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Modèle multi-échelles et mesures de l'endommagement pour optimiser l'utilisation des structures composites stratifiées

Optimizing the use of laminated composite structures from multiscale damage models to damage measurements

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Résumé

Bien que les modèles d'évolution et les mesures d'endommagement aient fait de grands progrès, la rupture des structures composites stratifiées reste un phénomène mal-maîtrisé, à la fois complexe et multi-échelle. En associant la modélisation et la mesure de l'endommagement, nous proposons une approche pour optimiser l'utilisation des structures composites stratifiées tout au long de leur durée de vie, depuis la validation de modèle jusqu'à l'analyse de la rupture. Cette approche s'appuie sur les mesures obtenues par micro-tomographie ainsi que sur le modèle développé au LMA. Ces mesures sont utilisées dans un premier temps pour valider le modèle de comportement. Dans un second temps, nous nous intéressons à l'estimation de la durée de vie des structures ainsi qu'à leur expertise post-rupture à partir de l'utilisation conjointe du modèle et des mesure d'endommagement.

Abstract

Fracture in composite materials is a difficult topic because it involves several complex mechanisms operating on various scales. The methods of damage measurement and damage evolution modelling available have progressed considerably, however. The method presented here, in which both damage measurement and damage modelling approaches are combined, provides an efficient means of optimizing the use of laminated composite structures.
This method based on MicroCT measurements combined with the damage behaviour model developed at our laboratory (LMA) was used to further develop the latter model and prove its validity. This combined approach can be used to study laminated parts throughout their lifetime, from the design process to the analysis of broken parts. Some potential applications for this combined damage measurement and damage modelling approach are presented, such as predicting the lifetime of manufactured parts and tracing the loading history of accidentally broken parts.

Mots Clés : Composites stratifiés , Mécanique de l'Endommagement, Calcul par Eléments Finis, Micro-tomographie
Keywords : Laminates, Matrix cracking, Damage mechanics, Finite Element Analysis, Micro-Computed Tomography

1. Introduction

Fracture in composite materials involves several mechanisms operating on various scales [1], such as matrix cracking, fiber/matrix debonding, transverse failure, delamination and fiber failure mechanisms. These damage processes are difficult to observe because they occur on such a small scale, and because the various damage processes involved tend to interact. However, the experimental methods for measuring damage in composite materials have improved considerably during the last few years. Those experimental methods depend on the type of damage involved and the scale on which the damage occurs.

On the macro-scale, the most widely used methods are high-frequency ultrasonic C-scan methods [2], computed tomography (CT) [3] and optical photography. Although ultrasonic scanning and computed tomography methods are rather limited by the resolution, they can also be used to detect small defects or the damage present on the meso-scale, which is the scale of the ply [4]. On the micro-scale, only a few methods have a sufficiently high resolution for measuring damage such as confocal microscopy [5] and scanning electron microscopy (SEM) [6]. Finally, the sub-micro-scale measurements are still in the early stages of development as for example cone-beam micro computed tomography [7] and synchrotron radiation computed tomography [8-9]. The images obtained with these methods reflect the density of the object examined: the denser the material, the higher the absorption will be.

Similarly, damage behavior models for composite materials have been developed on different scales, depending on the type of damage involved. Some models based on failure criteria were developed on the scale of the laminate (the macro-scale) in order to predict damage initiation [10]. On the scale of the ply (the meso-scale), these models have been based mostly on :

- continuum damage mechanics (CDM) in order to describe the effects of the damage on the behavior of the laminate [11-13]
- fracture mechanics in order to predict the initiation/propagation of the damage via cracks or delamination processes [14-15].

On the scale of the components (fibers and matrix, the micro-scale), models describe the damage processes occurring in laminates fairly accurately [16]. Lastly, multi-scale models combine all these one-scale models in order to be more consistent with the real nature of damage mechanisms [17].

The aim of this paper is to show that a combination between experimental measurements and numerical modeling methods provides excellent means of optimizing the use of laminated composite structures. Firstly, MicroCT measurements were used to validate the damage behavior model developed at the LMA (Laboratoire de Mécanique et d'Acoustique, Marseille). Previous works validated the non-local failure criterion of this model [18-20] based on the failure of various laminated structures subjected to tension loading conditions. In this paper MicroCT measurements are used to confirm the effects of transverse cracking, including matrix microcracks, fiber/matrix debonding and the inelastic shear strain, which is described by this model [21]. Secondly, we show how the maintenance and the investigation of failed parts can be improved with damage measurements and computations. The computations are used to identify where and what kind of damage have to be measured in order to prognostic lifetime (maintenance) or to diagnostic failure (investigation).

