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Combined Experimental and Modeling Approaches for Strength Analysis of 3D Woven Composites: From Elementary Coupons to Complex Aeronautical Structures

New generations of 3D woven composite materials have been recently developed to be used in aeronautics as an alternative to the classical laminated composite materials, for structures exposed to impact. Therefore, it has been necessary to determine precisely the damage and failure scenarios for such materials subjected to different kinds of loadings through a large experimental testing campaign performed at ONERA on unnotched coupons. These tests have been multi-instrumented to understand the different damage and failure mechanisms encountered in 3D woven composite materials. Based on these observations, a model, named ONERA Damage Model for Polymer Matrix Composites (ODM-PMC), has been developed specifically for such materials. This non-linear material approach takes into account the different observed sources of non-linearity (viscoelasticity of the matrix, in–plane matrix damage, inter-yarn debondings and fiber yarn failures) and has been validated through comparisons with available tests on unnotched specimens. Moreover, the predicted failure loads, obtained with the ODM-PMC model, on plates containing different kinds of geometrical singularities, such as a hole or a milled groove, have been compared successfully to multi-instrumented test results also performed at ONERA. Finally, the ODM-PMC model has been applied to large 3D woven composite structures, quite representative of real industrial components. The predicted damage and failure scenarios seem to be relevant as compared to data available in the literature. Moreover, the obtained computational times are compatible with usage in an industrial environment. Therefore, it has been demonstrated that this approach, implemented in a commercial finite element code, could be used in design offices in aeronautical industries.

Introduction

Some critical components of aircraft structures, such as center wing box, wings or fuselage, are nowadays manufactured from laminated composite materials, owing to their high specific mechanical properties. However, these materials are particularly sensitive to low-velocity/energy impact events, such as dropped tools, which induce a strong decrease in the residual strengths after impact. Therefore, due to the poor impact resistance of classical laminated composite materials, 3D woven composites have been recently developed to be used in industrial applications [1] exposed to impact. It has been demonstrated experimentally [2-6] for different kinds of loadings that the damage and failure mechanisms are strongly linked to the local architecture of these composite materials and are very different from those observed in classical laminated composites. Due to very attractive mechanical properties of the new generations of 3D woven composites, such materials are taken into consideration in order to manufacture some large components in aeronautics, possibly exposed to impact. These composite structures present a complex geometry, including some geometrical singularities which induce locally severe stress gradients. Moreover, these composite structures could be subjected to a wide range of multiaxial loadings, such as combined bending/tensile/compressive loadings.

The massive use of finite element simulations is an absolute necessity in order to efficiently design innovative 3D woven composite structures. This article deals with the development of a physically-based damage and failure approach developed specifically for 3D woven composite materials. Therefore, this material approach allows an accurate description of the different damage and failure mechanisms observed in elementary coupons subjected to different loadings; moreover, the resulting model has to be transferable and easy to use in design offices to predict the strength of large composite components, representative of industrial applications.

In order to improve the understanding of the damage and failure mechanisms encountered in new generations of 3D woven composites [7-9], a large testing campaign has been performed at ONERA. Simple coupons have been subjected to off-axis tensile, compressive and bending loadings, complementary to those already presented elsewhere [2-6]. These tests have been multi-instrumented, in order to establish the damage and failure scenarios for the different loading conditions under consideration: tension, compression, and bending. The ONERA Damage Model for Polymer Matrix Composite (ODM-PMC), specifically developed for 3D woven composite structures under static loadings, is briefly presented. Only the main ideas of the model are reminded. Some comparisons with the available experimental data on unnotched specimens are presented and the predictive capabilities of the model are discussed. Then, one of the objectives of this study is to evaluate the predictive capabilities of this material model on academic composite structures, containing geometrical singularities inducing stress gradients, such as holes or notches. Then, the multi-instrumented tests performed at ONERA on open-hole plates or notched specimens subjected to compressive loading are presented and the results are compared with the strength predictions of the ODM-PMC model, implemented in a commercial finite element code. Finally, this model is applied to a potential industrial component, to demonstrate the capabilities of this approach to be used in a design office in aeronautical industries.

Box 1 - Studied material

The material under investigation is a highly unbalanced 3D woven composite material consisting of carbon fiber yarns (48K) embedded in an epoxy matrix. Based on the generic architecture reported in Figure 1 [10], the studied 3D woven composite material has been optimized in order to prevent large delamination after impact and thus to obtain a good impact resistance (the exact architecture of this material is, however, confidential as requested by the manufacturer). The thickness of the tested material is about 9.5 mm, which is rather thick compared to classically studied laminates or other 3D woven composites. It should be noted that the Representative Elementary Volume of such a material is rather large (a few centimeters) as compared to other composite materials and thus prohibits the use of existing testing standards, and necessitates alternative designs of the testing samples even for the elementary coupons.

