Multiscale hybrid failure approach for strength analysis of composite structures subjected to complex 3D loadings

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SUMMARY

A micromechanical based hybrid mesoscopic approach is proposed to predict the failure of laminates under complex triaxial loadings, such as combined hydrostatic pressure and multiaxial in-plane loadings. The predictions of the proposed failure approach have been compared successfully on different tests cases found in the literature.

Keywords: Failure, Damage, Multiscale, Hydrostatic pressure.

INTRODUCTION

Due to their high specific properties, the use of fibre-reinforced composites has spread increasingly, over the past few years, for the conception of high performance structures in a large range of industrial applications. Nevertheless, due to the specific nature of composite materials, complex failure mechanisms occur and lead to a lack of confidence in the existing strength design tools and to high security margins that induce a loss of competitiveness of composite solutions. The capabilities of some existing multiscale failure approaches, to predict the final failure of laminates subjected to multiaxial in-plane loading, have been evaluated on different test cases defined in the framework of the first "World Wide Failure Exercise" (WWFE) [1]. A first attempt of multiscale progressive failure approach has been proposed by Onera and compared successfully on the different test cases proposed in the WWFE [2]. Nevertheless, the strength analysis of composite structures subjected to triaxial loadings, encountered in tapered specimens or in radius of corner L-angle specimens, or subjected to combined in-plane loading and hydrostatic pressure, remains a key problem in the design analysis.

Therefore, the aim of the present paper is to propose a multiscale Micromechanical based Hybrid Mesoscopic progressive failure approach which permits the determination of the final failure of laminates under complex triaxial loadings and especially under combined multiaxial in-plane loading and hydrostatic pressure.

This kind of approach permits to predict the final failure of laminate from the knowledge of the thermo-mechanical properties of the unidirectional (UD) ply and is thus predictive for different stacking sequences. This hybrid multiscale failure approach could be decomposed into five main steps: (i) the determination of the micro-damages within the UD ply which should affect the mesoscopic behaviour and strengths, (ii) the mesoscopic behaviour in order to estimate the stresses and strains at the ply scale, (iii) the failure criterion which permits to predict the ply failure, (iv) the damage modelling used to degrade progressively the mechanical properties of the failed ply inside the laminate until the final failure and (v) the method of change of scale from the UD ply to the laminate, available for 3D loadings. These five points are detailed in the following sections.

Then, the procedure of identification of the proposed modelling is presented and the different tests, which must be performed, are detailed.

In the last section, the predictions of the final failure of laminates subjected to multiaxial in-plane loadings are compared with experimental data provided in the first WWFE. Moreover, some simulations on laminates subjected to 3D complex loadings have been performed in order to insure the relevance of the proposed modelling.

PRESENTATION OF THE MULTISCALE HYDRID FAILURE APPROACH

Modelling of micro-damages within the UD ply

The main idea of the proposed hybrid multiscale failure approach consists in introducing, at the mesoscopic scale, the effects of failure occurring at the microscopic scale on the non linear behaviour and the strengths of the UD ply.

In order to model these micro-damages (μ_i), which could be fibre/matrix deboundings or cracks within the matrix, a damage law is proposed (in eq. 1 and 2) and depends on the elastic strain within the matrix (ε_m^e), obtained through a simple method of localization [3]. This scalar damage law assumes that the orientations of the cracks are imposed by the architecture of the material.

$$y_i = ({y_i^n}^{py} + a_{yi}{y_i^t}^{py})^{1/py} \quad with \quad \begin{cases} y_i^n = \frac{1}{2} C_{mii} {\varepsilon_{mi}^{e+}}^2 \\ y_i^t = \frac{1}{2} (b_i \, C_{mjj} {\varepsilon_{mj}^{e+}}^2 + b_i^p \, C_{mii} {\varepsilon_{mi}^{e+}}^2 \end{cases} \quad for \begin{cases} i = (2,3) \\ j = (4,5) \end{cases} \tag{1}$$

$$\mu_i = d_i^c \, (1 - e^{-\left(\frac{\left\langle \sqrt{y_i} - \sqrt{y_i^0} \right\rangle^+}{\sqrt{y_i^c}} \right)^{p_i}}) \quad with \quad \dot{\mu}_i \geq 0 \quad for \quad i = (2,3) \tag{2}$$

where C_m is the elastic stiffness of the matrix, ε_{mi}^{e+} the positive part of elastic strain tensor of the matrix, y_i the thermodynamical forces of the proposed damage law and $\langle\rangle^+$ are the Macauley brackets. The proposed modelling is thermodynamically consistent, takes into account the unilateral aspect and distinguishes the effects of opened micro-cracks from closed ones.

