A MULTISCALE PROGRESSIVE FAILURE CRITERION FOR COMPOSITE MATERIALS

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ABSTRACT

This paper presents a multiscale failure criterion for composite materials which permits to predict the failure of a laminate from elementary unidirectional ply data (behavior and strength). This kind of approach is predictive for difference stacking sequence and takes into account the effects of plies failure on macroscopic behavior, which is not possible with macroscopic failure criterion.

So, the present model allows to obtain a quite good approximation of the stress/strain curves and to predict the failure envelopes of multilayered composites under complex loading. For the first time to our acknowledge, the viscosity of the matrix has been introduced into the model to describe in a realistic way the mesocopic behavior. The failure criterion for the plies is based on Hashin's criterion [1.] and distinguishes two failure modes: fiber failure and inter-fiber failure mode. To describe the progressive failure of a laminate (ply after ply), a progressive degradation model has been developed. Finally, some results are presented and compared with test data which have been found in the literature [2.].

1. INTRODUCTION

Laminate composite materials are widely used in aerospace and automobile industries. Prediction of laminate composite failure is a key point for the design of engineering structures. Because of a lack of confidence into existing failure criteria, generous safety factors are applied for the analysis of composite structures. Thus, a great effort must be done in order to propose failure models based on physical approach and simple enough to be applied in a real application. It appears to be a hard scientific challenge.

Composite materials are characterized by their multiscale nature. Three main scales can be evidenced: (i) the microscopic scale (fiber and matrix scale), (ii) the ply scale, (iii) the composite laminate scale. It seems natural to use a multiscale approach to describe the failure mechanisms occurring at these scales.

Recently, in a World Wide Failure Exercise (WWFE) [2.], an important state-of-the-art method for the failure prediction of composites has been analyzed. Fourteen failure approaches were analyzed considering different test cases which were performed with different composite materials, representative stacking sequences, and complex loading conditions [3.]. This exercise was divided into two parts: (i) the authors had to make "*blind*" theoretical prediction of laminate's failure, and the results were compared with each other [4.], and (ii) an important collect of test data was realized in order to analyze the validity of the different approaches [5.].

The aim of this study is to develop a model for the determination of the final failure of the laminate from the strength of the unidirectional ply under plane stresses hypothesis and to validate this model with the WWFE tests data. The new global criterion is presented in section 2. The failure criterion used for each ply failure mode and the associated degradation model are presented in this section. Section 3 is devoted to the results and the comparison with experimental from WWFE. Finally, the last section is devoted to conclusion.

2. MULTISCALE FAILURE APPROACH

2.1. Principle of the approach

Multiscale criteria present two main advantages:

- The predictive aspect for different stacking sequences.

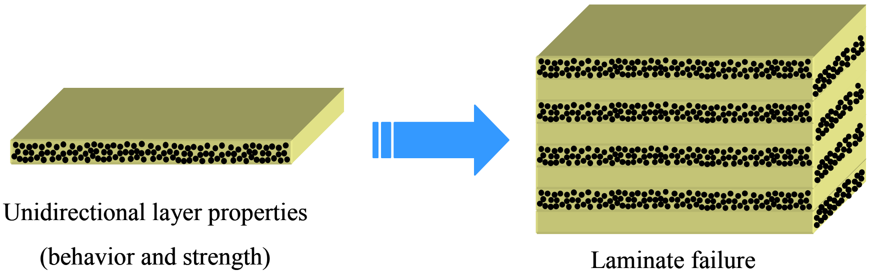


Fig. 1 : Predictive aspect

From the properties of the unidirectional ply (behavior and failure data), this kind of approach is theoretically able to predict the failure envelop of any laminate (Fig. 1) for every stacking sequence.

- Description / prediction of the progressive laminate's failure.

