X-ray µCT based assessment of thermal cycling induced cracks in non-crimp 3D orthogonal woven composite materials with porosity

M. Gigliotti¹*, Y. Pannier¹, Y. Sinchuk¹, R. Antoranz-Gonzalez¹, M.C. Lafarie-Frenot¹, S.V. Lomov²

¹Institut Pprime, University of Poitiers, ISAE-ENSMA, CNRS 3346 - Department of Physics and Mechanics of Materials - 1, Avenue Clément Ader F-86962 Futuroscope Chasseneuil, France
²Department of Materials Engineering, KU Leuven Kasteelpark Arenberg 44 bus 2450, 3001 Leuven, Belgium

* marco.gigliotti@ensma.fr

Abstract. This work focuses on X-ray micro-Computed Tomography (µCT) assessment of thermal cycling behavior of a carbon fiber/epoxy matrix composite material reinforced with a non-crimp 3D orthogonal woven preform (3DNCOW) with porosity. Porosity levels and damage mechanisms – i.e. matrix cracking - induced by thermal cycling are characterized by X-ray micro-computed-tomography (µCT). Qualitative and quantitative descriptions of the morphology and the evolution of cracks with thermal cycling are carried out through the analysis of µCT scans of samples at different cycle numbers, with emphasis on the influence of porosity on the damage mechanisms induced by thermal cycling. X-ray µCT image-based Finite Element models are employed to provide rational interpretation to the observed phenomenological scenario.

1. Introduction

Due to their low through-thickness mechanical properties, 2D laminated composites have somehow limited application associated to quite poor mechanical behavior along the transversal direction ([1]).

To overcome such shortcomings various types of composite materials with three-dimensional (3D) fiber structures incorporating fibers in the direction normal to the plane of the material, commonly known as 3D fiber textile composites, have been developed. Among others, the 3D non-crimp orthogonal woven (3DNCOW) developed at North Carolina State University [2-4] stands out for allowing industrial-scale production of unitized thick preforms by using 3D weaving machines which are fully automated. To be fully exploitable, the mechanical behavior of such material needs to be deeply characterized. Extensive characterization of the quasi-static tensile and fatigue tension behavior of such material has been carried out and reported in references [5-7]. Not much work has been carried out concerning the response of such materials to environmental solicitations and thermal cycling.

The aim of this work is to provide X-ray micro-Computed Tomography (µCT) assessment of thermal cycling behavior of 3DNCOW material with porosity. Following an experimental work by the same authors [8], the present paper reports first some experimental evidence ([8]) in Sections 2 and 3, concerning:
• porosity levels and matrix cracking induced by thermal cycling and characterized by X-ray micro-computed-tomography (μCT),
• qualitative and quantitative descriptions of the morphology and the evolution of cracks with thermal cycling carried out through the analysis of μCT scans of samples at different cycle numbers.

Emphasis is put on the influence of porosity on the damage mechanisms induced by thermal cycling due to constrained thermal deformation of polymer matrix between carbon yarns.

X-ray μCT image-based Finite Element models are then employed in Section 4 for simulations: the aim of this activity is not to show the capability to perform detailed simulation of the complete thermal cycling behavior but the emergence of the employment of realistic materials models with defects necessary to provide rational interpretation to the observed phenomenological scenario and for the development of proper Virtual Testing Tools.

It should be emphasized that there exist extensive literature on thermal cycling of composite laminates ([9]) made by pre-pregs with continuous long-fibres. In this case, thermal cycling solicitations induce regular matrix cracking patterns in the composite plies whose density increases with increasing number of cycles: for laminates with simple stacking sequence, the specificity of the cracking pattern allows employing semi-analytical methods based on the concept of Energy Release Rate for composite laminate configurations [10].

With respect to these literature studies, the issue of thermal loading of 3D textile materials involves higher complexity, intrinsic to the complexity of the fibrous texture ([11-14]): the employment of dedicated detailed FE models is of paramount importance to understand the complex damage phenomenological scenario.

2. Material, samples, experimental setup, image-based FE model construction
This section illustrates the material, the samples, the experimental setup and the basic steps leading to the image-based FE model construction. More details about the description of the experimental setup and the employed material samples are given in reference [8].

2.1. Material, samples, experimental setup
The studied material is a non-crimp 3D orthogonal woven carbon/epoxy composite (3DNCOW, commercial name is 3WEAVE®). It was manufactured in 2011 by 3TEX, Inc by using a Vacuum Assisted Resin Transfer Molding (VARTM) process [2-4].

