MODELING OF THE BEHAVIOR OF WOVEN LAMINATED COMPOSITES UNTIL RUPTURE

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SUMMARY:
In order to model the behavior of woven composite materials, we adapted the models developed for unidirectional plies. The model used is non-linear with damage and residual strains. The behavior of woven plies in the longitudinal and transverse directions is elastic and brittle. We use only one damage variable to describe the loss of rigidity of the shear modulus. The residual strains concerned only shear strains. The identification of the model has been done on two tensile tests.
A code which makes it possible to simulate the woven laminate behavior was developed. Tests of validation which compare numerical results and experimental results have shown the relevance of the model.

KEYWORDS: woven fabric, continuum damage mechanics, progressive damage, structure analysis, characterization tests.

INTRODUCTION

Although they show lower mechanical characteristics than those of the unidirectional tapes, the composite materials with woven reinforcement allow an easier laying for non-developable surfaces. Moreover, their organization limits the development of intra laminar macro cracks.
An optimum use of laminates made up of woven plies requires a modeling of their behavior until rupture.
From ply characteristics, the classical models used for the laminate [1] apply without restriction in the case of woven orthotropic plies, if the assumption of linear elasticity is valid.
The modeling of the progressive degradation of the composite plies within a laminate is a problem less understood as it has to take into account their non-linear damageable behavior.

Many work have been devoted for damageable unidirectional plies but they are much more rare in the case of woven plies.
Harry and Massard [2] described a method based on the use of the Tsai-Wu quadratic criterion. Of a simple use this method however requires to know the characteristics of a unidirectional ply representative of the warp and fill of fabric considered. It does not make it possible to simulate the progressive damage of the woven ply.
The periodic geometry of the woven ply led several authors to use numerical homogenization by finite elements. Léné and Paumelle thus provided a detailed description of the state of stress in a woven ply [3]. Other authors introduced a progressive rupture [4], [5]. In an incremental analytical approach, Naik supplemented the diagram of stiffness reduction of Blackketter by a nonlinear behavior of the matrix and a modeling of the bending and cracking of the yarns [6].

Finally Aussedat, Thionnet and Renard introduced the continuum damage mechanics into an analytical method supplemented by a numerical method using the observation of the cracks on the edge of the woven ply coupons [7].

In the approach suggested here, the objective of the authors is to answer to industrial needs which have to introduce the behavior of woven ply reinforced laminate in structural analysis. This analysis is intended for complex structures that must undergo some extreme loads with a high degree of reliability. For that it is necessary, on the one hand, to limit the number of stage of calculation (each one being partner with a simplifying assumption) and, on the other hand, to base the modeling on simple characterization tests usually practiced in the industrial laboratory at a limited cost. Finally our model has to be as simple as possible in order to conserve reasonable calculating times for structures presenting a great number of degrees of freedom.

BEHAVIOR OF NON-LINEAR DAMAGEABLE WOVEN PLIES

Presentation of material and choice of the hypothesis

This study relates to a carbon/epoxy composite G802/914 (Hexcel-Brochier). Matrix 914 is a thougthned epoxy. The reinforcement is a carbon fabric of the four harness satin type, balanced in warp and fill. The warp and fill consist of 3000 filaments carbon yarns (Toray).
In the warp and fill directions the woven ply shows a linear elastic behavior in tension (see Fig. 1). The damage following these directions does not influence the behavior of the ply under uniaxial traction load. However a traction in the warp direction generates micro cracks of the matrix within the warp yarns and also within the fill yarns [7], [8].

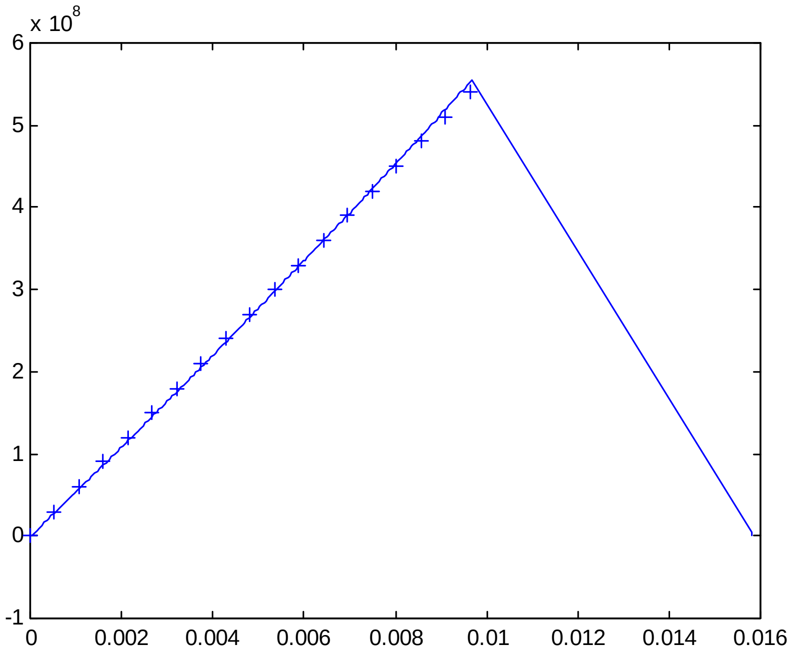

Fig. 1 : Evolution of the stress according to the strain for a tensile test on a $[0]_8$ laminate

