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To cite this version:

Pascal Casari, Pierre Ladevèze, Tsu-Wei Chou. Damage modeling and characterization of a three-dimensional woven composite. ICCM-12, 1999, Paris, France. hal-01008054

DAMAGE MODELING AND CHARACTERIZATION OF A THREE-DIMENSIONAL WOVEN COMPOSITE

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SUMMARY: The characterization and modeling of the inplane damage behavior of a three-dimensional woven composite are conducted with the use of the Mesoscale Composite Damage Theory, developed by Ladevèze. A first analysis of the composite fabric provides the main geometrical properties that can affect the mechanical behavior. A model previously established for aeronautical carbon/epoxy laminates is applied in a simplified version. It assumes an elastic and brittle behavior in the directions of the fibers, and degradation mechanisms like matrix micro-cracking and fiber debonding under a shear stress state. The model utilizes two experimental laws to be identified for the description of damage and inelastic strains. Then, the experimental procedure is presented by means of tensile tests on two relevant kinds of samples. The identification of the elastic, failure, damage and inelastic properties is performed. The comparison between complementary experiments and simulation shows a good fitting for small strains.

KEYWORDS: damage, 3D, woven composites, mechanical properties, mesoscale.

INTRODUCTION

This study deals with the characterization and modeling of damage in a 3D woven composite. A significant non-linear behavior can be observed through the mechanical response of this composite under inplane loading, except in the directions of the fibers. Then, a non-linear model, based upon the damage theory of Ladevèze [1], is applied in order to simulate the behavior of the composite.

This study relies on a modeling and an associated experimental methodology of long-fiber reinforced cross-ply composites, which have been presented in [2] and also in [3] for aeronautical composite laminates made of unidirectional reinforcement. The analysis of the constitution of the material allows the use of this model for the modeling of the inplane behavior of the 3D composite. This methodology must also take the step of the identification into account, in order to make the characterization of damage and inelastic behaviors possible. As elastic, brittle failure, damage and inelastic properties must be measured, two tests at [0°]

and [45°] from the warp direction have been chosen for their good sensitivity to these parameters. These classical uniaxial tension tests have been improved by measuring transverse strain and practicing loading-unloading cycles. Once the model has been identified, simulations of the behavior of cut-outs with orientations of [22.5°], [67.5°] and [90°] from 3D carbon plates have been performed. The comparison between tests response and simulation allow to predict the beginning of the stress/strain curves.

DESCRIPTION OF THE MATERIAL

The composite is manufactured under the shape of a plate made of a carbon woven preform and an epoxy resin. The orthogonal interlock fabric (Fig. 1) is made of T300 carbon fibers by Fiber Materials Inc. in one-run process.

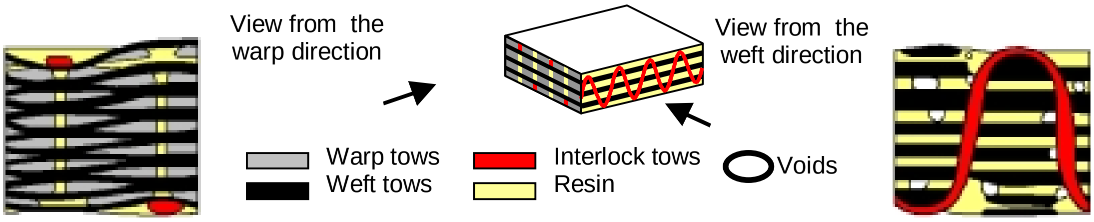


Fig. 1: Cross-sections of the composite in the warp and weft directions

The material can be described as a [0°/90°] laminate in which some through-the-thickness yarns are interlaced. It has been manufactured by Vacuum Assisted Resin Injection at room temperature with an epoxy resin West System 205. The last data are listed in Table 1:

Table 1: Geometrical characteristics of the composite.

	Warp direction	**Weft direction**	**Through-the-thickness**
# of plies	13	14	
Fiber volume fraction	22 %	22 %	1 %
Thickness		Total: 5.2 mm	Ply: 0.19 mm

After manufacturing, some defects have been observed under a microscope (Fig. 1):

- Many voids appear in the resin-rich parts of the composite. Indeed, the interlock yarns are generating some paths in the fabric, which allow the resin to go through during injection, and the voids to stay there.
- The weft tows are curved by the pressure of the through-the-thickness tows. This predicts a reduction of stiffness compared to the behavior in the warp direction,
- The warp tows remain straight.