Mesoscopic non linear behaviour

In order to predict accurately the final failure of laminates, it is necessary to describe in a correct manner the non linear behaviour of the UD plies. A non linear thermo-viscoelastic behaviour, defined at the ply scale, is reported in eq. 3.

$$\sigma = \tilde{C} : (\varepsilon - \varepsilon^{th} - \varepsilon^{ve}) \quad with \quad \begin{cases} \varepsilon^{th} = \alpha (T - T_0) \\ \dot{\varepsilon}^{ve} = g(\sigma) \sum_i \dot{\xi}_i \quad and \quad \dot{\xi}_i = \frac{1}{\tau_i} \left(m_i g(\sigma) \tilde{S}_R^{UD} : \sigma - \xi_i \right) \end{cases} \tag{3}$$

$$g(\sigma) = 1 + \left(\frac{\langle \sigma_{eq} \rangle^{+}}{\sigma_0^{UD}} \right)^{p^{UD}} \quad with \quad \sigma_{eq} = \sqrt{{}^{t}\sigma : M_d^{UD} : \sigma} + c^{UD}\ tr(\sigma) \tag{4}$$

$$\tilde{S}_R^{UD} = S_R^{UD} + \sum_{i=2}^{3} \mu_i H_i^{ve} \tag{5}$$

Where σ is the mesoscopic stress, $\tilde{C}$ the elastic apparent stiffness, ε the total strain, ε^{th} the thermal strain (with α the dilatation tensor, T_0 the stress free temperature and T the temperature of the tests), ε^{ve} the non linear viscoelastic strain [4] (assumed to be the sum of the elementary viscous mechanisms (ξ_i) defined through their relaxation time τ_i and their weight m_i). The proposed viscoelastic law presents two different sources of non linearities. The first non linearity is inherent to the viscosity of the matrix (eq. 4) and described through the non linear function $g(\sigma)$. The equivalent stress (σ_{eq}) distinguishes a deviatoric (M_d^{UD}) and a hydrostatic part in order to take into account the effect of a hydrostatic pressure on the mesoscopic behaviour. It is worth mentioning that the parameters of the mesoscopic viscoelastic behaviour are inherited from the identified parameters of the viscoelastic behaviour of the matrix. The second non linearity (eq. 5) is due to the coupling between the micro-damages (μ_2, μ_3) and the viscous compliance ($\tilde{S}_R^{UD}$), thanks to the introduction of the effects tensors (H_i^{ve}).

Failure criteria of the UD ply

The predictions of the ply failure within a laminate is performed using a multi-criterion, based on Hashin's hypotheses [5], which distinguishes the ply failure in fibre mode ($f_1^{\pm}$), in in-plane interfibre mode ($f_2^{\pm}$) and in out-of-plane interfibre mode ($f_3^{\pm}$).

Failure criteria in interfibre modes

In the interfibre failure modes, the in-plane failure mechanisms are distinguished from the out-of-plane ones. Moreover, ply failure in tension and in compression are treated separately, as reported in the figure 1.

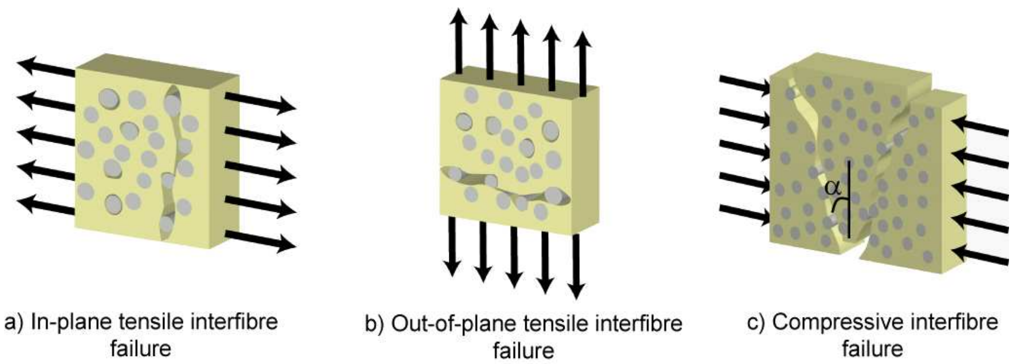

Figure 1: Interfibre failure mechanisms in tension (a, b) and compression (c)