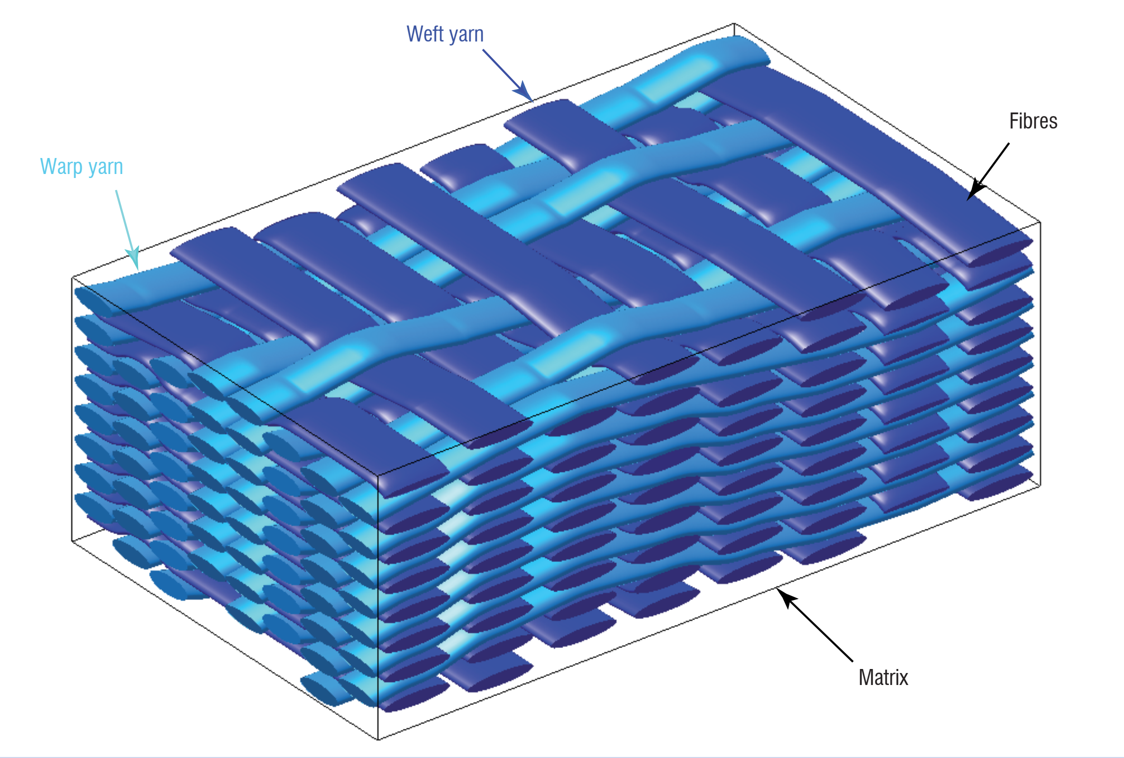


Figure B1-01 – Generic architecture of an unbalanced 3D woven composite material.

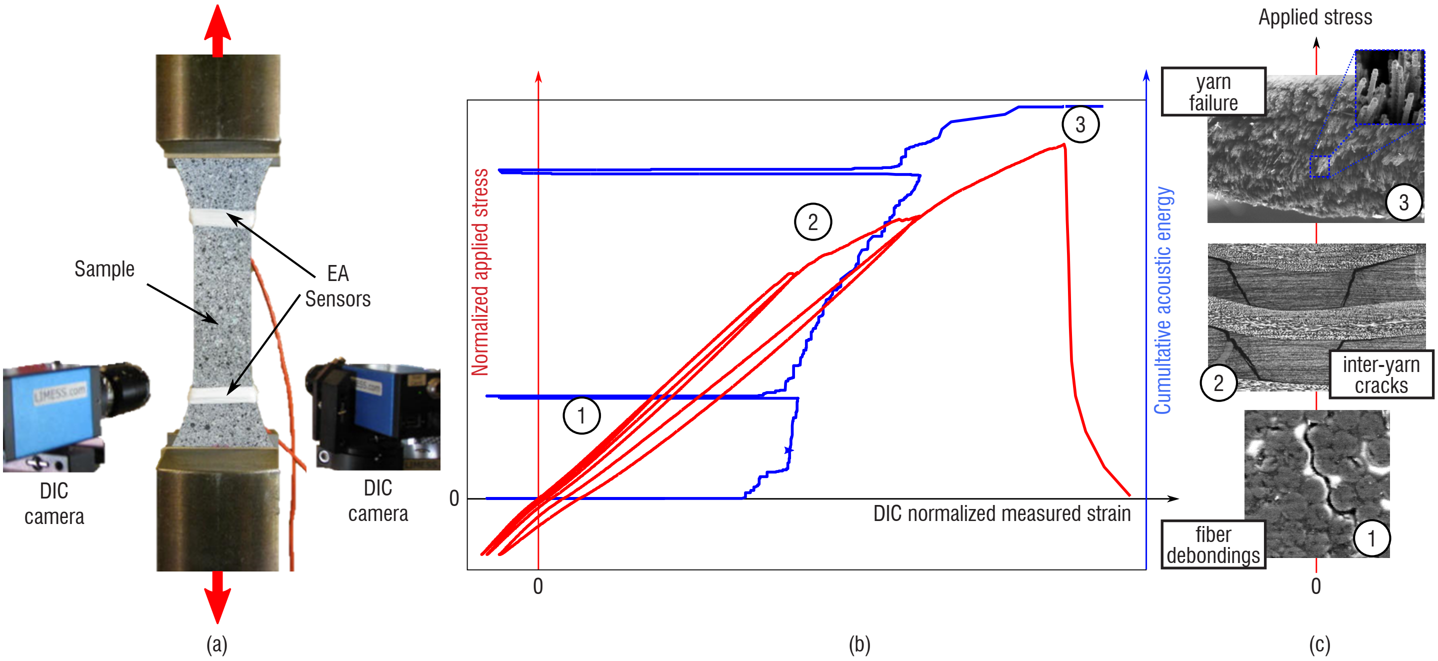


Figure 1 – Damage and failure scenario in tension in the weft direction. (a) Experimental set-up and associated multi-instrumentation, (b) macroscopic behavior, evolution of the applied stress with respect to strain and cumulative energy/strain evolution, (c) micrographs of the different damage and failure mechanisms.