The epoxy resin used in this material is the West System 105 with 209 Extra Slow Hardener, with a glass transition temperature (Tg) equal to around 54°C.

Figure 1 illustrates a material Unit Cell (UC): the preform is composed of three warp layers (red) and four fill (yellow) layers, separated by two Z yarns (green), the presence of which leads to some spaces, respectively between the warp and weft yarns.

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Figure 1. Schematic representation of the Unit Cell architecture of the 3DNCOW fabric (see also references [5-8]).
For the experimental activity, two different series of 8 samples were therefore cut in these regions, whose dimensions were determined based on the repetition of one (1 UC) or two (2×2 UC) geometric unit cells along the width and the length of the specimens. Table 1 reports experimental measurements of the specimens’ dimensions.

Table 1. Average specimens’ dimensions (8 samples per series, ± means standard deviation).

|        | 1 UC      | 2×2 UC    |
|--------|-----------|-----------|
| X (mm) | 5.7 ± 0.3 | 10.8 ± 0.3|
| Y (mm) | 5.0 ± 0.1 | 10.8 ± 0.1|
| Z (mm) | 2.7 ± 0.01| 2.7 ± 0.01|

Specimens were subjected to triangular thermal cycles (+50°C/-50°C, the maximum temperature slightly lower than T_g), with constant heating and cooling rates of 4°C/min, up to 1400 cycles, corresponding to laboratory conditions.

The X-ray micro-tomography imaging technique employed to visualize the 3D architecture of the composite material as well as the different defects present in the virgin sample or induced by thermal cycling employs UltraTom CT scanner, manufactured by RX-Solutions, allowing achieving a minimal resolution of around 0.25 µm. A sealed type micro-focus X-ray source with Tungsten target was used. Filament voltage and current were 60kV and 72µA leading to a focal spot around 5µm. For each specimen, 1440 radiographies were recorded with a Varian flat panel of 1920×1536 pixels. Reconstruction was achieved by FBK algorithm with XAct RX-Solutions software.

All the details of the image segmentation protocol including segmentation of matrix, yarns, porosity and cracks are reported in reference [8]: for the purpose of illustration, Fig. 2 shows a 2D slice of a 1 UC sample with a detail of the different phases to be segmented (Fig. 2a) and the corresponding gray values histogram (Fig. 2b).

![Figure 2](image-url)

**Figure 2.** Example of a 1 UC 2D slice obtained from the 3D tomographic reconstruction a) detail of the different phases to be segmented b) corresponding histogram of gray values (see also reference [8]).

The range between 5000 and 10000 gray levels is relatively narrow in comparison with the full image dynamic range (0 to 65536), showing that the contrast between the different phases is quite low. The darkest gray values correspond to the lowest intensity values (more to the left in the histogram) while the lightest ones correspond to highest intensities (more to the right in the histogram). Fig. 3b shows that there are two well-differentiated peaks; the first one corresponding to porosity and exterior air, the second one including matrix and yarns. However, since the matrix is slightly darker than the yarns, a
left dissymmetry of the second peak can be noted. The cracks gray levels result between these two main peaks.

All segmentations are performed with the aid of Avizo® segmentation editor (a commercial editor that facilitates Boolean operations on labeled materials) and by employing a semi-manual procedure (see also reference [8] for more details).

One of the main interests of 3D scan of composite samples with complex texture is to get the real geometry of the composite. Figure 3 illustrates a 3D reconstruction of a 1 UC sample obtained by segmenting a XRay µCT scan of a virgin specimen. The shapes of the specimen and the yarns are obtained here by contouring them manually in different orthogonal slices. The final 3D shapes are then obtained by interpolations between successive contours.

![Figure 3](image)

**Figure 3.** 3D representation of the different constituents of a real 3DNCOW Unit Cell after segmentation: a) full ample, b) sample without matrix, c) matrix with porosity ([8]).

Figure 3 illustrates the different constituents of the sample: red and yellow entities illustrate, respectively, warp and fill yarns, green entities illustrate the yarns in the through-the-thickness direction while blue entities illustrate the polymer matrix with porosity.

Table 2 resumes average and standard deviation global porosity volume fraction values (% \( V_{fp} \)) for 1 UC and 2×2 UC samples.