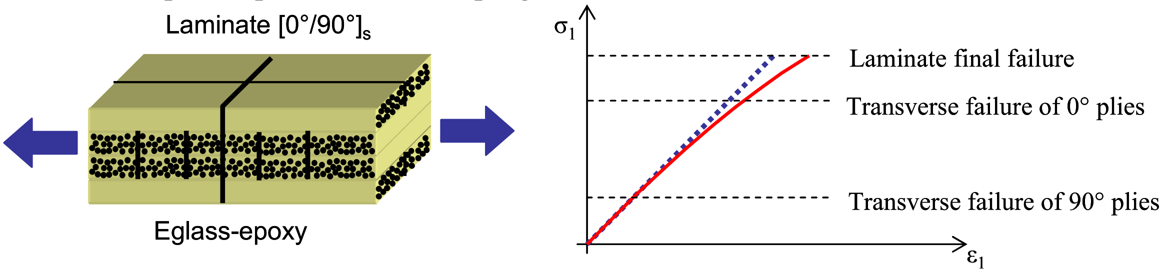


Fig. 2 : Progressivism of laminate's failure

The Fig. 2 illustrates the progressive failure in longitudinal tension of a $[0°/90°]_s$ E-glass/Epoxy laminate. The 90° plies break first, so its mechanical properties are degraded and the other plies are over-loaded. Nevertheless, the 90° plies still support a part of the loading due to load transfer between plies. At a higher macroscopic loading, the 0° plies fail in transverse tension (parallel to the loading) and finally break in longitudinal tension (fiber failure), leading to the final failure of the laminate. Taking into account the effect of the progressive failure on the macroscopic behavior (of a lamina) is a major difference with macroscopic failure criteria.

The present approach can be shared into four sub problems (Fig. 3).

- Choice of the mesoscopic behavior
- Definition of failure criterion for each ply
- Implementation of the degradation model of the ply in the laminate
- Definition of the laminate's failure

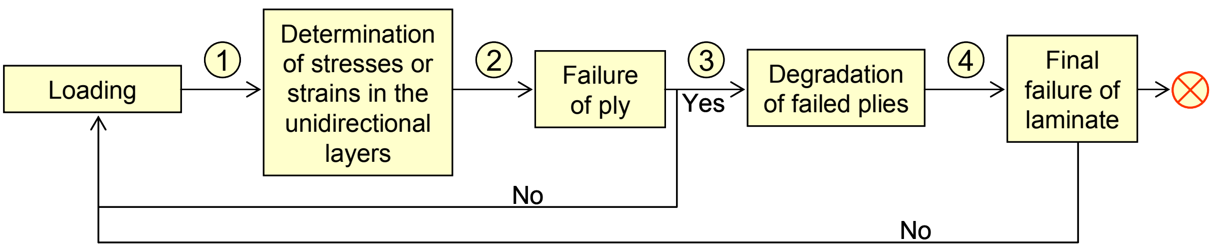


Fig. 3 : Algorithm for a progressive approach

2.2. *Mesoscopic behavior*

In order to predict a ply failure, it is necessary to have a good estimation of the load it carries and for this purpose to take into account a precise description of the mesoscopic behavior at the layer scale.

The simplest model should at least describe a thermo-elastic behavior [6.] to take into account the strong influence of residual stresses :

$$\sigma = C_0 : (\varepsilon^T - \varepsilon^{th}) \text{ With } \varepsilon^{th} = \alpha(T - T_0) \quad (1)$$

Where C_0 is the elastic rigidity tensor, ε^T the total deformation, ε^{th} the thermal strain, α the thermal tensor, and T_0 the stress free temperature.

The residual transverse stress can reaches 50% of the first ply failure strength for a $[0°/90°]_s$ laminate. Generally, they affect the first ply failure and further the relaxation (or overloading) of the other plies, thus influencing the whole progressive failure process.

Nevertheless, it is very difficult to estimate them in a correct way with a simple thermo-elastic behavior (this approach often overestimated residual stresses); we think that it would be better to measure them and to use these experimental stresses directly in the calculation.

