DURABILITY OF A 3D WOVEN COMPOSITE ASSISTED BY FINITE ELEMENT MULTI-SCALE MODELLING

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Keywords: textile composite, multi-scale analysis, finite element, stress concentration coefficient, durability

Abstract

The textile composite studied is a 3D woven composite. A unit cell is defined by using microscopic examinations of the microstructure. A multiscale approach assisted by the finite element method is performed in order to estimate the effective properties of the composite and then to access to local stress field. This approach allows the determination of the kind of load to which warp yarns are subjected. Moreover, detailed analysis of damaged model using different configurations of broken yarns are treated. The evolution of the stress concentration coefficient highlight the load transfers due to consecutive yarn breaks.

1 Introduction

Fiber reinforced composite materials such as textile composites exhibit complex microstructure. The damage phenomena appearing in those heterogeneous materials depend generally on local mechanisms occurring within the fabric reinforcement scale of yarns. The knowledge of their mechanical response is of prime importance to better understand the development of the damage related to stress concentrators that may lead to premature failure of the textile composite.

Recent improvements of multiscale methods (localization/homogenization) associated to finite element modeling (FEM) have been developed [1,4,5]. These numerical methods allow to estimate the elastic effective properties of the composite [7] and can give an access to the local heterogeneous stress/strain field [8]. The aim of this study is to link the global loading of the composite material to the local stress field at the scale of a prescribed warp yarn. The purpose is then to better understand the mechanisms leading to yarn failure. To simulate the macroscopic response of the composite textile and to analyze the local mechanisms, multiscale analyses have been used by means of finite element modeling. The stress field was firstly determined by localization approach for a given macroscopic tensile load. A detailed analysis along the warp yarn was then carried out. Several configurations were studied at the mesoscopic scale by incorporating one or many breaks in a periodic cell called representative volume elements (RVE). This failure approach aims at evaluating the influence of the amount of broken yarns on the stress field. A stress concentration coefficient was then defined, for which the sensitivity with respect to the number of broken yarns is investigated. This work focused on transverse isotropic elasticity case to evaluate the load transfer mechanisms around a broken yarn.

2 Presentation of the material

2.1 The microstructure of the material

The composite fabric under consideration is a 2.5D angle interlock woven with a polyvinyl chloride (PVC) matrix. The textile reinforcement consists of poylethylene terephtalate (PET) fibers in the warp direction and polyamide-66 (PA66) fibers in the weft direction. The shape of microstructure's design and their characteristic lengths were determined from the transverse sections of the composite, using X-ray tomography examinations (fig. 1). The warp yarns lift and lower through two layers of weft yarns to form the interlacing patterns.

Among this textile reinforced composite, three structural levels can be distinguished. At the macroscopic scale, the composite is assumed to be orthotropic homogeneous material. The mesoscopic scale takes the textile reinforcement into account by considering that yarns and matrix are homogenous and orthotropic. This level of organization was described by a repeatable unit cell of fabric. It was composed of 4 layers of warp and weft yarns woven together. The microscopic scale showed that fibers were bundled into yarns. In this study, our main interest is to have a better understanding of the mesoscopic key scale and its implications in the macroscopic scale.