2 Validity of the damage model

Comparisons between experimental damage measurements and the numerical predictions were performed to analyze the matrix cracking process which occurs under static and fatigue loading conditions. Two interacting mechanisms that merge and lead to transverse failure process were involved: matrix micro-cracking and fiber/matrix debonding [22]. In the case of woven ply material, the transverse failure is prevented by the woven texture. The extent of the damage is very small and therefore is difficult to detect. The effect of these mechanisms on the behavior of the material is modeled with three parameters. The following two assumptions were adopted:

- the damage evolution law is defined by the values of the stresses [11]
- cumulative damage law is used in the case of fatigue loading [23].

2.1 The damage evolution law

The model, which was based on a CDM approach, describes the effects of the damage in a unidirectional ply (UD), focusing on the matrix cracking process. Multidirectional plies are assumed to (UD) assembly. Small cracks develop in the matrix and run along the fibers, and the stiffness of the material is thus decreased. The variable d is taken to denote the damage as follows:

- d_1 is the damage in the fiber direction,
- d_2 is the damage in the transverse direction,
- d_{12} is the damage in the shear direction.

Matrix cracks are assumed to have effects in both the transverse and shear directions. The behavior is linear and elastic in the fiber direction. The effects of the damage on the stiffness are written as follows:

$$E_2 = E_2^0\left(1-d_2\right) \quad \& \quad G_{12} = G_{12}^0\left(1-d_{12}\right) \qquad \text{(Eq. 1)}$$

where E^0_2 is the initial Young's modulus in the transverse direction and G^0_{12} is the initial shear modulus.

The damage evolution law is then written as a function of both the transverse and shear stresses [21]. In the case of static loading conditions, it is defined as follows:

$$d_2 = \left\langle 1-e^{-\left(a\cdot Yd_2^m + b\cdot Yd_{12}^n - Y_0\right)}\right\rangle_{+}. \quad \& \quad d_{12} = cd_2 \qquad \text{(Eq. 2)}$$

where:

$$Yd_2 = \frac{\langle \sigma_2 \rangle_{+.}^2}{2E_2^0(1-d_2)^2} \quad \& \quad Yd_{12} = \frac{\sigma_{12}^2}{2G_{12}^0(1-d_{12})^2} \qquad \text{(Eq. 3)}$$

In this model, the behavior of woven ply is assumed equivalent to that of [0/90] laminate consisting of two UD plies [18,24]. For these laminates, the damage evolution in the warp direction corresponds to transverse damage d_2 in the 0°-oriented plies. The damage evolution in the weft direction corresponds to transverse damage d_2 in the 90°-oriented plies.

Let us now compare the damage evolution predicted with the model and measured by MicroCT. A $[0]_8$ Carbon/epoxy laminates consisting of balanced woven plies were studied under tension loading conditions experimentally. The test was stopped before failure of the specimen occurred and same loading conditions were used in the model to predict the level of damage at the end of the experiment. This level of damage was predicted to reach 0.11 in the warp direction and 0.57 in the weft direction. Experimental measurements of the damage were then performed on the $[0]_8$ specimen by MicroCT. These results are presented in *Fig. 1.*, where the presence of matrix cracks are observed in both warp and weft directions, as predicted by the model. A change in the crack density between the two directions is also perceptible.

This result confirms the first assumption of the model that damage is related to the stresses and not the strains, which are negative in the weft direction, due to the Poisson's coefficient. This damage increased in the direction perpendicular to the load (weft) as well as in the direction parallel to the load (warp). This result shows also that the level of damage can be directly estimated with the matrix crack density that is visible in MicroCT images. Nevertheless, this estimation is still qualitative and further works are in progress to obtain a quantitative estimation of damage.