The failure criteria for the in-plane tensile interfibre ply failure (f_2^{+}) and for the out-of-plane tensile interfibre ply failure (f_3^{+}) are stress criteria expressed in eq. 6.

$$f_i^+ = \frac{Y_{i+}^{eq}}{Y_{i+}^0} = 1 \quad with \quad \begin{cases} Y_{i+}^{eq} = {}^t\sigma : F^{i+} : \sigma \\ \widetilde{Y}_{i+}^0 = Y_{i+}^0 (1 - \mu_f) \end{cases} \quad and \quad \mu_f = 1 - e^{-\left(\frac{\left\langle \sigma_{11}^f - \sigma_1^{0f} \right\rangle^+}{\sigma_1^{cf}}\right)^m} \quad for \ \ i = (2,3) \tag{6}$$

$$\begin{cases} F_{22}^{2+} = \eta_2 / \widetilde{Y}_t^{\,2},\ F_{23}^{2+} = 1/\widetilde{S}_{23}^{\,2} \ et \ F_{12}^{2+} = 1/\widetilde{S}_{12}^{\,2} \\ the\ other\ components\ of\ the\ tensor\ F^{2+} are\ null \end{cases} \quad with \quad \begin{cases} \widetilde{Y}_t = Y_t^0 / (1 + h_{2t}\,\mu_2)^2 \\ \widetilde{S}_{23} = S_{23}^0 / (1 + h_{23t}\,\mu_2)^2 \\ \widetilde{S}_{12} = S_{12}^0 / (1 + h_{12t}\,\mu_2)^2 \end{cases} \tag{7}$$

$$\begin{cases} F_{33}^{3+} = \eta_3 / \widetilde{Z}_t^{\,2},\ F_{23}^{3+} = 1/\widetilde{S}_{23}^{\,2} \ et \ F_{13}^{3+} = 1/\widetilde{S}_{13}^{\,2} \\ the\ other\ components\ of\ the\ tensor\ F^{3+} are\ null \end{cases} \quad with \quad \begin{cases} \widetilde{Z}_t = Z_t^0 / (1 + h_{3t}\,\mu_3)^2 \\ \widetilde{S}_{23} = S_{23}^0 / (1 + h_{23t}\,\mu_3)^2 \\ \widetilde{S}_{13} = S_{13}^0 / (1 + h_{13t}\,\mu_3)^2 \end{cases} \tag{8}$$

$$with \ \ \eta_2 = \begin{cases} 1 \ \ si\ \sigma_{22} \geq 0 \\ 0 \ \ si\ \sigma_{22} < 0 \end{cases} \quad and \quad \eta_3 = \begin{cases} 1 \ \ si\ \sigma_{33} \geq 0 \\ 0 \ \ si\ \sigma_{33} < 0 \end{cases} \tag{9}$$

where F^{i+} are the associated failure tensors (eq. 7 and 8) and depend on the effective in-plane and out-of-plane tensile strengths ($\widetilde{Y}_t$ and $\widetilde{Z}_t$), and on the in-plane and out-of-plane shear strengths ($\widetilde{S}_{12}$, $\widetilde{S}_{13}$ and $\widetilde{S}_{23}$). These effective strengths are defined as function of the "virtual" mesoscopic strengths without any micro-damage (Y_t^0, Z_t^0, S_{12}^0, S_{13}^0 and S_{23}^0) and of the micro-damages (μ_2, μ_3) degrading the effective strengths.

The variables $\widetilde{Y}_{i+}^0$ (for i=2,3) represent the onsets of the failure tensile criteria and are defined as a function of the damage due to premature single fiber failure (μ_f).These premature fiber failures are due to a statistical effect on the fiber strengths and lead to fiber/matrix deboundings which facilitate the emergence of the first transverse crack in the UD ply.