These remarks will help for the analysis of the stress-strain curves.

MODELING OF THE COMPOSITE

The mechanical behavior of the composite is modeled by means of damage mechanics. The goals of damage mechanics are to simulate the non-linear response of a material in the presence of damage and to predict the conditions for failure. The damage theory that serves as the foundation for this model was proposed by Ladevèze in 1986. It has been demonstrated in [4] that, compared to the properties of a 2D laminate, the interlaminar fracture toughness of this composite is enhanced by adding through-the-thickness reinforcement. Our goal is not to analyze delamination in the composite, but to characterize the inplane behavior and then to evaluate the influence of the weaving on the inplane properties of the 3D composite

Mesoscale composite damage theory

In our configuration, the theory is called the mesoscale composite damage theory. It considers that damage is uniform through the thickness of individual layers of the composite. Mesoscale indicates that the scale of the analysis is between micro-mechanics (i.e., the level of the fiber and the matrix) and laminate analysis. Then the composite becomes a laminated structure made of two elementary constituents : layers (or plies) of composite and interfaces that separate the composite layers. The interface is considered to be a mechanical surface connecting two adjacent composite layers. Here delamination is not of interest, so the model is just an assemblage of composite layers. The main assumption is that the response of a damaged layer, at any load state, can be expressed in terms of elastic moduli degradation and inelastic strains due to damage and/or matrix plasticity, as depicted in Fig. 1. Degradation of the elastic moduli is expressed in terms of damage parameters that are functions of the associated thermodynamic forces which serve as damage evolution parameters. The modulus degradation parameters are internal variables, and the thermodynamic forces are the corresponding associated variables. The micro-level damage mechanisms taken into account are matrix micro-cracking, fiber debonding and fiber fracture. They are not identified explicitly in the mesoscale damage model ; damage evolution is identified on the stress-strain curves of tests on samples. Indeed, as damage occurs, the material loses stiffness and exhibits nonlinear, inelastic response with permanent strains after unloading.

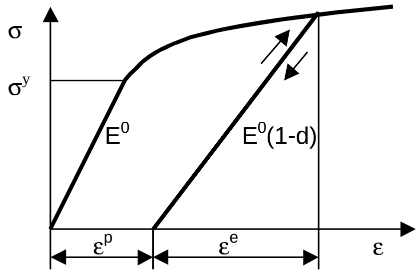


Fig. 1: Theoretical inelastic stress/strain response of damaged composite

The damage theory is explained below in a simplified case for this particular material because only two tests have been taken into account for characterization, which doesn't allow the full identification of a more complete model that would take damage in the transverse direction into account.

Modeling of the elementary ply

The laminate, made of a stacking sequence of 13 plies in the warp direction and 14 plies in the weft direction, is considered to be in a plane stress state. The elementary ply is here any of the warp or weft layers, considered to have the same behavior. In what follows, subscripts 1 and 2 designate, respectively, the fiber direction and the transverse direction of the elementary ply. The developments of the model are based upon the classical laminate theory in a plane stress state. The initial values of moduli (Fig. 1) are indicated E^0. In the direction of the fibers, the behavior is linear and brittle. In shear, a progressive damage is generating a non-linear behavior.

Effective Stress and response

The effective stresses are the stresses acting over the damaged area that effectively resists the forces. In a general case, any stress component σ_i can be affected by a damage parameter d_i ranging from 0 (undamaged state) to 1 (macroscopic damage or failure). Here only the shear stress is affected by the damage variable d as shown: In the usual applications of damage theory [2], a damage variable also affects the transverse stress. Here, in order to show a simple application, this variable has not been taken into account:

$$\tilde{\sigma}_{11} = \sigma_{11}, \qquad \tilde{\sigma}_{22} = \sigma_{22}, \qquad \tilde{\sigma}_{12} = \frac{\sigma_{12}}{(1-d)} \tag{1}$$

