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AN ADVANCED DAMAGE AND FAILURE APPROACH FOR STRENGTH PREDICTIONS OF AERONAUTICAL COMPOSITE STRUCTURES

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ABSTRACT

Although the use of fibre-reinforced composites has spread increasingly in the design of primary structures, the prediction of the behaviour and damage until the final failure of structure subjected to complex multiaxial loadings still remains a major problem in the design of composite parts. An advanced damage and failure approach, which permits to predict accurately the damage and failure of composite structures subjected to complex multiaxial 3D loadings, has been proposed. This approach has been compared successfully with test results on laminates subjected to multiaxial loadings extracted from the literature or performed at Onera. Moreover, finite element simulations on different structures subjected to complex loadings have also been performed to determine the predictive capabilities of such an approach.

1. 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 into the existing strength design tools and to high security margins that induce a loss of competitiveness of composite solutions. The successive World Wide Failure Exercises (WWFE) have aimed to make a state of the art on the predictive capabilities of existing approaches to predict (i) the behaviour and failure of different laminated composites subjected to in-plane multi-axial loadings (WWFE-I [1]), (ii) the strength analysis of structures subjected to triaxial loadings (WWFE-II [2]) and (iii) to predict accurately the damage (evolution of the crack density) until the final failure of the composite structure (WWFE-III [3]).

In the framework of the three World Wide Failure Exercises, an advanced damage and progressive failure Model [4,5] has been developed to predict in a correct manner the evolution of the crack density and the final failure of laminated composite structures subjected to 3D complex loading. 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 also describe accurately the effect of the damaged ply on the macroscopic behaviour and on the prediction of the final failure. Finally, this approach has been implemented into a finite element code in order to predict the strength of composite structures and especially the strength of open-hole plates subjected to tensile or compressive loadings. The main ideas of the proposed modelling, which permits to predict accurately the damage and the failure of laminates subjected to 3D complex loading, are reminded in the section 2. The section 3 is devoted to the comparisons between the predictions of the proposed approach - evolution of crack density and final failure of the laminate – and test

results available in literature [6] or performed at Onera. Finally, the damage and strength prediction obtained through finite element simulations on perforated laminated plates are also presented and discussed in this article.

2. MULTISCALE DAMAGE AND FAILURE APPROACH

The proposed multiscale damage and failure approach can be divided into five main parts: (i) the method of change of scale which permits determine from the 3D applied loading to the laminate, the strain field within the constitutive plies, (ii) the determination of micro-damages and their effects on the behaviour and strengths of the UD ply, (iii) the constitutive equations to determine mesoscopic stresses and strains, (iv) the failure criterion to predict the rupture of the different plies and (v) the damage model to estimate the evolution of the crack density and the associated local delamination within the laminate until the final fracture.

2.1 MODELING OF MICRO-DAMAGES WITHIN THE UD PLY

One of the main ideas of the proposed hybrid multiscale failure approach consists in introducing, at the mesoscopic scale, the effects of failure occurring at the microscopic scale (which could be fibre/matrix debondings or cracks within the matrix) on the non-linear behaviour and the strengths of the UD ply.

In order to model these micro-damages (δ_2, δ_3) observed within the ply, the proposed damage law depends on the elastic strain within the matrix (ε_m^e), obtained through a simple method of localization. This scalar damage law assumes that the orientations of the cracks are imposed by the architecture of the material. The proposed micro-damage modelling is thermodynamically consistent, takes into account the unilateral aspect and distinguishes the effects of opened micro-cracks from closed ones. The micro-damage variable (d_f) represents these premature fibre failures, due to a statistical effect in the fibre strength, leading to fibre/matrix debondings which facilitate the emergence of the first transverse cracks within the UD ply.