For a loading in shearing one observes a reduction of the Coulomb modulus and residual strain (see Fig. 2). The decrease of this modulus is a consequence of the ply shear stress, but also of the stress in the fiber direction [8] that generate some matrix micro cracks within warp and fill yarns.
Up to now, the behavior in compression has not been experimentally studied, but, as for the unidirectional ply behavior, it is assumed to be brittle for the warp and fill directions.

The damage will be regarded as constant along the thickness of the ply. The plies will be regarded as homogeneous orthotropic. The residual strains observed will be represented by non-linear deformations. We will consider a state of plane stresses. Finally we will consider only small strains and displacements.

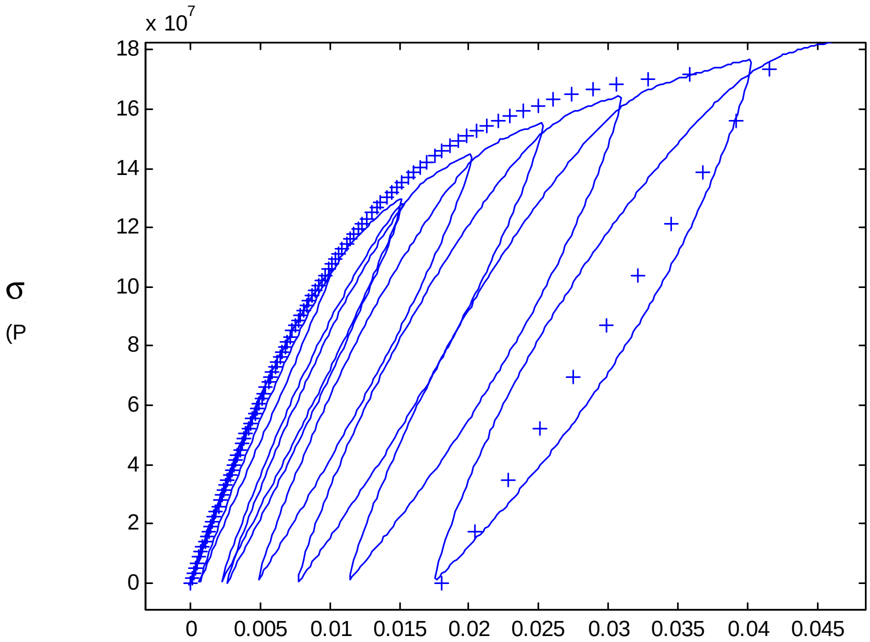

Fig. 2 : Evolution of the stress according to the strain for a tensile test on a $[45]_8$ laminate

Damage modeling for a woven ply

On the basis of continuum damage mechanics, models describing the physical progressive damage in unidirectional plies have been already proposed and validated by Ladevèze [9]. These models use a thermodynamic formalism where internal variables are associated to the decrease of the elastic moduli.
To model the behavior of the composites with woven reinforcement, we adapted the models quoted above.
The kinematics of the damage chosen uses three internal variables for damage (d_1, d_2, d_{12}) which are related respectively to the brittle fracture of fibers in the direction of the warp, the direction of the fill and the decrease of stiffness in shear. Under the assumption of plane stresses, we can write the strain energy of the woven ply in the following form:

$$E_D^{cp} = \frac{1}{2}\left[\frac{\langle\sigma_1\rangle_+^2}{E_1^0(1-d_1)} + \frac{\langle\sigma_1\rangle_-^2}{E_1^0} - 2\frac{\nu_{12}^0}{E_1^0}\sigma_1\sigma_2 + \frac{\langle\sigma_2\rangle_+^2}{E_2^0(1-d_2)} + \frac{\langle\sigma_2\rangle_-^2}{E_2^0} + \frac{\sigma_{12}^2}{G_{12}^0(1-d_{12})}\right] \tag{1}$$

Where $< . >_+$ is the positive part.