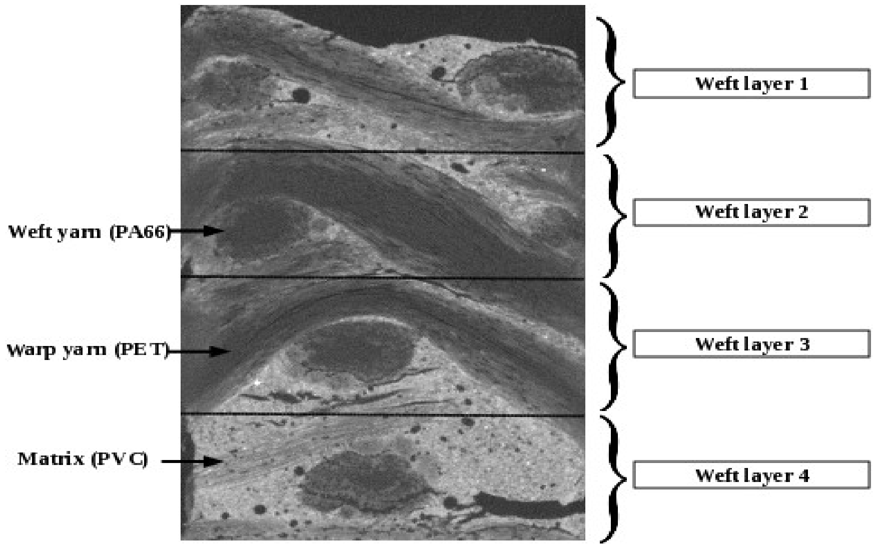

Figure 1. Longitudinal cross-sections of the textile composite

2.2 Microstructural changes in degraded textile composite

The composite undergoes complex mechanical loading during its service, which leads to its degradation. Tensile tests carried out on samples extracted from an in-service structure showed a fall in the stress failure which reduces dramatically the durability of the composite.

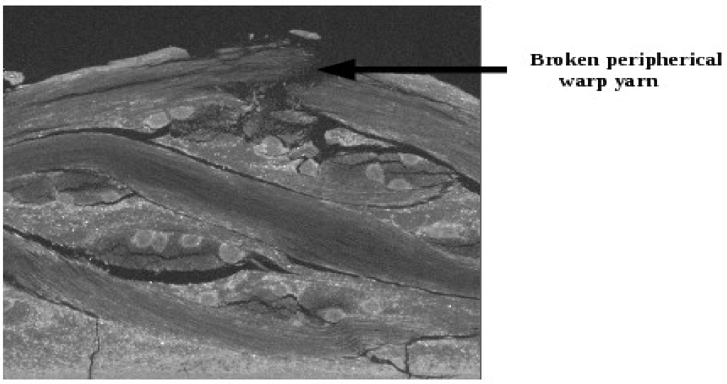

Figure 2. Mechanism failure of textile composite

X-ray tomography images of the degraded composite (fig. 2) showed the failure of the peripherical warp yarn in the woven fabric, the crack surface being roughly perpendicular to the warp direction.

3. Multiscale finite element modelling

The multiscale procedure (homogenization/localization) allows to establish a relationship between the mechanical properties at both macroscopic and mesoscopic scales. For the multi-scale analysis, a periodic cell was identified from the macroscopic observations.

3.1 Meshing of a periodic cell

Discretization of this periodic cell was carried out by consecutively using four meshing softwares. A geometrical model was first obtained by Wisetex, a software package of 3D woven fabric modeling developed by the Katholic Universiteit of Leuven [2]. This model was transferred into the ANSYS FE code [3,5] which created a file adapted to the ABAQUS FE code.

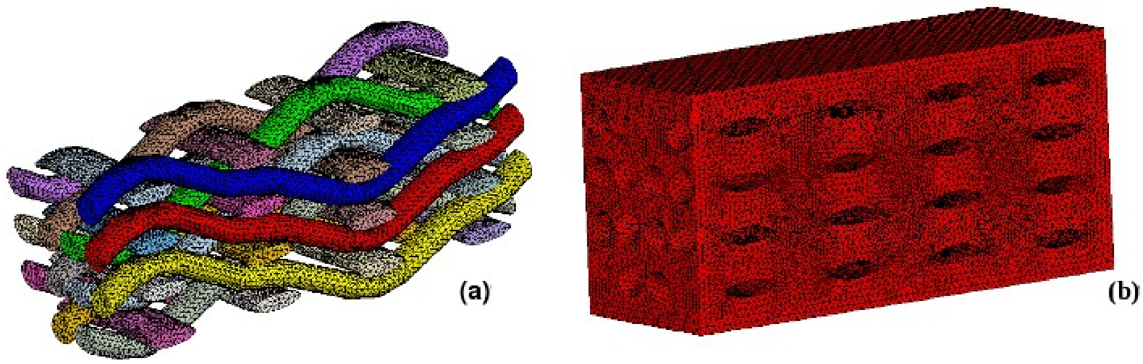

Figure 3. Meshing of periodic cell: (a) Meshing of fabric (b) Meshing of matrix

The cell meshing was then performed with ABAQUS software by controlling relevant periodic conditions. Namely both surfaces at the opposite sides of the cell were identical. This periodic cell was then transferred into an in home Zebulon FE code [6], with which the FE computations were performed. The overall (matrix and yarns) cell mesh (fig. 3) is composed of tetrahedral linear elements, consisting of 202,583 nodes and 1,166,485 elements. The used meshing technique allowed a total control of the mesh size value for the finite element.