2.2 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. 1.

$$\underline{\underline{\sigma}} = \underline{\underline{\tilde{C}}} : (\underline{\underline{\varepsilon}} - \underline{\underline{\varepsilon}}^{th} - \underline{\underline{\varepsilon}}^{ve} - \underline{\underline{\varepsilon}}^p) \quad \text{with} \quad \underline{\underline{\tilde{C}}} = \underline{\underline{\tilde{S}}}^{-1} \quad (1)$$

where $\underline{\underline{\tilde{C}}}$ is the apparent stiffness which depends on the mesoscopic damages, $\underline{\underline{\sigma}}$ the stress, $\underline{\underline{\varepsilon}}$ the total strain, $\underline{\underline{\varepsilon}}^{th}$ the thermal strain, $\underline{\underline{\varepsilon}}^{ve}$ the viscoelastic strain and $\underline{\underline{\varepsilon}}^p$ the permanent strain. It is essential to take into account the thermal residual stresses in order to estimate accurately the first ply failure in a laminate. The viscoelastic model permits to predict accurately the failure of $[\pm\theta^\circ]_s$ laminates, to take into account the effects of the loading rate and to estimate the failure during creep or relaxation tests. The proposed viscoelastic law presents two different sources of non-linearities: (i) the first non-linearity is inherent to the viscosity of the matrix and is described through a non-linear function depending on an equivalent stress which distinguishes a deviatoric and a hydrostatic part in order to take into account the effect of a hydrostatic pressure on the mesoscopic behaviour and (ii) the second non-linearity is due to the coupling between the micro-damages (δ_2, δ_3) and the viscous compliance. Moreover, a permanent strain, describing the residual strain after unloading, has been introduced in order to describe more accurately the cyclic behaviour. This

permanent strain is a linear function of the evolution of the matrix micro-damages within the ply.

2.3 MESOSCOPIC FAILURE CRITERIA

The predictions of the ply failure within a laminate is performed using a multi-criterion, based on Hashin's hypotheses [7], 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).

2.3.1 Fibre failure criteria

In the fibre failure mode, ply failure in tension and in compression are treated separately. The tensile fibre failure criterion (f_1^+) is a maximal strain criterion expressed in Eq. 2, depending on the effective longitudinal tensile strain at failure of the UD ply (\tilde{X}_{α}^-), which is a function of the effective micro-damages (δ_2, δ_3). In fact, it has been experimentally demonstrated that the effective longitudinal tensile strain at failure 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.

$$f_1^+ = \eta_1 \frac{\varepsilon_{11}}{\tilde{X}_{\alpha}^-(\delta_2, \delta_3)} = 1 \quad \text{with} \quad \eta_1 = \begin{cases} 1 & \text{if } \sigma_{11} \geq 0 \\ 0 & \text{if } \sigma_{11} < 0 \end{cases} \quad (2)$$

The longitudinal compressive ply failure is due to fibre kinking. The compressive fibre failure criterion (f_1^-) could be considered as an energy criterion (reported in Eq. 3) expressed in the fracture planes (1, 2) or (1, 3). The variable \tilde{Y}_{1-}^0 represents the onset of the compressive fibre failure criterion (initially equal to 1) which depends on the micro-damages ($\delta_f, \delta_2, \delta_3$) within the ply. Again, the state of degradation of the matrix has a strong influence on the apparent compressive strength. The g_n^{1-}, g_t^{1-} are material parameters which have to be identified. It is worth mentioning that the coupling between the different failure mechanisms is due to the effects of the micro-damages on the effective strengths of the UD ply.

$$f_1^- = \frac{\text{Max}_{i=\{2,3\}} \left(\sqrt{g_n^{1-} (\sigma_{11} - \sigma_{ii})^2 + g_t^{1-} \tau_{ii}^2} \right) \cdot \varepsilon_{11}^-}{\tilde{Y}_{1-}^0} = 1 \quad (3)$$

2.3.2 Interfibre failure criteria

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. 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. 4.