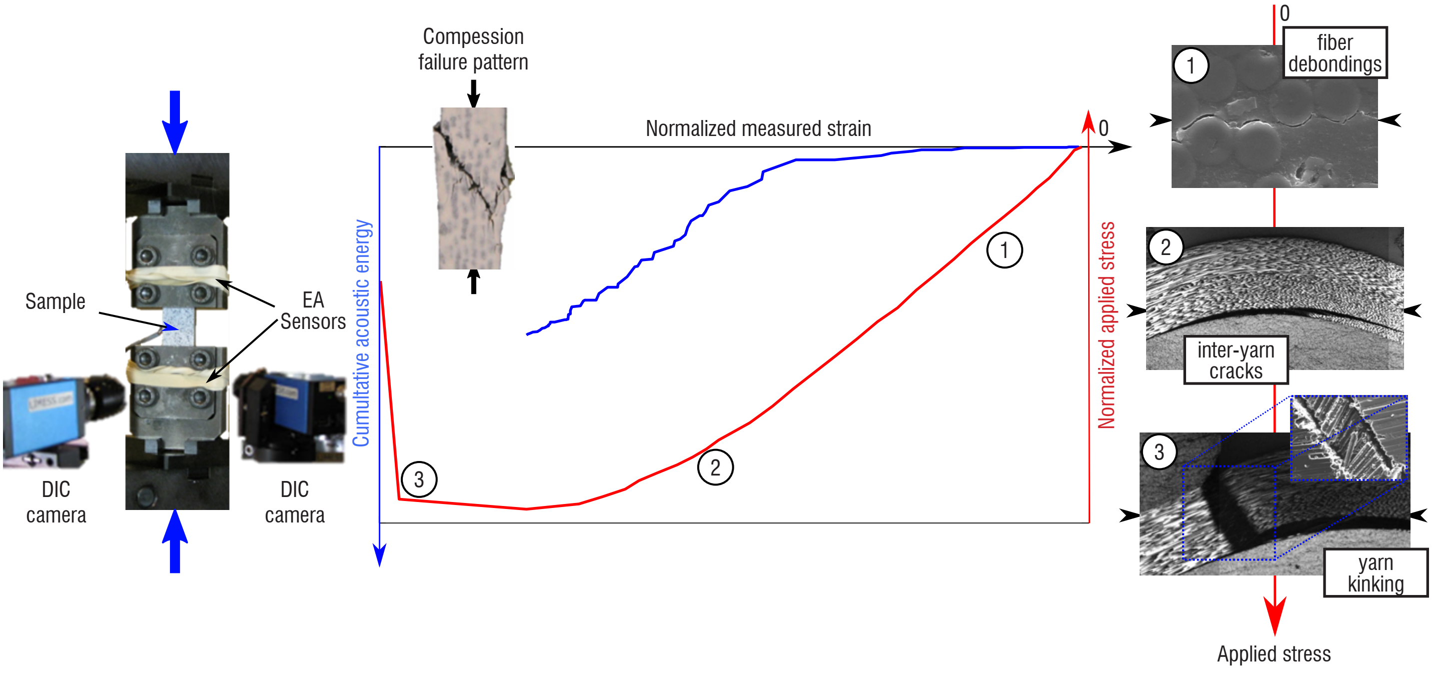
Experimental study of the behavior of a 3D woven composite

Experimental testing campaign

In order to study the behavior of a new generation of 3D woven composite materials (see the box entitled studied material), an experimental testing campaign has been performed at ONERA. An electro-mechanical Schenck machine (150 kN maximum capacity) is used. The material is tested under tensile (Figure 1a) and compressive (Figure 2a) loadings. Because of the specific unbalanced architecture of the material, the behavior is investigated in different material axes (*i.e.*, tests are performed at 0°, corresponding to the warp direction, 45° and 90°, corresponding to the weft direction). Each test is repeated in order to estimate the potential result scattering (which remains rather low for this material). Tension tests are load-controlled, whereas compression tests are displacement-controlled. This testing campaign is aimed at understanding non-linear behavior sources and at observing the damage and rupture mechanisms under different loadings applied in different directions. Hence, multi-instrumentation is used for each mechanical test. Digital Images Correlation (DIC) is performed with the commercial code Vic3D© to measure displacement fields on the specimen surface, to estimate the strain fields [7,8,11] evolution during the tests, or to detect surface cracking [12,13]. Optical microscopy [11,14] enables the observation of the different kinds of damage on one edge of the sample, establishing the damage scenarios precisely. Acoustic Emission (AE) records acoustic events within the sample (volume information) and provides useful information on the evolution of the damage [10,15]. Moreover, X-Ray micro-tomography is performed on some samples after interrupted tests, in order to complete and validate, through the volume of the material, the scenarios established using surface microscope observations. Thanks to the information collected during these tests, it is possible to (i) cross-validate the different measurements [13] and improve the confidence in the measurements, and (ii) to establish the damage and failure scenarios for different loadings, specific for this material. Damage and rupture scenarios have been established in tension and compression and are rather different. These scenarios are similar in the warp and weft directions and detailed in the following sections.

Damage and failure scenario in tension

Under tensile loading, the non-linear response of the material can be decomposed into three main phases, as reported in Figure 1b: (i) a viscoelastic non-linear behavior, (ii) the onset and evolution of different matrix damage mechanisms (mostly in-plane transverse cracking and inter-yarn debondings), and (iii), finally, the rupture of the fiber yarns, which induces the failure of the elementary tested specimens. For low stress levels, the observed non-linearity is rather moderate and is mainly due to the viscous behavior [16] of the composite material (due to the polymer matrix). This point has been enhanced through creep tests, especially for off-axis tension at 45°. The second phase of the macroscopic behavior is clearly non-linear, as reported in Figure 1b for a tensile test in the weft direction, and is due to mesoscopic damage. This damage mostly consists in in-plane inter-yarn cracks, as illustrated in Figure 1c. The mesoscopic damage is clearly governed by the architecture of the material and through the analysis of X-Ray tomography only diffuse damage in the material is observed. It can be noted that the mesoscopic damage observed in classical 2D woven composites is very different, and is located mostly within the fiber yarns [17-19]. Moreover, at inter-yarn crack tips, inter-yarn debondings are generated. Again, no large delamination crack is observed, the different matrix cracks being confined in the microstructure of the material. The last phase of the scenario corresponds to the failure of the coupon when fiber yarns break. A Scanning Electron Microscope (SEM) examination of a yarn after failure (Figure 1c) enables failure patterns (with failed fiber clusters [18,20]) to be observed, which are classically observed in 2D woven and laminated composites with unidirectional plies.



(a) (b) (c)

Figure 2 – Damage scenario in compression in the weft direction. (a) Experimental set-up and associated multi-instrumentation, (b) global behavior, evolution of the applied stress with respect to strain and cumulative energy/strain evolution and (c) micrographs of the different damage and failure mechanisms.