The failure criteria for the in-plane compressive interfibre ply failure (f_2^- in eq. 10) and for the out-of-plane compressive interfibre ply failure (f_3^- in eq. 11) are energy criteria, expressed respectively in the fracture planes (3,2) and (2,3) making an angle $\pm\alpha$ with respect to the axis 2 and 3.

$$\max_{\pm\alpha}\left(g_n^{2-}\tau_n^{(3,2)\pm\alpha}\gamma_n^{(3,2)\pm\alpha}\right) + \max_{\pm\alpha}\left(g_t^{2-}\tau_t^{(3,2)\pm\alpha}\gamma_t^{(3,2)\pm\alpha}\right) = \widetilde{Y}_{2-} \quad if \quad \sigma_2 < 0 \tag{10}$$

$$\max_{\pm\alpha}\left(g_n^{3-}\tau_n^{(2,3)\pm\alpha}\gamma_n^{(2,3)\pm\alpha}\right) + \max_{\pm\alpha}\left(g_t^{3-}\tau_t^{(2,3)\pm\alpha}\gamma_t^{(2,3)\pm\alpha}\right) = \widetilde{Y}_{3-} \quad if \quad \sigma_3 < 0 \tag{11}$$

$$with \ \ \widetilde{Y}_{i-} = Y_{i-}^0 \frac{1 - \mu_f}{1 + h_{i-}(\mu_2 + \mu_3)} \quad for \ \ i = (2,3) \tag{12}$$

where $\tau_n^{(2,3)\pm\alpha}$, $\tau_t^{(2,3)\pm\alpha}$, $\gamma_n^{(2,3)\pm\alpha}$, $\gamma_t^{(2,3)\pm\alpha}$ and $\tau_n^{(3,2)\pm\alpha}$, $\tau_t^{(3,2)\pm\alpha}$, $\gamma_n^{(3,2)\pm\alpha}$, $\gamma_t^{(3,2)\pm\alpha}$ are respectively the normal and tangential shear stresses and strains in the fracture planes

(3,2) and (2,3) making an angle ±α with respect to the axis 2 and 3. The variables $\tilde{Y}_{i-}^{0}$ (expressed in eq. 12) represent the onsets of the failure compressive criteria and are defined as a function of the micro-damages (μ_2, μ_3) and of the damage due to premature single fiber failures (μ_f). The angles of the fracture planes in in-plane and out-of-plane interfibre compression are assumed to be equal to α=45° for the sake of simplicity. Moreover, it has been insured that the influence of the angle of the fracture plane (for instance, by using an angle α=53° as recommended by Puck [6]) remains limited on the final failure predictions.

Failure criteria in fibre mode

Again, it is an absolute necessity to distinguish the tensile failure mechanism from the compressive one in the fibre mode, as reported in figure 2.

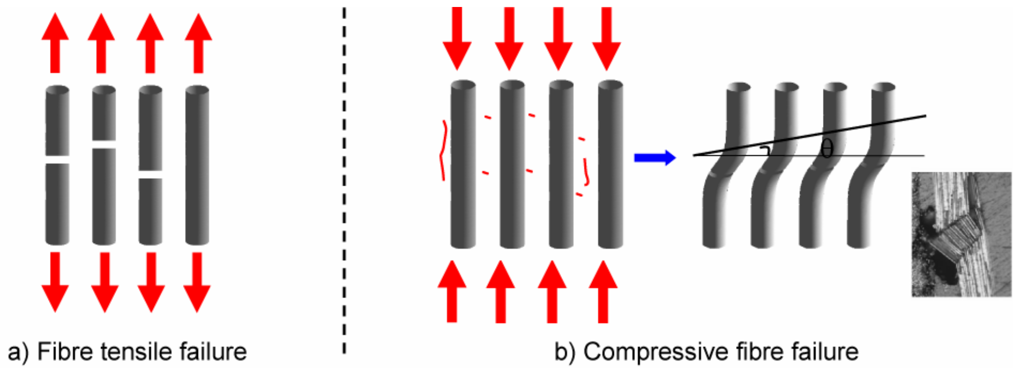

Figure 2: Fibre failure mechanisms in tension (a) and in compression (b)