$$f_i^+ = \frac{Y_{i+}^{eq}}{\tilde{Y}_{i+}^0} = 1 \quad \text{with} \quad \begin{cases} Y_{i+}^{eq} = \sigma : F^{i+} : \sigma \\ \tilde{Y}_{i+}^0 = Y_{i+}^0 (1 - \delta_f) \end{cases} \quad \text{for } i = (2,3) \quad (4)$$

$$\begin{cases} F_{22}^{2+} = \eta_2 / \tilde{Y}_t (\delta_2)^2, F_{23}^{2+} = 1 / \tilde{S}_{23} (\delta_2)^2 \text{ and } F_{12}^{2+} = 1 / \tilde{S}_{12} (\delta_2)^2 \\ F_{33}^{3+} = \eta_3 / \tilde{Z}_t (\delta_3)^2, F_{23}^{3+} = 1 / \tilde{S}_{23} (\delta_3)^2 \text{ and } F_{13}^{3+} = 1 / \tilde{S}_{13} (\delta_3)^2 \\ \text{the other components of tensors } F_{\approx}^{2+} \text{ and } F_{\approx}^{3+} \text{ are null} \end{cases} \quad (5)$$

where F^{i+} are the associated failure tensors (Eq. 5) and depends on the effective in-plane and out-of-plane tensile strengths (\tilde{Y}_t, \tilde{Z}_t), and on the in-plane and out-of-plane shear strengths ($\tilde{S}_{12}, \tilde{S}_{23}, \tilde{S}_{13}$). The matrix micro-damages (δ_2, δ_3) tend to decrease the apparent mesoscopic strengths. The onsets of the fibre failure criterion noted \tilde{Y}_{i+}^0 for $i=\{2,3\}$ are also function of the premature fibre failure (δ_f). The activation indexes η_i for $i=\{2,3\}$ permits to distinguish the failure in tension and in compression.

The failure criteria for the in-plane compressive interfibre ply failure (f_2^- in Eq. 6) and for the out-of-plane compressive interfibre ply failure (f_3^- in Eq. 7) 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.

$$f_2^- = \frac{\text{Max}_{\theta=\{-\alpha,+\alpha\}} \left(g_n^{2-} |\tau_n^{(3,2)\theta} \gamma_n^{(3,2)\theta}| + g_t^{2-} |\tau_t^{(3,2)\theta} \gamma_t^{(3,2)\theta}| \right)}{\tilde{Y}_{2-}^0} = 1 \quad \text{if } \sigma_2 < 0 \quad (6)$$

$$f_3^- = \frac{\text{Max}_{\theta=\{-\alpha,+\alpha\}} \left(g_n^{3-} |\tau_n^{(2,3)\theta} \gamma_n^{(2,3)\theta}| + g_t^{3-} |\tau_t^{(2,3)\theta} \gamma_t^{(2,3)\theta}| \right)}{\tilde{Y}_{3-}^0} = 1 \quad \text{if } \sigma_3 < 0 \quad (7)$$

where $\tau_n^{(2,3)\theta}, \tau_t^{(2,3)\theta}, \gamma_n^{(2,3)\theta}, \gamma_t^{(2,3)\theta}$ and $\tau_n^{(3,2)\theta}, \tau_t^{(3,2)\theta}, \gamma_n^{(3,2)\theta}, \gamma_t^{(3,2)\theta}$ are respectively the normal and tangential shear stresses and strains in the fracture planes (3,2) and (2,3) making an angle $\pm\alpha$ with respect to the axis 2 and 3. The onsets of the failure compressive criteria ($\tilde{Y}_{2-}, \tilde{Y}_{3-}$) depend on the micro-damages ($\delta_f, \delta_2, \delta_3$). $Y_{1-}^0, g_n^{1-}, g_t^{1-}$ and h_{1-} are material parameters. The angles of the fracture planes in in-plane and out-of-plane interfibre compression are assumed to be equal to $\alpha=45^\circ$ for the sake of simplicity.

2.4 TRANSVERSE CRACK MODELLING

The proposition of a damage law able to predict accurately the crack density and the associated local delamination rate is one of the major improvements introduced into the present multiscale damage and failure approach. These local delamination cracks have an important effect on the saturation of transverse cracking. This is the reason why, two damage variables are taken into account in the present model: $\bar{\rho}$ which is the normalized crack density (i.e. the crack density multiplied by the thickness of the considered ply) and $\bar{\mu}$ which is the delamination rate (i.e. the total length of local delamination cracks divided by the total length of the interface).