2.2 Fatigue description of damage

The damage behavior model was previously developed in the case of static loading conditions. The extension to the case of fatigue loading conditions is based on a cumulative damage concept [23]. The behavior of the material was therefore modeled under cyclic loading conditions. As similar damage mechanisms were assumed to occur under both static and fatigue loading conditions, we define the total damage parameter as the sum of two damage parameters associated to static case and fatigue case :

$$d_2 = d_{2s} + d_{2f} \qquad \text{(Eq. 4)}$$

The first loading cycle is similar to static loading conditions and results in the level of damage d_{2s} defined by (EQ. 2). The damage d_{2f} then increases with the number of cycles, N, as follows:

$$\frac{\partial d_{2f}}{\partial N} = (1-d_2)^{\gamma} \langle a_f \cdot (Yd_2)^{\beta_1} \cdot (\Delta Yd_2)^{\beta_2} + b_f \cdot (Yd_{12})^{\beta_3} \cdot (\Delta Yd_{12})^{\beta_4} - Y_0^f \rangle_{+.} \qquad \text{(Eq. 5)}$$

where Y_0^f is the endurance limit: the damage due to cyclic loading evolves up to this threshold, and :

$$\Delta Yd_2 = \frac{\left(\langle \sigma_2^{max} \rangle_{+.} - \langle \sigma_2^{min} \rangle_{+.}\right)^2}{2E_2(1-d_2)^2} \quad \& \quad \Delta Yd_{12} = \frac{\left(\langle \sigma_{12}^{max} \rangle_{+.} - \langle \sigma_{12}^{min} \rangle_{+.}\right)^2}{2G_{12}(1-d_2)^{12}} \qquad \text{(Eq. 6)}$$

Static and fatigue tests were performed on $[0]_8$ laminate consisting of carbon/PEEK woven plies. The specimens were subjected to tension loads. Both tests were stopped before the final failure of the specimens. The fatigue tests consisted in applying the same tension load to the specimens as in the static tests. The number of cycle N was changed to estimate the damage evolution as the fonction N. Results of the MicroCT measurements are presented in Figure 2. Image (a) shows the damage occurring in the material after static loading, a few matrix cracks are observed. Image (b) shows an increased number of matrix cracks compared