Besides, the nonlinear aspect of the behavior mainly due to the viscosity of the matrix under shear loading is addressed. So, we have added a viscoelastic strain (ε^{ve}) into Eq. 2. which is calculated using a nonlinear viscoelastic spectral behavior developed at Onera [7.]. The main idea of this approach consists in decomposing the viscosity in a sum of elementary viscous mechanisms:

$$\sigma = C_0 : (\varepsilon^T - \varepsilon^{ve} - \varepsilon^{th}) \text{ With } \dot{\varepsilon}^{ve} = g(\sigma) \sum_{i=1}^{nb\_meca} \dot{\xi}_i \quad (2)$$

Each elementary viscous mechanism is defined by its relaxation time (τ_i) and its weight (μ_i). The weights are supposed to have a Gaussian form, so only few coefficients have to be identified (Fig. 4).

i ème elementary viscous mechanism :

$$\dot{\xi}_i = \frac{1}{\tau_i}(\mu_i g(\sigma) S_r : \sigma - \xi_i)$$

$$\tau_i = e^i \qquad \mu_i = \frac{1}{n_0\sqrt{\pi}} e^{-\left(\frac{i-n_c}{n_0}\right)^2}$$

Non linear function :

$$g(\sigma) = 1 + \gamma(\sqrt{\sigma : S_r : \sigma})^p$$

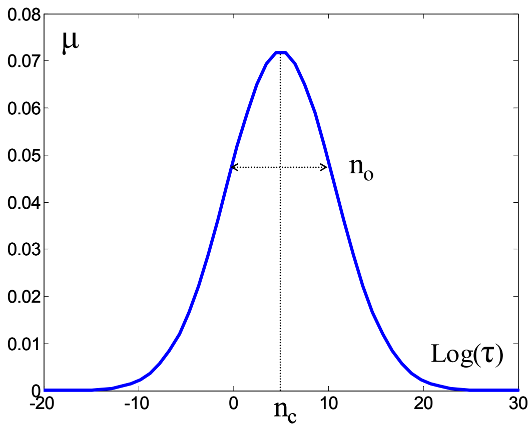


Fig. 4 : Viscous elementary mechanism equation

The composite materials (E-glass/Epoxy) or (Carbon/Epoxy) have a nonlinear viscosity behavior, and to describe this, a nonlinear function $g(\sigma)$ was introduced into the model.

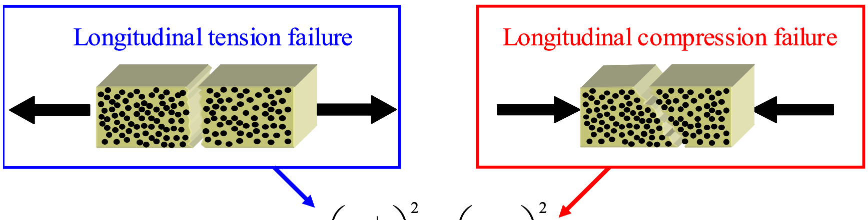
This model can describe creep and relaxation tests but also take into account the influence of the loading rate. If the composite is subjected to a global constant rate loading, the loading rate into each ply is different and not constant during the test (for $[\pm 55°]_s$ laminate by example). This is a major difference with models which describe the nonlinear behavior of ply with spline functions [8.] or polynomial forms [9.].

2.3. *Failure criterion*

Two independent failure modes [1.] are distinguished within the defined failure criterion: fiber failure and inter-fiber failure mode. Note that these two modes are decoupled, which is a common but very restrictive hypothesis that will be released in future work.

- <u>fiber failure mode</u> :

Two different mechanisms of failure are distinguished in this mode: tension failure and compression failure (due to micro-buckling of fibers) (see Fig. 5).



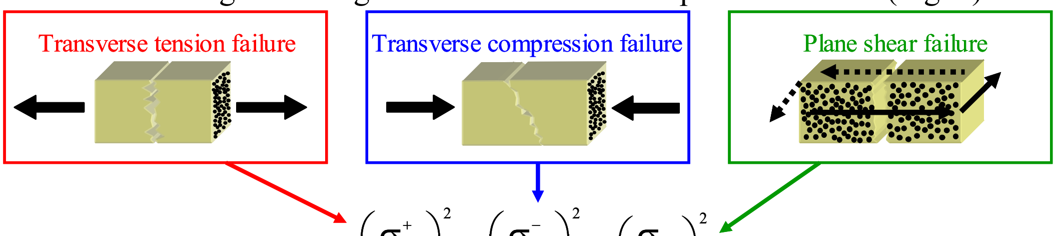
$$f_1 = \left(\frac{\sigma_{11}^{+}}{X_t}\right)^2 + \left(\frac{\sigma_{11}^{-}}{X_c}\right)^2$$

Fig. 5 : Fiber failure mode

Where X_t and X_c are respectively longitudinal tension and compression strengths.