In order to develop a mesoscopic damage law, it is first necessary to identify the effect of the damage on the stiffness of the damaged ply. The identification of the effect of the damage (transverse cracks and associated local-delamination) is usually determined through finite element simulations performed on a unit cells. The effects of damage on the effective compliance tensor ($\Delta \tilde{S}(\bar{\rho}, \bar{\mu})$) are defined in the present model as reported in Eq. 8, where the effect tensors $H^{a,b,c,d,e}$ are diagonal and identified through the FE simulations.

$$\Delta \tilde{S}(\bar{\rho}, \bar{\mu}) = \bar{\rho} \cdot H^a + \frac{\bar{\mu}}{1-\bar{\mu}} \cdot H^b + \bar{\rho}^2 \cdot H^c + \bar{\rho} \cdot \frac{\bar{\mu}}{1-\bar{\mu}} \cdot H^d + \frac{\bar{\mu}}{(1+\bar{\rho}-\bar{\mu})^2} \cdot H^e \quad (8)$$

The damage kinetics are given by the Eq. 9, where h is the thickness of the ply, (y_I, y_{II}, y_{III}) are the thermodynamic forces depend on the effective compliance $\Delta \tilde{S}(\bar{\rho}, \bar{\mu})$, $(y_I^0, y_{II}^0, y_{III}^0)$ are the thresholds of the damage and $(\alpha_I, \alpha_{II}, \alpha_{III}, n)$ and (a, b) are material parameters and $\langle \cdot \rangle_+$ are the Macauley brackets.

$$\begin{cases} \bar{\rho} = h (1 - \bar{\mu}) \left[\alpha_I \langle y_I - y_I^0 \rangle_+^n + \alpha_{II} \langle y_{II} - y_{II}^0 \rangle_+^n + \alpha_{III} \langle y_{III} - y_{III}^0 \rangle_+^n \right] \\ \bar{\mu} = \langle a_h \bar{\rho}^2 + h b_h \bar{\rho} \rangle_+ \end{cases} \quad (9)$$

It is worth mentioning that the local delamination is an explicit function of the crack density. Moreover, the local delamination tends to slow down the kinetics of the transverse cracks until the saturation and permits to describe accurately the available experimental results, especially for the Eglass/Epoxy materials. It is worth mentioning that the kinetics of the transverse cracks and of the associated local delamination are linked to the thickness of the ply. It has been experimentally demonstrated that the threshold of the damage and the evolution of the crack density are a function of the thickness of the ply [8]. Experimental observations lead us to consider that the onset of transverse cracking needs to fulfil a mixed criterion based on the competition between a “stress” criterion and an “energy” criterion. Both conditions are complementary and necessary, and are reported in Eq. 10.

$$y_I^o = \max \left[\frac{y_I^{oE}}{h}, y_I^{o\sigma} \right], y_{II}^o = \max \left[\frac{y_{II}^{oE}}{h}, y_{II}^{o\sigma} \right] \text{ and } y_{III}^o = \max \left[\frac{y_{III}^{oE}}{h}, y_{III}^{o\sigma} \right] \quad (10)$$

where $(y_I^{oE}, y_{II}^{oE}, y_{III}^{oE})$ are the thresholds associated to the “energy” criterion which have to be identified (linked to the toughness of the materials) and $(y_I^{o\sigma}, y_{II}^{o\sigma}, y_{III}^{o\sigma})$ are the thresholds of the stress criterion which are the thermodynamical forces calculated when the in-plane interfibre criterion (f_2^+) is first fulfilled.

Finally, the degradation of the mechanical properties associated to the catastrophic failure mode (it means fibre failure and interfibre compressive failure) are function of the value of the different failure criteria (detailed in section 2.3) and the kinetics of these damage variables lead to softening behaviours (sudden and huge decrease of the mechanical properties of the failed ply).