Now the principle of strain equivalence states that "any deformation behavior of a damaged material is represented by the constitutive laws of the virgin material in which the usual stress is replaced by the effective stress". Thus, the elastic constitutive equations for the damaged material in plane stress can be written as follows:

$$\varepsilon_{11}^{e} = \frac{\sigma_{11}}{E_1^0} - \frac{\nu_{12}^0}{E_1^0}\sigma_{22}, \qquad \varepsilon_{22}^{e} = \frac{\sigma_{22}}{E_2^0} - \frac{\nu_{12}^0}{E_1^0}\sigma_{11}, \qquad \varepsilon_{12}^{e} = \frac{\sigma_{12}}{2G_{12}^0(1-d)} \tag{2}$$

From Eqn (2), we see that the damage parameter d is the internal variable representing the reduction of the shear modulus:

$$G_{12} = G_{12}^0(1-d) \tag{3}$$

Thermodynamic force and progressive damage evolution law

The strain energy density E_D is defined by:

$$E_D = \frac{1}{2}\left[\frac{\sigma_{11}^2}{E_1^0} + \frac{\sigma_{22}^2}{E_2^0} - 2\frac{\nu_{12}^0}{E_1^0}\sigma_{11}\sigma_{22} + \frac{\sigma_{12}^2}{G_{12}^0(1-d)}\right] \tag{4}$$

The thermodynamic force, Y_d, associated to the internal damage variable d can be related to the mean value of the strain energy density E_D by the partial derivative and then in term of stress component and damage variable:

$$Y_d = \left.\frac{\partial E_D}{\partial d}\right|_{\tilde{\sigma}=\mathrm{cnst}} \qquad Y_d = \frac{{\sigma_{12}}^2}{2G_{12}^0(1-d)^2} \tag{5}$$

Now, in order to express the evolution of damage, a relation between d and Y_d is required. Damage will grow as Y_d increases, but no more damage will occur for any value of Y_d beneath a previous maximum value already reached. This is expressed by the definition of the maximum value $\underline{Y}_d$ of the thermodynamic force Y_d attained throughout the load history:

$$\underline{Y}_d = \max_{0 \le \tau \le t}\{Y_d(\tau)\} \tag{6}$$

In the damage theory, the damage evolution law is material dependent.

A convenient law, already established for carbon and glass laminates, can be written in the form:

$$d = \frac{\left\langle \sqrt{\underline{Y}_d} - \sqrt{Y_0} \right\rangle_+}{\sqrt{Y_C}} \tag{7}$$

where Y_0 and Y_C are damage evolution parameters determined from experimental results. This law is depicted in Fig. 3 with the experimental data.

Inelastic strains coupled with damage and evolution law

As depicted in Fig. 1, the type of composite studied here exhibits non-linear response when stressed beyond some elastic limit stress, σ^y. When the material is completely unloaded from a stress in excess of this limit, there are inelastic (permanent) strains ε^p. As carbon fibers exhibit linear, elastic response, plasticity effects are associated with the matrix, and mostly under shear stress state. The formalism for the inelastic strains is that of classical plasticity, with an elastic domain function depending on the current effective stress $\tilde{\sigma}_{12}$, and the accumulated effective inelastic strain $\tilde{p}$, based upon the use of the effective inelastic shear strain rate $\dot{\tilde{\varepsilon}}^p_{12}$:

$$\dot{\tilde{p}} = 2\dot{\tilde{\varepsilon}}^p_{12} \qquad \text{with} \qquad \dot{\tilde{\varepsilon}}^p_{12} = \dot{\varepsilon}^p_{12}(1-d) \tag{8}$$

$\tilde{p}$ can also be expressed in the form:

$$\tilde{p} = \int_0^{\varepsilon^p_{12}} 2(1-d)\, d\varepsilon^p_{12} \tag{9}$$

For no (or neglected) inelastic strains in the fiber direction and in the transverse direction, the elasticity domain function is defined by:

$$f(\sigma, R) = \tilde{\sigma}_{12} - R(\tilde{p}) - R_0 \leq 0 \tag{10}$$

where $R(\tilde{p})$ is a function of $\tilde{p}$ and R_0 is the initial threshold value for R. A typical result for carbon/epoxy is expressed as follows, where α and β are material parameters:

$$R(\tilde{p}) = \beta \tilde{p}^{\alpha} \tag{11}$$

Failure prediction

In the mesoscale damage theory, failure may occur by one of three mechanisms, depending on the multi-axial stress level: fiber brittle failure, transverse tensile failure or instability condition defined as a zero slope on the stress/strain curve. Then the brittle failure is predicted by means of the failure stresses σ^F_{11} and σ^F_{22} of the ply. The non-linear simulation software called Damlam, which has been developed by Ladevèze and co-workers, is used to simulate the mechanical response of the composite until final failure by any of these criteria.