- <u>Inter-fiber failure mode</u> :

Two mechanisms are again distinguished: tension and compression failure (Fig. 6):



$$f_2 = \left(\frac{\sigma_{22}^{+}}{Y_t}\right)^2 + \left(\frac{\sigma_{22}^{-}}{Y_c}\right)^2 + \left(\frac{\sigma_{12}}{S}\right)^2$$

Fig. 6 : Interfiber failure mode

Where Y_t, Y_c are respectively transverse tension and compression strengths, and S the plane shear strength.

Only five tests are necessary to identify this criterion (same number of tests than for the maximum stress criterion). Contrary to other quadratic approaches as Tsai-Wu [10.], the identification of this criterion doesn't need multi-axial tests, which are difficult to realize.

To conclude on the failure criterion, we have chosen a simple form which distinguishes two principal failure modes, where each term has a clear physical signification; moreover each term of this criterion is quite easy to identify.

2.4. *Degradation model*

Concerning the [0°/90°]$_s$ example, when the first ply fails (90° ply), its stiffness is progressively degraded and leads to a modification of the macroscopic behavior.
Therefore, a progressive degradation model has been introduced for each broken ply in the laminate:

$$S_{eff} = S_0 + d_1 H_1 + d_2 H_2 \quad (3)$$

Where S_0 is the elastic (initial) stiffness, d_1H_1 and d_2H_2 are tensors that represent respectively the effect of fiber failure and inter-fiber failure on the stiffness of the broken ply.

- Fiber failure mode

In the present approach, the kinetic of degradation due to fiber failure and its effects are distinguished:
The degradation's kinetic of the broken ply is defined as follows:

$$d_1 = \alpha\left\langle \sqrt{f_1} - 1 \right\rangle \text{ With < > are the McCauley bracket} \quad (4)$$

The fiber failure is usually catastrophic, leading to the final failure. In a practical manner, the calculation is stopped, so the coefficient α doesn't need an identification.
For the effect tensor of a fiber failure, the effect of a tension failure H_1^t and compression failure H_1^c are separated:

$$H_1 = \eta_1 H_1^t + (1-\eta_1) H_1^c \text{ with} \quad (5)$$

$$H_1^t = \begin{bmatrix} h_{11}^t S_{11}^0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & h_{66} S_{66}^0 \end{bmatrix}, \; H_1^c = \begin{bmatrix} h_{11}^c S_{11}^0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & h_{66} S_{66}^0 \end{bmatrix} \text{ and } \eta_1 = \begin{cases} 1 & si\,\sigma_{11} \geq 0 \\ 0 & si\,\sigma_{11} < 0 \end{cases} \quad (6)$$

η_1 is called activation index and represents the open (η_1=1), or closed cracks (η_1=0) effect.

- Inter-fiber failure mode

The degradation's kinetic of the broken ply is defined by:

$$d_2 = \beta\left\langle \sqrt{f_2} - 1 \right\rangle \quad (7)$$

The coefficient β represents the kinetic of degradation of a broken ply **in** a laminate, so its identification necessitates a test on a laminate.
As previously, the effect of transverse tension failure H_2^t, and transverse compression failure H_2^c are separated:

$$H_2 = \eta_2 H_2^t + (1-\eta_2) H_2^c \text{ with} \quad (8)$$

$$H_2^t = \begin{bmatrix} 0 & 0 & 0 \\ 0 & h_{22}^t S_{22}^0 & 0 \\ 0 & 0 & h_{66} S_{66}^0 \end{bmatrix}, \; H_2^c = \begin{bmatrix} 0 & 0 & 0 \\ 0 & h_{22}^c S_{22}^0 & 0 \\ 0 & 0 & h_{66} S_{66}^0 \end{bmatrix} \text{ and } \eta_2 = \begin{cases} 1 & si\,\sigma_{22} \geq 0 \\ 0 & si\,\sigma_{22} < 0 \end{cases} \quad (9)$$

The coefficients h_{22}^t (tension), h_{22}^c (compression), h_{66} of the effect tensors are determined with a micromechanical approach [11.] which is based on failure mechanics [12.] and no test is necessary for their identification.

