropriate candidates to meet the previous challenges. Hence, they are nowadays increasingly integrated in the design and manufacture of several mechanical and structural parts for vehicles.
However, it is well known that thermoplastic resins are highly sensitive not only to physical environmental parameters such as temperature and relative humidity but also to strain rate which can strongly affect their mechanical properties ([1-3]).
The thermal sensitivity in such materials has been invastigated in the litterature. It results from these studies that crystal plasticity in lamallae stacks, can be thermally activate since the temperature decresases the critical resolved shear stress [1]. It is also important to highlight that viscous dissipative phenomena are mostly prominent around the glass transition temperature (T_g) of polymeric materials. So that, the mechanical properties of polymer matix composites can change dramatically in a

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temperature range around and above T_g: Young's modulus for example decreases notably while the ultimate strain increases.

In addition, the influence of the relative humidity is also of great importance, as composites materials are frequently exposed in environments where moisture content can vary as a direct consequence of the climatic variations. The water absorption can lead to different types of degradation; the most recognizable being the plasticizing effect. The plasticizing effect relates to the diffusion of water between chains of macromolecules causing an expansion of the polymer structure due the separation of macromolecules. The plasticization has a negative effect on the mechanical cohesion of the material since it lowers the intermolecular bonding forces [7]. The material stiffness decreases and the ultimate strain increases are the direct consequences of this phenomenon at the macro-scale [1]. The absorption of water molecules also induces a decrease of the glass transition temperature of hygroscopic polymers like polyamides. Swelling and matrix hydrolysis have been also reported in the literature as other types of degradation due to water absoption [6].

The present work is dedicated to the validation of a numerical model available in the literature against an experimental campaign carried out on thermoplastic composites fabric especially a woven glass fiber reinforced polyamid 66. The model is initially developed by [4] and already validate successfully in the case of glass fabric/epoxy [4-5]. It has also been extended to the description of strain rate effects [8-9]. The outline of the paper is as follow. Section 2 presents the composite fabric ply damage model. Section 3 presents the material of this study, the experimental protocols and the first results. Some conclusions and outlooks are given in section 4.

2. Composites fabric ply damage model

2.1. Thermodynamic and dissipation potentials

The model is written at the mesoscale of the layer. The fabric reinforced composite ply is modelled as a homogeneous orthotropic elastic or elastic-plastic damaging material whose properties are degrading on loading by microcraking prior to ultimate failure. A continuum damage mechanics formulation is used in which ply degradation parameters are internal state variables which are governed by damage evolution equations. From now, the subscripts 1 and 2 stand for the orthogonal fill and warp fiber directions. Once the state variables, damage and irreversible strain associated to fill, warp and in-plane shear directions, we postulate the existence of a thermodynamic potential (Helmotz free energy) from which the state laws are derived.

$$\begin{cases} 2\psi = C_{11}^0(1-d_{11})(\varepsilon_{11}^e)^2 + C_{22}^0(1-d_{22})(\varepsilon_{22}^e)^2 + 2\nu_{12}^0 C_{12}^0(\varepsilon_{11}^e\varepsilon_{22}^e) \\ \qquad +2G_{12}^0(1-d_{12}) + 2\dfrac{Q}{\beta+1}p^{\beta+1} \end{cases} \tag{1}$$

To deal with reversible and irreversible effects, a classical split of the total strain ε_{ij}^t is assumed:

$$\varepsilon_{ij}^t = \varepsilon_{ij}^e + \varepsilon_{ij}^p \tag{2}$$

Where ε_{ij}^e stands for the elastic strain and ε_{ij}^p stands for the plastic strain. Assuming that plastic there are plasticity occurs only in shear, where fibers cannot prevent plastic flow, the different components of the plastic strain vector are: $\varepsilon_{11}^p = \varepsilon_{22}^p = 0$, and $\varepsilon_{12}^p \neq 0$. The first and second principles of thermodynamic are resume in the Clausius Duhem inequality. By introducing the specific free energy function, for small perturbations, the dissipation Φ is written as follows:

