NON-LINEAR CONSTITUTIVE LAW FOR A GLASS-PA66 FABRIC COMPOSITE DEDICATED TO NUMERICAL SIMULATIONS IN CRASH STUDIES

Mamadou A. MBACKE[1], mamadou.mbacke@irt-jules-verne.fr
Patrick ROZYCKI[2], patrick.rozycki@ec-nantes.fr

[1]IRT Jules Verne, Chemin du Chaffault, 44340 Bouguenais, France
[2]Ecole Centrale de Nantes/GeM, 44321 Nantes Cedex 3, France

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In the automotive field, it is important to predict materials behavior and thereby the components behavior with high accuracy. The first part of paper deals with a complete experimental characterization both for quasi-static and dynamic loadings. In quasi static, we carried out trials at three different temperatures (-40°C, 23°C and 80°C) for which, each time, three different levels of hygrometry (RH=0%, RH=50% and RH=85%) have been imposed. In dynamic, we tested the fabric for four different levels of strain rate (from 10^{-3}/s up to 400/s) at the ambient temperature (23°C) and for three same previous levels of hygrometry. The second part of the paper deals with the writing of an adapted constitutive law for the fabric. Thanks to [1-2], we developed and implement a new law which is able to take into account the evolutions of elastic strains, irreversible strains and damages, the strain rate sensitivity and the hygrometry effect.

1. Introduction

Due to the public authorities, the current economic and ecological contexts impose to the car manufacturers to reduce the fuel consumption of their vehicles, which leads to reduce the weight of these ones. At the end of 2013, the European Parliament and the Council of the European Union proposed two regulatory proposals on CO_2 emissions by 2020: a limitation of the average emissions for the new passenger car standards at 95 g/km of CO_2 and a limitation of the average emissions for the new light-commercial vehicle standards at 147 g/km of CO_2 [3].
To achieve these objectives of weight saving, some new solutions related to materials must be identified: composites ones appear to be good candidates to meet these expectations, especially fibers reinforced thermoplastic resin. These type of composites are excellent composite materials which combine high levels of mechanical performance and low density; they are both less expensive and easier to process. In the automotive field, the composite materials are an essential issue. That is the reason why IRT Jules Verne is driving the COPERSIM project whose aim is the modelling of a Glass-PA66 fabric composite for crash studies. Indeed, 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 [4-6]. These physical phenomena were confirmed by the various mechanical tests that we carried out on the material. Moreover, these various influential parameters (temperature, relative humidity, strain rate) are closely bound up to one of a particular property of thermoplastic materials namely their glass transition temperature (T_g) [4,5,7]. So that, the mechanical properties of polymer matix composites can change dramatically in a temperature range around and above T_g. In the context of severe certifications for vehicles, it is important to have knowledge and to understand its behavior with a view to model it and integrate the work within a commercial explicit software (Abaqus®). To satisfy the demand, a first requirement is to possess a methodology of experimental characterization to investigate the composite material behavior used. A complete experimental characterization both for quasi-static and dynamic loadings are performed to investigate the influence of temperature, relative humidity and strain rate.

The second requirement is to have an adequate numerical model to simulate the automotive parts. Following an analysis of the experimental tests and a bibliographic study on the models found in the literature and on the models available in the commercial codes, it was decided to develop a new model of behavior inspired by the works of A.F. Johnson et al. [1], P. Rozycki [2] and S. Marguet [8]. This is a model initially suggested for glass/epoxy fabrics, whose approach to describe the behavior is based on the many studies conducted by P. Ladevèze et al. [9,10] on unidirectional composites. The new model is able to take into account the evolutions of elastic strains, irreversible strains, damages and the strain rate sensitivity adapted to any couple temperature/hygrometry. It has been implemented in Abaqus/explicit as an user subroutine VUMAT. The outlines of the paper are as follow. Section 2 presents the material of this study, the experimental protocols and the results. Section 3 presents the theorical formulation of the model and the numerical results obtained with the user subroutine implemented within Abaqus/Explicit. Some conclusions and outlooks are given in section 4.

2. Experimental analysis

A complete experimental characterization of four orientations of the fabric (0°, 45°, 90° and 30°) both for quasi-static and dynamic loadings have been carried out. 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 × 25 × 2 mm and dynamic tension specimens with dimensions of 80 × 19 × 2 mm.