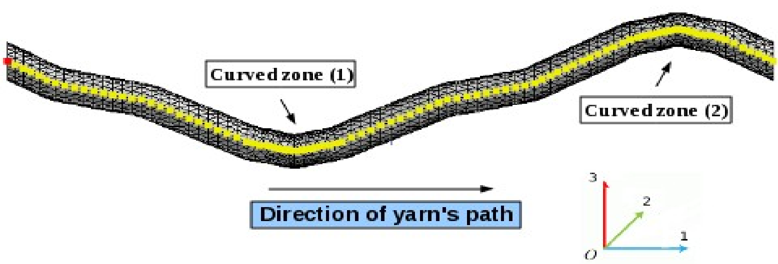

Figure 4. Path of a warp yarn

A path was created along the warp yarn in order to make easier the analysis of local stress disctribution. A central path was created along the warp yarn (fig. 4) in order to make easier the analysis of local stress distribution. Therefore, a warp yarn could be represented by a global coordinates system, defining the unit cell coordinates system (1, 2, 3), as well as local material coordinates (x_{local}, y_{local}, z_{local}), due to the yarn undulation. These coordinates were both handled at each integration point of yarn.

3.2 Anisotropic elastic properties

To better understand the mechanical behavior of the composite as well as the damage evolution within it, an identification using experimental analysis was performed including not only the composite material (macroscopic scale) but also the constituents of the composite(mesoscopic scale). Figure 5-a showed the representative stress-strain curves of the composite material in the weft and warp yarns. The Young's modulus, obtained in the linear region of stress-strain curve, was found to be higher in the warp direction: 1100 MPa and 160 MPa respectively in the warp and weft directions. The stress failure was also higher in the warp direction and reached the value of 100 MPa, compared with 40MPa in the weft direction. Tensile tests of yarns showed the same anisotropy in stiffness and stress failure [3]. Note that the stress failure of warp yarn for a uniaxial tensile test was about 650 MPa. This leads to a ratio of 6.5 between the two stresses at failure (yarn/composite).

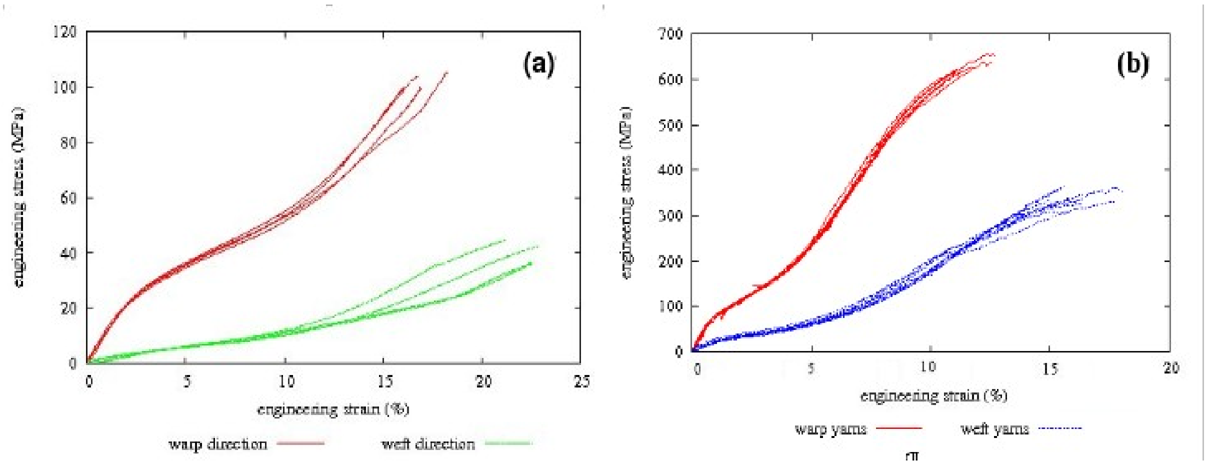

Figure 5. Stress-strain diagrams for the composite (a) and yarns (b)

According to these experimental results, the constitutive relationships (elastic parameters) of the constituents were assumed to be transverse isotropic for the yarns and orthotropic for the matrix. The unit cell is subjected to a macroscopic (mean) stress $<\sigma_{11}>$ equal to the stress failure of the composite, whereas $<\sigma_{22}>$ and $<\sigma_{33}>$ were kept equal to zero in order to simulate a uniaxial test on the composite material. A set of coefficients was determined by using an inverse method of optimization accounting for both homogenous effective properties at the macroscopic scale and the required (but not measured experimentally) material properties of each constituents. For instance, the average Young's Modulus was obtained as the ratio of average stress $<\sigma_{11}>$ to average strain $<\varepsilon_{11}>$.

