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EXPERIMENTAL AND NUMERICAL STUDY ON THE TRANSVERSE CRACKING IN A COMPOSITE MATERIAL WITH A THERMOPLASTIC MATRIX

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Abstract: *The proposition of innovative and competitive designs of aeronautical structures manufactured with composite materials made of carbon fibres and thermoplastic matrix, presenting high potential for recyclability and interesting welding capabilities, cannot be performed without a deep understanding of the different sources of non-linearities specific to those high performance materials. The objective of the present study consists therefore in understanding the underlying physical phenomena leading to transverse cracking in a new generation of composite material with carbon fibres and thermoplastic matrix and in highlighting their specificities compared to a UD ply made of the same carbon fibres but associated with an epoxy matrix.*

Keywords: Composite with thermoplastic matrix; Multi-instrumented tests; Transverse cracking; Damage modelling; Fracture toughness

1. Introduction

Laminated composites constituted with unidirectional plies made of carbon fibres associated with a thermoplastic matrix are now being considered for the production of primary aeronautical structures due to the welding possibilities offered and the high potential for recyclability. In addition, these materials allow parts to be manufactured out-of-autoclave with an interesting production rate. Due to the recent development of these high performance materials, it is necessary to determine precisely their specificities; in terms of behaviour, damage mechanisms and fracture; compared to Carbon/Epoxy materials widely studied in the literature. This point is addressed in the present article from an experimental point of view. Indeed, in section 2, the experimental test campaign, designed to study the onset and evolution of transverse cracks, is presented. Some major differences have been observed between the test results obtained on this material and those obtained on a classical carbon/Epoxy material constituted with the same Carbon fibre but with an Epoxy matrix and different explanations have been experimentally investigated in section 3. Once this stage of understanding the specificities of damage mechanisms in a carbon/thermoplastic composite material been completed, the section 4 addresses the relevance of non-linear models, initially developed for carbon/epoxy composites, for thermoplastic matrix composites and to determine the modifications to be performed in such models in order to be consistent with the test results.

2. Experimental study of transverse cracking in a Carbon/Thermoplastic material

2.1 Presentation of the studied composite material

The laminated composite material, considered in this study, is made of T700GC carbon fiber associated with a TC1225 thermoplastic matrix supplied by Toray Advanced Composites with a

unidirectional ply architecture. The characterization specimens manufactured in this study ($[(45_m/-45_m)_n]_s$, $[(0_n/90_m)_p]_s$ cross-ply laminates, and $[(90/\pm 45)_p]_s$, $[(45/90/-45/0)_p]_s$ multilayered plates) were produced at ONERA under a heated press in accordance with the curing cycle recommended by the manufacturer. The manufactured specimens were all controlled by C-Scan and microscopic observations to ensure the quality of the initial state of the specimens.

2.2 Experimental device and associated multi-instrumentation

The tensile tests have been performed at ONERA on a hydraulic testing machine with a maximal capacity equal to 100 kN, with associated hydraulic jaws.

