ARCHITECTURAL DESIGN OF 3D WOVEN COMPOSITES ASSISTED BY FE MULTISCALE MODELLING

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Abstract
Composite materials reinforced with three-dimensional polymeric yarns fabric are investigated. This study aims at providing some rules for an architecture optimization of woven composites in regard with the failure processes. Textile composites degradation mechanisms, under tensile and/or bending loading have been identified through multiscale experimental observations. Dissimilar failure mechanisms at the mesoscopic scale were observed: a fracture in “sudden death” of yarns was found for tensile load while a yarns progressive failure was observed in the case of tensile/bending. Motivated by the above mentioned degradation mechanisms, a multiscale finite element modelling was performed on a representative periodic cell. The largest principal stress was found to be the relevant mechanical parameter driving the failure mechanisms at the mesoscopic scale. Furthermore, by using a procedure of element erosion, based on the largest principal stress, numerical modelling could reproduce the two above mentioned failure mechanisms. The same numerical approach has then been used to investigate the damage tolerance of the complex woven composites. Various architectural settings were identified and a systematic study of each parameter has been carried out. The variation of the largest principal stress was then highlighted to be responsible for the damage in the yarns. These results allow design rules for any 3D architecture of woven composite to be established.

1. Introduction

The recent improvement of weaving technique allowed the development of complex 3D woven reinforcements [1]. Due to their high performance as structural materials, composites with three-dimensional fabric reinforcements have gained a great interest in the aeronautic and automative industries, among others. 3D woven composites can also offer a higher strength to delamination than traditional 2D composites with the presence of reinforcing yarns, known as binders, which interweave the through-thickness fabric. However, this complex internal geometry of such materials renders the mechanical properties difficult to predict.

This study, based on a multiscale experimental and numerical analyses, deals with the failure mechanisms of the warp yarns. Indeed, the failure of these yarns is considered, in a first approximation, as the main source of the fracture of the overall composite structures. As already mentioned in previous works [2]

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[3] [4], the textile composites degradation was identified by using micro-computed tomography (μCT) on many degraded samples. The tomographic analyses have revealed partial or complete failure of the composite interzones (IZ) [3] [4] containing the warp yarns. Furthermore, it has been seen that the crack surfaces were perpendicular to the yarns axis, located at the peaks and troughs where the curvature of the yarn are the greatest. The experimental study also shows dissimilar failure mechanisms at the mesoscopic scale: a fracture in "sudden death" of yarns was found for stabilized cyclic tensile load while a yarns progressive failure was observed in the case of bending combined with small tension similar to in-service loading.

Motivated by the above reported degradation mechanisms, a multiscale finite element modelling was performed on a periodic cell of the Representative Volume Element with two kinds of loading conditions (tensile and combined bending with a small tensile load). The purpose of this numerical study is to simulate, during the calculation, the failure mechanisms of the warp yarns for the woven composite experimentally studied. The yarn failure is based on a critical value of the maximum of the largest principal stress.

Finally, a second numerical study has focused on the decomposition of various architectural settings. A systematic examination of parameters (yarn waviness, Young's modulus ratio, and yarns inter-distance distributions) was carried out, so as to observe their respective influences on the largest principal stress value.