2.5 STRENGTH PREDICTIONS OF COMPOSITE STRUCTURES

The present damage and failure approach has been implemented into the in-house finite element code ZeBuLoN, in order to predict the strength of composite structures subjected to bending or to predict the failure of open-hole plates subjected to tensile or compressive loadings with different diameters of the hole and different thicknesses of the constitutive plies. Between the plies, cohesive zone elements have been introduced between the different plies to describe the delamination. This model, based on [9], is defined with two criteria: a strength (σ_{max}) and a toughness (G_c). The original point of the proposed approach consist in the introduction of a coupling between the apparent strength of the interface ($\tilde{\sigma}_{max}$) and the local delamination rate $\bar{\mu}$ observed at the tips of the transverse cracks.

It is worth mentioning that in order to avoid localization problems, two different numerical methods have been selected among the existing approaches found in the literature: (i) the reformulation of the problem in a non-local framework associated with (ii) the introduction of a delay effect in the mesoscopic damage.

3. COMPARISONS WITH AVAILABLE EXPERIMENTAL DATA

The objective of the present study consists in proposing an approach able to predict the damage and the failure of laminated composite structures for the 39 test cases proposed in the framework of the three “World Wide Failure Exercises” for the 10 different materials (Eglass/Epoxy and Carbon/Epoxy). 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. The following comparisons with the available experimental data have permits to validate both the proposed approach and the associated identification procedure.

The first exercise WWFE-I was dedicated to the predictions of the failure of UD ply and laminates subjected to in-plane multiaxial loading. The proposed approach has already been validated through the comparisons with the experimental data [6]. The Figure 1.a presents the predicted mesoscopic failure envelope of an Eglass/MY750 UD ply in the stress plane (σ_{11} , σ_{22}) and the available experimental data [6]. 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. The Figure 1.b presents the predicted macroscopic behaviour of a Eglass/MY750 $[0^\circ/90^\circ]_s$ laminate subjected to a uniaxial tensile loading and the available experimental data [6]. 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].

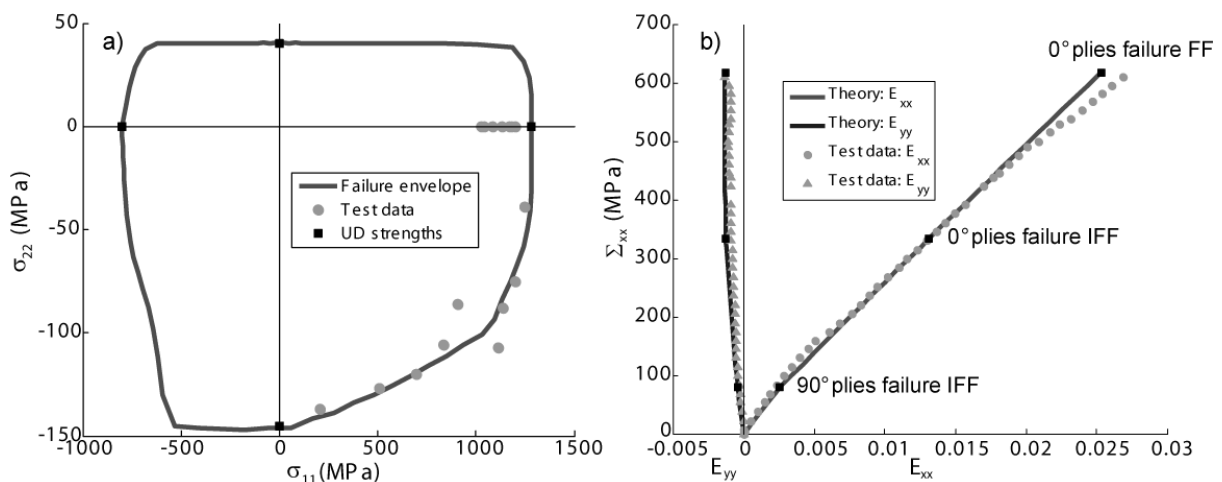


Figure 1: Comparisons between simulations and test results [6] on (a) the mesoscopic failure envelope of a Eglass/MY750 UD ply in the stress plane (σ_{11} , σ_{22}) and on (b) the macroscopic behaviour up to the rupture of an Eglass/MY750 $[0^\circ/90^\circ]_s$ laminate subjected to uniaxial tensile loading

The second exercise WWFE-II was dedicated to the predictions of the failure of UD ply and laminates subjected to (i) in-plane loading combined to hydrostatic pressure or to (ii) triaxial complex loading.