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$$\Phi = \left(\sigma_{ij} - \rho\frac{\partial\psi}{\partial\varepsilon_{ij}^{e}}\right)\dot{\varepsilon}_{ij}^{e} + \sigma_{ij}\dot{\varepsilon}_{ij}^{p} - R(p)\dot{p} - \rho\frac{\partial\psi}{\partial d_{ij}}\dot{d}_{ij} \geq 0 \tag{3}$$

2.2. Thermodynamic potential and state laws

State laws and thermodynamic forces associated to damage variables are obtained with Clausius Duhem inequality. Clausius Duhem is verified for each thermodynamical transformation and then, a classical hypothesis permit to cancel some terms in this inequality independently for:

$$\sigma_{ij} = \rho\frac{\partial\psi}{\partial\varepsilon_{ij}^{e}} \quad Y_{ij} = -\rho\frac{\partial\psi}{\partial d_{ij}} \quad \Phi = \sigma_{ij}\dot{\varepsilon}_{ij}^{p} - R(p)\dot{p} + Y_{ij}\dot{d}_{ij} \geq 0 \tag{4}$$

2.3. Thermodynamic potential: complementary laws

In order to obtain the evolutions laws, the existence of a dissipation potential function of the stress and additively decomposed into three parts is assumed: $\varphi_1(\sigma_{ij}, d_{ij})$ which stands for the disspated energy per unit volume due to plasticity, $\varphi_2(\dot{\varepsilon}_{ij}^{e}, \dot{d}_{ij})$ for viscous elastic effects and $\varphi_3(Y_{ij}, d_{ij})$ for the damage mechanisms.
Following this assumption total stress is computed as following:

$$\sigma_{ij} = \rho\frac{\partial\psi}{\partial\varepsilon_{ij}^{e}} + \frac{\partial\ \varphi_2(\dot{\varepsilon}_{ij}^{e}, \dot{d}_{ij})}{\partial\dot{\varepsilon}_{ij}^{e}} \tag{5}$$

In order to take into account the strain rate sensitivity, one possibility in accordance to the experimental results, is to add function to the elastic moduli as [10]:

$$\begin{cases} \sigma_{11} = C_{11}^{0}\Lambda_{11}(\dot{\varepsilon}_{11}^{e})(1-d_{11})\varepsilon_{11}^{e} + C_{12}^{0}\Lambda_{12}(\dot{\varepsilon}_{11}^{e}, \dot{\varepsilon}_{22}^{e})\varepsilon_{22}^{e} \\ \sigma_{22} = C_{21}^{0}\Lambda_{21}(\dot{\varepsilon}_{11}^{e}, \dot{\varepsilon}_{22}^{e})\varepsilon_{11}^{e} + C_{22}^{0}\Lambda_{22}(\dot{\varepsilon}_{22}^{e})(1-d_{22})\varepsilon_{22}^{e} \\ \sigma_{12} = C_{12}^{0}\Lambda_{1212}(\dot{\varepsilon}_{12}^{e})2\varepsilon_{12}^{e} \end{cases} \tag{6}$$

The elastic strain rate coefficients are:

$$\begin{cases} \Lambda_{ii}(\dot{\varepsilon}_{ii}^{e}) = 1 + \nu_{ii}.\,ln\left(\frac{|\dot{\varepsilon}_{ii}^{e}|}{\dot{\varepsilon}_{ref}}\right) \\ \Lambda_{ij}(\dot{\varepsilon}_{ii}^{e}, \dot{\varepsilon}_{jj}^{e}) = 1 + ln\left(\frac{|\dot{\varepsilon}_{ii}^{e}|^{\nu_{ii}} + |\dot{\varepsilon}_{jj}^{e}|^{\nu_{jj}}}{\dot{\varepsilon}_{ref}^{\nu_{ii}+\nu_{jj}}}\right)^{\frac{1}{2}} \end{cases} \tag{7}$$