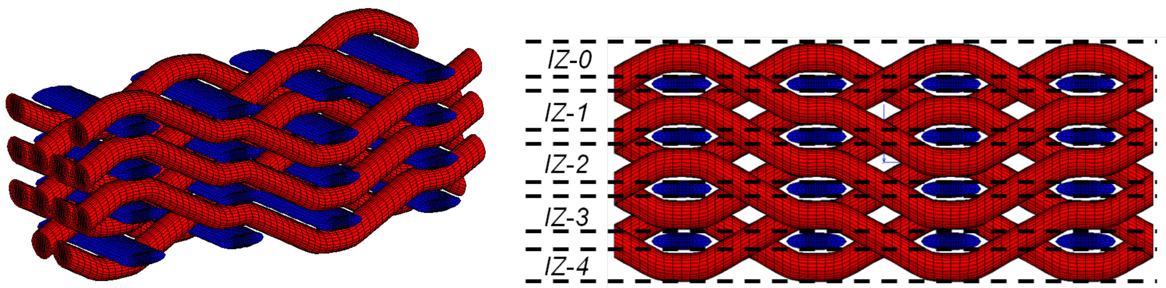
2. Materials and experiments

2.1. Materials

The composite material under study is composed essentially of polymer materials as contituents. The architectures of the woven composites were made of 3D fabrics embedded in a polyvinyl chloride (PVC) matrix. The carcass was composed of polyethylene terephthalate (PET) fibres for the warp yarns and polyamide 6-6 (PA66) fibres for the weft yarns. The yarns are assumed to be dry.

2.2. Interzones

A 2.5D angle interlocked fabric was considered here, the architecture of which is defined in Fig.1 (a). The weft yarns are straight whereas the warp yarns undulate surrounding the weft yarns. The Fig.1 (b) shows the concept of interzones detailed by *A. Thionnet et al* [3] [4]. The interzones, for this example, are market out by 4 horizontal planes constructed with the different horizontal planes of weft yarns. The 5 resulting volumes are called interzones and referred to as IZ i ($i \in \{0, 1, 2, 3, 4\}$). These interzones are very convenient to describe the failure of woven composites caused by the failure of the warp yarns.



a b

Figure 1. Architecture (a) and Interzones (b) for 2.5D angle interlocked woven fabric.

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2.3. Experiments

The mechanical properties of each constituent (warp yarns, weft yarns and matrix) were characterized in the previous works [2][5]. Tensile tests on individual warp yarns allowed the determination of the stress at break noted as σ_R (Fig. 2). The failure of tested yarns occurred without any apparent necking in a brittle manner.

Additionally, the degradation mechanisms of this textile composite, under tensile and/or bending loading have already been identified through experimental observations including µCT [2] [3] [4]. Dissimilar failure mechanisms at the mesoscopic scale were then highlighted:

- A failure by "sudden death" of warp yarns was found for tensile load: all warp yarns, thus all interzones were broken perpendicularly to the load direction, parallel to warp yarns axis;
- A fraction of warp yarns failed in the case of tensile/bending. The µCT analyses revealed that all warp yarns in the upper interzone (IZ0) were broken, whereas no warp yarn was damaged in the other IZ's. The crack surfaces of broken warp yarns were also observed to be perpendicular to the yarns axis. Moreover, the location of the crack within the broken warp yarns was systematically at the peak and/or the trough position, where the curvature of the yarn is the greatest.

3. Finite Element (FE) modelling

An "in-house" FE code [6] was used to carry out simulations on a 3D periodic cell, meshed with almost 600,000 tetrahedral linear elements. Two kinds of loading were applied to this mesh.

3.1. Loading conditions

The loading conditions simulate the two sollicitations leading to dissimilar failure mechanisms as reported in the section 2.3:

- the tensile loading was applied in the axial direction represented by the principal warp direction. The usual periodic boundary conditions were imposed on the periodic cell of the RVE;
- the combined bending/tensile loading, used a shell homogenization with in-plane periodicity constraints (no thickness periodicity) [7]. The bending rotation axis is collinear to the weft direction.

3.2. Constitutive models

In the previous works [2][5], the matrix was assumed to be purely isotropic linear elastic. Both reinforcing warp and weft yarns, showed an anisotropic non linear behaviour. The non linear domain was modelled by an elastic-plastic behaviour with two isotropic hardening terms (Eq.1).

$$R = R_0 + Q\left(1 - e^{-\mathrm{bp}}\right) + A\left(e^{\mathrm{Bp}} - 1\right). \tag{1}$$

where p is the the cumulated effective plastic strain, and R_0, Q, b, A and B are the material parameters.