It is important to note that this progressive degradation model takes into account the unilateralism of damage. This approach can simulate complex loading, including non proportional loadings.

2.5. Definition of the laminate failure

In aeronautic industry, the definition of laminate's failure is usually the first ply failure (which is very restrictive); for tank made of composite materials, this is the failure of all the plies (sealing criterion). An other definition of laminate's failure is a X% loss of rigidity in the loading direction (loss of functionality). Classically the laminate's failure occurs when fiber failures happen.

The definition of laminate's failure depends on the industrial application. In this paper, fiber failures (in tension and in compression) and also transverse compression failure have been considered as ultimate failure for the material.

3. MODEL/TESTS COMPARISON

The results obtained, using the present model, have been compared with the test results collected for the WWFE. All multi-axial tests are realized on composites tubes [5.], but the UD strengths are obtained on plate tests [3.]. For this exercise, the residual stresses have been neglected (as all other authors in the WWFE) because of a lack of confidence in the obtained value. The nonlinear viscoelastic model has been identified from the shear stress/strain curves obtained with UD tests [3.].

First, the failure criterion for a unidirectional ply is compared with experimental tests data:

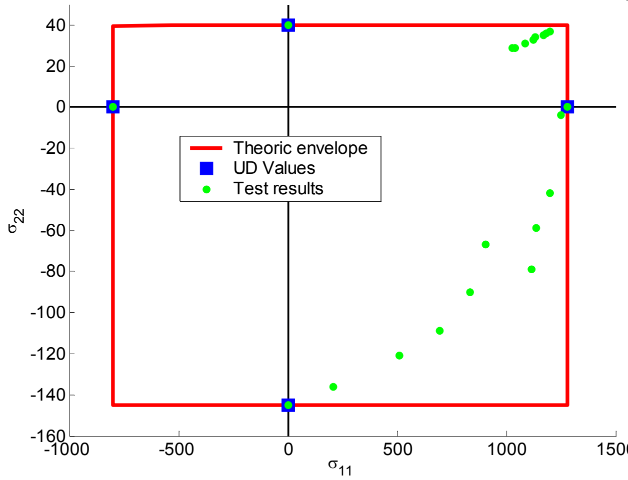


Fig. 7 : Failure enveloppe of UD in E-glass/MY750

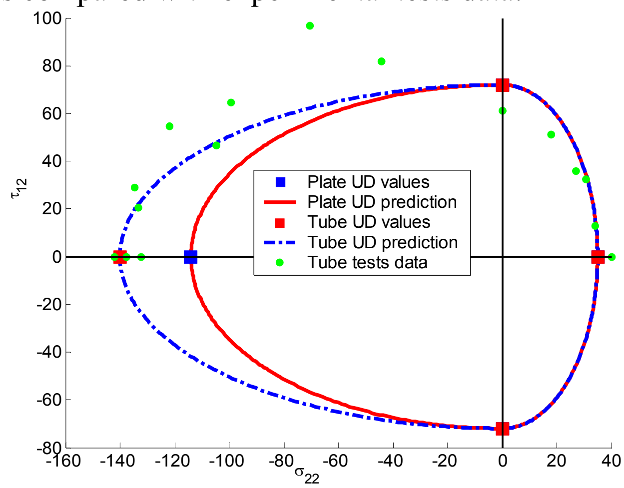


Fig. 8 : Failure envelope of UD in E-Glass/LY556

(Where points noted UD values have been used for the identification of the failure criterion).

On Fig. 7, the failure envelope of the E-glass/MY750 UD in the plane (σ_{11}, σ_{22}) is represented. There is an important coupling between longitudinal tension and transverse compression, probably due to Poisson effect. This coupling is actually neglected but this point is now under investigation.