The coupling between plasticity and damage is realized through the introduction of effective shear stress in the expression of the plastic yield surface f:

$$f = \frac{\sigma_{12}}{1-d_{12}} - R(p) - R_0 \text{ with } R(p) = \beta p^{m} \tag{8}$$

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β and m are two material parameters; R_0 the initial threshold value for inelastic strain behavior. It follows from the normality requirement that $f = 0$, $\dot{f} = 0$, which leads to the condition:

$$\dot{\varepsilon}_{12}^{p} = \dot{\lambda}\frac{\partial f}{\partial \sigma_{12}} \qquad \dot{p} = -\dot{\lambda}\frac{\partial f}{\partial R} \tag{9}$$

where $\dot{\lambda} \geq 0$ is a proportionality parameter to be determined. Substituting (Eq. 8) in (Eq. 9) leads to $\dot{\lambda} = \dot{p}$ and hence:

$$\dot{\varepsilon}_{12}^{p} = \frac{\dot{p}}{1-d_{12}} \quad \text{giving} \quad p = \int_0^{\varepsilon_{12}^{p}}(1-d_{12})d\varepsilon_{12}^{p} \tag{10}$$

3. Experimental

3.1. Tested material and methods

A 2/2 twill woven glass fabric impregnated with polyamide 6,6 resin is choosen as the subject material in this paper. The glass fiber reinforcement has a weight of 650 g/m² and is balanced in both warp and weft directions; the behaviors are thus equivalent in the two directions. The material was provided as plates of 2 mm thick and two types of rectangular specimens were cut using abrasive water jet cutting process: static tension specimens with dimensions of 250 mm × 25 mm × 2 mm and dynamic tension specimens with dimensions of 80 mm × 19 mm × 2 mm. In order to describe the anisotropy resulting from the fabric orientation, two different stacking sequences $[0]_4$ and $[\pm45]_s$ was studied. Rectangular heels were laid on 50/30 mm from each end of the static/dynamic specimens and gripped in the jaws of the test machine.

Different hygrothermal conditons (T,RH) were tested. For this purpose, the composite samples were first conditioned at equilibrium, according to an accurate industrial protocol. Three levels of moisture content have been investigated: samples were either dried in an oven at 90°C under vacuum and without humidity (RH0), or rewetted from RH0 to RH50 and RH85 (respectively 50% and 85% of relative humidity) by conditioning in a climatic chamber where both the temperature and the relative humidity contained in the air can be monitored. The samples have been weighted to ensure that water equilibrium is reached in each case.

3.2. Mechanical testing

A serie of monotonic tensile and cyclic shear tests were performed on the composites specimen. All the quasi-static tests were performed using a classical INSTRON traction machine with a load capacity of 100 kN and the dynamic tests at different strain rates in a range of 0.1 at 1000 s^{-1} using a 20 kN capacity load cell of an MTS servo-hydrolic testing machine and a mechanical crossbow system. The composite samples, conditioned at RH% of relative humidity, have been tested at three different temperatures (20°C, 80°C and -40°C). For each (T,RH) condition, five tests until rupture for samples in stacking sequence $[0]_4$, two tests until rupture and three cyclic shear tests for samples in the stacking sequence in $[\pm45]_s$. An identification protocol of materials parameters for the composites fabric ply damge model was also developed from the results of tests.

Figures 1 and 2 respectively show the quasi-static tensile and cyclic shear stress-strain curves at room temperature (T=23°C) and differents relative humidity. The influence of the relative humidity on the behavior in the fibers direction is very low (Fig. 1). However, the behavior of the thermoplastic matrix shows a high sensitivity to this latter (Fig. 2).

Figures 3 and 4 depict strain rate effects in the orthotropic directions. It may be noted the incresase of the Young modulus in the reinforcement directions (Fig. 3) and that of the shear modulus in the

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behavior of the matrix (Fig. 4). An increase of the ultimate stress and strain is also denoted in both cases. The investigation of strain rate effects on the behavior of the studied composite material is in progress for higher strain rates up to 1000/s.