The anisotropic behaviour was taken into account with a transversely isotropic elastic coefficients together with anisotropic yield stress with a Hill criterion [8]. In addition, to ensure the orthotropic condi-

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tions for the yarn undulations, a local frame is defined for all integration points of each yarn. These local frames, using the Euler angles, were calculated and updated at each increment of the FE computation.

3.3. Algorithm of warp yarn's breakage

A complete FE analysis of the stress states (gradient, triaxiality ratio and eigen vector orientation) in the warp yarns was performed in previous works for the same 2.5D angle interlock fabric [2] [4]. It was concluded that the largest principal stress σ_{p1} was the driving parameter of the failure mechanisms, at the scale of yarns. More details, using the principal stresses σ_{pi} ($i \in \{1, 2 , 3\}$) with $\sigma_{p1} \geq \sigma_{p2} \geq \sigma_{p3}$, are given here below:

- Each warp yarn is subjected to an uniaxial stress state corresponding to σ_{p1} with $\sigma_{p2} = \sigma_{p3} \simeq 0$;
- The σ_{p1} eigen vector is contantly collinear to the warp yarn axis following the yarn weave;
- The crack surfaces are normal to the σ_{p1} eigen vector ;
- The σ_{p1} maximum value is located at the peaks and troughs of the yarn ;
- The woven composite degradation mechanisms loaded in the warp direction are led by the warp yarns failure.

An algorithm, based on the maximum of σ_{p1} was implemented into the FE code [6]. The approach consisted in systematically comparing σ_{p1}^{max} of each warp yarn integration point with σ_R, at the current time step (at the end of the time increment). Several scenarii were considered at a given time step:

- If $\sigma_{p1}^{max} < \sigma_R$, then move to the next time increment;
- If $\sigma_{p1}^{max} > (\sigma_R + \delta_R)$ with δ_R a tolerance fixed by the user, a new smaller time increment is proposed;
- If $\sigma_R \leq \sigma_{p1}^{max} \leq (\sigma_R + \delta_R)$. The affected elements are eroded, the time step remains unchanged and the local forces balance are operated.

This computational algorithm, using an erosion procedure of broken elements, does not require neither meshing nor failure kinetics information. Moreover, the time increment influence is controlled by the tolerance value δ_R.

A FE simulation of the tensile test on an individual warp yarn was first carried out. The stress state was obesrved to be uniaxial during the whole test even at the failure. Therefore, the macroscopic tensile stress Σ is thus equivalent to σ_{p1}. The FE result using the above mentioned failure criterion was compared with the experiments in the Fig. 2.

3.4. FE results

As observed experimentally, FE results showed dissimilar failure mechanisms at the mesoscopic scale for the two loading cases. Indeed, for the tensile loading in the warp direction, all the interzones were cut in avalanche at the same time step. The failure of the woven composite was in "sudden death". For combined tensile/bending loading, only the interzone IZ0 was broken, all the other warp yarns belonging to the other inerzones were intact. The level of the load transfer between IZ0 and the intact interzones was not high enough to induce further yarns breakage. For both cases, all the broken yarns were sectioned orthogonally to the yarn axis and located at the peaks and troughs. These results are fully in agreement with the experimental observations reported in section 2.3.