From this potential, we define the thermodynamic forces associated with the tension and shear internal variables d_1, d_2 and d_{12}:

$$\begin{aligned} Y_{d_i} &= \frac{\partial\langle\langle E_D^{cp}\rangle\rangle}{\partial d_i} = \frac{\langle\langle\langle\sigma_i\rangle_+^2\rangle\rangle}{2E_i^0(1-d_i)^2} \\ Y_{d12} &= \frac{\partial\langle\langle E_D^{cp}\rangle\rangle}{\partial d_{12}} = \frac{\langle\langle\sigma_{12}^2\rangle\rangle}{2G_{12}^0(1-d_{12})^2} \end{aligned} \tag{2}$$

Where << . >> is the average over the thickness.

The evolution of the internal variables depends on these thermodynamic forces, and more precisely on their maximum values during the history of the loading. In traction, the evolution of d_1 and d_2 is brutal in order to represent the brittle behaviors according to the warp and the fill directions.
To take into account the traction-shear coupling during the evolution of d_{12}, we define the equivalent thermodynamic force:

$$\underline{Y} = \alpha(\underline{Y}_{d_1} + \underline{Y}_{d_2}) + \underline{Y}_{d12} \qquad where \qquad \underline{Y}_{d_i}(t) = \sup_{\tau\le t}(Y_{d_i}(\tau)) \tag{3}$$

and α is the tension/shear coupling constant.
As for the unidirectional plies, we will take as first approximation a linear law of evolution for the damage variables with respect to the square root of Y. The coefficients of this evolution law are determined by a tensile test on the $[45]_n$ laminate for which the plies are loaded mainly in shear. The coefficient of coupling α can be determined by a test on the $[0]_n$ laminate subjected to a multiple loading path (traction then shearing). At first approximation it is also possible to determine α from the study of a [0/90] laminate made of unidirectional plies with the same components as the studied woven plies [10].

Modeling of the residual strains

After loading on a laminate, residual strains are observed. These strains can be linked to the plasticity of the matrix, but also to the phenomena of slip with friction between fibers and matrix due to the damage. We will describe this residual strains by a plastic hardening model. The coupling between the damage and plasticity is taken into account using the stresses and the effective strains [9]. The effective stresses and the effective strains are defined as:

$$\tilde{\sigma}_{12}\tilde{\varepsilon}_{12}^p = \sigma_{12}\varepsilon_{12}^p \qquad where \quad \tilde{\sigma}_{12} = \frac{\sigma_{12}}{(1-d_{12})} \quad and \quad \tilde{\varepsilon}_{12}^p = \varepsilon_{12}^p(1-d_{12}) \tag{4}$$

It is assumed that the stresses σ_1 and σ_2 do not influence the elastic field defined by:

$$f(\tilde{\sigma}_{12}, p) = |\tilde{\sigma}_{12}| - (R(p) + R_0) \tag{5}$$

where *p* is the indicator of cumulated plasticity and *R(p)* the hardening function chosen such as:

$$R(p) = Kp^{\gamma} \tag{6}$$

Using the consistency conditions, the evolution of the plastic strains rate is determined such as:

$$\dot{\tilde{\varepsilon}}_{12}^{p} = \dot{p}\frac{\partial f}{\partial \tilde{\sigma}_{12}} = \dot{p}\frac{\tilde{\sigma}_{12}}{R + R_0} \quad with \quad \dot{p} \geq 0 \tag{7}$$

The plasticity parameters are determined with a test on a $[45]_8$ laminate (see figure 2).

BEHAVIOR OF LAMINATED WOVEN PLIES UP TO EXTREME LOADS

Assumptions and progressive degradation for the laminate

We will use the model of the woven plies previously defined to obtain the behavior of a laminate. We chose to represent this behavior according to the assumptions of Love-Kirchhoff.

An incremental method is used where strains or stresses can be prescribed. For each increment, the stiffness matrix of the laminate, the strains and the stresses in each ply, are calculated using an iterative approach which stopped when damage convergence criterion and plasticity convergence criterion are reached.
A computer code (FatLam 3) to simulate the laminate behavior with woven plies at a point of a structure was developed [10]. This code also makes it possible to simulate the behavior of unidirectional plies [11].

Comparison with the experimental results

The code FatLam 3 makes it possible to analyse coupons subjected to a uniform loading. It was used for a first validation of the previously described modeling.
Several tests of validations were carried out on laminates loaded in traction ($[67.5]_8$, $[-20,+20]_{2s}$, $[0,45]_{2s}$). The comparison between the simulations carried out with FatLam 3 and the experimental recordings are satisfactory (for example see the figure 3).