In quasi-static, a series of monotonic tensile and cyclic shear tests were performed on the composites specimen :

- monotonic tests carried out on specimens oriented at 0° and 90° to determine properties in the warp and weft directions and to check the balance between the warp and weft directions.
- cyclic shear tests carried out on test specimens oriented at 45° to determine the shear properties.
- additional tests carried out on specimens oriented at 30° for verification and validation.

We carried out trials at three different temperatures (-40°C, 23°C and 80°C) for which, each time, three different levels of hygrometry (RH=0%, RH=50% and RH=85%) have been imposed. The data analysis highlighted the strong influence of both temperature and relative humidity (RH) on the composite behavior. It leads to define new type of evolution law for the shear damage and the evolutions of elastic and failure quantities have been estimated. This influence of hygrometry and temperature observed on the behavior of our study material is corroborated with the conclusions of Launay et al. on a similar material, in particular short glass fibre reinforced polyamide [2]. Indeed, Launay et al. had also demonstrated that temperature and hygrometry affect the mechanical behavior through the modification of the glass transition temperature.

In dynamic, we tested the fabric for four different levels of strain rate (from 10^{-3}/s up to 400/s) at the ambient temperature (23°C) and for three same previous levels of hygrometry. The data analysis shows a sensitivity to the strain rate which is quite original: as the strain rate induces a local rise of temperature, the behavior changes drastically in respect of the glass transition temperature of the PA66.

Only a part of the experimental results is presented in this paper.

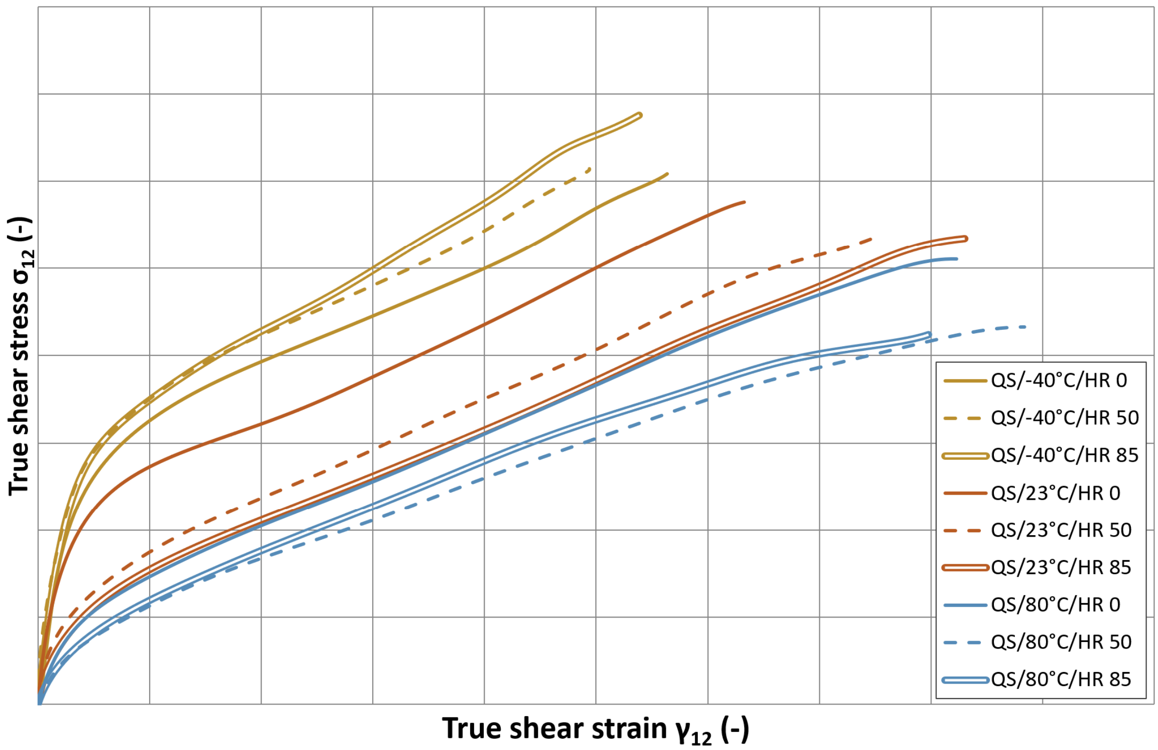

Figure 1. Quasi-static tensile tests for the 45° fabric for different temperature and RH.