The Fig. 8 presents the failure envelope of the E-glass/LY556 Epoxy UD in the plane (σ_{11}, τ_{12}). There is an important difference between the transverse compression strength of UDs if they have been measured on plate tests or on tube tests (because of the fabrication's processes which are very different). In this paper, the UD values have been identified on tube tests.

For limited compression and high plane shear loading, the composite seems to be more resistant. This phenomenon could be explained by micromechanics: the compression loading increases the load transfer capability of the fiber/matrix interface and retards the percolation of micro-damages which are due to shear loading. This kind of coupling is neglected here but will be introduced in the model quickly.

The UD failure criterion being identified and validated, it is now possible to predict stress/strain curves of multilayered composite and finally the failure envelopes of laminates.

The Fig. 9 presents the behavior (Σ_y / E_y and Σ_y / E_x) of a quasi-isotropic laminate (AS4/3501-6 Epoxy) subjected to a bi-tension $\Sigma_x : \Sigma_y$=1 : 2.

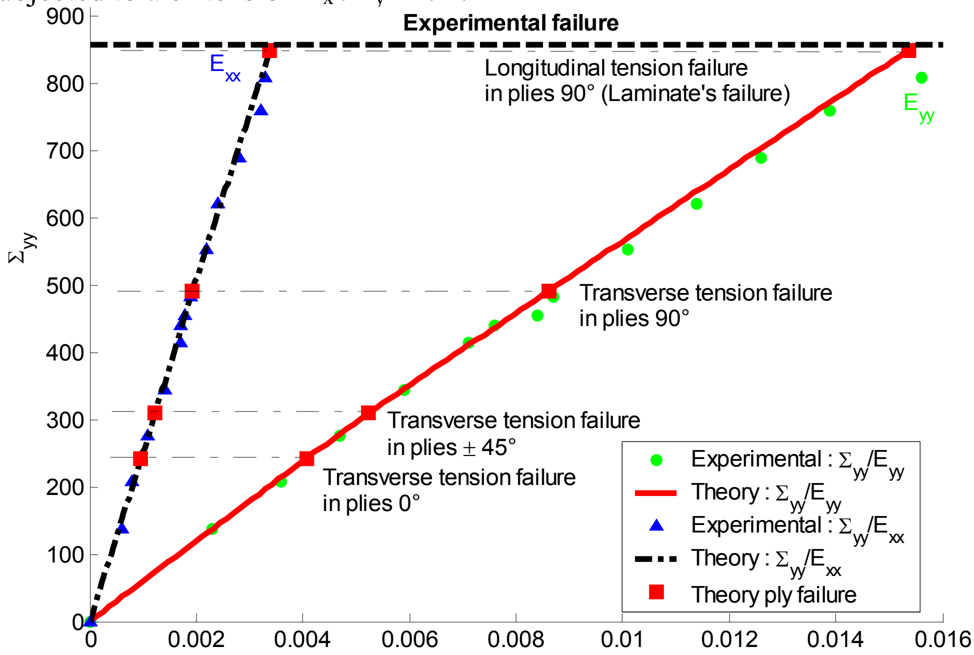


Fig. 9 : Behavior of Quasi-isotropic laminate in AS4/3501-6 Epoxy

Quasi-isotropic behavior being dominated by the behavior of the 0° layers, the macroscopic behavior could be considered as elastic. Nevertheless, viscosity has a quite important effect on the ±45° layers failure but also on first ply failure which occurs later than with an elastic behavior, (transverse stress being relaxed by viscosity).

The Fig. 10 shows the prediction of a $[\pm 55°]_s$ laminate behavior (Eglass/MY750 epoxy) subjected to a transverse tension $\Sigma_x : \Sigma_y$=0 : 1.