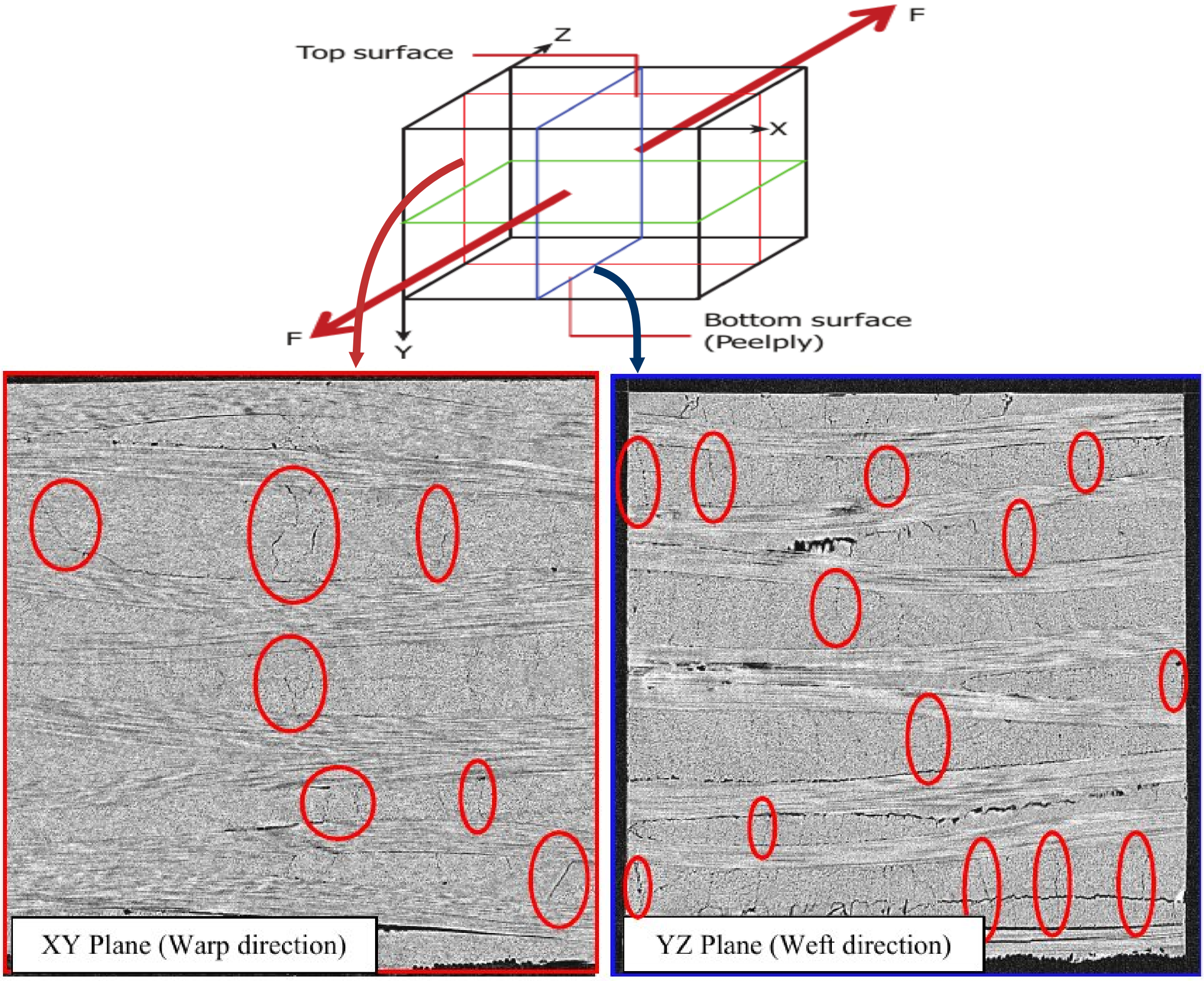

Fig. 1. MicroCT measurement of matrix cracks in a carbon/epoxy [0]8 woven laminate under tension loading conditions.

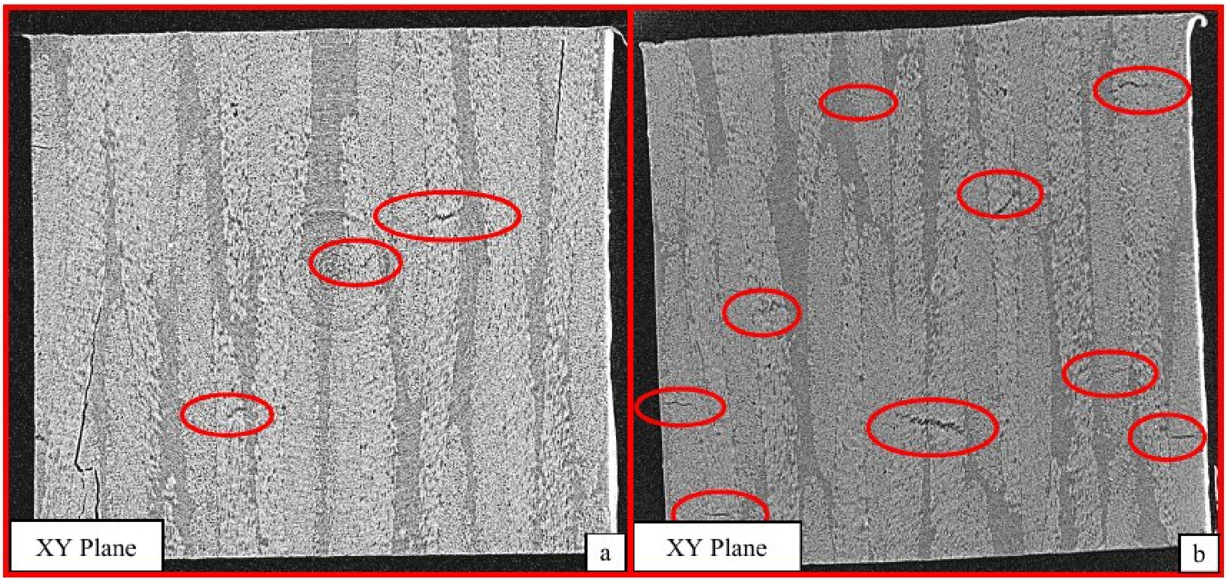

Fig. 2. Damage evolution in carbon/peek woven laminate from a) static loading to b) fatigue loading The number of loading cycle is the only parameter changed between these two images.

to image (a). This image corresponds to a MicroCT after the fatigue loading for the same tension load as the static loading. Because MicroCT is a destructive measurement method, these MicroCT images were made from different specimen. Comparison between static and fatigue loadings is impossible with the same specimen.