Damage and failure scenario in compression

Under compressive loading, the macroscopic behavior can also be decomposed into three main phases, as reported in Figure 2b: (i) a viscoelastic behavior, (ii) a slightly non-linear part, mainly due to inter-yarn debondings, and (iii), finally, the rupture of the fiber yarns leading to failure of the tested elementary specimen. The first phase is again due to the matrix viscosity, which has been further evidenced through the analysis of 45°-off-axis compressive creep tests. The non-linear behaviors in tension and in compression are different [21,22]. Indeed, in tensile creep tests, fiber/matrix debondings within the fiber yarns (or matrix micro-cracks), normal to the applied loading (see Figure 1c), are observed, thus increasing the apparent non-linearity. In compression creep tests, fiber/matrix debondings are generated through the Poisson effect and are thus parallel to the loading direction, as shown in Figure 2c. Therefore, this micro-damage has a negligible influence on the viscosity in the loading direction. The second phase, which is slightly non-linear, is due to inter-yarn debondings resulting from the compressive loading of the fiber yarns presenting the larger initial waviness, as illustrated in Figure 2c. Then, inter-yarn debonding promotes the failure of the fiber yarns due to kinking of the latter, also linked to the initial waviness of the yarns. Kinking of yarns always occurs in the vicinity of inter-yarn debondings, as observed in Figure 2c. It can be noted that the result scattering is rather low compared to that of classical unidirectional plies because the initial waviness of the fiber yarns is controlled during the manufacturing process.

The ONERA Damage Model for 3D woven Polymer Matrix Composites (ODM-PMC)

As mentioned previously, only diffuse damage (in-plane inter-yarn matrix cracking and inter-yarn debondings) is observed, contrary to damage studied in laminates constituted of unidirectional plies. The ONERA Damage Model for Composites with a Polymer Matrix (ODM-PMC) is based on a continuum damage approach [23] and is defined at the macroscopic scale to be used for the strength predictions of academic composite structures, but also for large composite structures representative of industrial components. For new generations of 3D woven composites, multiple sources of non-linearity have been determined experimentally through the analysis of quasi-static tests.

The ODM-PMC model has been proposed, in order to describe the non-linear behavior, damage and failure of 3D woven composites subjected to quasi-static loadings. Only the main ideas of this model are presented here; more details can be found in [8,9,11,24-26]. This approach is thermodynamically consistent and the macroscopic behavior, expressed in Eq. 1, derives directly from the Helmholtz free energy.

$$\underline{\sigma} = \underline{\underline{C}}^{eff} : (\underline{\varepsilon} - \underline{\varepsilon}^{ve} - \underline{\varepsilon}^{th} - \underline{\varepsilon}^{0}) - \underline{\underline{C}}^{0} : (\underline{\varepsilon}^{s} + \underline{\varepsilon}^{r} - \underline{\varepsilon}^{0}) \qquad (1)$$

where $\underline{\sigma}$ is the stress tensor, $\underline{\varepsilon}$ is the total strain tensor, and $\underline{\varepsilon}^{ve}$ is the viscoelastic strain tensor. Taking into account the viscosity of the polymer matrix is essential to accurately describe the macroscopic behavior of specimens subjected to off-axis loadings, as presented previously. The viscoelastic approach, taking into account the influence of micro-damage (noted δ_1, δ_2, δ_3) on the viscosity, used in this study is thus not detailed here, but more information can be found in [27,28].

In Eq.1, $\underline{\underline{C}}^{0}$ corresponds to the initial elastic stiffness tensor ($\underline{\underline{S}}^{0}$ is the initial elastic compliance) and $\underline{\underline{C}}^{eff}$ is the effective elastic stiffness tensor taking into account the effects of the different damage and failure mechanisms, as expressed in Eq. 2.

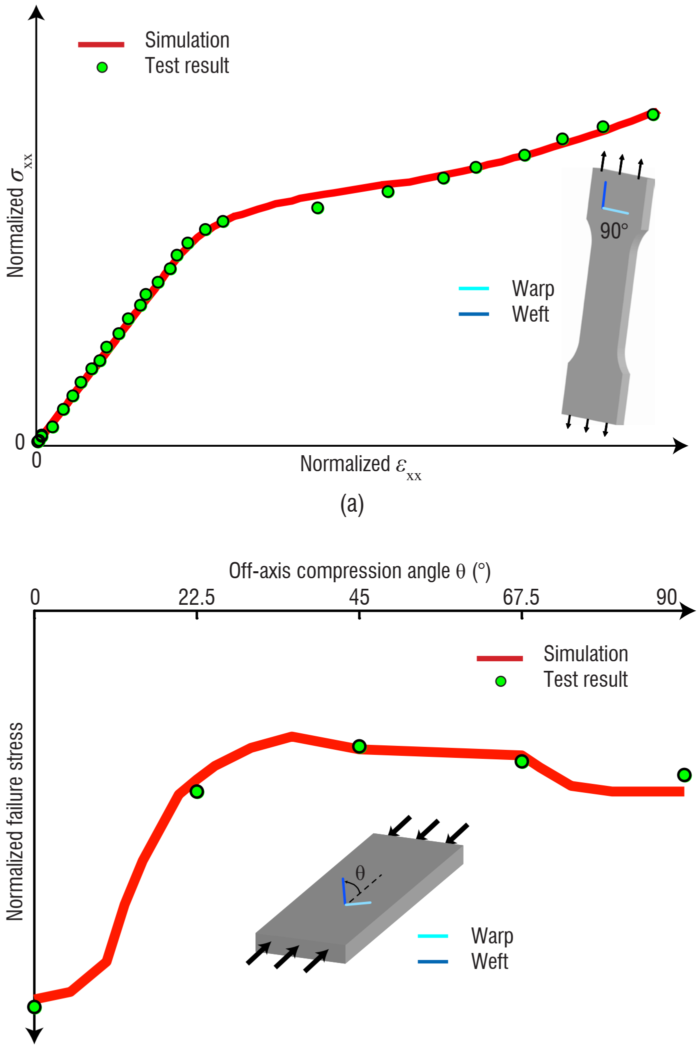
$$\underline{\underline{C}}^{eff} = \left(\underline{\underline{S}}^0 + \sum_i d_i \, \underline{\underline{H}}_i^m + \sum_j \left(D_j^t \underline{\underline{H}}_j^{ft} + D_j^c \underline{\underline{H}}_j^{fc} \right) + D_3 \underline{\underline{H}}_3^f \right)^{-1} \quad (2)$$
$$\text{with} \quad (i,j) = \{1,2\}$$

For such a material, the high contrast between the mechanical properties of the constituents (matrix and fiber yarns) leads to crack orientations induced by the microstructure. Therefore, each damage or failure mechanism is described in the model by a scalar variable. In this approach, these different damage variables are classified by their effects on the macroscopic behavior. Indeed, two types of variables are considered: (i) mesoscopic damage variables induce a non-negligible non-linearity in the macroscopic behavior and (ii) macroscopic rupture variables lead to a violent decrease in the apparent rigidity.