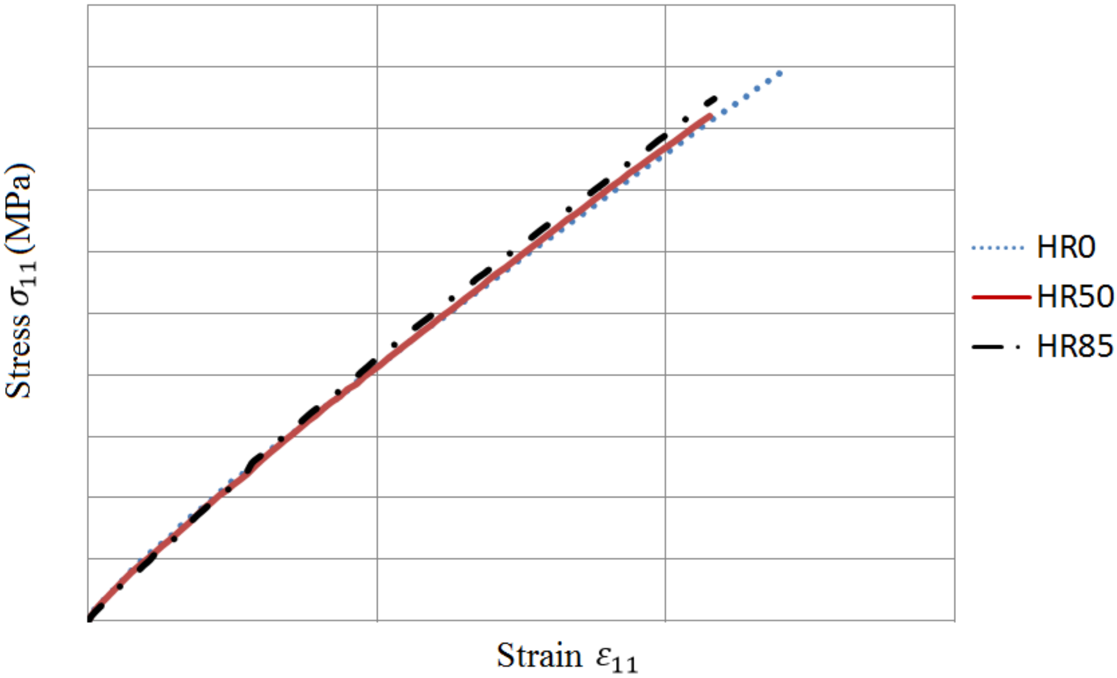

Figure 1. Fabric composite Glass fiber/PA66 $[0]_4$: quasi-static tensile stress-strain curves for different levels of relative humidity