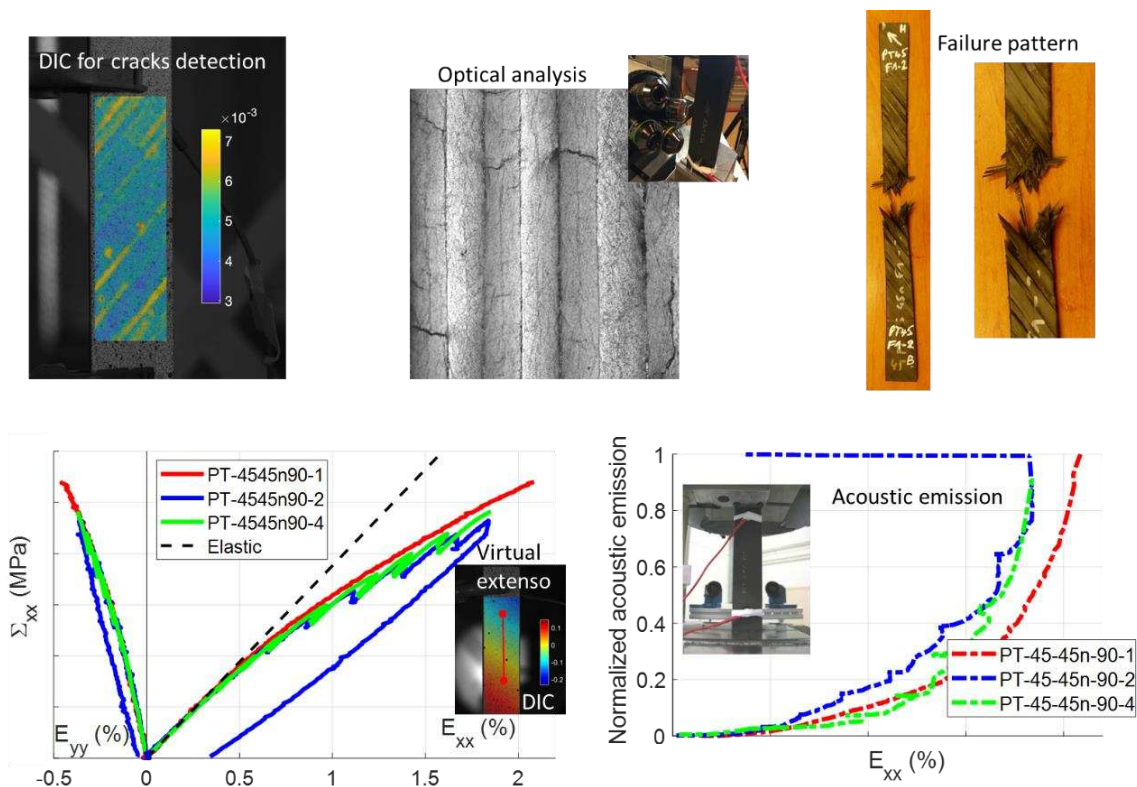


Figure 1: Presentation of the measurement techniques on tensile tests performed at Onera

Those tensile tests have been multi-instrumented, as reported in Figure 1, in order to understand the different sources of non-linearity encountered in such a new material, with :

- 1 acoustic emission (AE) sensor to monitor the evolution of damage [1] during the test. The acquisition system is the AEWin system supplied by MISTRAS and the acoustic sensor is a Nano80 sensor type.
- All the tests were monitored using stereo-correlation of digital images (DIC), carried out using Vic3D software [2]. Two 12bits cameras with 2000x2000 resolutions were used. A black and white speckle was made on the upper face of each specimen.
- For some specimens, a special attention has been paid to the transverse cracking evolution [3,4]. During those tests, after significant acoustic events, the applied displacement has been maintained while many pictures are taken with a CCD camera (12 bits with a resolution of 1379x1024 pixels) associated to a microscope with different objectives (x5 or x10). This

camera is fixed on a micrometre table with 3 axes which allows taking many pictures (between 20 and 50) on one edge of the specimen, previously polished. Then, these pictures are merged to obtain a large micrograph of the whole area of interest of the specimen as illustrated in Figure 2. The observed area is about 80 mm to be statically representative of matrix cracking in plies.

- Finally, the failure pattern of the different specimens were analysed optically and using SEM to confirm the ruin scenarios established using the other measurements.