These comparisons confirmed the validity of the cumulative damage concept for fatigue loading. The damage starts with static loading and this damage increases with the number of fatigue cycles. Moreover, only the density of the damage was found to evolve during fatigue loading in the cases studied. That is also confirmed by Poisson's ratio evolution of woven ply laminates in static and fatigue loading conditions [24]. Further works are in progress to increase experimental result in order to quantify the damage evolution for fatigue loading.

3 Toward the optimum use of composite material laminates

3.1 Improving the maintenance

The maintenance for composite structure is based on the detection of a characteristic crack length. This length is currently determined by the barely visible rule. Composite parts have to be repaired as soon as a crack is seen by the maintenance crew. Nevertheless, this rule is empirical and the recent results about model validity range can help to decide precisely whether the part has to be replaced or repaired or not. The characteristic crack length is obtained by simulations made on the notched part. This length corresponds to the maximal length before crack propagation.

For example, figure (3) shows the monitoring of a crack propagation on a glass/epoxy specimen. The initial state of the specimen, a)., corresponds to a barely visible crack length. Fatigue loading is applied to the specimen then, and the corresponding crack propagation is monitored. We observe that this crack is stable which means that the propagation depend on the number of cycles. The part lifetime is therefore increased with these loading cycles. This observation is made when the size of the initial crack is small in comparison to the structure. When the crack becomes large enough and reaches a characteristic length, then the propagation become unstable and the structure failed.

The application of this method in aeronautics depends mainly on the validity of the model. Some work are in progress to validate crack initiation on real composite structure. The proposed approach is to :

- Detect a crack initiation.
- Compute the supplementary lifetime expressed as a number of loading cycles.
- Decide whether this lifetime is acceptable or not.
- Instrument the cracked part if this cracked part is conserved in order to monitor crack propagation for security reason.

3.2 Investigating failed parts

The following example of how the present method can be applied is that of accidentally failed structures, Investigations are necessary to understand whether the accident was due to faulty design, manufacturing errors, or misuse. But, composite failure is difficult to investigate, since much of the information available at the fracture surface is destroyed during this failure process. However, failure also affects a larger region, which is not completely destroyed by the propagation of the damage. Combining damage measurement with the modeling approach helps therefore to investigate a fractured part.

Figure 4 shows the damage evolution in a holed plate under tension loading. This simulation is linked with MicroCT measurement made on a tested specimen. The regions with a high level of damage are correctly predicted by the model. This result is observed on the MicroCT image of figure 4. The analysis of postmortem damage in specific region leads therefore to identify whether the loading conditions were tension or not depending on the correlation between the model predictions and the measurements.

This approach was confirmed by performing simulations on a carbon/epoxy $[0]_8$ woven laminate