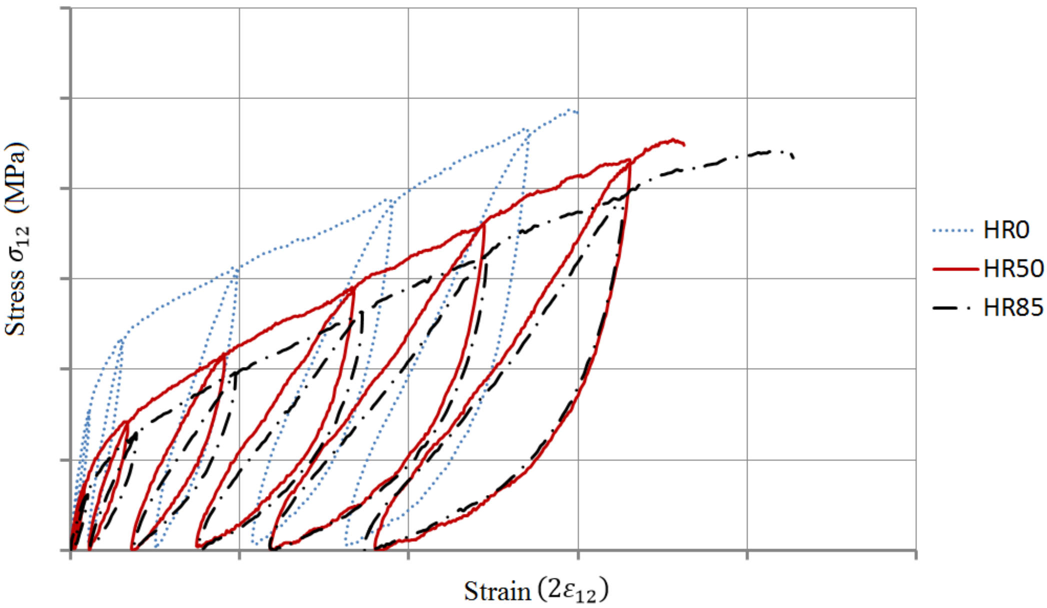

Figure 2. Fabric composite Glass fiber/PA66 $[\pm 45]_s$: quasi-static cyclic shear stress-strain curves for different levels of relative humidity

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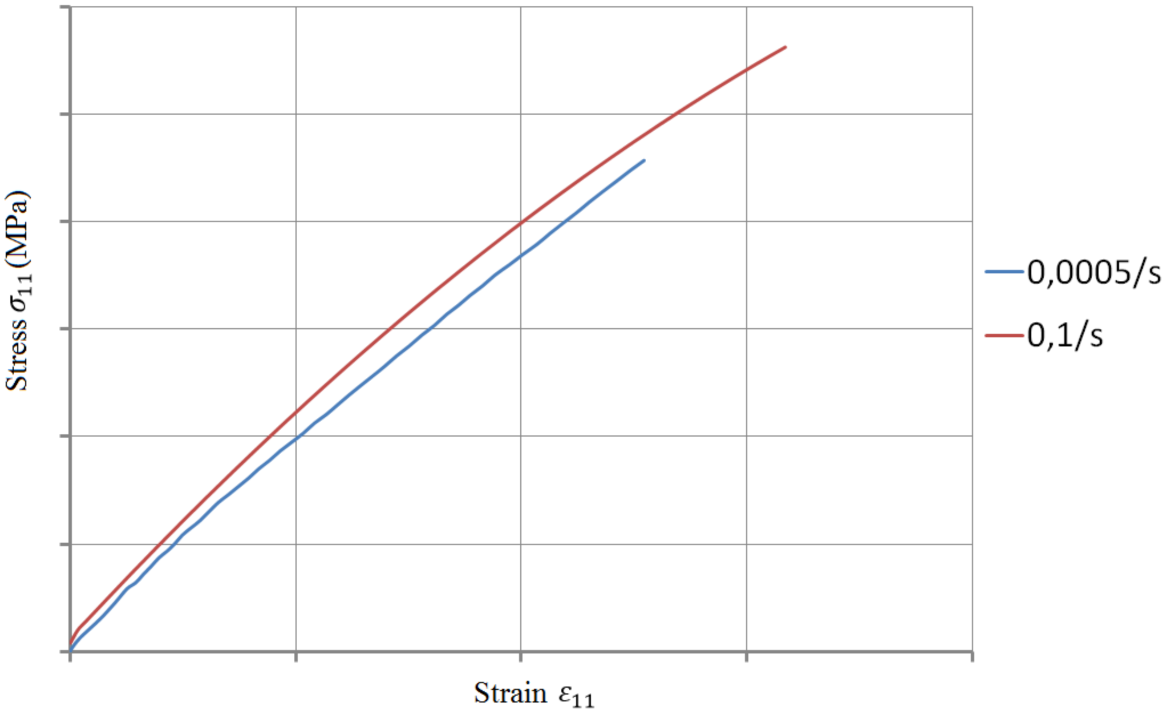