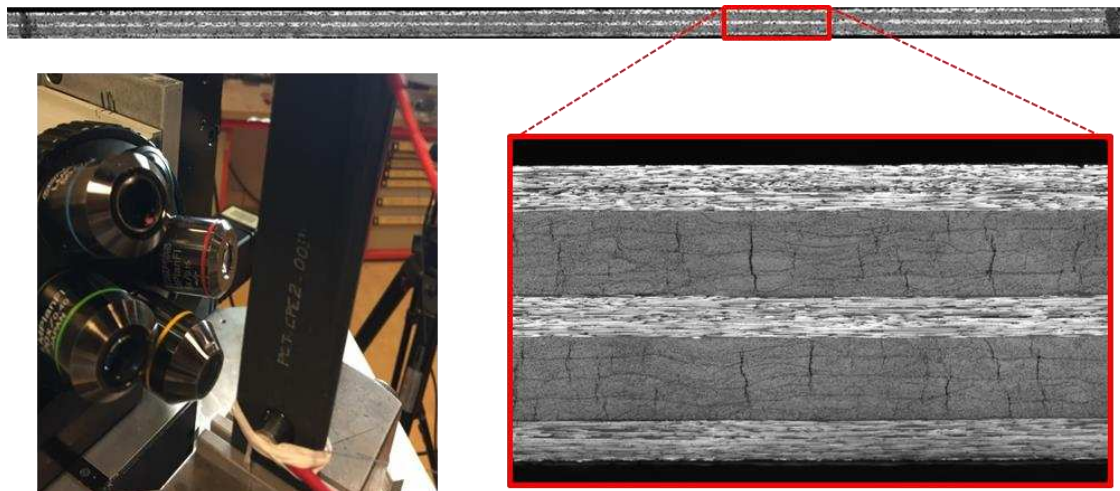


Figure 2: Fine observation of damage pattern in a T700GC/TC1225 cross-ply $[0_2/90_4/0]_s$ laminate

The damage onset and evolution of transverse cracking have been analysed through the analysis of tensile tests on two different stacking sequences. Cross-ply $[0/90_2/0/90_2/0]_s$ and $[0_2/90_4/0]_s$ laminates have been tested to determine the influence of the ply thickness on the apparent onset of damage but also on its evolution, as already observed on classical Carbon/Epoxy materials [3,5–7]. Figure 3a presents the macroscopic behaviour for the two cross-ply laminates which is almost linear, while lots of cracks are observed, due to the presence of 0° plies. The analysis of the acoustic emission allows determining the onset of damage, as reported in Figure 3b, which seems to be insensitive to the ply thickness. This point constitutes the first major difference with classical Carbon/Epoxy material.

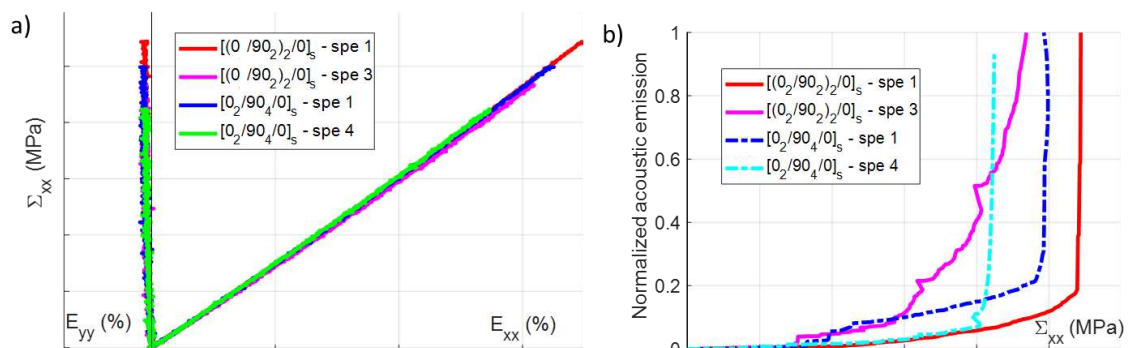


Figure 3: a) Macroscopic behavior of $[0/90_2/0/90_2/0]_s$ and $[0_2/90_4/0]_s$ laminates subjected to tensile loading and b) evolution of the cumulative acoustic energy as a function of the applied stress

The crack density evolution, monitored with AE and optical observation, seems to be sensitive to the ply thickness, as for the carbon/Epoxy materials. This point is confirmed considering the macroscopic failure stresses of these two laminates, which is higher for the thinnest 90-ply, because of lower loading report of less damaged 90-ply to the same 0-ply.