The tensile fibre failure criterion (f_1^+) is a stress criterion expressed in eq. 13, where F^{1+} is the associated failure tensor (eq. 14) and depends on the longitudinal tensile strength of the UD ply (X_t^{UD}), on the strength of a dry fibre bundle (X_t^{yarn}) and on the micro-damages (μ_2, μ_3) within the considered UD ply.

$$f_1^+ = \frac{Y_{1+}^{eq}}{Y_{1+}^{0}} = 1 \quad with \quad \begin{cases} Y_{1+}^{eq} = {}^t\sigma : F^{1+} : \sigma \\ Y_{1+}^{0} = 1 \end{cases} \tag{13}$$

$$\begin{cases} F_{11}^{1+} = \eta_1 / \tilde{X}_t^{\,2} \quad with \quad \tilde{X}_t = X_t^{UD} e^{-h_{1t}(\mu_2+\mu_3)} + X_t^{yarn}(1 - e^{-h_{1t}(\mu_2+\mu_3)}) \\ \eta_1 = \begin{cases} 1 \quad si\ \sigma_{11} \geq 0 \\ 0 \quad si\ \sigma_{11} < 0 \end{cases} \quad and\ the\ other\ components\ of\ the\ tensor\ F^{1+} are\ null \end{cases} \tag{14}$$

Indeed, it has been experimentally demonstrated [7] that the effective longitudinal tensile strength of the UD ply depends on the state of degradation of the matrix. This coupling permits to obtain conservative final failure predictions, especially for Eglass/Epoxy composite materials.

The longitudinal compressive ply failure is due to the kinking of the fibres [8] (see figure 2b). The compressive fibre failure criterion (f_1^- reported in eq. 15) is an energy criterion, expressed in the fracture planes (1,i) for i=(2,3) making an angle ±θ with respect to the axis 1.

$$\max_{\pm\theta}\left(g_n^{1-}\tau_n^{(1,i)\pm\theta}\gamma_n^{(1,i)\pm\theta}\right)+\max_{\pm\theta}\left(g_t^{1-}\tau_t^{(1,i)\pm\theta}\gamma_t^{(1,i)\pm\theta}\right)=\widetilde{Y}_{1-}\quad for\quad i=(2,3) \tag{15}$$

$$\widetilde{Y}_{1-}=Y_{1-}^{0}\frac{1-\mu_f}{1+h_{1-}(\mu_2+\mu_3)} \tag{16}$$

where $\tau_n^{(1,i)\pm\theta}$, $\tau_t^{(1,i)\pm\theta}$, $\gamma_n^{(1,i)\pm\theta}$, $\gamma_t^{(1,i)\pm\theta}$ are respectively the normal and tangential shear stresses and strains in the fracture planes (1,i) making an angle ±θ with respect to the axis 1. The variable $\widetilde{Y}_{1-}^{0}$ represents the onset of the fiber failure compressive criterion and is as a function of the micro-damages (μ_2, μ_3) and premature fiber failures (μ_f) as proposed for the interfibre compressive criteria. The angle of the fracture plane in a UD ply under longitudinal compression is assumed to be equal to θ=45° for the sake of simplicity. It has been also insured that the influence of the angle of the fracture plane remains limited on the final failure predictions.

Degradation of the mechanical properties of the failed ply

The mechanical properties of a failed ply within the laminate, in interfibre modes, are progressively degraded until the final failure of the specimen. The proposed degradation modelling is based on damage laws developed at Onera [9], and consists in increasing the elastic compliance (S^0) as a function of the terms $d_2H_2^{eff}$ and $d_3H_3^{eff}$ describing respectively the effect of the in-plane and out-of-plane interfibre ply failure (eq. 17).

$$\widetilde{S}=S^0+\sum_{i=2}^{3}d_iH_i^{eff}\quad avec\quad d_i=\alpha_i\left\langle\frac{\sqrt{Y_i^{eq}}}{\sqrt{Y_i^{0}}}-1\right\rangle^{+}\quad et\quad \dot{d}_i\geq 0 \tag{17}$$

For each degradation mode, the kinetics of degradation (d_i) and their effects on the behaviour (H_i^{eff}) are distinguished. The proposed damage modelling is thermodynamically consistent, takes into account the unilateral aspect and distinguishes the effects of opened meso-cracks from closed ones.