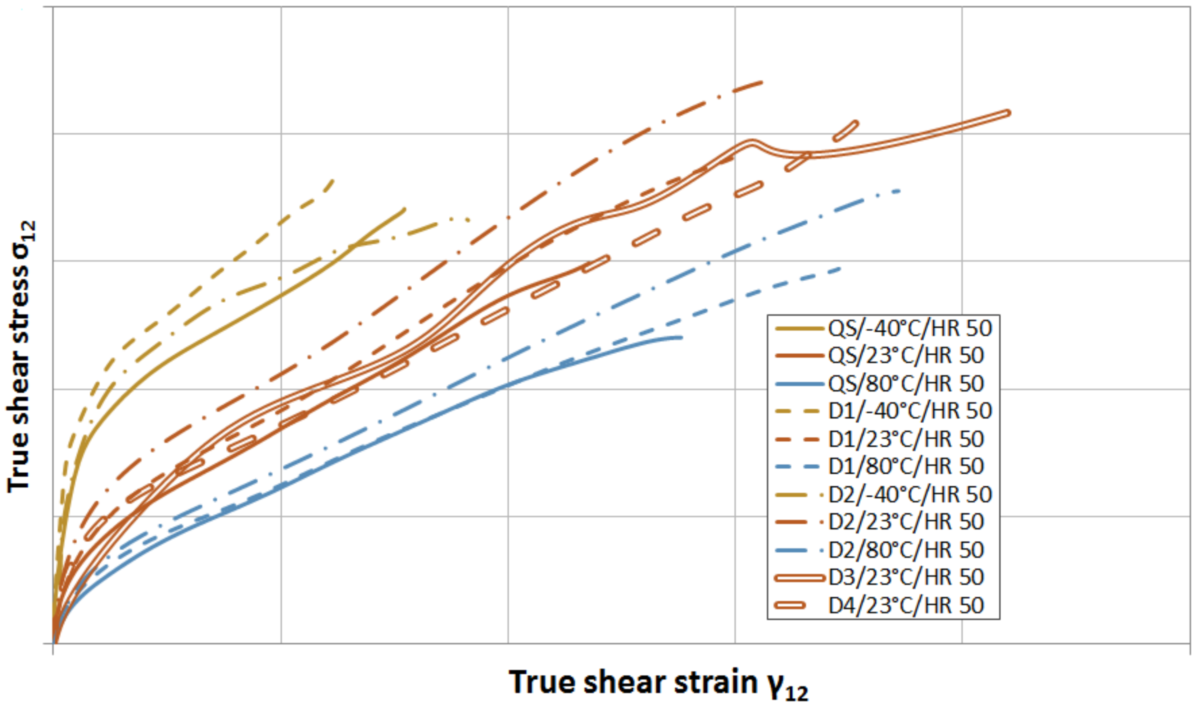

Figure 2. Dynamic tests for the 45° fabric for different temperature and RH.

3. Numerical analysis

3.1 Theorical formulation of the behavior law

Following an analysis of the experimental tests, a new model of behavior inspired by the work of AF Johnson et al. [6] and of P. Rozycki [7] is formulated in order to take into account the evolutions of elastic strains, irreversible strains and damages and the strain rate sensitivity.

The model is written at the mesoscale of the layer and in plane stress state. The model is implemented in two versions:

- a damage elastic-plastic model (quasi-static model)
- a strain rate dependent model (dynamic model)

The quasi-static model is formulated within the framework of thermodynammics: it is postulated the existence of a thermodynamic potential (Helmotz free energy ψ) from which the state laws are derived. A continuum damage mechanics formulation is used in which ply degradation parameters are internal state variables. These latter are governed by damage evolution equations d_{ij} $\{ij = (11, 22,12)\}$. The potential ψ is defined as the sum of two stored energies: elastic part ψ_e and plastic part ψ_p .

