Experimental and Numerical Study of Polypropylene Composite Reinforced with Jute Fibers

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Abstract. This paper is devoted to the study of the mechanical response of polypropylene (PP) thermoplastic composite reinforced with jute fibers. In order to use these composites in structural applications it is necessary to understand the mechanisms governing their mechanical behavior and damage. For this purpose, we have fabricated two kinds of PP/jute laminates: $[0°/90°]_{2S}$ and $[+45/-45°]_{2S}$ with the fibers direction, using the molding technique under compression. The mechanical properties of the material are then characterized by tensile and compressive tests. The numerical part of this work concerns the incorporation of the Matzenmiller, Lubliner, and Taylor (MLT) damage model to take into account the post-elastic-peak and the post-peak strain softening responses observed in the the PP/jute composite. This is possible by using formulation with two criterions. The 3D constitutive law has been implemented into the finite code Abaqus using an explicit scheme. In order to assess the capability of this model to describe the material behavior, comparisons are made between numerical and experimental results. Excellent agreements are found between numerical predictions and experimental observations. The model also captures correctly the zones where damage occurs in the two kinds of laminates.

Keywords: PP/jute, mechanical behavior, damage, laminate, modeling.

1 Introduction

Composite thermoplastic (PP) reinforced with natural fibers are mainly used in industrial transport [1]. The use of these composites materials, made of natural fibers, have for objective the substitution of the synthetic fibers like glass fibers [2]. Exotic fibers are attractive because of their low-cost, their high strength, their stiffness and their less impact on the environment in comparison to the other fibers [3-9]. This work is concerned by jute fibers which are incorporated into a polypropylene matrix containing up to 50 vol% fibers. In this study we are particularly interested on the study of mechanical behavior and damage of this composite.

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The modeling approach adopted assumes that the material degradation occurs within two steps. The first one is due the formation discontinuities in the matrix. The second is happen before total failure of the composite. A model is proposed and implemented in order to describe the mechanical response until total material failure. For this purpose we make use of a formulation with two criterions.

2 Material and Experiment

2.1 Material

The material adopted in this study is a polypropylene (PP) thermoplastic composite reinforced with jute fibers (PP/jute). Two stacking sequences of laminates are fabricated: [0°/90°]2S, [+45/-45°]2S, with the angle referred to the longitudinal direction as shown in figure 1. The laminates [0°/90°]2S are used for the material characterization in the orthotropic directions, while the [+45/-45°]2S lamina are used to identify the material shear response. All the specimens are fabricated by the technique of molding by compression.

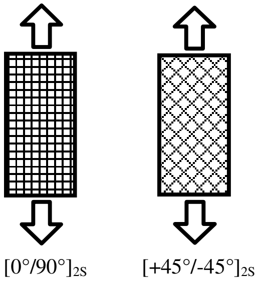

Fig. 1 Schematization of the two laminates kinds: $[0°/90°]_{2S}$ and $[+45/-45°]_{2S}$

2.2 Fabrication Process

In this study, the matrix is a polypropylene (PP) resin with a density of 0.89 g/cm3; the jute fibers with a density of 1.46 g/m3 are employed as reinforcement. The PP/jute composites are realized by the technique of molding under compression. This technique consists on putting the grains of polypropylene and the jute fibers oriented in the desired direction in a mold and to apply a constant pressure. During this thermal compression, the mould is heated over the fusion point temperature. After what the composite is kept at the ambient temperature of 25 °C during 48h before the mechanical testing.

2.3 Tensile Test

The mechanical properties of PP/jute composite materials have been investigated on an IBERTEST testing machine with a load-cell of 10 KN. The tests are displacement-controlled with a speed of 2mm/min. According to ISO-527-5 standard, the dimensions of the [0°/90°] laminates are 250 mm in length and 25 mm in width and the dimensions of the [+45°/45°] laminates are 250 mm of length and 25 mm of width according to ISO 3518 standard. The tensile tests of this second kind of laminates correspond to shear loeading for the jute fibers. The mechanical properties of PP/jute composite obtained during tensile tests are listed in Table 1.

Table 1 Mechanical properties of Jute/PP composite

Properties	$E_1(MPa)$	$E_2(MPa)$	$G_{12}(MPa)$	ν_{12}
Value	1912	1878	979.8	0.27

At a certain strain stage, [0°/90°] laminates exhibit a non-linear behavior until maximal stress, then softening is observed until final material failure The non-linear part of the curve indicates that significant loss of rigidity occurs in the material due to formation of micro-cracks. The responses of [+45°/45°] laminates to tensile loading is linear until it reaches onset of damage. The material seems to be not significantly damaged. After this post-elastic peak, micro-cracks appear and increase causing loss of rigidity and final failure occurs suddenly.