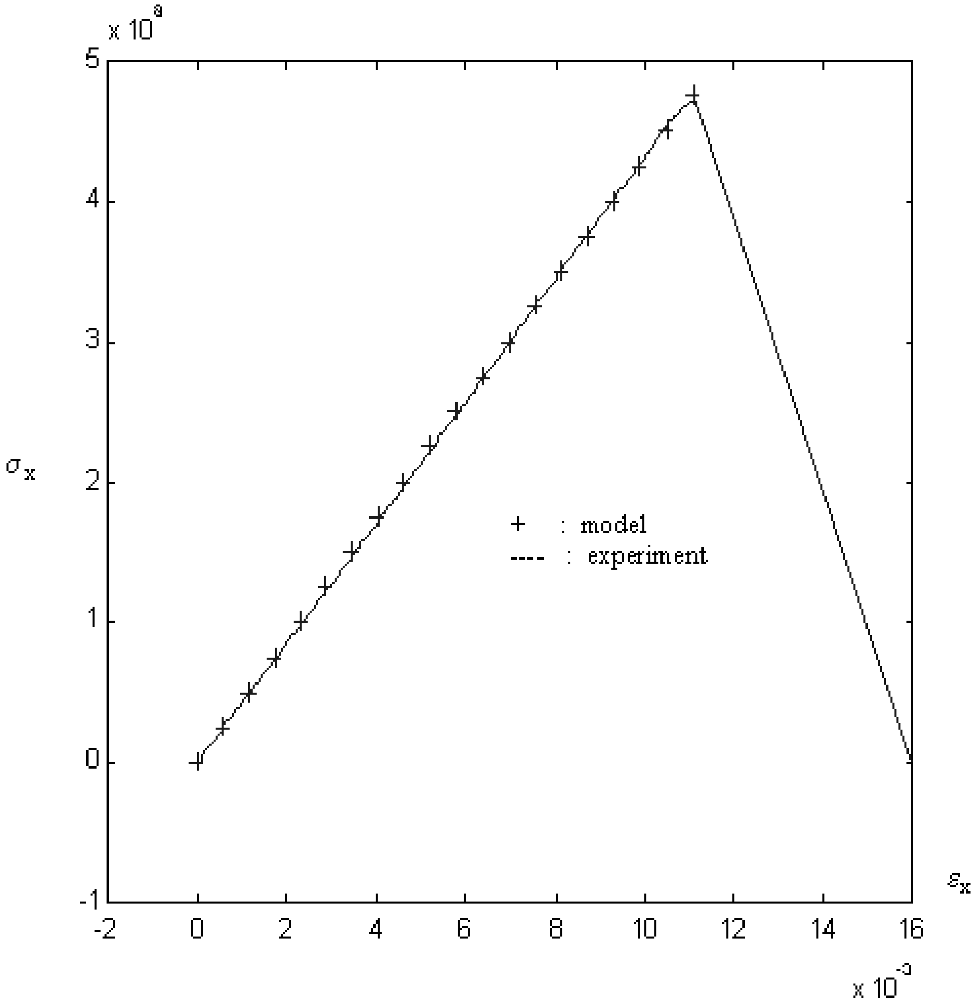

Fig. 2 : Evolution of the stress according to the strain for a tensile test on a [+20,-20]$_{2s}$ laminate

It should be noted that the modeling of the damage of the plies is sufficient to describe the rupture of the [-20, +20] $_{2s}$ laminate when this one is made of woven plies. We note thus that the difficulties due to the phenomena of delamination [12] met for unidirectional ply laminate do not appear here.

Application to a complex structural analysis

FatLam 3 allows a post processing of an elastic finite element analysis of a complex structure. This post analysis consists to use the code with the generalized loads in a single point as input data. The validity of this calculation is correct if the ultimate strains are not or very little different of that obtained with the elastic behavior. If the ultimate strains are different of those obtained by the elastic model, the analysis in a point is no more valid. It is then necessary to extend the zone of post-analysis. For that it becomes necessary to add the modeling suggested for the woven plies to a finite elements code.

CONCLUSION

The behavior until rupture of laminated composites made of unidirectional plies was extended here to woven plies. A non-linear damage model was defined and implemented. First validations were carried out and agree well with experimentation.

The model obtained uses only one damage variable with progressive evolution. This model is simple and could be easily used jointly with a finite element code and thus make it possible to solve optimization problems.

The characterization of the model uses classical industrial laboratory tests. The characteristics are obtained directly form these tests without complex calculation. These two points guarantee the maximum of reliability for the prediction of the behavior of structures up to extreme loads.
The model of this study does not depend explicitly on the constitution of the woven ply. If this constitution is changed, new tests of characterization are to be made. This model is thus not adapted for parametric studies intended to optimize the constitution of a woven ply. It is thus complementary to micro-mechanics models. The coupling of the model presented here and micro-mechanics models will allow a complete approach which could satisfy the needs of the material design and the requirements of the structural analysis.

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