Method of change of scales mesoscopic/macroscopic

In the present paper, because of the limitations of the classical laminate theory to in-plane loading, a 3D meso/macro change of scale method is proposed, based on the transformation field analysis method [10]. The relations which permit to determine the stress (σ_r) and strain (ε_r) of the r^{th} ply, from the knowledge of the stress (Σ) and strain (E) of the laminate are reported in the eq. 18.

$$\sigma_r=B_r:\Sigma-\sum_{s=1}^{n}F_{rs}:C_s:\varepsilon_s^{nl}\quad and\quad \varepsilon_r=A_r:E-\sum_{s=1}^{n}D_{rs}:\varepsilon_s^{nl} \tag{18}$$

where C_s is the elastic stiffness of the s^{th} ply, ε_s^{nl} a non linear strain (taking into account all the non linearities), A_r and B_r are the localization tensors of the r^{th} ply, D_{rs} and F_{rs} are the influence tensors and n is the number of plies constituting the laminate. The localisation and influence tensors are determined analytically through the knowledge of the elastic properties of the UD ply and by assuming that all the in-plane strains and out-of-plane stresses, expressed in the loading system, are the same in all the plies.

PROCEDURE OF IDENTIFICATION OF THE PROPOSED APPROACH

The proposed hybrid multiscale failure approach necessitates the identification of an important number of coefficients. Nevertheless, the number of parameters to be identified could be drastically reduced thanks to mechanical considerations, such as the assumption of transverse isotropy of the UD ply. A procedure of identification of the proposed hybrid failure approach has been established, by using few simple tests at the different scales of the problem: (i) at the matrix scale, a tension and compression test have to be performed to identify the parameters of the viscoelastic behaviour of the matrix, (ii) at the UD ply scale, a transverse compression test and an in-plane shear tests have to be performed to identify the parameters of the kinetics and of the effects on viscosity of the micro-damages, (iii) at the ply scale, the five classical uniaxial strengths of the UD ply permit to identify the "virtual" mesoscopic strengths and the effects of micro-damages on the strengths of the UD ply and finally (iv) at the laminate scale, a uniaxial tensile test has to be performed to identify the kinetics of mesoscopic degradation of the failed ply within the laminate.

Moreover, the progressive multiscale failure approach previously proposed [2], has been validated on test cases defined in the first WWFE and necessitates only few tests at the mesoscopic scale to be identified. Therefore, some simulations, on laminates subjected to multiaxial in-plane loading, have been used as results of "virtual testing" to identify some coupling terms between the different failure mechanisms in the present hybrid multiscale failure approach. All the parameters of the proposed hybrid failure approach have been identified from the tests results at the microscopic and mesoscopic scales provided by the organisers of the second WWFE [11] (see figure 3) and thanks to "virtual testing" simulated with the previous in-plane failure approach.

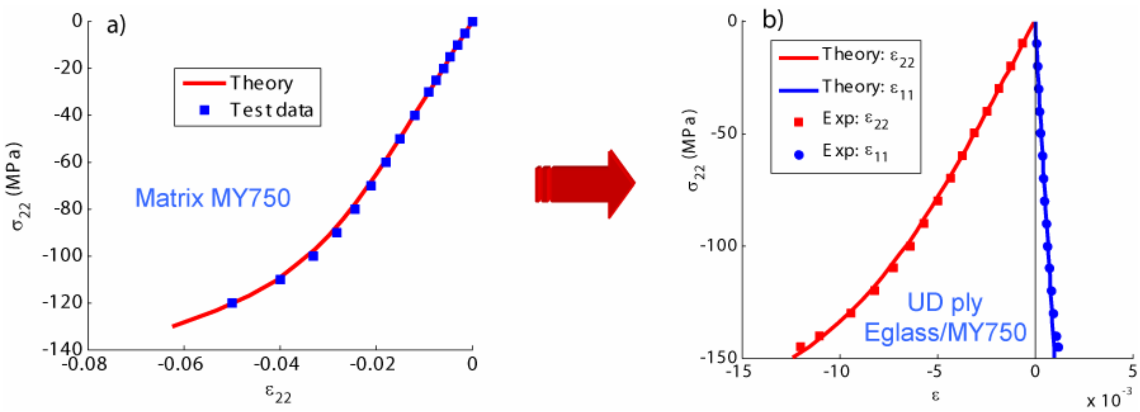

Figure 3: identification of (a) the parameters of the viscoelastic behaviour of the matrix thanks to a compression test and (b) the parameters of the micro-damage modelling thanks to a transverse compression test