3 Numerical Modeling

Commonly, composite materials don't exhibit significant plastic deformation. So, the damageable constitutive laws used to describe the progressive damage of such material are elastic-brittle. In the case of thermoplastic composites reinforced by fibers, three zones can be distinguished. The first one is the elastic undamaged zone. The second begins where a decrease of the rigidity appears. It concerns the nucleation, generally in the matrix, of first discontinuities. However during this stage, the linear or non-linear macroscopic composite response still less affected by this damage: the curve continue to increase and material deformation needs higher stresses levels to be achieved. The last zone corresponds to the material softening before total failure of the reinforced composite. Formation and evolution of microcracks (surfaces discontinuities) and cavities (volume discontinuities) are observed during this stage. Initially, the material behavior of the laminates is assumed elastic orthotropic: and can be modeled using the relation

$$\{\varepsilon\} = [E]\{\sigma\} \tag{1}$$

Where $[E]$ is the classical compliance matrix defined using the original elasticity constants of the undamaged laminate E_i, ν_{ij} and G_{ij}. When significant damage occurs in the material, this matrix should include variables taking into effect the decrease or the loss of the material rigidity. Consequently, the $[E]$ can be rewritten:

$$[E]=\begin{bmatrix} \frac{1}{(1\text{-d}_{11\text{-k}})E_1} & \frac{-\nu_{21}}{E_2} & \frac{-\nu_{31}}{E_3} & 0 & 0 & 0 \\ \frac{-\nu_{12}}{E_1} & \frac{1}{(1\text{-d}_{22\text{-k}})E_2} & \frac{-\nu_{32}}{E_3} & 0 & 0 & 0 \\ \frac{-\nu_{13}}{E_1} & \frac{-\nu_{23}}{E_2} & \frac{1}{(1\text{-d}_{33\text{-k}})E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{(1\text{-d}_{12\text{-k}})G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{(1\text{-d}_{23\text{-k}})G_{23}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{(1\text{-d}_{13\text{-k}})G_{13}} \end{bmatrix} \tag{2}$$

The damage parameters $d_{ij\text{-k}}$ vary from 0 (undamaged material) to 1 (total failure) and represent the modulus reduction under different conditions. They are introduced to take into account effect of progressive material damage on the longitudinal, transverse and in-plane shear response respectively. As it will be seen later, subscribe k $(k=1,2)$ indicates either the material behavior is in the post-elastic zone $(k=1)$ or in the softening zone $(k=2)$.

The (MLT) [14] damage model is adopted to characterize the damage onset and the material hardening. So, the damage evolution law is done in the case of [0°/90°] laminates by

$$d_{ij-k}=1-\exp\left[\cdot\cdot-\frac{-\ln\beta_{ij}}{e}\left(\frac{E_{ij}\varepsilon_{ij}}{\sigma_f}\right)^m\right] \quad with\ \beta_{ij}=\frac{\varepsilon_f}{\sigma_f}E_{ij} \tag{3}$$

σ_f is the maximal stress, its corresponds to the onset of the total material failure, ε_f is the strain corresponding to σ_f. The m parameter should be defined from the Young's modulus, the maximum stress and the corresponding strain. The damage parameters $d_{ij\text{-}1}$ describe the nonlinear material behavior observed experimentally. For [+45/-45] laminates, it is written

$$d_{ij-1}=\left(\frac{\varepsilon^q-\varepsilon^q_{\lim}}{\varepsilon^q_f-\varepsilon^q_{\lim}}\right)^{\frac{1}{n}} \tag{4}$$

The q and n material parameters represent the rigidity loss in the post-elastic curve and describe the development of the different failure modes. The rapid material failure is similar for both laminates. Generally, it corresponds to fibers failure, so the load carrying capacity of that lamina is completely loosed. The formation and propagation of macroscopic cracks cause this final failure. This physical phenomenon is modeled by introducing a second damage variable d_{ij-2} given by the following equation:

$$d_{ij-2} = \left(1 - d_{ij-1}\right)\left(\frac{\varepsilon^q_{ult}}{\varepsilon^q_{ult} - \varepsilon^q_f}\left(1 - \frac{\varepsilon^q_f}{\varepsilon^q}\right)\right)^{\frac{1}{n}} \tag{5}$$

ε^q_{ult} is the ultimate failure strain as schematized in figure 2.

The material behavior is linear before the first peak $(\varepsilon \leq \varepsilon_{\lim})$. In this zone the material is assumed undamaged. So the onset of damage is governed by Raghava and al. criterion. The material failure begin when the Tsai Wu criterion

Table 2 Tensile strength of Jute/PP composite

	$[0°/90°]_{2S}$ laminates		$[+45/-45°]_{2S}$ laminates	
Properties	$\sigma_f\,(MPa)$	ε^{ult}_t	$\sigma_f\,(MPa)$	ε^{ult}_t
Value	27.17	0.019	16.62	0.033

Figures 2 and 3 show the nonlinear behavior in tensile responses of [0°/90°]2S and [+45/-45°]2S laminates. The damage variables d_{ij-1} are quite favorable to describe the damage part (non-linear curve softening) due to the effect of gradual micro-cracking formation. The damage variables d_{ij-2} are quite favorable to describe the failure part (strain-softening).