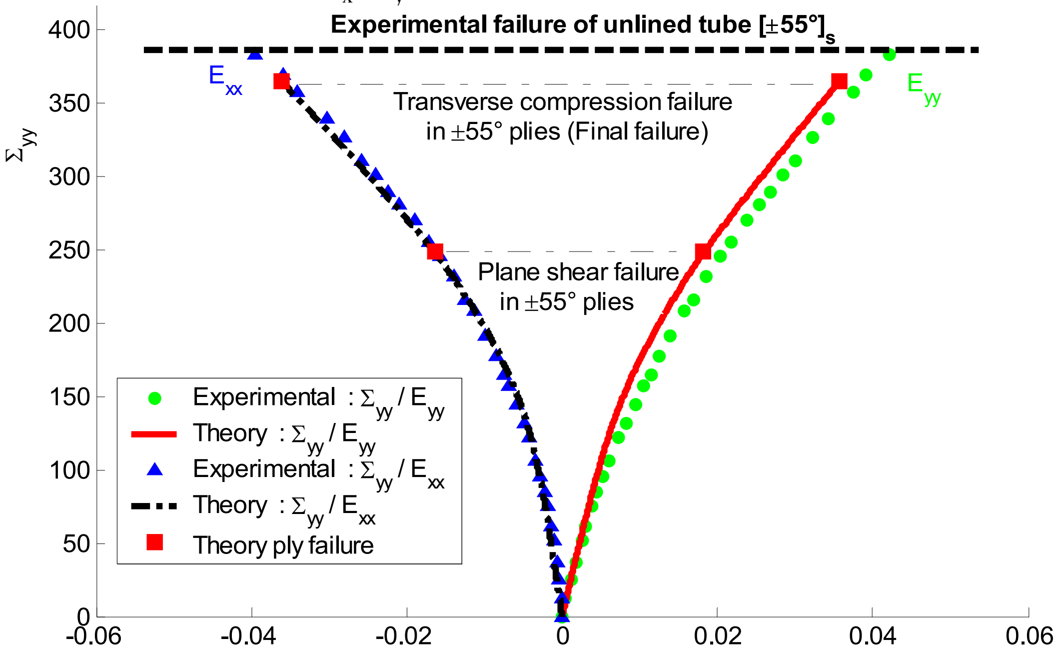


Fig. 10 : Behavior of [±55]s laminate in Elass/MY750 Epoxy

The experimental data are in good agreement with model and the prevision of the final failure is conservative. For this test case (and for all $[\pm\theta]_s$ laminates), it is essential to take into account the viscosity of the matrix which have an important effect on the failure sequence of the plies and also on the macroscopic behavior.

The Fig. 11 presents the failure envelope of a AS4/3501-6 Epoxy quasi-isotropic laminate in the plane stress (Σ_x, Σ_y).

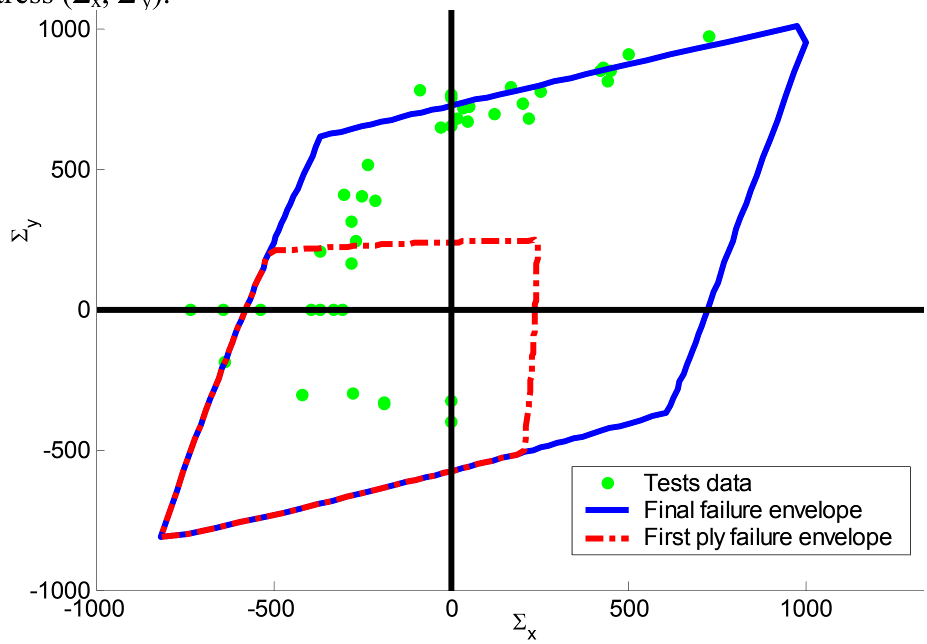


Fig. 11 : Failure envelope of quasi-isotropic laminate in AS4/3501-6 Epoxy

The model describes correctly the envelope in the bi-tension quadrant, but the predictions for bi-compression loading overestimate the failure. It is well known that the prevision of compression failure is still a challenge even on common laminates as quasi-isotropic ones.