**Table 2.** Average and standard deviation global porosity volume fractions values for 1 UC and 2×2 UC samples.

| Size      | % \( V_{fp} \) | Resolution |
|-----------|---------------|------------|
| 1 UC      | 0.99 ± 0.06   | 8.34 µm    |
| 2×2 UC    | 0.85 ± 0.03   | 8.34 µm    |

2.2. µCT image-based FE model construction

The basic principles of the µCT image-based FE model construction are presented in detail – for a different textile material – in references [13, 14]. Generally, the technique can be referred as a “global-local” approach, since it allows simulating hierarchically - at different scales – the behavior of a tested sample. The approach involves:

- the employment of a voxel mesh FE model at the sample scale; this is referred as global model,
- the employment of smooth interface reconstruction followed by tetrahedral volumetric meshing at the yarn/matrix interface scale; this is referred as local model.

The FE analysis carried out by the global model at the sample scale allows identifying critical zones that are then analyzed in more detail through the use of the local model, which is refined both in terms of resolution and in quality of the mesh.

All models are developed within the framework of the ABAQUS® FE commercial software. Global and local models are linked by using the ABAQUS® submodeling technique, since the submodels have
relatively small influence on the higher level models behavior. Simulation at the higher scale is performed independently from the lower scale model. By employing the node-based submodeling technique, the submodel boundary conditions are taken from the output file of the upper level simulation. Boundary condition setting needs to select all external nodes as set of driven nodes: then, ABAQUS® automatically interpolates the boundary conditions at driven nodes based on nodal values of a global (upper level) simulation.

2.2.1. Global model. X-ray µ-CT data of a 1 UC sample (8.34 µm resolution) are used for the construction of the global model at the sample scale. The 3D image has dimension 702×343×630 voxel (in X, Y, Z axis directions, respectively), with voxel size 0.00834 mm. The first necessary step of model creation is segmentation of the image. For the purpose of model construction, the ImageJ® software is employed for segmentation, by a semi-manual procedure including the selection of yarn cross-section regions and manual improvement by filling of tiny artificial gaps between the yarns and yarns interpenetrations. The pore segmentation was performed by separating the pores from the initial image using brightness/contrast adjustment, then by smoothing the pores by median filter application and by removing very tiny pores; finally, the pores were combined with the result of tow segmentation.

Figure 4. Voxel mesh model of a composite sample (192×97×174 voxels, 3 times decreased initial resolution): a) full sample b) porosity c) through-the-thickness yarns (with corresponding orientations) d) matrix phase e) warp and f) fill yarns.

The polymer matrix is considered as an isotropic material, while yarns are considered as orthotropic, whose behaviour is calculated by analytical and numerical homogenisation tools [13, 14].
For yarn orientation recognizing and assignment, it is assumed that the orientations of warp and fill yarns are along the X and Y directions, while concerning through-the-thickness yarns orientation, the orientation of the yarn central line is calculated along a discrete set of axial points: the yarn axes obtained by skeletonizing 2D cross-sections along the XZ plane. After that, manual selection of some marker points along the yarn axis is carried out and the coordinates of such points are stored in text format file using ImageJ® scripting. The orientation at each yarn segment between two marker points is calculated as the orientation of the straight line going through two marker points. The obtained values are used in Abaqus ORIENT subroutine for getting material orientation at any point of the vertical tows.

A MATLAB® script is implemented for generating FE model as Abaqus .INP files from 3D image segmentation results: the resulting FE mesh has regular grid structure where sets of elements correspond to different voxels colours. Decreasing image resolution with the aim of reducing the model size is acceptable as long as models with decreased resolution give comparable results with respect to models with full resolution. In the present case, it is found that the initial resolution can be reduced by 3 without degrading the quality of the output result. Fig. 4 illustrates in detail the resulting voxel mesh FE model: this model employs 192×97×174 voxels with a 3 times reduced initial resolution.

A non-porous sample can be obtained by numerically filling all pores with material matrix elements or by idealisation of the texture geometry (Fig. 5): in this last case, starting from 2D µCT manual tracing by splines and lines along real images in Abaqus CAE environment allows building a CAD sample draw. By doing this drawing it is assumed that the surfaces between warp and fill yarns are planar, which is close to the real microstructure. The employment of semi-idealised model allows adopting tet-meshing strategies. The resolution of the non-porous semi-idealised model in Fig. 5 is very close to the voxel mesh based model in Fig. 4.

Figure 5. Semi-idealised tet-mesh model of a composite sample: a) full sample b) through-the-thickness yarns c) fill yarns d) warp yarns e) non-porous matrix phase.