The Figure 2.a 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 2.b presents the predicted macroscopic failure envelope of a IM7/8551-7 $[0^\circ/90^\circ]_s$ laminate in the stress plane $(\sigma_{zz}, \sigma_{yz})$. 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.

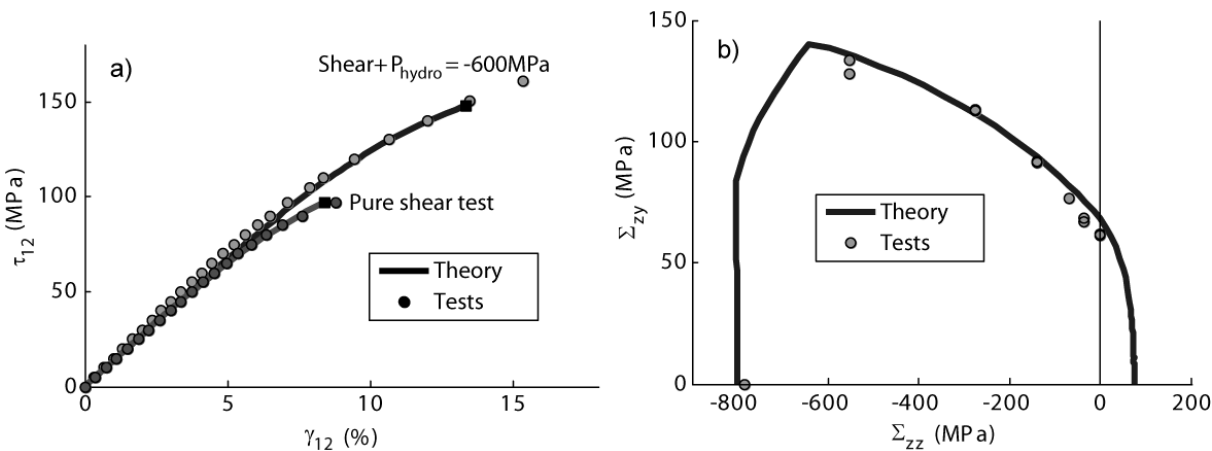


Figure 2. Comparisons between the test results and the simulations for (a) the behaviour of a T300/PR319 UD ply subjected to combined in-plane shear loading and hydrostatic pressure and for (b) the macroscopic failure envelope of a IM7/8551-7 $[0^\circ/90^\circ]_s$ laminate in the macroscopic stress plane $(\sigma_{zz}, \sigma_{yz})$.

The third exercise WWFE-III was dedicated to (i) the prediction of the evolution of the transverse cracks in laminate and their effects on the macroscopic behaviour until the final failure and (ii) to the strength prediction of composite structures (laminate plates subjected to four-point bending loading, or open-hole plate subjected to uniaxial tension and compression tests).

The Figure 3 presents a) the evolution of the normalized crack density as a function of the applied loading and b) the evolution of the length of the local delamination associated to the crack density on different T700GC/M21 laminates $[0_2^\circ/90_n^\circ/0_2^\circ]$ with $n=\{1,2,4,6\}$ subjected to uniaxial tensile loading. The test results performed at Onera [10], reported in Figure 3, are in good agreement with predictions of the present approach.