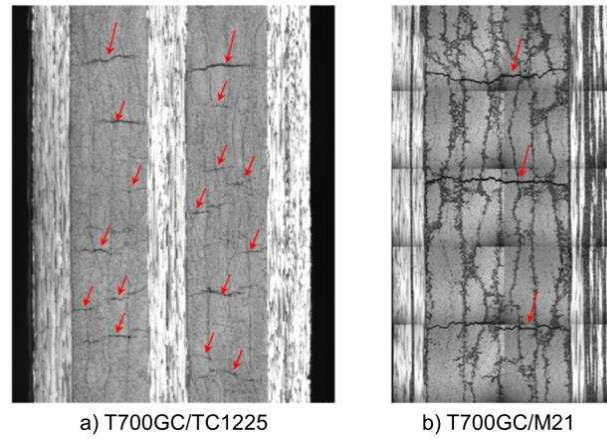


Figure 4: Comparison of damage patterns within cross-ply a) T700GC/TC1225 and b) T700GC/M21 $[0_n/90_m]_s$ laminates.

Finally, the damage patterns observed on T700GC/TC1225 laminates are carefully compared to those observed on other composite materials with thermoset matrix, as reported in Figure 4. Indeed, in cross-ply Carbon/Epoxy laminates made of T700GC fibre (same fibres) associated with an epoxy M21 matrix [3] proposed by Hexcel the transverse cracks propagate through the whole thickness of the ply whatever the thickness of the ply and local delamination at the tips of cracks are also observed. For the T700GC/TC1225 material, the cracks are spread over the ply thickness and present short lengths. A huge number of small cracks appear in the different plies prior the final failure, which is very specific and constitutes an original point of this study, which is discussed in the next section.

3. Explanation of specificities of the observed damage patterns

3.1 Possible physical explanations of diffuse cracking

As highlighted in the previous section, the damage pattern observed for the cross-ply T700GC/TC1225 laminates (but also for quasi-isotropic lay-ups presented in the sequel) is very specific compared to that observed on T700GC/M21 laminates. As proposed in [6,7], a mixed criterion can be relevant to explain the influence of the ply thickness on the onset of damage and on the damage pattern. It is assumed that a transverse crack can appear when a stress criterion (associated to the occurrence of local fibre/matrix debondings), and an energy criterion (associated to the propagation of this micro-crack) are both fulfilled. As mentioned previously, tensile tests have been performed on $[90]_{16}$ plies to determine the transverse strength used in the stress criterion and the obtained value is very similar to that obtained on T700GC/M21 90° plies [3]. Therefore, the mode I fracture toughness used in the energy criterion has been experimentally investigated in the next section.

3.2 Experimental study of the fracture toughness in mode I

In order to determine the fracture toughness for mode I, Double Cantilever Beam (DCB) tests have been performed at ONERA on $[0_{12}]_s$ laminate containing a Upilex insert as a pre-crack with a length equal to 60 mm. The experimental device is illustrated in Figure 5a with the associated multi-instrumentation. A special attention has been paid to the development of an automated method, based on DIC, to measure the delamination crack length evolution during the loading. Moreover, few C-Scan analyses have been performed during interrupted DCB tests to control the crack front through the width and increase the confidence into the test results.