Mesoscopic damage variables (d_1 in the warp direction, d_2 in the weft direction) are related to in-plane matrix cracking and induce a notable non-linear effect on the macroscopic behavior through the term ($\sum_{i=1}^{2} d_i \underline{\underline{H}}_i^m$) in Eq. 2.

The ($\underline{\varepsilon}^0$, $\underline{\varepsilon}^s$) strain tensors allow the unilateral aspect of damage to be taken into account in this model, while ensuring the continuity of the macroscopic behavior for any kind of complex non-linear loading. The unilateral aspect of damage means that the model takes into account the fact that the cracks, opened under tensile loading, will close under compressive loading. Therefore, the effects of damage mechanisms in a material subjected to tension are very different from those under compressive loading, due to crack closure. This point is essential to perform robust finite element simulations taking into account the unilateral aspect of damage. Moreover, the residual strain ($\underline{\varepsilon}^r$) describes the remaining strain after unloading at null stress, which is assumed to be strongly connected to the in-plane mesoscopic damage generated during the loading phase, as proposed by [29,30]. It has been demonstrated [31] that the introduction of this residual strain is essential to predict the permanent indentation after impact.

The out-of-plane macroscopic damage (D_3), which corresponds to the inter-yarn debondings, can play a major role in the macroscopic behavior, for instance during an impact test or a bearing test, and its effects are taken into account through the term ($D_3 \underline{\underline{H}}_3^f$) in Eq. 2.



(a)

(b)

Figure 3 – a) Comparison between the experimental strain/stress curves and the prediction obtained with the ODM-PMC model for a tensile test in the weft direction and b) comparison between the measured and predicted stresses at failure for different off-axis compressive tests on unnotched samples.

As explained, for unnotched specimens the rupture in the material axis is due to the failure of fiber yarns. The failure mechanisms are different in tension and in compression, and are thus distinguished in the proposed modeling. The macroscopic variables (D_1^t , D_2^t) describe the effects of yarn failures in tension, in the warp and weft directions respectively, and the variables (D_1^c , D_2^c) describe the effects of yarn failures in compression. These yarn failures induce a violent and softening macroscopic behavior through the term $\sum_{j=1}^{2} \left(D_j^t \underline{\underline{H}}_j^{ft} + D_j^c \underline{\underline{H}}_j^{fc} \right)$ in Eq. 2. It can be noted that the influence of the hydrostatic pressure on the apparent strength of fiber yarns in compression is taken into account based on previous studies performed on laminated composites [32]. The description of the softening behavior due to yarn failures is necessary, in order to accurately predict the final failure of composite structures containing geometrical singularities, such as open-hole plates or notched specimens.

The identification process for viscoelasticity, mesoscopic damage, residual strains, and the onset of inter-yarn debondings and yarn failure is well established through the analysis of unnotched coupons subjected to off-axis tensile and compressive loadings. The comparison between the measured and predicted macroscopic behavior for tensile tests in the weft direction is reported in Figure 3a, and the proposed model is able to accurately describe the various phases of the macroscopic behavior. Moreover, in Figure 3b, the predicted macroscopic stress at failure for various off-axis compressive tests are compared successfully with the available experimental results on unnotched samples tested at ONERA. Nevertheless, the parameters linked to the evolution law of the fiber yarns cannot be determined on unnotched samples because the first yarn failure induces the final failure of the tested unnotched specimens. The degradation law associated with the fiber yarn failure can only be determined through the analysis of tests performed on structures containing geometrical singularities, as presented in the following section.

Strength prediction of composite structures with geometrical singularities

The definition of the final rupture of high stress gradient parts of composite components, especially for open-hole plates, cannot be reduced to the first fiber yarn failure, due to the high stress gradient around the hole. Such a definition of final failure will lead to underestimating the failure strength by a factor of 2 or 3. It is therefore an absolute necessity to describe the progressive degradation of the mechanical properties due to fiber yarn failure, especially for compressive loading. In order to evaluate the predictive capacities of the ONERA Damage Model for Polymer Matrix Composites (ODM-PMC), a large experimental campaign on academic composite structures with different geometrical singularities subjected to compressive loading is performed. Two different kinds of geometrical singularities are thus considered: (i) classical circular open-hole plates with different diameters, and (ii) plates containing a milled groove or milled double notches, which generate more severe local stress gradients.

Strength prediction of open-hole plates subjected to compressive loading

For the open-hole plates subjected to compressive loading, four configurations were tested with different hole diameters, from 6 mm to 40 mm with a constant w/d ratio (plate width to hole diameter) equal to 6, as illustrated in Figure 4a. These tests, performed in the warp and weft directions, are instrumented with 2 CCD cameras for Digital Images Correlation (DIC) and Acoustic Emission (AE) sensors, in order to monitor the evolution of the various damage and failure mechanisms. A hydraulic Maser machine with a 500 kN maximum capacity was used, as reported in Figure 4b. Two different load cells have been used as a function of the hole diameter and the associated width. The tests were performed in the machine-controlled displacement mode and a constant (0.1 mm/min) displacement rate is imposed. The dimensions of the samples were chosen through a preliminary FE analysis, in order to avoid premature buckling of the specimens before kinking of the fiber yarns. Each test was repeated three times, in order to estimate scattering. The failure patterns, shown in Figure 4c, are rather similar for the various configurations tested in the warp and weft directions, and failure is due to kinking of the fiber yarns. The observed macroscopic crack is normal to the in-plane loading direction and presents a through-the-thickness angle, strongly linked to the architecture of the material and to the yarn kinking propagation through the thickness, as observed in smooth specimens (Figure 2b). The progressive propagation of the fiber yarn cracks through kinking is clearly evidenced through the analysis of the displacement field measured by DIC, as reported in Figure 4d.