TESTING AND CHARACTERIZATION

The testing procedure is based on tensile tests on which the longitudinal strain ε_L, the transverse strain ε_T and the stress σ_L are measured, and load-unload cycles are practiced in order to characterize damage and inelastic parameters. The samples chosen for the tests must be sensitive to the properties of the elementary ply to be measured. Usually, for laminates based on unidirectional plies, tensile tests on specially fabricated laminates of [0], [±45] and [±67,5] are performed. The [±67,5] test is necessary for the characterization of damage in the transverse direction, and also for the measure of coupling of damages in shear and transverse tension. In the present case, this degree of freedom is not allowed because no specific fabrication can be made, and the influence of the transverse behavior never seems to be significant.

Analysis of the test results

The tests are performed on samples cut in a three-dimensional composite plate at [0°] and [45°] from the warp direction (Fig. 2). This selection of tests already allows the identification of most of elastic, damage and failure properties of the ply.

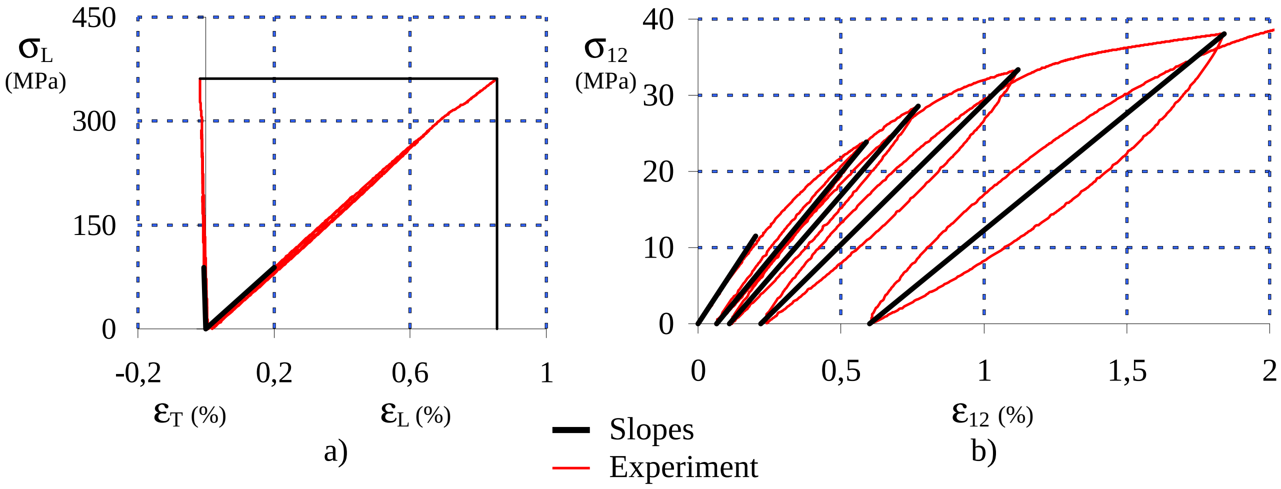


Fig. 2: Stress/strain curves of a) [0°] and b) [45°] tension tests used for characterization.

The elastic properties of the laminates, like elastic moduli and Poisson's ratios, and the brittle failure behavior have been characterized by the initial slope and the maximum stress point of the stress/strain curves (Fig. 2 and Table 2).

Table 2: Elastic and failure properties of the laminates.