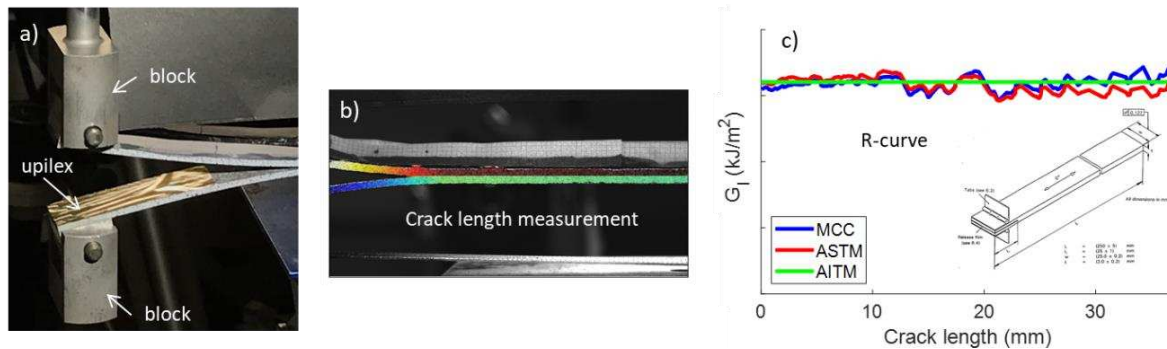


Figure 5: a) DCB experimental device, b) crack measurement length method with DIC and c) R-curve determined using different data reduction methods

In order to determine the R-curves and then the apparent fracture toughness from the knowledge of the displacement / load / crack length measurements, different data reduction methods, available in the literature [8,9], have been considered. Figure 5c presents the R-curves, estimated with the modified Compliance Calibration method and two other methods available in ASTM and AITM standards, which are consistent and allow estimating precisely the mode I fracture toughness. The measured fracture toughness of the Carbon/Thermoplastic material is 4.5 times higher than that of the Carbon/Epoxy material, as reported in Figure 6a.

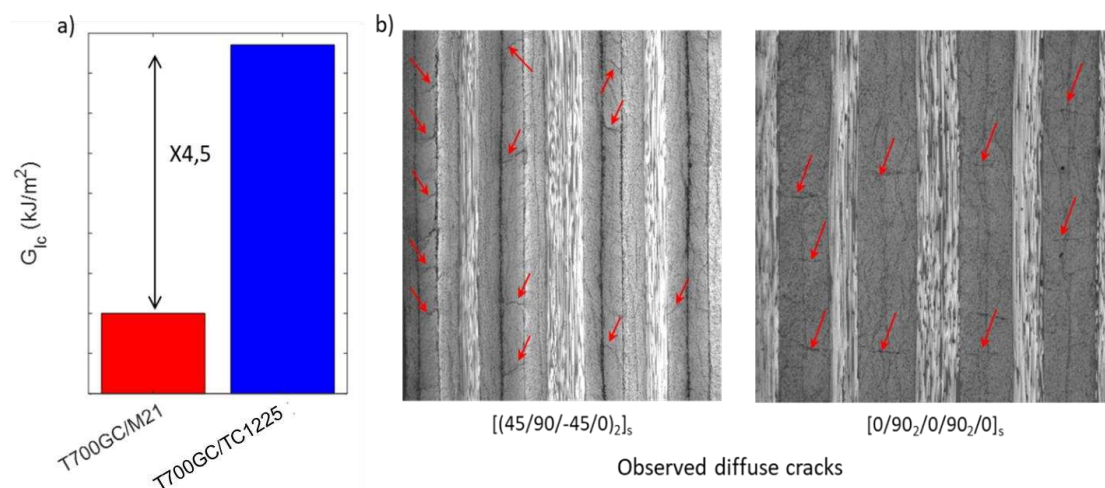


Figure 6: a) Comparison of the fracture toughness of T700GC/M21 and T700GC/TC1225 material and b) crack damage patterns observed on quasi-isotropic and cross-ply T700GC/M21 laminates

This very high fracture toughness may explain the short lengths of the observed transverse cracks and justifies probably the diffuse damage patterns, reported in Figure 6b for different

(quasi-isotropic and cross-ply) lay-ups, which is very different from those observed on Carbon/Epoxy materials presenting lower fracture toughness. It can be noted that plasticity, confined at the tips of the transverse cracks, can also partially explain the short lengths of the cracks and the diffuse damage pattern. Nevertheless, preliminary creep tests and measurements of permanent strains during regular unloading in tensile tests have not showed major differences in the non-linear behaviour prior cracks compared to the T700GC/M21 material.

To conclude this experimental study, diffuse damage patterns have been observed during tensile tests performed on different lay-ups which is a major difference compared to classical Carbon/Epoxy materials. Moreover, in-situ effect for the onset of damage, well established for carbon/epoxy materials, seems to be not relevant for this material probably due to the very high fracture toughness of the material in mode I.