2.2.2. Local model. At the local level (yarn/matrix interface), the model image is taken from the initial image of the whole composite sample (Fig. 6a), tetrahedral meshing with smooth material interface is used, with refined representation of the material interfaces and void contours (Figs. 6b and 6c).
The model with pores in Fig. 6 contains 1592120 elements, the equivalent model without pores (obtained by pore filling) contains 1462717 elements (more elements due to pore filling, less mesh refinement at the voids contour).

3. **Thermal cycling induced cracks: experimental evidence**

The experimental scenario of thermal cycling induced cracks is exhaustively reported in reference [8], here the main results of the experimental activity are recalled.

Fig. 7 illustrates the 3D representation of 1 UC and 2×2 UC samples and the development of matrix cracks (in blue) after 200, 800 and 1400 thermal cycles. After 200 thermal cycles (Figs. 7a and 7b), few small cracks can be observed in each sample. These first cracks are observed in an inter-warp plane, close to the surface of the sample. These critical regions correspond to zones with severe yarn curvature. Crack onset at specific critical locations is also affected by the presence of random defects (texture defects, porosity ...).

After 800 thermal cycles (Figs. 7c and 7b) the crack system is much more developed: for both samples, almost all the critical zones close to the curved Z yarns are cracked. The cracks are observed along the Z-yarns in the inter-warp planes and also on the upper and lower surfaces of the specimen in the inter-fill matrix-rich zones.

After 1400 thermal cycles (Figs. 7e and 7f), significant crack propagation can be noted: almost all the vertical interfaces of the Z-yarns are fully cracked, and the cracks present in the upper and lower inter-fill matrix layers tend to coalesce.

The crack patterns and their evolution with the number of cycles appear very similar in 1 UC and the 2×2 UC samples: the cracking scenario (highly schematically) includes:

- crack onset at the most critical sites (interfaces between curved Z yarns and matrix),
- multiplication of cracks up to saturation of all the “available” critical sites,
- crack propagation mainly along the thickness direction.

This scenario is quite schematic but is observed almost systematically. However, no information is gained about the effect of pores.
Figure 7. Cracking system for 2×2 UC (left), and 1 UC (right) samples; a) and b) 200 cycles, c) and d) 800 cycles, e) and f) 1400 thermal cycles. The resolution of the tomography scans is 8.34 µm (see also reference [8]).

Figure 8 shows a 2D tomographic section of the material after 1400 thermal cycles, visualizing a z-yarn in an inter-warp plane (section AA), and two orthogonal sections BB and CC. The comparison between BB and CC sections points out the deformations of the fill yarns and the z-yarns induced by the weaving near the exterior surfaces of the plate. The cracks present in this specimen after 1400 cycles are displayed in these images in blue, green and red colors: blue cracks initiate and propagate inside the specimen at the interface of the z-yarns, red cracks develop in the surface inter-fill matrix rich regions. The green colour allows differentiating the intra z-yarn cracks that connect the red and the blue cracks.

Figures 8a and 8b show clearly the presence of a pore is correlated to a highly cracked zone: moreover, when a pore is close to this zone, the crack is slightly deviated from the interface or passes through the porosity. The same observations can be made for the cracks in the resin pockets within the inter-fill planes, an example of which is given in Fig. 8c. The tortuous trajectory of the cracks is deviated locally by the presence of a nearby void.
Figure 8. Crack morphology in a) through-the-thickness and b), c) in-plane slices after 1400 thermal cycles along through-thickness z yarns in concave zones (blue), in surface resin rich region (red), and inside z yarn (green) (see also reference [8]).

4. Discussion based on FE model simulations
As shown in Section 3, µCT experimental measures allow identifying zones which are particularly sensible to thermal cycling, that is, prone to develop damage due to thermal cycling: Fig. 9 illustrates the results of µCT scan carried out on the 1 UC sample after 1400 thermal cycles.

Figure 9. µCT images of 1 UC sample after 1400 thermal cycling: a) µCT scan of the whole sample b) severely damaged yarn c) concentration of damage in a zone with severe curvature d) in the presence of porosity (1 void close to the curved yarn).
The scan of the complete sample (Fig. 9a) allows capturing a severely damaged yarn (Fig. 9b), particularly in a zone with severe curvature (Fig. 9c) and in the presence of some porosity (Fig. 9d): one relatively big void (diameter around 0.25 mm) is close to the curved yarn (Fig. 9d). This zone has been the location of damage onset at an early number of thermal cycles (around 200 thermal cycles) and is much more damaged than adjacent curved yarns without voids. Moreover, voids act as crack attractors.