COMPARISON WITH EXPERIMENTAL DATA

For laminated plates without geometrical singularities, the ply failure in fibre mode and in interfibre compressive modes are assumed to be catastrophic for the laminate. Moreover, an important loss of macroscopic rigidity (>50%) is also considered in the following as catastrophic, what is essential to predict final failure of $[\pm\theta°]_s$ laminates.

Comparisons with test results on laminates subjected to complex in-plane loadings

In order to evaluate the predictive capabilities of the proposed hybrid multiscale failure approach, some comparisons with test results provided in the first WWFE (laminates subjected to multiaxial in-plane loadings) have been performed.

The figure 4a presents the predicted mesoscopic failure envelope of a Eglass/MY750 UD ply in the stress plane (σ_{11}, σ_{22}) and the available experimental data [12]. The predicted failure envelope is in very good agreement with test results. The coupling between the different failure mechanisms is due to the effects of the micro-damages on the effective strengths of the UD ply.

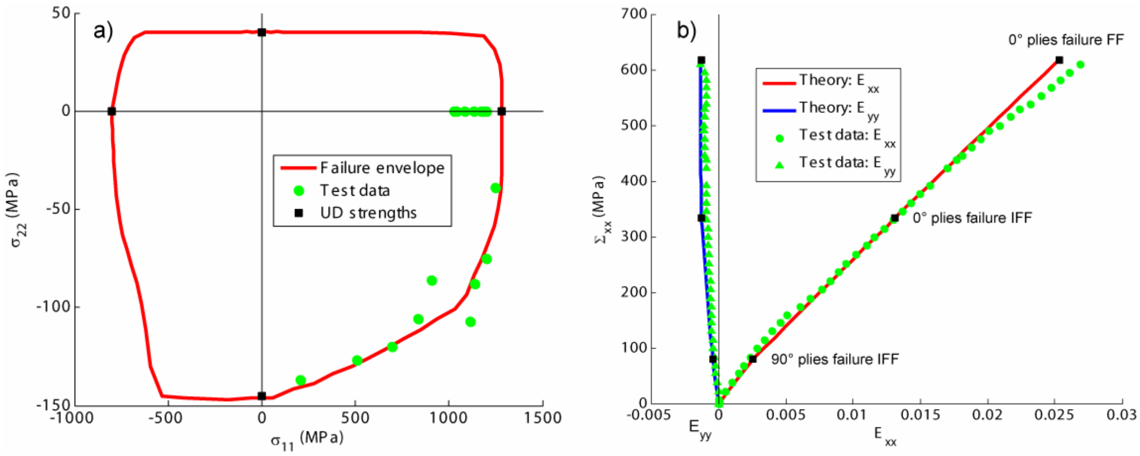

Figure 4: Comparisons between simulations and test results [12] on (a) the mesoscopic failure envelope of a Eglass/MY750 UD ply in the stress plane (σ_{11},σ_{22}) and on (b) the macroscopic behaviour up to the rupture of an Eglass/MY750 $[0°/90°]_s$ laminate subjected to uniaxial tensile loading

The figure 4b presents the predicted macroscopic behaviour of a Eglass/MY750 $[0°/90°]_s$ laminate subjected to a uniaxial tensile loading and the available experimental data [12]. The predicted macroscopic behaviour and the predicted sequence of ply failures are in very good agreement with test results. The coupling between the longitudinal tensile strength and the state of degradation of the matrix permits to obtain conservative predictions on this test case contrary to most of the evaluated failure approaches in the first WWFE [1].

Failure predictions of laminates subjected to complex 3D loadings

In this section, some simulations on UD plies and laminates, subjected to complex 3D loadings, have been performed in order to insure the relevance of the modelling.