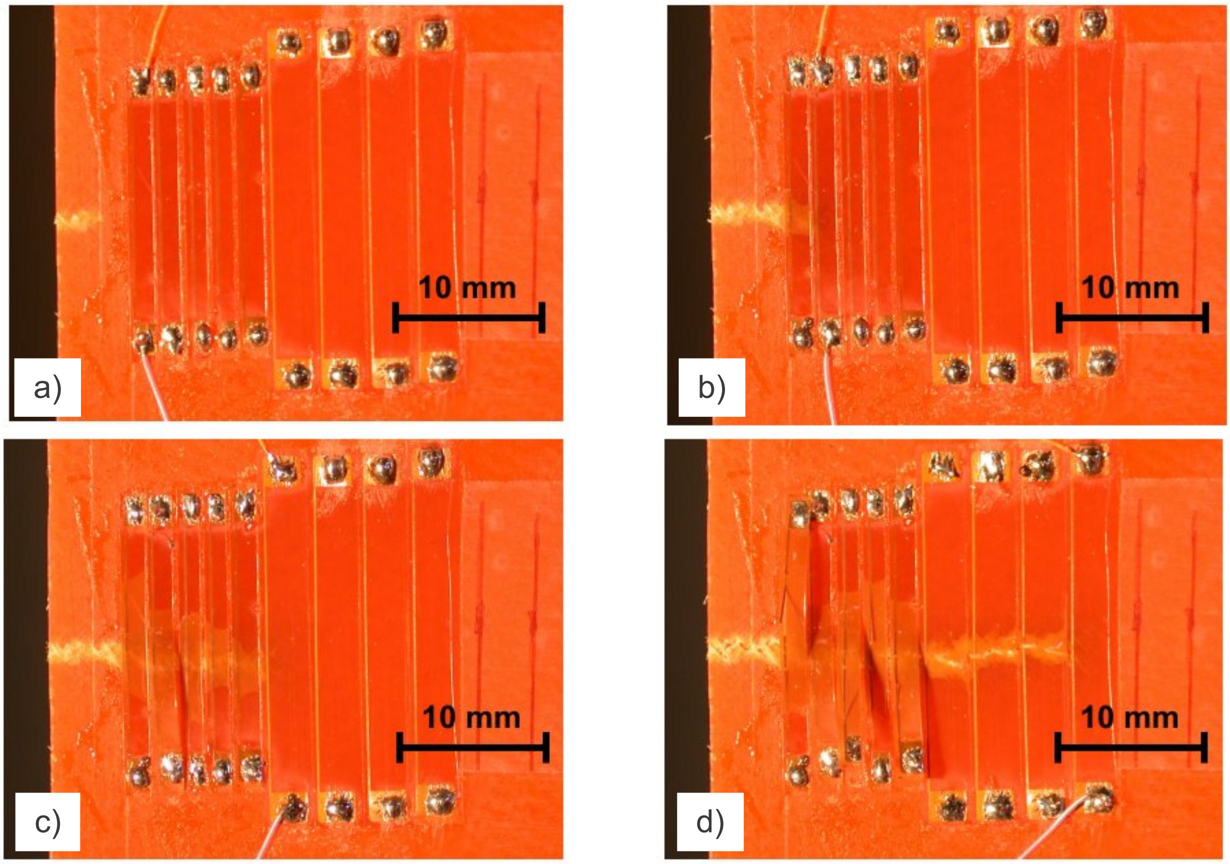

Fig. 3. Crack propagation and measurement in fatigue. This propagation is observed with a high number of loading cycles.