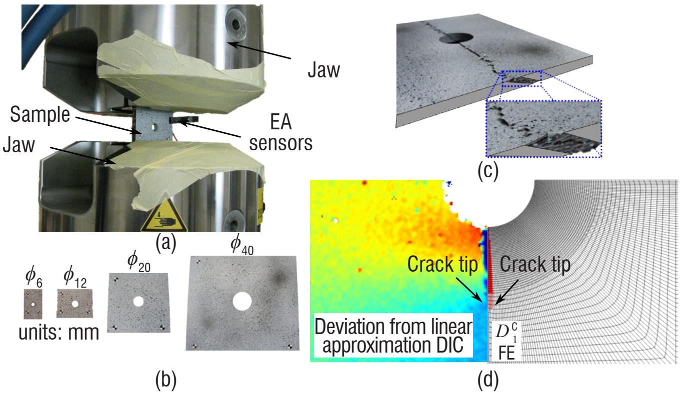


Figure 4 – a) Experimental set-up and associated multi-instrumentation to test open-hole plates subjected to uniaxial compressive loading, b) presentation of the tested open-hole plates with scale effects (ϕ_6 means $\phi = 6$ mm), c) observed failure pattern for open-hole plates in the warp and weft directions and d) comparison of the measured (with the deviation from the linear approximation of the displacement [12]) and predicted macroscopic crack lengths at the peak load for the open-hole plate with a 40 mm in diameter hole

In order to predict the strength of 3D woven composite structures, the ODM-PMC model has been implemented in the Abaqus/standard commercial finite element code. It can be noted that, because macroscopic failure variables (i.e. yarn failures and inter-yarn debondings) induce a softening behavior, it is necessary to introduce a regularization technique in order to avoid mesh dependence and localization of the solution. The delay effect method [33] is associated with yarn failure to avoid these problems, for the sake of simplicity.

To simulate these tests, Finite Element (FE) calculation conditions (geometry and mesh) have been established. The mesh size in the vicinity of the geometric singularity is the same for all of the tested configurations, because of the chosen regularization technique. The configuration, with a 6 mm in diameter hole, is used to identify the evolution law of fiber yarns under compression in the warp and weft directions. For the other configurations, the predicted failure loads are obtained with the same set of material parameters. In order to evaluate the benefit of using such a complex material approach, as compared to the classical semi-empirical models widely used in design offices in aeronautics, the Point Stress Method [34,35] is also applied to open-hole plates subjected to compression as a post-treatment of a linear finite element simulation and is described in the box entitled Presentation of the Point Stress Method. The characteristic distance d_0 is also identified in the configuration with a hole diameter equal to 6 mm in the warp and weft directions.

Box 2 - Presentation of the Point Stress Method

The Point Stress Method [34,35] is a semi-empirical method widely used in design offices to predict the strength of open-hole plates because of its simplicity. The main idea, illustrated in Figure B2-01, consists in evaluating, as a post-treatment of a linear elastic Finite Element simulation, a failure criterion at a given distance d_0 from the geometrical singularity, such as a hole, which induces the stress gradient. The specimen is considered as broken when this criterion is fulfilled for the first time at one point within the structure.

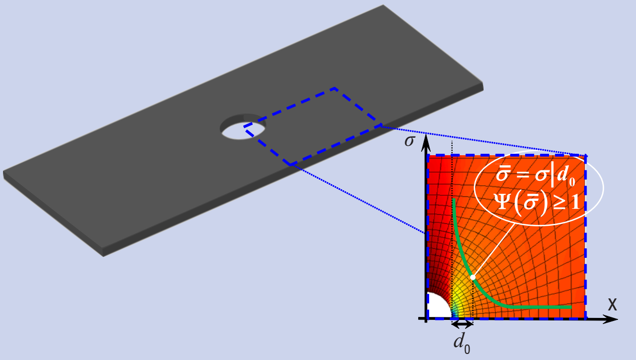
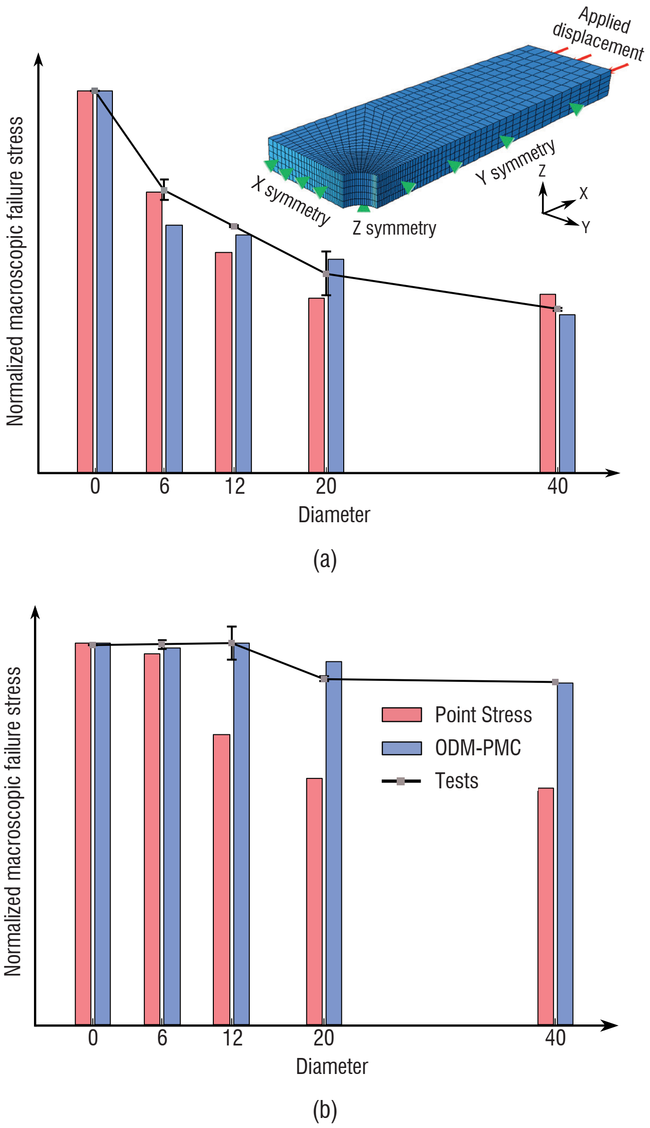


Figure B2-01 – Principle of the Point Stress Method applied to an open-hole plate.