4. Results and Discussions

4.1 Local parameters distribution

The above mentioned multi-scale analysis allows comparison of the computed local variables (within each constituent) with respect to the mechanical parameters applied and measured at the macroscopic scale. Due to the complex architecture of the composite material, the local stress tensor is multiaxial. To better analyze this multiaxial stress state, the principal stresses σ_{p1}, σ_{p2} and σ_{p3}, (where $\sigma_{p1}>\sigma_{p2}>\sigma_{p3}$) as well as their corresponding eigenvectors were computed at each integration point. In the following, the first results consist of plots according to the curvilinear abscissa of warp yarn central path (fig. 4).

Figure 6-a depicts the distribution of the 3 principal stresses in the warp yarn. It can be observed that the maximum principal stress σ_{p1} ranges from 250 MPa in curved zone to 390 MPa in the straight zones, whereas σ_{p2} and σ_{p3} are close to zero. To go further, the stress triaxiality ratio τ_σ is defined as [5] :

$$\tau_{\sigma} = \frac{\sigma_h}{\sigma_{eq}} \tag{1}$$

where σ_h is the hydrostatic pressure $\sigma_h = (\sigma_{p1}+\sigma_{p2}+\sigma_{p3})/3$ and σ_{eq} is the von Mises equivalent stress. τ_σ is a measure of the multiaxiality of stress state which takes the value 0.33 for classical tensile test under uniaxial condition. Note that in this case $\sigma_{eq} \approx \sigma_{p1}$.
Figure 6-b shows that τ_σ is close to 0.33 (uniaxial) along the warp yarn. Actually, the stress triaxiality ratio τ_σ varies from 0.33 (uniaxial) in the curved zones to 0.35 in the straight zones. The fluctuation of σ_{p1} can be correlated to that of τ_σ. It can then be concluded that the area where the crack appears (fig.2) corresponds to the value of the largest principal stress σ_{p1} under uniaxial condition $\tau_\sigma = 0.33$.

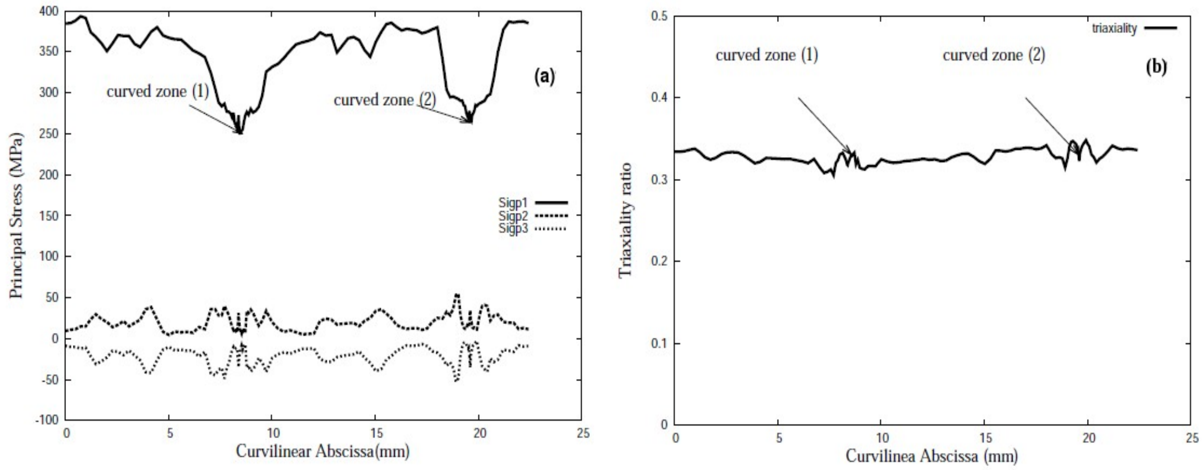

Figure 6. Distribution of the principal stresses (a) and the triaxiality ratio in the warp yarn (b)

Due to the yarn undulation, a study of the local orientation (yarn axis) was carried out. Indeed, in the curved zones, the local orientation coincides with that of the composite material (direction 1). By referring to this direction 1, the orientation (denoted alfa) of σ_{p1} is defined by the components of its eigenvector v_{p1}. On the other hand , the angle beta can be defined as the angle between the direction 1 and the local axis of the yarn due to the undulation. Figure 7 clearly shows that both angles coincide all along the central path of the warp yarn. The warp yarn is subjected to uniaxial tensile load along its axis in spite of the undulations. The crack surfaces observed in figure 2, perpendicular to the yarn axis can be attributed to this effect of the orientation.