4. A damage model for Carbon/Thermoplastic composites

4.1 Presentation of the damage and failure model

The objective of this section was to apply the existing Onera Progressive failure approach (OPFM), developed at Onera since many years for composite materials with thermoset matrix [10], to the T700GC/TC1225 in order to determine its advantages and drawbacks. The behaviour of the T700GC/TC1225 up to failure should be modelled considering the different sources of non-linearity (thermal residual stresses, viscosity, elastic non-linearity, intra-ply damage) at the ply scale using a laminate theory extended to non-linear behaviour. The prediction of the local non-linear mesoscopic behaviour up to the specimen failure is performed with the progressive failure approach proposed in [10], which is briefly summarized in this section. The present multiscale failure approach considers the unidirectional (UD) ply as the elementary entity of modelling and is predictive for different stacking sequences. It could be decomposed into four main steps. Firstly, in order to predict accurately the failure of a ply in a laminate, it is necessary to estimate correctly the mesoscopic stresses and strains. A non-linear thermo-viscoelastic behaviour has been proposed in Eq. 1.

$$\underline{\underline{\sigma}} = \underline{\underline{\tilde{C}}}: (\underline{\underline{\epsilon}} - \underline{\underline{\epsilon}}^{th} - \underline{\underline{\epsilon}}^{ve} - \underline{\underline{\epsilon}}^{nl}) \quad (1)$$

where $\underline{\underline{\sigma}}$ is the mesoscopic stress, $\underline{\underline{\tilde{C}}}$ the effective rigidity, $\underline{\underline{\epsilon}}$ the total strain, $\underline{\underline{\epsilon}}^{th}$ the thermal strain (in order to take into account the thermal residual stresses, which are essential to predict accurately the first ply failure), $\underline{\underline{\epsilon}}^{nl}$ the non-linear elastic strain (in order to describe the hardening observed experimentally on UD plies subjected to longitudinal tensile loadings and especially on new generations of composite materials such as T700GC/M21 [3] or observed on the studied material), and $\underline{\underline{\epsilon}}^{ve}$ the viscous strain. Secondly, the prediction of the ply failure within the laminate is performed with a failure criterion, based on Hashin's hypotheses [11], distinguishing the fibre failure mode and the in-plane interfiber failure mode and modelling separately the failure mechanisms in tension and in compression for each failure mode. The two main improvements of the fibre failure criterion, as compared to Hashin's criterion, are (i) the introduction of coupling between the intralaminar damage d_2 and the longitudinal tensile strength X_t (allowing to obtain conservative predictions for complex multiaxial loadings) and (ii) to take into account the influence of the in-plane shear on the ply failure in compression. The main improvement of the interfiber failure criterion is a better description of the reinforcement

of the apparent strength of the material for combined in-plane shear and transverse compressive loadings. Thirdly, when a ply within the laminate is broken in interfiber mode (*i.e.* when transverse cracks are present in the ply), its mechanical properties are progressively degraded using a thermodynamical degradation approach based on damage modelling already developed at Onera [10]. A continuum damage model is relevant for the T700GC/TC1225 due to the diffuse cracks observed within the ply. Fourthly, for a laminated unnotched coupon, the final rupture could be due to the first ply failure in fibre mode or in transverse compression.