In order to better understand these issues, numerical simulations are carried out by employing the µCT image-based FE (global and local) models described in Section 2. In this analysis, the entire sample is subjected to a static step involving a temperature difference, \( \Delta T \) (\( \Delta T = 100^\circ\text{C} \)), between 50°C (close to the material Tg, at which the sample is assumed to be stress free) and -50°C (minimum temperature value during thermal cycling); the analysis is purely elastic, the material properties in Table 3 are employed: the matrix is isotropic, the yarn is orthotropic; the yarn properties are calculated by numerical homogenization [13, 14].

**Table 3.** Material properties for FE simulations.

|                         | Matrix | Yarn (longitudinal) | Yarn (transverse) |
|-------------------------|--------|---------------------|-------------------|
| Young’s Modulus [MPa]   | 3600   | 147500              | 17600             |
| Poisson’s ratio [–]     | 0.3    | 0.23                | 0.26              |
| Coefficient of Thermal Expansion [K\(^{-1}\)] | 5×10\(^{-5}\) | 0.45×10\(^{-6}\) | 17.3×10\(^{-6}\) |
| Density [g/cm\(^3\)]   | 1.23   | 1.56 (rule of mixtures) |

The global analysis carried out by the voxel-model containing porosity (Fig. 10a and 10b) allows identifying the zone of critical stress concentration (round circle in Fig. 10a, Fig. 10b) which is the same captured experimentally by µCT scans; in this zone the average Von Mises stress is around 70 MPa.

![Figure 10. FE simulations (static elastic analysis (\( \Delta T = 100^\circ\text{C} \))]: a) global voxel-model with porosity b) detail of a severely stressed zone (max Von Mises stress) c) local tet-mesh model of the critical zone d) global semi-idealised tet-mesh model without porosity e) detail of a severely stressed zone f) local tet-mesh model of a critical zone.](image)

A more detailed analysis carried out by the refined local model (Fig. 10c) allows understanding that the stress concentration is particularly high in the vicinity of the void and on the void external surface.
(with Von Mises stress values between 57 MPa and 88 MPa at the void external surface): stress concentrations tend to “deviate” from the yarn/matrix surface to the void external surface. The observed behaviour is related to the consistent difference in the coefficients of thermal expansion of matrix and tows, the tow regions represent a true constraint to the free thermal expansion (or contraction of the matrix); this constraint effect is then amplified by the presence of pores.

The same analysis carried out on the semi-idealised tet-mesh model without porosity (Figs. 10d and 10e) does not allow discriminating between different yarns and – within a severely curved yarn – does not allow discriminating between curved zones with close values of curvatures: the average Von Mises stress in these zones is around 60 MPa that is 15% lower than that captured by the voxel-mesh model in the most critical zone with porosity (comparison between Figs. 10b and 10e). An analysis carried out by a local tet-mesh model of a critical zone (Fig. 10f) confirms this trend; moreover – differently from the model with porosity (Fig. 10c) - stress concentrations lay entirely on the yarn/matrix interface (with values around 65 MPa, that is 30% lower than those calculated by the model with porosity on the external pore surface). This analysis is purely comparative between different configurations since the critical values of stress are not available for these materials.

The analysis illustrated in Fig. 11 is of different type: this analysis is carried out by employing the local tet-mesh model in a material with porosity and consists in calculating the elastic energy release rate when passing from a configuration where a crack initially located very close to the fiber/matrix interface (Fig. 11a, configuration O) either propagates along the fiber/matrix interface (Fig. 11b, configuration A) either deviates to a close pore (Fig. 11c, configuration B): the analysis is comparative (no critical energy release rate values are available), the three cracks configurations have the same surface (equal to around 0.004 mm²).

![Figure 11](image)

**Figure 11.** Schematic illustration of the calculation of the energy release rate a) configuration O, crack emanating close to the matrix/yarn interface b) configuration A, crack propagating along the matrix/yarn interface c) configuration B, crack deviating towards a void.

It is calculated that the energy release rate for passing from O to B is around 50% lower than passing from O to A which means that the transition O to B is preferred from an energetic point of view (based on a purely elastic analysis).

Fig. 12 illustrates an analysis qualitatively similar to that illustrated in Fig. 10: in this case the local tet-mesh model with porosity is used to calculate the elastic energy release rate when passing from a
configuration where a crack initially located (originating from) on the pore surface (Fig. 12a, configuration O’) propagates along the fiber/matrix interface (Fig. 12b, configuration C).

![Figure 12](image-url)

**Figure 12.** Schematic illustration of the calculation of the energy release rate a) configuration O’, crack emanating from a void b) configuration C, crack propagating along the matrix/yarn interface.