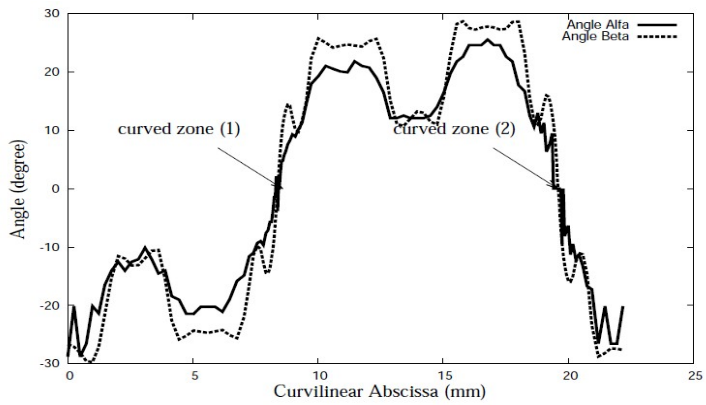

Figure 7. Variation of undulation angle and principal stress angle as function of curvilinear abscissa of yarn's path

4.2 Yarn failure approach: stress concentration coefficient K_σ

The failure mechanism investigations revealed broken yarns in the periphery of the woven fabric (fig.2). The previous subsection demonstrates that σ_{p1} plays a major role in these failure mechanisms by taking the localization and the orientation into account. It was then attempted to link σ_{p1} to the global parameter $<\sigma_{11}>$. Let σ_{p1}* be the value of the largest principal stress in the curved zone at the top surface of a given warp yarn within the periodic cell. A stress concentration coefficient can be defined as :

$$K_\sigma = \frac{\sigma^*_{p1}}{\langle \sigma_{11} \rangle} \tag{2}$$

K_σ represents the ratio between the stress at failure of the warp yarn and that of the composite material at the macroscopic level. For the safe periodic cell (initial architecture/curved zone(2)) and with the obtained set of materials coefficients, K_σ = 2.6. This value is clearly underestimated when compared with the experimental data of 6.5. However, the following study of the trend of K_σ can be carried out by normalizing the K_σ values by 2.6.

The next step aims at analyzing the evolution of K_σ by consecutively cutting the warp yarns located at the top surface. This study is performed in order to estimate the decrease in the global stress at failure with respect to the amount of broken yarns. To this end, broken yarns were then numerically incorporated into the meshing of the initial periodic cell. Figure 8 shows different periodic cell configurations in the composite material corresponding to one, two and three broken yarns in the periphery of the woven fabric.