$$\psi = \psi_e + \psi_p \quad (1)$$

With

$$2\rho\psi_e = C_{11}^0(1-d_{11})(\varepsilon_{11}^e)^2 + C_{22}^0(1-d_{22})(\varepsilon_{22}^e)^2 + 2\nu_{12}^0 C_{12}^0(\varepsilon_{11}^e\varepsilon_{22}^e) + G_{12}^0(1-d_{12})(2\varepsilon_{12}^e)^2 \quad (2)$$

$$\rho\psi_p = \frac{Q}{\beta+1}p^{\beta+1} \quad (3)$$

Variables $\boldsymbol{Y_{ij}}$ called thermodynamic variables are introduced. They are deduced by derivation of the elastic strain energy with respect to the damage variables $\boldsymbol{d_{ij}}$:

$$Y_{ij} = -\rho\frac{\partial\psi_e}{\partial d_{ij}} \quad (4)$$

The evolution laws of the variables of damage are then defined according to the thermodynamic variables:

$$d_{ij} = f_{ij}(\underline{Y}_{ij}) \quad (5)$$

Functions $\boldsymbol{f_{ij}}$ are approximation functions adapted to experimental observations.
The evolution of the variables d_{11} and d_{22} is described by one linear function while the evolution of the variable d_{12} is particularly described by two coupled functions (one linear function and one logarithmic function) .

$$\underline{Y}_{ij} = Sup_{\tau\le t}\left(\sqrt{\underline{Y}_{ij}(\tau)}\right) \quad (6)$$

Irreversible shear behavior is obtained by coupling between plasticity and damage d_{12}. This coupling is realized through the introduction of effective shear stress in the expression of the plastic yield surface f:

$$f = \frac{\sigma_{12}}{1-d_{12}} - R(p) - R_0 \text{ with } R(p) = Qp^{\beta} \tag{7}$$

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:

$$\dot{\varepsilon}_{12}^{p} = \dot{\lambda}\frac{\partial f}{\partial \sigma_{12}} \qquad \dot{p} = -\dot{\lambda}\frac{\partial f}{\partial R} \tag{8}$$

where $\dot{\lambda} \geq 0$ is a proportionality parameter to be determined. Substituting (Eq. 7) in (Eq. 8) leads to $\dot{\lambda} = \dot{p}$ and hence:

$$\dot{\varepsilon}_{12}^{p} = \frac{\dot{p}}{1-d_{12}} \quad \text{giving} \quad p = \int_0^{\varepsilon_{12}^{p}} (1-d_{12})\, d\varepsilon_{12}^{p} \tag{9}$$

The dynamic model is an extension of the quasi-static model by introducing a strain rate function $F_{\gamma}(Y)$ for each mechanical property $\gamma(\dot{\varepsilon})$ sensitive to the strain rate. This function also takes into account hygrometry sensitivity of the properties and is defined indirectly according to the current strain rate $\dot{\varepsilon}$.

$$Y = \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right)^{\alpha} \tag{10}$$

$$\gamma(\dot{\varepsilon}) = \gamma(\dot{\varepsilon}_{\text{ref}}).\, \mathrm{F}_{\gamma}(Y) \tag{11}$$

With

- $\boldsymbol{\gamma}(\dot{\boldsymbol{\varepsilon}})$ represents the mechanical properties at the current strain rate $\dot{\boldsymbol{\varepsilon}}$.
- $\boldsymbol{\gamma}(\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{ref}})$ represents the mechanical properties at the reference strain rate (quasi-static strain rate) $\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{ref}}$.

It is later implemented in abaqus/explicit as user subroutine called VUMAT and includes sixty-three parameters.

3.2. Experimental and numerical correlations

The user subroutine is used to reproduce numerically all the mechanical tests defined in section 2.
In quasi-static loading, this involves simulating a test specimen subjected to a monotonic tensile test and a shear test. A very good correlation is obtained between the numerical results and the experimental results for all test configurations (temperature and hygrometry).
In dynamic loading, the validation phase consists of numerically simulating the experimental tests using the experimental average strain rate determined for each test configuration. The model perfectly reproduces the evolution of the mechanical properties as observed experimentally: increasing or decreasing properties according to the strain rate.

Figure 3. Localization of damage (d_{12}) in test specimen – shear test.