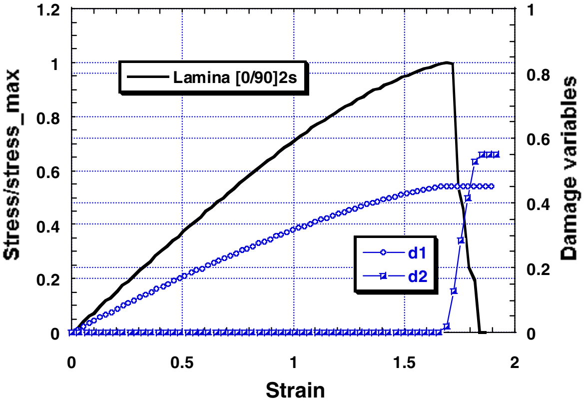

Fig. 2 Damage evaluation Model due to combined damage variables d_{ij-1} and damage variables d_{ij-2} of the lamina $[0°/90°]_{2S}$

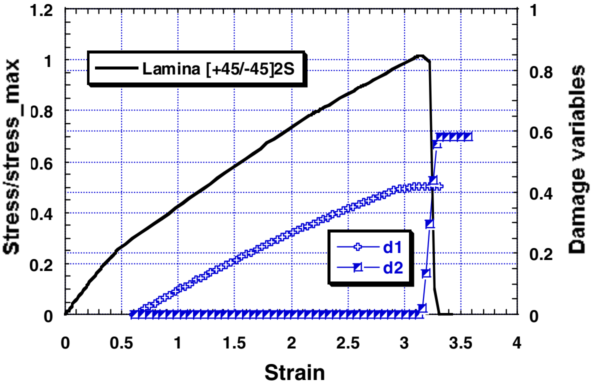

Fig. 3 Damage evaluation Model due to combined damage variables d_{ij-1} and damage variables d_{ij-2} of the lamina [+45/-45]$_{2S}$

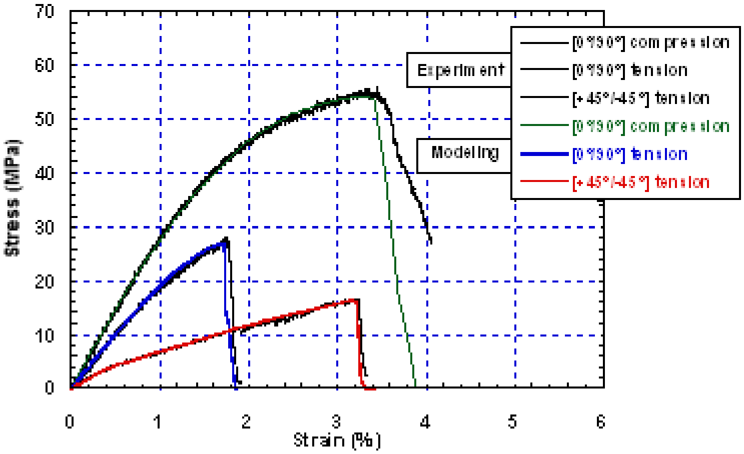

Fig. 4 A comparison between the results of these simulations and the results obtained experimentally for the tension and shear tests

4 Results and Discussions

The model proposed in the previous section has been implemented into the finite code Abaqus using an explicit scheme [20] and used to perform some simulations. Abaqus allows the implementation of user defined models using the Vectorized User MATerial (VUMAT) subroutine. The two kinds of laminates are modeled in 3D.

In order to assess the capability of this model to describe the PP/jute laminates responses, we show in the figure 4 comparison between longitudinal stresses calculated numerically and experimentally versus the strain for the [0/90]2S and [+45/-45]2S laminates. The mechanical behaviors of these specimens are different. The [+45/-45]2S laminates presented strength values lower and less rigidity than the [0/90]2S laminas. This situation can be explained by the influence of the fibers orientation on the less adhesion at the matrix/fiber interface in the case of shear loading.

5 Conclusion

The purpose of this work is twice: experimental characterization of the mechanical response of fiber-reinforced composites and formulation and assessment of a damage model describing the damage and behavior of these laminates. The material used is a polypropylene (PP) thermoplastic reinforced with jute fibers. The mechanical characterization of the two kinds of PP/jute laminates ($[0°/90°]_{2S}$ and $[+45/-45°]_{2S}$ with the fibers direction) used in the study is done by tensile and compressive tests.

The Matzenmiller, Lubliner, and Taylor (MLT) damage model is coupled to an damaged elastic law to include the failure stage (coupling damage-failure) using a formulation with two criterions. This constitutive law has been implemented into the finite code Abaqus using an explicit scheme. In order to assess the capability of this model, comparisons are made between numerical and experimental results. Excellent agreements are found between numerical predictions and experimental observations. The $[+45/-45]_{2S}$ laminates presents lower strength values and less rigidity than the $[0/90]_{2S}$ laminates. For the $[0/90]_{2S}$ laminates, cracks are germinated perpendicularly to the loading direction. $[+45/-45]_{2S}$ laminates exhibit the formation and propagation of cracks with an angle of approximately 45° with the loading direction. This crack propagation direction corresponds to the fibers orientation.

As perspectives to this work, we can propose:

- Including thermal heating generated by the material dissipation due to damage and hardening.
- Including other degradation mechanism like ageing and moisisture… and incorporate the humidity effects which play an important role in the life cycle of thermoplastic polymers.

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