A more original laminate was proposed in the WWFE, a E-glass/LY556 epoxy with stacking sequence $[90°/\pm30°]_s$. The Fig. 12 draws the failure envelope in the stress plane (Σ_x, Σ_{xy}):

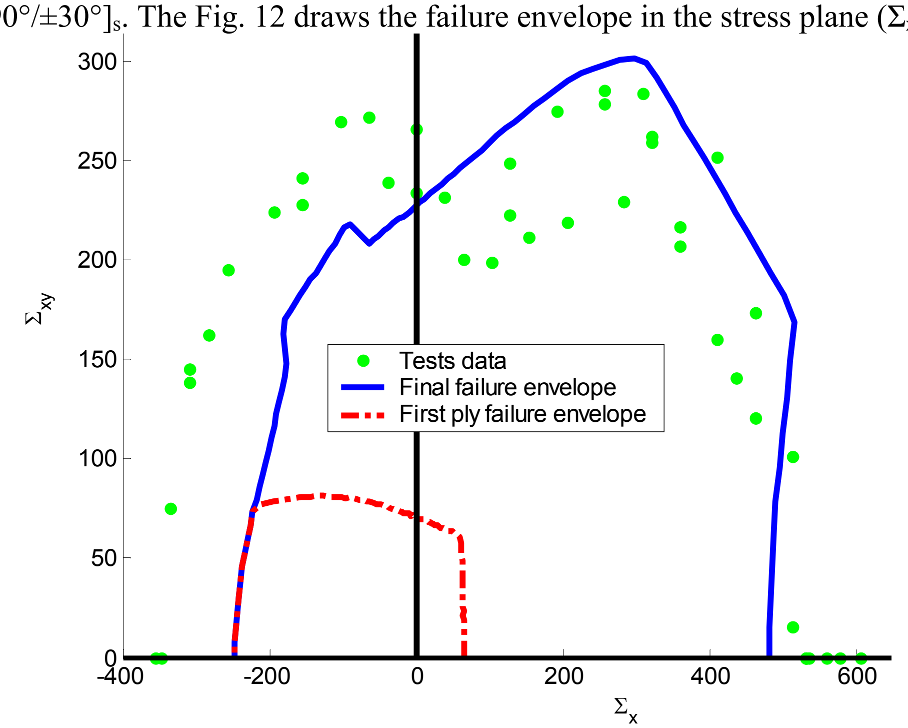


Fig. 12 : Failure envelope of [90°/±30°]s laminate in E-glass/LY556

Under a longitudinal tension (Σ_x:Σ_{xy}=1:0), this laminate fails due to a longitudinal compression failure of the 90° layers because of an important macroscopic Poisson effect. It is impossible for a macroscopic criterion to predict this kind of effect, longitudinal tension strength of the laminate being controlled by the longitudinal compression strength of the unidirectional ply.

CONCLUSION

The progressive multiscale approach, which is proposed in this paper, is able to predict macroscopic stress/strain curves and failure envelopes of laminates from properties of the unidirectional ply. Considering test cases provided in the WWFE, this model is as "mature" as other approaches [8.] [13.], especially on $[\pm\theta]_s$ laminate where effects of matrix viscosity are preponderant.

We are now improving the mesoscopic failure criterion. The coupling between longitudinal tension and transverse compression and the coupling between plane shear and transverse compression are under investigation.
The present approach is based on the plane stress hypothesis (WWFE hypothesis). The extension of this model for 3-D problems is also under investigation.

One of the main conclusions of the WWFE is the difficulty to describe the compression failure (longitudinal or transverse compression). This is a real challenge to reach this goal in the immediate future in order to propose a better analysis of composite materials failure.

ACKNOWLEDGEMENTS

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