Test	Elastic modulus (GPa)	Poisson's ratio	Failure stress (MPa)	Failure mode
[0°]	44.2	0.02	361	Brittle
[45°]	9.9	0.83	120	Instability

Damage variables and inelastic strains have been measured on the [45°] test by means of loading-unloading cycles. The stress-strain curve in shear $(\sigma_{12},\varepsilon_{12})$ (Fig. 2) was built from the linear relation between the longitudinal strain ε_L, the transverse strain ε_T and the macroscopic stress σ_L (Eqn 12).

$$\sigma_{12} = \frac{\sigma_L}{2} \qquad \varepsilon_{12} = \frac{\varepsilon_L - \varepsilon_T}{2} \qquad \sigma_{12} = 2.G_{12}.\varepsilon_{12} \tag{12}$$

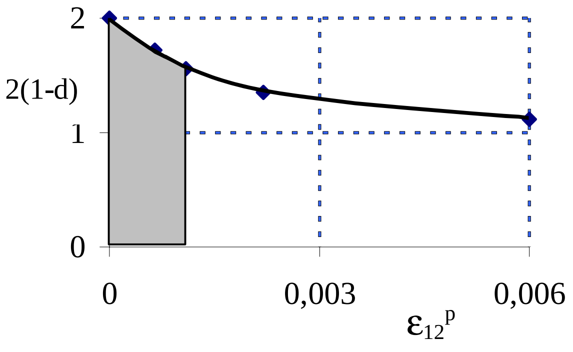
The failure strain of this sample is 8% (Fig. 5-b). This value is not due to the material's behavior, but due to an effect of the heterogeneity occurring during the test. Thus, some cycles have been practiced only in the strain range from 0 to 2%. For each load cycle "i", a set of the following quantities is measured:

- The damage variable d_i characterized on the stress-strain curve by a reduction of the elastic modulus.
- The thermodynamic force Y_{di} evaluated with Eqn (5) and the measure of the stress σ_i.
- The permanent strain ε_i^P measured at the zero stress points after unloading.
- The threshold value ($R+R_0$) (Eqn 10) obtained from the measurement of the shear stress

Table 3: Data measured from the shear stress-strain curve

Cycle	**d**	$\sqrt{\underline{Y}}_d$ **(MPa)**	ε_{12}^p	**R+R₀ (MPa)**
1	0,12	0,37	0.00065	27
2	0,17	0,48	0.0011	35
3	0,35	0,71	0.0022	52
4	0,40	0,88	0.006	64

These four data points are reported on the damage master curve (Fig. 4). The construction of the plastic master curve expressed by Eqn (11) from ε_{12}^p and R requires a complex processing. The expressions of the plastic threshold and the cumulate plastic strain have been established in Eqn (10). The variable p is obtained from Eqn (9) and evaluated by the gray area on Fig. 3. Furthermore, the values of p are calculated and marked on the plastic master curve (Fig. 3).



Cycle	**p**
1	0.0013
2	0.0022
3	0.004
4	0.0086

Fig. 3: Integration for calculating the cumulated plastic strains

Measurement of the properties of the ply

The elastic properties of the ply are deduced from the classical laminate theory. The parameters Y_C and Y_0 of the damage master curve (Eqn (7)) are identified from the experimental points (Fig. 4). The parameters R_0, β and γ are calculated by a fitting of the four experimental points. The results of the identification of the properties are reported in Table 4.