The figure 5a presents the predicted influence of the hydrostatic pressure on the in-plane shear behaviour up to the rupture of a T300/PR319 UD ply. It is observed that (i) the hydrostatic pressure induces a decrease of the non linearity of the mesoscopic behaviour which tends to the elastic behaviour and (ii) that the effective in-plane shear strength increases with hydrostatic pressure which tends to delay the onset of micro-damages.

The figure 5b presents the predicted macroscopic failure envelope of a IM7/8551-7 $[0°/90°]_s$ laminate in the stress plane (Σ_{zz}, Σ_{yz}). An important reinforcement of the apparent out-of-plane shear strength is observed for combined out-of-plane compression and shear loading because the out-of-plane compression tends to delay the onset of the micro-damages within the UD plies. Moreover, it is also demonstrated that taking into account the thermal residual stresses (TRS) permits to obtain conservative predictions, especially for compressive loadings.

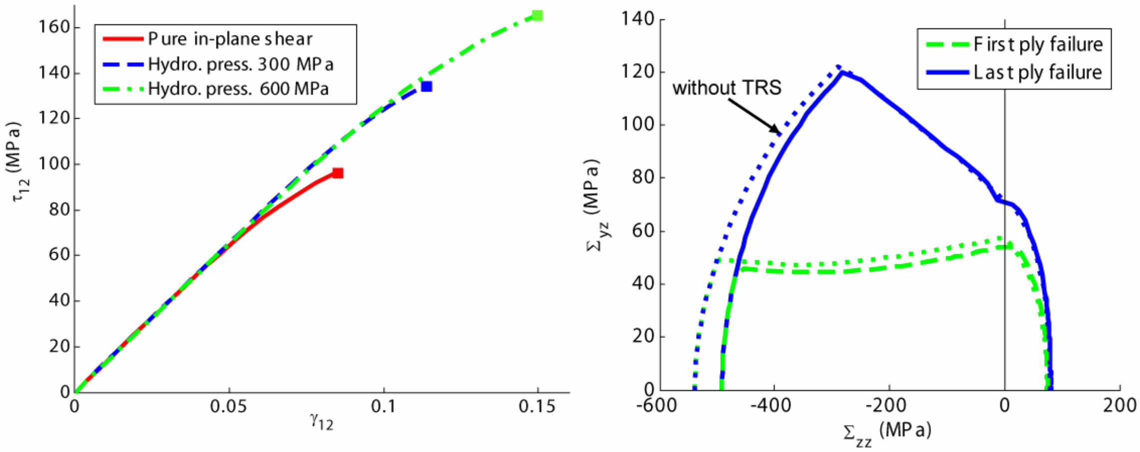

Figure 5: Simulations of (a) the behaviour of a T300/PR319 UD ply subjected to combined in-plane shear loading and hydrostatic pressure and (b) a macroscopic failure envelope of a IM7/8551-7 [0°/90°]$_s$ laminate in the macroscopic stress plane (Σ_{zz}, Σ_{yz})

CONCLUSIONS / PERSPECTIVES

An hybrid multiscale failure approach, which permits to predict the failure of laminates subjected to complex 3D loadings, has been proposed. The main idea of the proposed hybrid multiscale failure approach consists in introducing, at the mesoscopic scale, the effects of the failures occurring at the microscopic scale on the non linear behaviour (taking into account the viscosity of the matrix) and the strengths of the UD ply. The main improvement of the proposed approach is the introduction of the effects of the micro-damages on the strengths of the UD ply, which permits to obtain accurate predictions under complex multiaxial loadings.

The failure predictions of laminates subjected to multiaxial in-plane loading obtained with the present approach have been compared successfully with experimental data provided in the first WWFE. Moreover, some simulations on laminates subjected to complex 3D loadings have been performed in order to insure the relevance of the predicted mechanisms, such as the influence of the hydrostatic pressure on the mesoscopic behaviour and strengths.

For the second WWFE, an important amount of 3D test results has been collected by the organisators and decomposed in 12 test cases with 5 different composite materials [11]. The present hybrid multiscale failure approach has been proposed in the framework of this exercise [13], and the comparisons with experimental data, which should be performed soon, should permit to evaluate the predictive capabilities of the proposed approach.

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