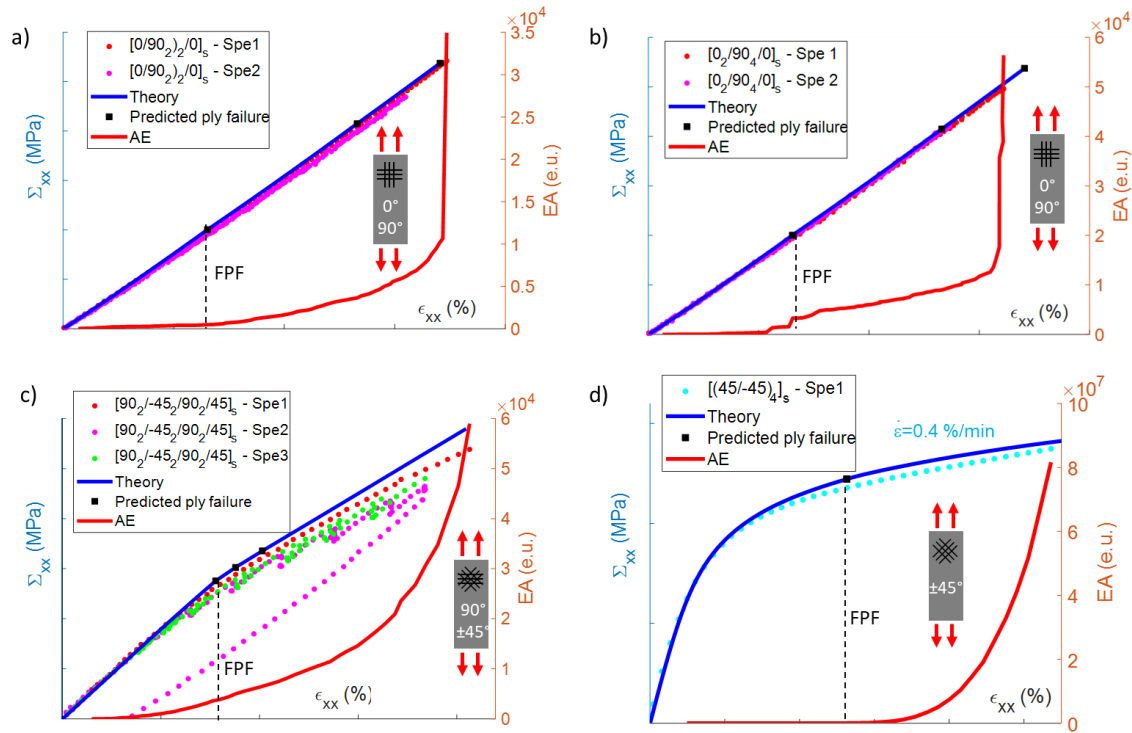


Figure 7: Comparisons between tests and model predictions for a [0/90₂/0/90₂/0]_s laminate subjected to tensile loading, b) a [0₂/90₄/0]_s laminate subjected to tensile loading, c) a [90₂/-45₂/90₂/45]_s laminate subjected to tensile loading, and d) a [(45/-45)₄]_s laminate subjected to tensile loading

Finally, the model has been identified on the available tests and applied successfully to other tests for validation. The tensile tests on 0° and 90° plies and [±45°]_s laminate have been used for identification of the model. For the two considered cross-ply laminates, while the thickness of the 90-ply has been doubled, the apparent strength of the ply seems to remain constant, as reported in Figure 7. Additional test on cross-ply laminates will be performed soon. The predicted macroscopic behaviour for the [90₂/-45₂/90₂/45]_s laminate is in rather good agreement with experimental data while the first ply failure is overestimated. Finally, the first ply failure within [(45/-45)₄]_s laminate is accurately predicted by the model. Additional tests on laminates with different ply thickness should be performed soon to determine the ply thickness influence on apparent in-plane shear strength.

5. Conclusion / Perspectives

This study is a first step towards the characterization of the T700GC/TC1225 thermoplastic matrix material by trying to identify the similarities and differences with the carbon/epoxy

materials conventionally used in the aerospace industry. Particular attention was paid to the transverse cracking pattern presenting a diffuse nature of the damage within the plies, which constitutes a strong difference with the observations performed usually on carbon/epoxy materials. These diffuse damage patterns are probably due to the very high fracture toughness in mode I of the material (4.5 times higher than that of T700/M21). Finally, the Onera model, initially developed for thermoset matrix composites, was applied to the study material. Although the first simulations are in relatively good agreement with the test data, it seems necessary to take into account the plasticity of the matrix in the model and to introduce a particular management of the influence of the thickness of the plies on the transverse cracking (no influence on threshold but on the evolution law).

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