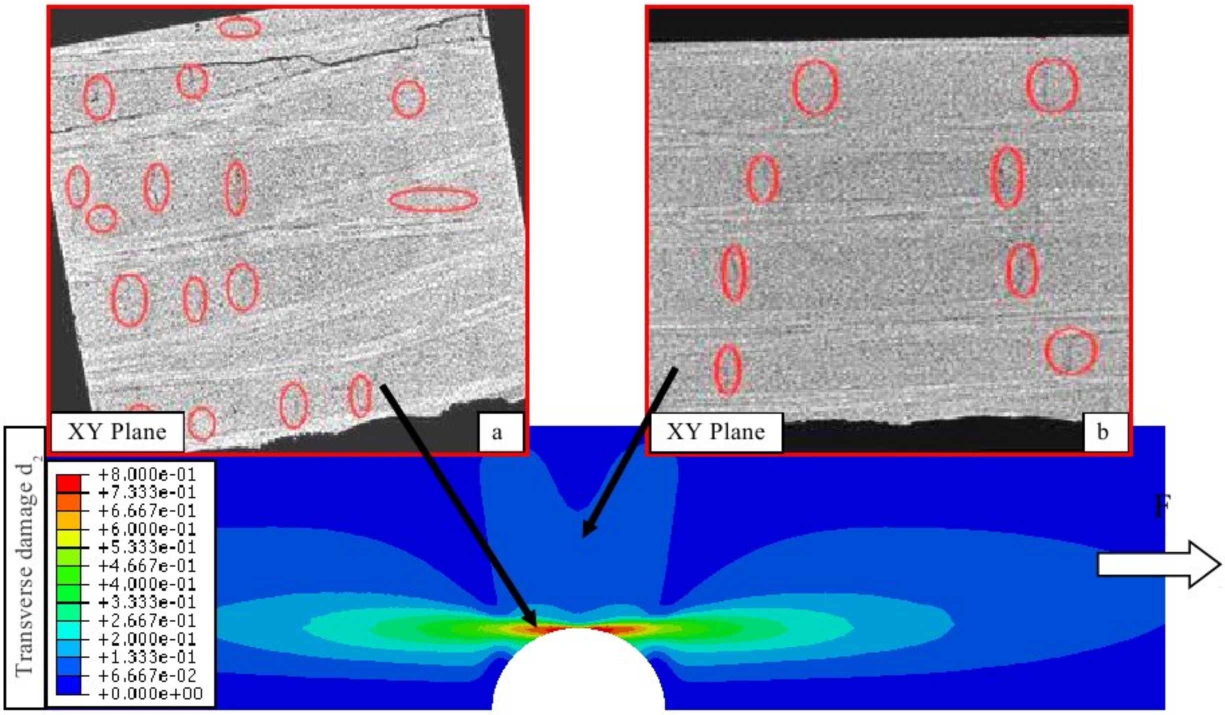

Fig. 4. Comparison between MicroCT measurements of matrix cracks and numerical simulation of the level of damage in a [0]8 woven laminate with a hole under tension loading. a) MicroCT image close to the hole. b) MicroCT image far from the hole.

tube with a hole. Three different loading conditions were applied to the structure : a) tension load,b) torsion load, and c) combined tension/torsion load. The damage maps obtained by performing the numerical simulations are presented in Figure 5 in the three loading situations. The damage distribution dependent strongly on the type of load applied to the structure. This result shows the interest of measuring damage in particular region in order to identify the type of loading conditions that led to the structural failure. This approach is based on the model predictions to choose the observed region.

If we want to know what type of load undergone by the real tube before it failed, MicroCT measurements of the damage have to be performed on specimens taken at various points around fractured zone. By comparing the levels of damage predicted by the model with the data giving the damage density in the various specimens, it is possible to retrieve the loading history. Several loading situations have to be simulated in order to obtain which situation matches the pattern of damage distribution observed experimentally. Experiments are in progress now to validate this identification procedure.

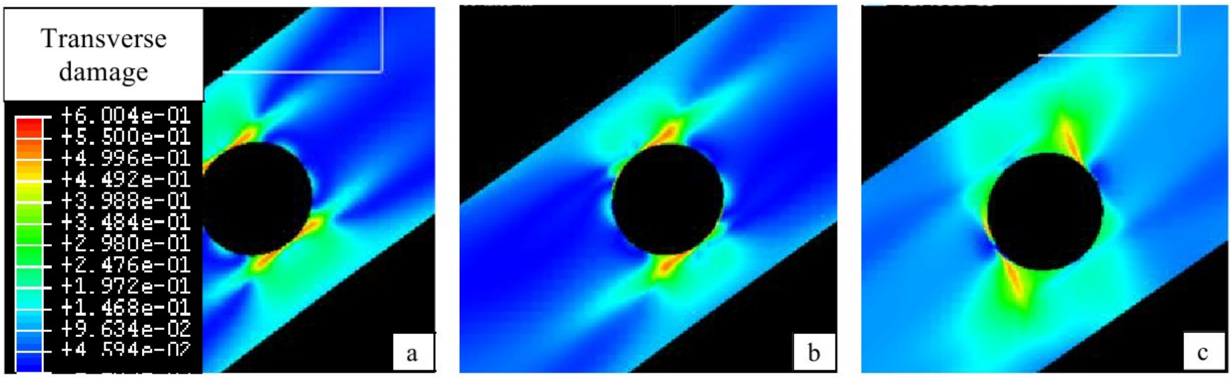

Fig. 5. Influence of the loading on the damage evolution inside a tube with a hole.
a) Tension load b) Torsion load c) Combined Tension/torsion load

4 Conclusion

In the method presented here, damage measurements were combined with damage modeling with a view to optimizing the use of laminated composite structures and predicting their behavior throughout their lifetime. We use MicroCT in order to qualitatively validate the composite material model developed at LMA, and in order to show the application of combining model and experiment to optimize the use of composite structures during maintenance and failure investigations process.

This method was applied to various cases, including composites with thermoset and thermoplastic resins under static and fatigue loading conditions. Studies are now in progress with a view to quantifying these preliminary results and with a view to extending the use of this method to studies on the durability of carbon/epoxy woven ply laminates. The effects of temperature and moisture on the damage evolution in the material are also being investigated.

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