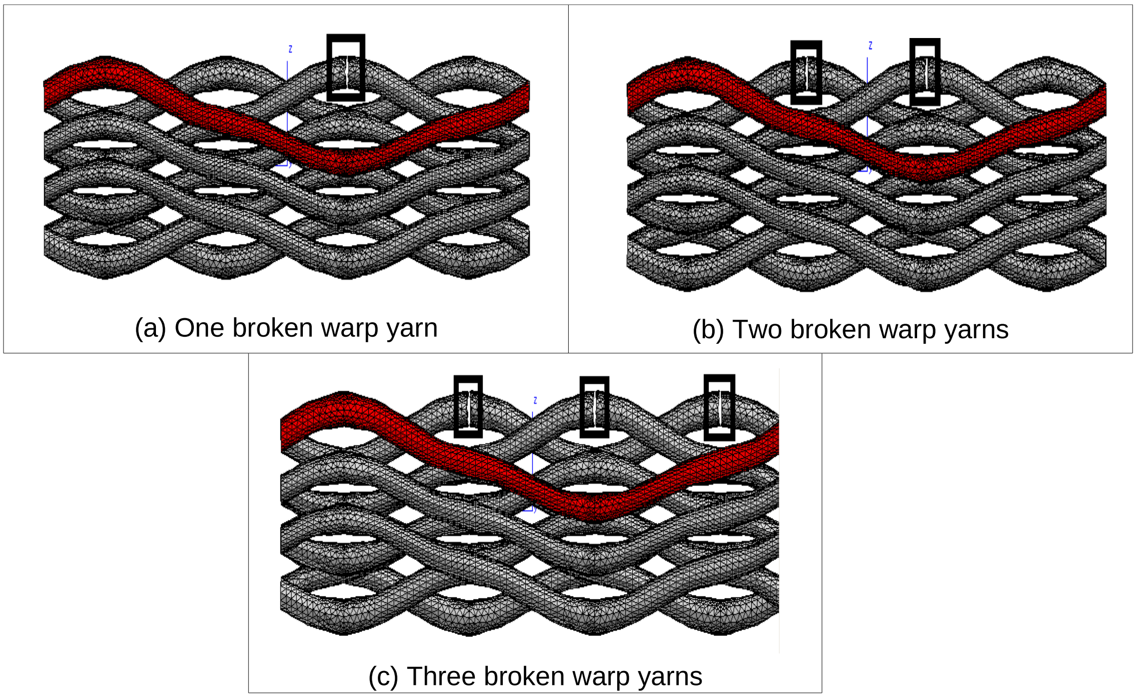

Figure 8. Representative cell's fabric of three damage states

K_σ values were systematically calculated in the warp yarn that was not broken, in order to estimate gradual load transfer to this prescribed yarn. Figure 9 shows the evolution of the normalized K_σ as a function of number of broken yarns. A slight increase of K_σ is observed up to 2 broken yarns. Unexpectedly, a decrease is even shown for the third break. In fact, the load transfer is redistributed elsewhere than in the location under consideration here. Since the increase in K_σ results in a decrease in $<\sigma_{11}>$ at failure, provided that σ_{p1}* value is fixed, this redistribution of the load transfer is currently under investigation.

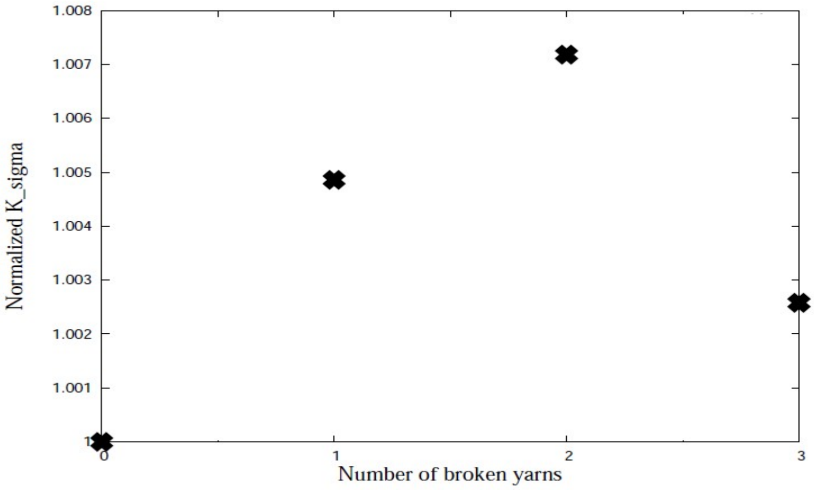

Figure 9. K coefficient in the intact yarn neighbouring the broken yarns

5. Conclusions

A mutiscale approach of the mechanical response of fabric reinforced composite was presented. This approach, using the finite element method, is based on a periodic unit cell that takes the undulations of yarns in account. The woven microstructure of the composite was first identified. A meshing of the unit cell was then carried out by using various meshing tools. Transverse isotropic elastic properties of the constituents were identified thanks to mechanical tests but also by using an inverse optimization method (homogenization). Then, the principal local stress field was studied. It was observed that warp yarns were subjected to a uniaxial tensile load when a macroscopic stress is applied in the unit cell. Moreover, the crack orientation, deduced by the direction of the largest principal stress, was parallel to the warp direction. It confirmed the crack orientation showed in the experimental analysis of damaged composite. The study carried out on various configurations of damaged states contained in the periodic cell has allowed the estimation of load redistrubtion on an intact (warp) yarn neighbouring the broken yarns. The analysis of load transfer will lead to the prediction of lifetime of the textile composite.

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