Figure 3. Fabric composite Glass fiber/PA66 $[0]_4$: stress-strain curves for different strain rates (T = 23°C and HR0)

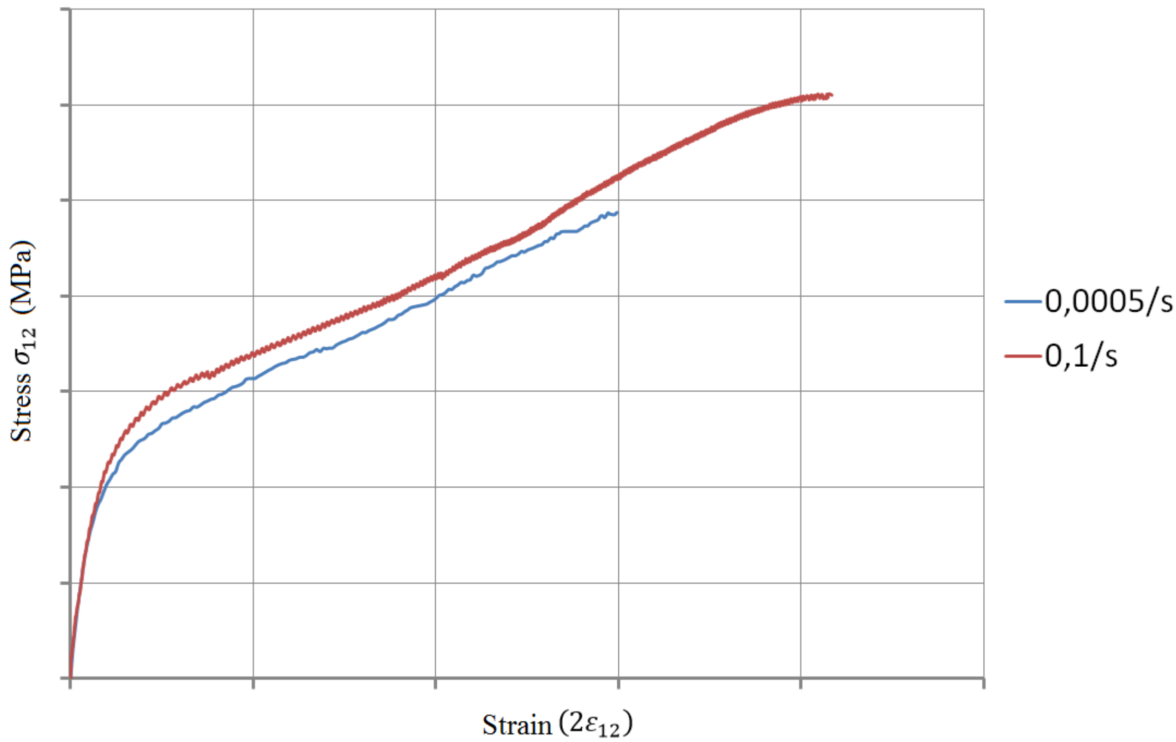

Figure 4. Fabric composite Glass fiber/PA66 $[\pm 45]_s$: stress-strain curves for different strain rates (T = 23°C and HR0)

4. Conclusions

A numerical model and experimental study on Glass fiber reinforced polyamide 66 are presented in this paper. The proposed model is written at the mesoscale of the ply and special attention was paid to describe quasi-static and dynamic effects. The experimental campaign aims to study the influence of the environmental conditions such as temperature and humidity on the evolution of material properties: the main conclusions are that the humidity and the temperature have different influence in regard of the orthotropic directions. Indeed, when the matrix plays a great role in the behavior of the composite material, the environment conditions leads to generally deteriorate the static mechanical properties. What we have also observed during the dynamics tests, is that the strain rate effects have mainly a strong influence on the shear behavior. All the parameters have been identified in respect of our theoretical model. However, its implementation is still in progress in order to compare numerical and experimental results.

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