It is calculated that the energy release rate for passing from O’ to C is around 70% higher than passing from O to A and 40% higher than passing from O to B: this means that the transition O’ to C is very unlikely to occur based from an energetic point of view (purely elastic analysis). This has a plausible physical explanation: in the material/structure illustrated in Fig. 12, a crack emanating from a void is “arrested” by the presence of a nearby yarn (effect very similar to that observed in structures with cracks propagating towards rigid crack arresters).

The conclusion of this numerical study is that:

- based on a simple elastic analysis, the global voxel-mesh model built on µCT images, including all defects captured by the µCT resolution (e.g. voids, texture defects), is able to catch the location of stress concentrations, thus identifying the locations where damage is likely to onset, when compared to µCT images of damaged samples. The critical zones include pores in the vicinity of a yarn/matrix interface (stress concentrations are calculated on the pore external surface),
- by the same analysis, the global semi-idealised tet-mesh model without defects is not able to discriminate between similar critical zones (e.g. curved yarns are almost all critical at the same extent),
- the global voxel-mesh model based on µCT images and the related local tet-mesh model (extracted from the global model after identification of criticalities) predicts average Von Mises stresses that are around 15% higher than those calculated in the same zones by the semi-idealised tet-mesh model. The defect plays a decisive role in the determination of stress concentrations that promote then damage onset and propagation,
- based on simple energetic considerations and on the explicit calculation of energy release rate by means of the local tet-mesh model with porosity, the simulation predicts that a crack emanating from a yarn/matrix interface is more likely to deviate towards a void (when the void is close to the interface) than propagating along the yarn/matrix interface. This analysis depends obviously on the distance of the pore from the yarn/matrix interface, but this study has not been carried out, only a comparative calculation has been performed,
- based on simple energetic considerations and on the explicit calculation of energy release rate by means of the local tet-mesh model with porosity, the simulation predicts that a crack emanating from a pore is not likely to propagate along the yarn/matrix interface, since the yarn...
acts as a “crack arrester”. Therefore either a crack is not likely to onset at a pore surface, either a crack that onsets at a pore surface are arrested by the presence of a yarn.

5. Conclusions and perspectives
The experimental results of thermal cycling (up to 1400 thermal cycles) between 50°C and -50°C show that the crack patterns and their evolution with the number of cycles appear very similar in 1 UC and the 2×2 UC samples: the cracking scenario (highly schematically) includes:

- crack onset at the most critical sites (interfaces between curved z yarns and matrix), multiplication of cracks up to saturation of all the “available” critical sites,
- crack propagation mainly along the thickness direction.

In this scenario, the presence of a pore is correlated to a highly cracked zone: moreover, when a pore is close to this zone, the crack is slightly deviated from the interface or passes through the porosity. The tortuous trajectory of the cracks is deviated locally by the presence of a nearby void.

The numerical analysis carried out by employing µCT image-based FE models at the sample (global) scale (voxel-mesh and semi-idealised tet-mesh models) and at the matrix/yarn interface (local) scale (tet-mesh model) allows concluding that:

- based on a simple elastic analysis, the global voxel-mesh model based on µCT images, including all defects captured by the µCT resolution (e.g. voids, texture defects), is able to catch the location of stress concentrations, thus identifying the locations where damage is likely to onset, when compared to µCT images of damaged samples. The critical zones include pores in the vicinity of a yarn/matrix interface (stress concentrations are calculated on the pore external surface); by the same analysis, the global semi-idealised tet-mesh model without defects is not able to discriminate between similar critical zones (e.g. curved yarns are almost all critical at the same extent),
- based on simple energetic considerations and on the explicit calculation of energy release rate by means of the local tet-mesh model with porosity, the simulation predicts that a crack emanating from a yarn/matrix interface is more likely to deviate towards a void (when the void is close to the interface) than propagating along the yarn/matrix interface: the simulation predicts also that a crack emanating from a pore is not likely to propagate along the yarn/matrix interface, since the yarn acts as a “crack arrester”. Therefore, either a crack is not likely to onset at a pore surface, either a crack that onsets at a pore surface is arrested by the presence of a yarn.

Work is in progress to enhance both the experimental capability to catch the damage scenario through the realization of in-situ tests capable to capture the details of damage onset and propagation and the numerical capability to perform multi-physical simulations taking into account realistic material model behavior. These efforts should allow gaining a better understanding of the phenomenological scenario and pave the way to the development of Virtual Testing tools.

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