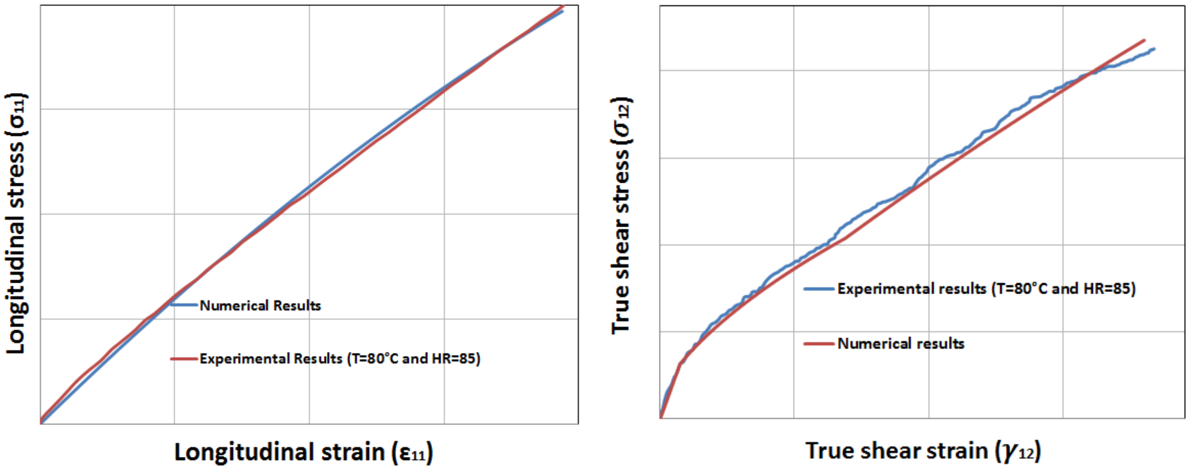

Figure 4. Comparison quasi-static experiments/numerical simulations for the 0° and 45° fabric at 80°C and RH=85%.

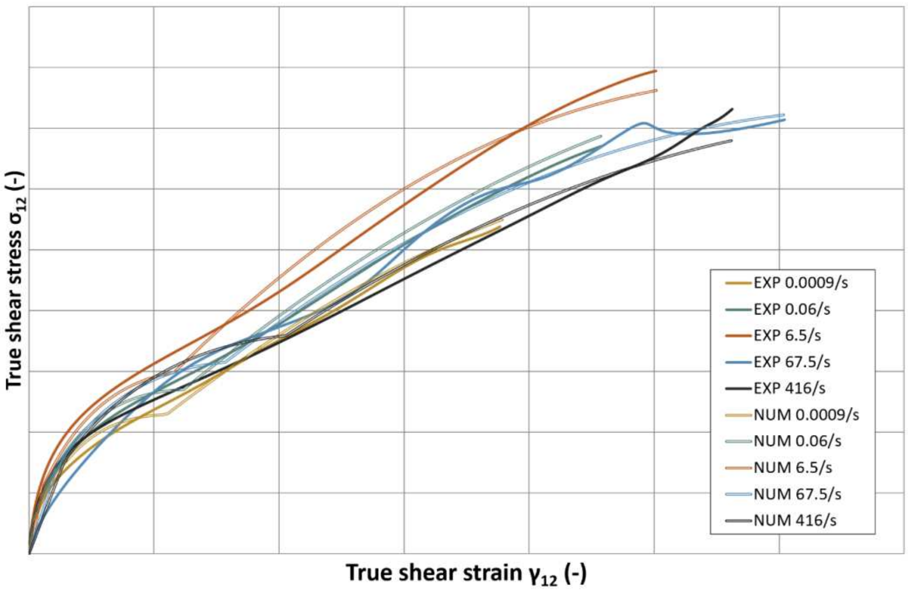

Figure 5. Comparison dynamic experiments/numerical simulations for the 45° fabric at 23°C and RH=50%.

4. Conclusions

A complete experimental characterization both for quasi-static and dynamic loadings are performed to investigate the influence of temperature, relative humidity and strain rate. The data analysis highlighted the strong influence of both temperature and relative humidity (RH) on the composite behavior and its sensitivity to the strain rate.
We have proposed a quasi-static and dynamic non-linear behavior law formulation to take into account both hygrometry and velocity sensitivity. This model is implemented in abaqus/explicit as user subroutine and is used to reproduce numerically all the mechanical tests defined in section 2
Finally, numerical simulations of experimental characterization testing show good correlations and offer some new future prospects such as formally linking the temperature, HR and strain rate.

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