In the present approach, owing to the introduction of the progressive degradation of the mechanical properties due to the fiber yarn rupture, the predicted failure macroscopic stresses at failure, defined as the failure load (peak force) divided by the real section of the tested specimen, are in good agreement with the experimental measurements for open-hole plates with different diameters subjected to compression in the warp direction, as illustrated in Figure 5a. Moreover, the predicted length of the fiber yarn cracks at the experimental peak load is compared successfully with that measured by DIC, as reported in Figure 4d. The predictions obtained with the Point Stress Method, reported in Figure 5a, are also in good agreement with experimental data. These results are not surprising because the macroscopic behavior is almost linear up to failure due to the high yarn ratio in this material direction.

Figure 5b shows the comparison between the experimental macroscopic stresses at failure in the weft direction and those predicted with the ODM-PMC model and the Point Stress Method. Failure strengths have been normalized to the failure strength of the un-notched specimen, corresponding to the 0 mm hole diameter. Firstly, the scale effect on the macroscopic stress at failure is not the same in the warp and weft directions. While the evolution with respect to the hole diameter in the warp direction is similar to that observed in laminated composites with unidirectional plies [36], the influence of the hole diameter is markedly different in the weft direction. Indeed, for a hole diameter smaller than 12 mm its influence on the stress at failure is negligible, but for larger hole diameters the apparent strength decreases. In the weft direction, the Point Stress Method predicts an evolution of the macroscopic stress at failure similar to that obtained in the warp direction, and is thus not in good agreement with available experimental data. Nevertheless, the ODM-PMC model enables the prediction of the scale effect on an open-hole plate, both in the warp and weft directions, very accurately. The difference between the two different directions is due to the amount of mesoscopic damage (in-plane matrix cracking) and inter-yarn debondings, which is higher in the weft direction in the present case of a highly unbalanced 3D woven composite. Moreover, it also explains the fact that the Point Stress Method, used as a post-treatment for linear elastic FE simulations, leads to results that are in poor agreement with experimental data in the weft direction.



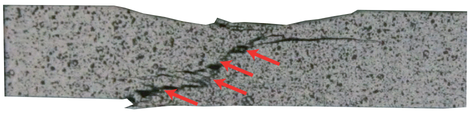
(a)

(b)

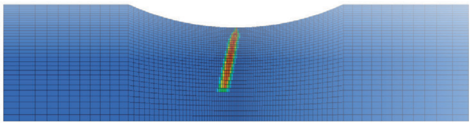
Figure 5 – Evolution of the normalized macroscopic stresses at failure measured and predicted with the ODM-PMC model and the Point Stress Method for open-hole plates subjected to compression in the a) warp and b) weft directions.

Strength prediction of machined plates subjected to compressive loading

In order to validate the predictive capabilities of the ODM-PMC model, additional machined composite structures have been subjected to uniaxial compressive loading. Three plates containing a milled groove have been machined, as illustrated in Figure 6. The radius of the groove is 90 mm and its depth in the plate is equal to 4 mm. Moreover, three additional plates containing milled double notches (*i.e.*, notches located on two opposite edges) have been machined and are illustrated in Figure 6b. The radius of the milled notches is 45 mm and their depths (along the width and through the thickness)

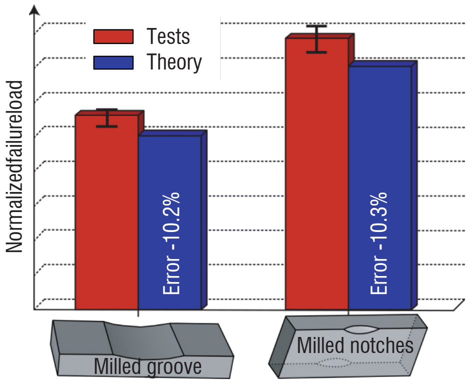


Observed failure pattern in a milled grooved specimen



Predicted failure pattern in a milled grooved specimen

(a)



(b)

Figure 6 – a) Observed and predicted failure patterns in a milled grooved 3D woven composite plate, b) comparison of the measured and predicted failure loads for different machined plates subjected to compression in the warp direction.

are equal to 5 mm. The geometry of these specimens has been controlled through stereo-digital image correlation.
These tests on machined specimens are performed only in the warp direction. The testing machine and the associated multi-instrumentation are similar to those already presented. The failure patterns for these two test configurations are very similar to those already observed for unnotched specimens and open-hole plates.

The finite element simulations are performed with the ODM-PMC model and the material parameters identified previously. Again, the size of the element of the mesh close to the geometrical singularities is similar to those used for open-hole plates, which is non-trivial for the complex geometries under consideration.

The damage and failure scenario for such complex structures is described correctly by the proposed approach. Indeed, inter-yarn debondings are first predicted close to the singularities, due to the compressive loading and, finally, fiber yarn kinking is predicted in the vicinity of the singularities and then propagates through the thickness with a given angle, which is rather consistent with the observation, as reported in Figure 6a. Moreover, Figure 6b presents the comparison between the predicted and measured failure loads for the two configurations of machined structures, inducing different local stress gradients. The predictions are conservative as compared to the experimental data and are in good agreement with experimental data (the error is around -10%).

To conclude, this non-linear material approach ODM-PMC enables the prediction of the final failure load of open-hole plates with scale effects, as well as the strengths of composite structures containing more complex singularities, such as a milled groove or milled double notches. Moreover, the damage and failure scenarios for all of the composite structures considered are accurately described by the proposed modeling. Finally, the benefit of using an advanced damage and failure approach as compared to semi-empirical approaches, such as the Point Stress Method, is demonstrated for some configurations inducing an important amount of matrix damage.