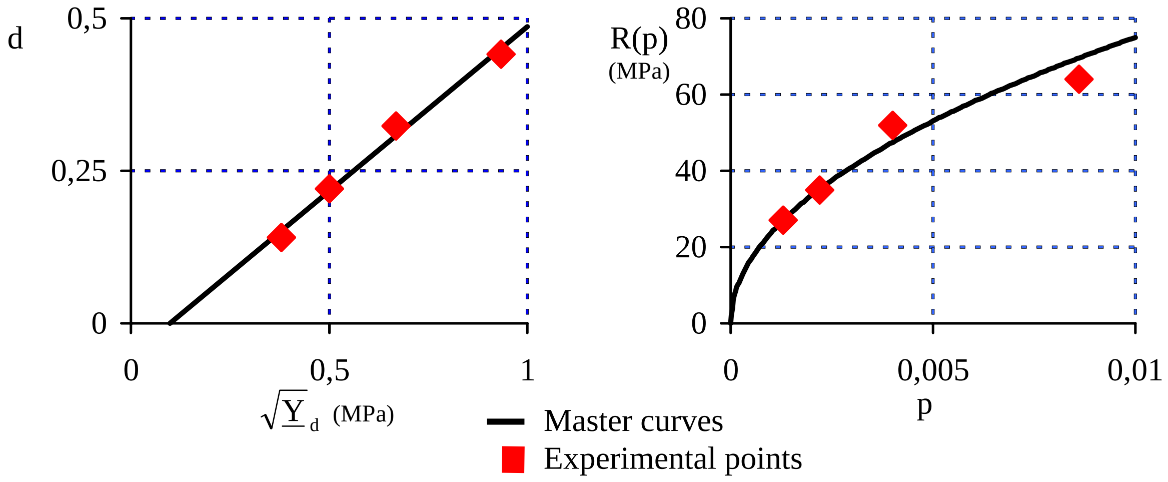


Fig. 4: Damage and plastic master curves

Table 4: Properties of the elementary ply

Elastic	**Damage**	**Inelastic**	**Failure**
$E_{11}^0 = 84$ GPa, $E_{22}^0 = 7.5$ GPa	$Y_0 = 0.01$ MPa	$\gamma = 0.5$	$\sigma_{11}^F = 720$ MPa
$G_{12}^0 = 2.6$ GPa, $\nu_{12}^0 = 0.2$	$Y_C = 3.43$ MPa	$\beta = 750$ MPa	$\sigma_{22}^F =$ not identified
		$R_0 = 15$ MPa	

COMPARISON BETWEEN EXPERIMENTS AND SIMULATION

The parameters identified above are directly used for the simulations. The non-linear simulations are performed with Damlam. At first, the simulations fit the experimental responses until failure for brittle samples like [0°] and [90°] with a little higher predicted stiffness for [90°]. This is due to the waviness of the weft yarns which affects the elastic modulus of the plies oriented in this direction (Fig. 2, Fig. 5-a). The response of the [45°] tension test is well simulated until 1.5% of strain (Fig. 5-b), but for higher strains, it seems that the yarns undergo frictional sliding under the load, whereas they are probably debonded but still constrained by the interlock yarns. Thus, the damage mechanism changes and the modeling of this behavior would require an extension of the damage master curve for high damage values and also for damage in transverse tension.

A simulation is performed on two other samples cut at [22.5°] and [67.5°] from the warp direction of the composite (Fig. 5-c Fig. 5-d). The [22.5°] and [67.5°] results are well fitted until a stress around 100 MPa, but the same yield behavior with frictional sliding and inelastic strains seems to occur and allows the composite to deform to a higher stress level. The difference of "knee point" and failure stress between these two tests is probably due to a higher stiffness of the plies in the warp direction than in the weft direction. However, the first part of the non-linear behavior is always predicted until a strain around 1.5 %, which is already higher than the failure strain in the [0°] and [90°] directions.