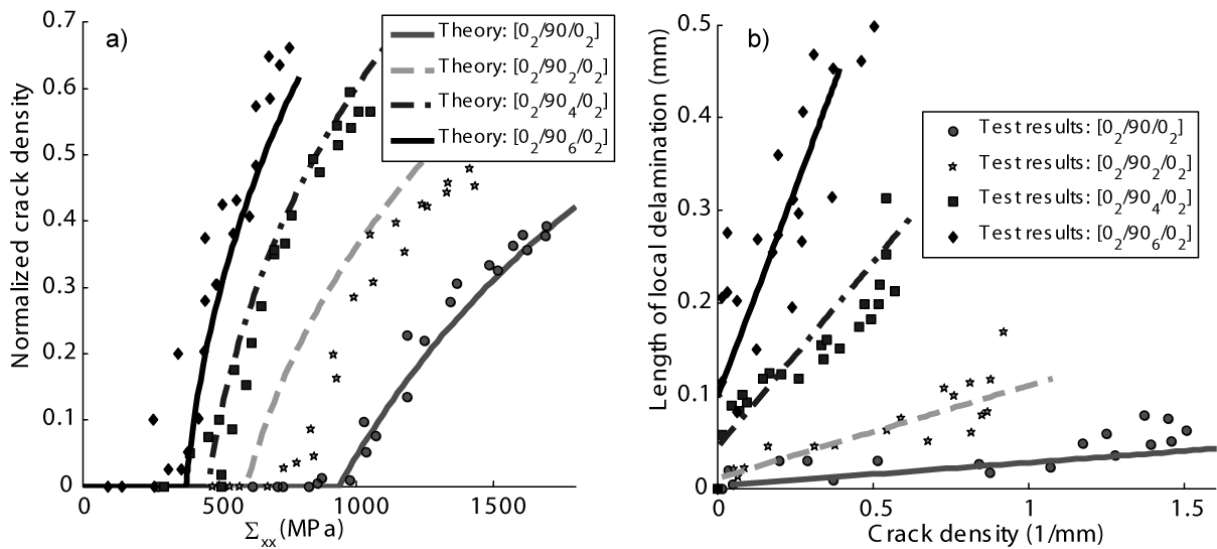


Figure 3. Uniaxial tensile tests on $[0_2/90_n]_s$ T700GC/M21 laminates with $n=(0.5, 1, 2, 3)$ a) measured and predicted normalized crack density in 90° ply as a function of the applied macroscopic stress and b) measured and predicted length of local delamination as a function of the crack density in 90° ply.

The predictions of the damage patterns and of the failure loads of IM7/8552 quasi-isotropic $[45_4/90_4/-45_4/0_4]_s$ open-hole plates with different diameters of hole have also been studied in the framework of the WWFE-III. Indeed, it is well known that composite structures can be weakened by the introduction of geometrical singularities such as holes, notches or cut-outs. Consequently, the strength analysis of high stress gradient parts of the structures still remains a key problem in the design of engineering structures.

The Figure 4 presents the damage pattern (transverse cracks and delamination) just prior the failure of the open-hole plate with a hole diameter equal to 3.175mm and subjected to uniaxial tension loading. A coupling between the transverse cracks and the delamination, experimentally observed, is accurately predicted with the proposed approach. Moreover, the proposed approach permits to obtain a damage pattern which is clearly oriented by the micro-structure of the composite laminates.

4. CONCLUSIONS / PERSPECTIVES

An advanced multiscale damage and failure approach, which permits to predict accurately both damage and the failure of laminates subjected to complex 3D loadings, has been proposed. The obtained predictions have been compared successfully with test results on laminates subjected to complex 3D loadings extracted from the literature or performed at Onera. Finally, this approach has been implemented in a finite element code to predict the strength of composite structures and the damage and failure predictions are promising.

The comparisons with experimental data, which should be performed soon in the framework of the WWFE-III, should permit to evaluate the predictive capabilities of the proposed damage and failure approach.