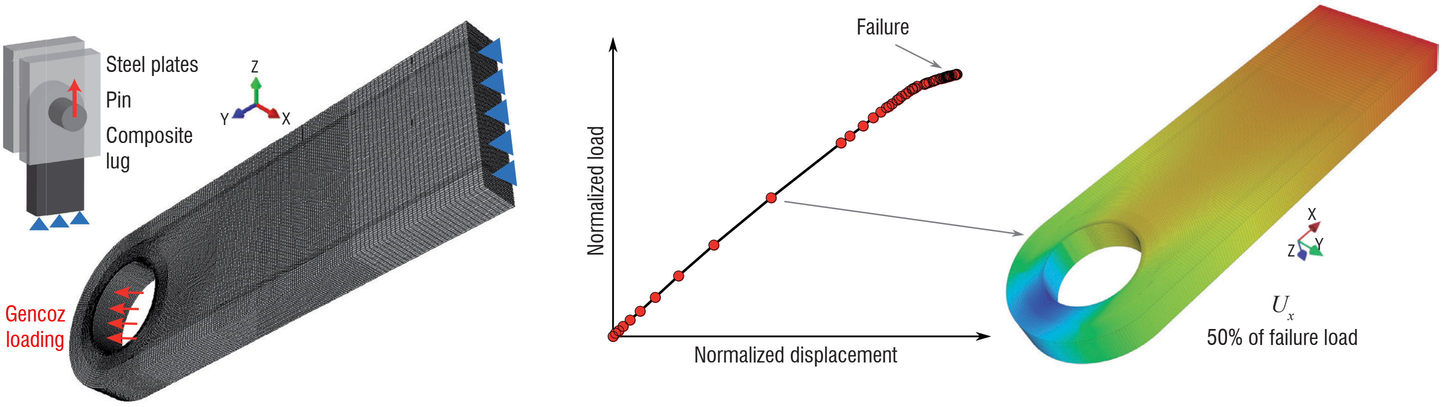
Application to a composite component

Since the ODM-PMC model has been validated on simple smooth specimens and composite structures containing geometrical singularities, such as holes, grooves or notches, this approach can be applied to 3D woven composite components, such as those tested in the higher levels of a validation pyramid.

The considered test case consists in a classical lug [37,38] subjected to tensile loading through an iron pin, as illustrated in Figure 7a. The geometry has been slightly simplified for the considered study. Based on [39], an empirical formula is used to describe the distribution of bearing pressure for pin and lug contact, in order to avoid managing contact and thus to reduce the computational time. The finite element mesh of such a structure contains 1.1 million degrees of freedom and necessitates 35 GB of RAM for non-linear calculation with the ODM-PMC model. It can be noted that special attention has been paid to the computation of the consistent tangent matrix, to ensure the convergence of such a complex material model. Moreover, the implementation in Abaqus/standard is consistent with multithread requirements, in order to reduce the time of computation. Therefore, the computational time for this test case is around seven hours with 30 CPUs, which could match the requirements of a design office in aeronautical industries, whereas the predicted global response, reported in Figure 7b, is markedly non-linear from 80% of the failure load. The predicted damage and failure scenario seems to be rather consistent with those reported in the literature for bolted joint problems applied to 3D woven composite materials [40,41], and with those observed in woven composite lugs tested in industry [38]. Further works should consist in performing, at ONERA, multi-instrumented tests on 3D woven composite lugs subjected to tensile or compressive loading, in order to validate this approach, especially through comparisons between the predicted displacement fields, as reported in Figure 7c, and those measured through DIC during the tests.

Conclusions / Perspectives

Due to the poor impact resistance of classical laminated composite materials, 3D woven composites have been recently developed to be potentially used in industrial applications exposed to impact. These composites having been recently developed, it has been necessary to determine precisely the damage and failure scenarios for such materials subjected to different kinds of loadings. Therefore, a large experimental testing campaign has been conducted at ONERA on smooth elementary coupons subjected to tensile, compressive or bending loadings. These tests have been multi-instrumented,



(a) (b) (c)

Figure 7 – Large structural test case: a) Boundary conditions and mesh of a lug subjected to tensile loading b) normalized predicted macroscopic displacement / load curve and c) predicted displacement field Ux at 50% of the failure load.

with Digital Image Correlation, acoustic emission, and X-Ray tomography, in order to understand the different damage and failure mechanisms encountered in 3D woven composite materials. It has been demonstrated that the matrix damage (in-plane matrix cracking and inter-yarn debondings) is diffuse within the material, confined to the local architecture, which constitutes a major difference compared with laminated composites.

Therefore, a model, named ONERA Damage Model for Polymer Matrix Composites (ODM-PMC) and based on the continuum damage theory, has been developed specifically for such a material. This non-linear material approach takes into account the different sources of non-linearity observed in smooth samples, such as the viscoelasticity of the matrix, in–plane matrix damage, inter-yarn debondings, and fiber yarn failures. The predictions of this approach, in terms of non-linear behavior, matrix damage evolution, and failure predictions, have been validated through comparisons with available tests on simple unnotched specimens.

Moreover, in order to evaluate the capability of the ODM-PMC model to predict the strength of 3D woven composite structures, it has been implemented in the Abaqus/standard commercial finite element code. Then, the model has been applied to plates containing different kinds of geometrical singularities, such as an open-hole, a milled groove, or milled double notches, subjected to compressive loading. These different singularities generate different local stress gradients, enabling the validation of the failure load predicted by the model over a wide range of structural configurations. Moreover, since these structural tests have been multi-instrumented, it has been demonstrated that the damage and failure scenario is also accurately described by the proposed approach.

Finally, the ODM-PMC model has been applied to a large 3D woven composite structure, quite representative of industrial components. The considered structural test consists in a lug subjected to bearing loading. The predicted damage and failure scenario is very promising compared to those reported in the literature for 3D woven composite materials. The corresponding tests should be performed soon at ONERA, in order to validate this approach. Moreover, given that special attention has been paid to the quality of the implementation in Abaqus/standard, the obtained computational times match the industrial requirements. Therefore, this approach, implemented in a commercial finite element code, could be transferred to design offices in aeronautical industries.

Further work would consist in estimating the residual strengths and predicting the fatigue lifetime of large industrial structures with a unified approach based on the ODM-PMC model, initially developed to predict the strength of composite structures subjected to quasi-static loadings. These developments are currently being performed in collaboration with other French research laboratories [9,10,42,43] ■

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Acronyms

3D	(3 Dimensional)
2D	(2 Dimensional)
ODM-PMC	(ONERA Damage Model for Polymer Matrix Composites)
DIC	(Digital Image Correlation)
AE	(Acoustic Emission)
SEM	(Scanning Electron Microscope)
FE	(Finite Elements)
GB	(Giga Byte)
RAM	(Random Access Memory)
CPU	(Central Process Unit)

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