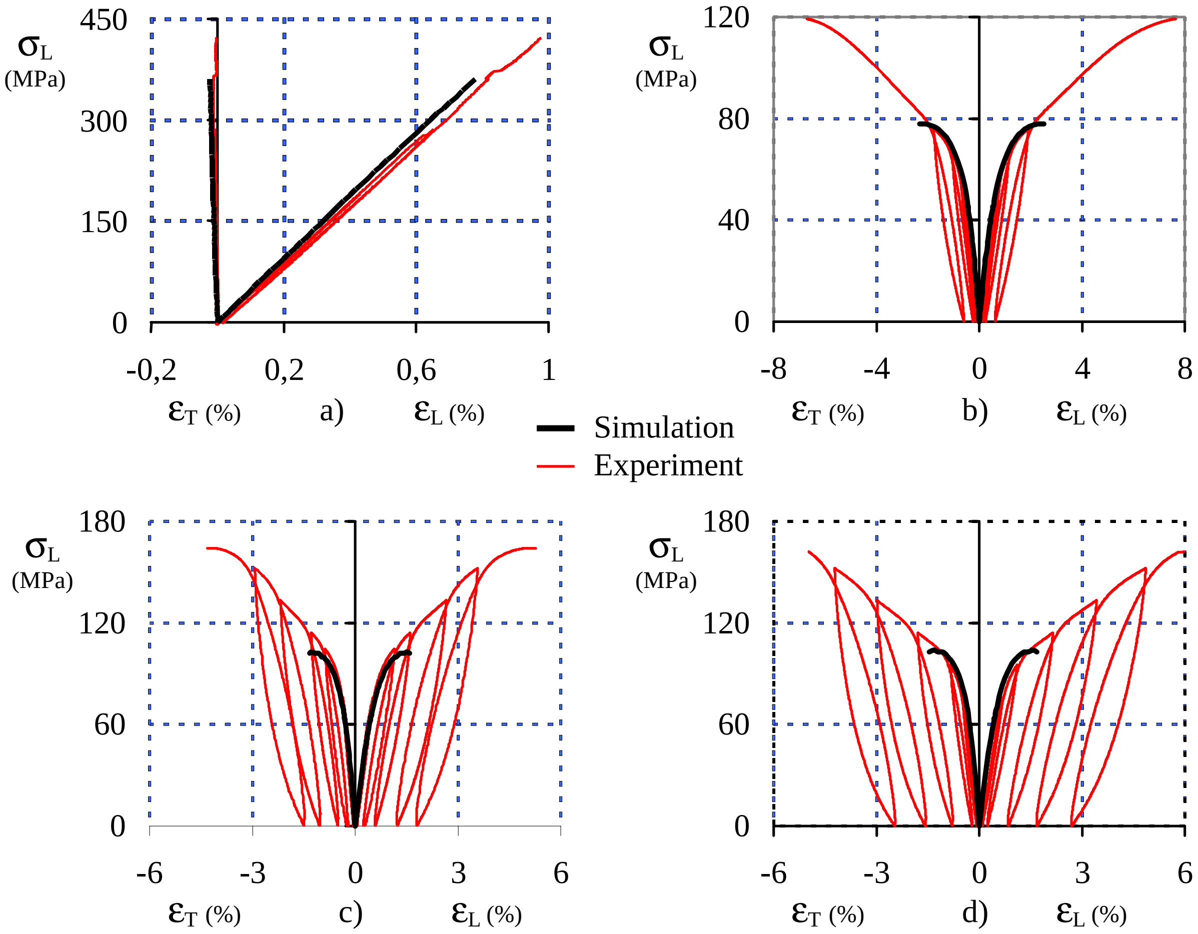


Fig. 5: Comparison between experimental and theoretical responses of tension tests: a) [90°], b) [45°], c) [22.5°], d) [67.5°],

CONCLUSIONS

The inplane mechanical behavior of the three-dimensional woven composite has been modeled as a laminate of two-dimensional damageable elementary plies. Moreover, an associated experimental procedure has been performed in order to identify the properties of the ply. The application of this approach led to the following conclusions:

- The model requires only two extra behavior laws, which are represented by the damage and the plastic master curves, to describe the non-linear behavior of the composite, and to quantify damage evolution.
- The experiments based on the standard tests for loading-unloading cycles enable a better understanding of the behavior of the composites.
- This simple approach already increases significantly the representation of the mechanical behavior of the composite up to failure.

Then, the damage theory is used as a tool for the analysis and the characterization of the three-dimensional composite. The results indicate that:

- The comparison of the [0°] and [90°] test responses seem to show that the waviness of the weft yarns affect the stiffness of the composite and enhance the strength in the weft direction.
- The damage behavior, observed on [45°] specimen, is enhanced by the through-the-thickness yarns that constrain the warp and weft yarns and cancel delamination.

- The validations performed on [22.5°] and [67.5°] specimens are successful if we consider the stress-strain curves up to the knee around 100 Mpa.

The first goal of this study was to present the damage theory through the use of a very simple model and its direct characterization.

This model is extremely simple compared to the potential of damage theory. The presentation of the model under this simple version allowed a direct characterization, otherwise a numerical fitting is necessary. The full modeling of the behavior of the composite requires a second damage variable in order to describe damage evolution in transverse tension.

This work will then be extended in this way.

ACKNOLEDGEMENTS

Tsu-Wei Chou thanks the partial support of the U.S. Air Force Office of Scientific Research Grant No. F49620-98-0384, Program Manager Major Brian Sanders.

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