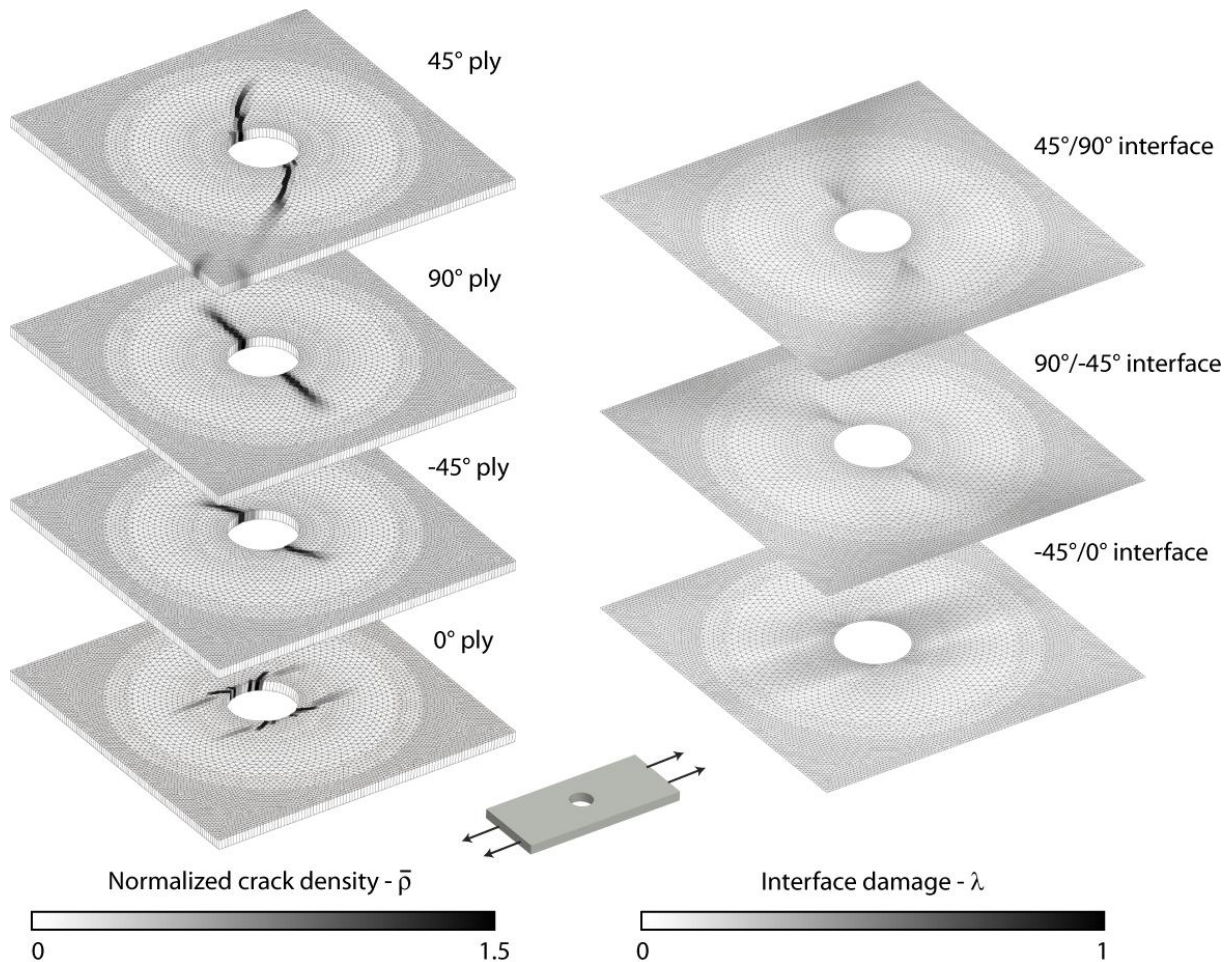


Figure 4. Patterns at failure load of in-plane mesoscopic damage in each ply and delamination at each interface in the $[45^\circ/90^\circ/-45^\circ/0^\circ]_s$ IM7/8552 open-hole plate with $d=3.175\text{mm}$.

While the complexity and the associated computational time of such an advanced damage and failure approach, the present modelling associated to a specific computational strategy can be currently used in industries as a help for the design of complex composite industrial structures. Indeed, the idea consists in using the present advanced approach to predict the failure of different simple test cases (such as open-hole plates, notched plates subjected to multiaxial loadings ...) and thus to generate a virtual test data basis. This virtual data basis, as a complement of an existing experimental test campaign, can improve the identification / fit of existing semi-empirical approaches currently used in design offices. Finally, these fast computational semi-empirical approaches can predict the strength of complex composite structures representative of industrial problematic without being fitted against large test campaigns, permitting thus to reduce the time of development and the associated cost of innovative and competitive composite components.

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