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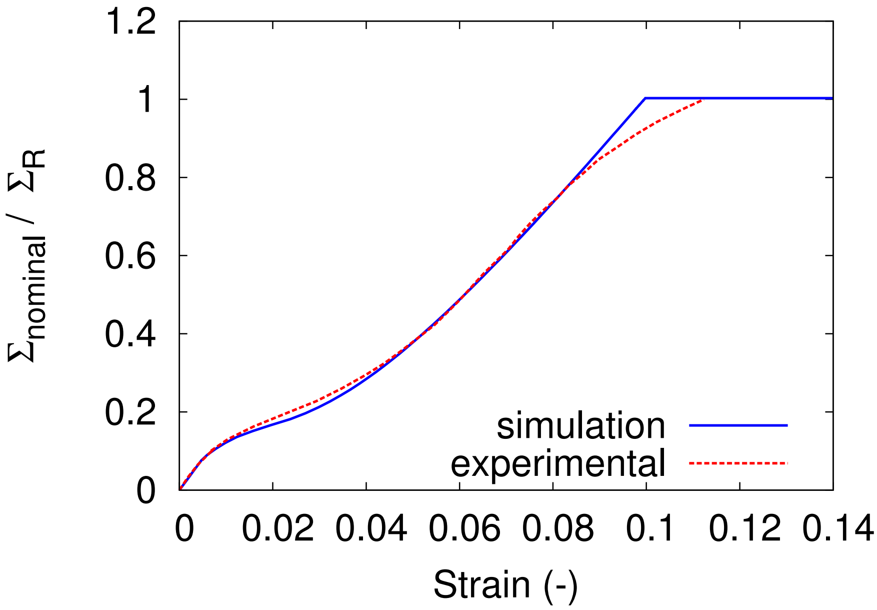

Figure 2. Macroscopic normalized stress-strain response on a warp yarn in monotonic tensile test.

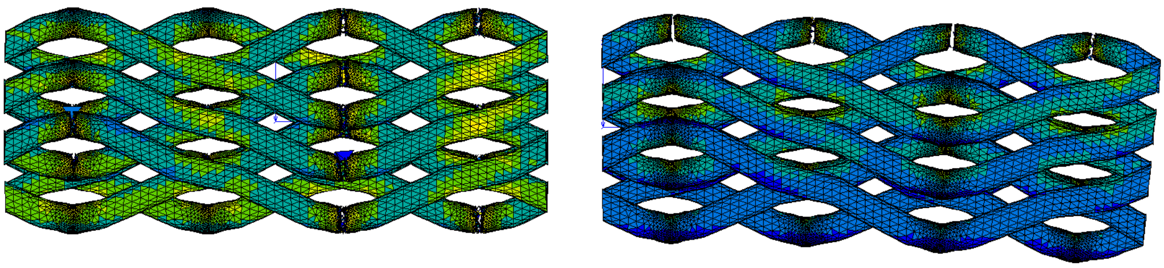

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Figure 3. σ_{p1} contour maps and illustration of the yarns' breakage: a) for tensile loading; b) combined tensile/bending loading.

3.5. Architectural optimization assisted by FE computations

The general purpose of this second numerical study is to investigate the influence of woven composites architecture on σ_{p1} level, assumed to be the driving parameter for the yarns breakage. The high complexity of 3D woven composites led to sort some architectural settings to be investigated.

3D periodic cells as shown in Fig. 4 were selected, the architectural paramaters of which are described as follows:

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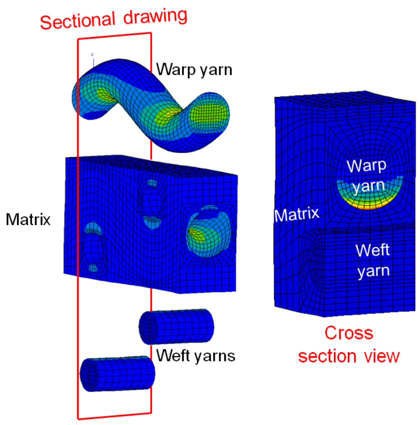

Figure 4. Example of an elementary 3D periodic cell.

- Waviness

The FE simulations were performed on elementary 3D periodic cell with an unique warp yarn. The waviness is defined by the difference between the yarn and cell lengths divided by the cell length. Therefore, unidirectional yarns are considered to have zero waviness. Various "wavinesses" were considered with a fixed yarn volume fraction. The results (Fig. 5) showed that the higher the waviness value, the higher the σ_{p1}^{max} level inducing a premature failure of the woven composite. Recall that the waviness of the 2.5D angle interlocked fabric considered here is 7.2%

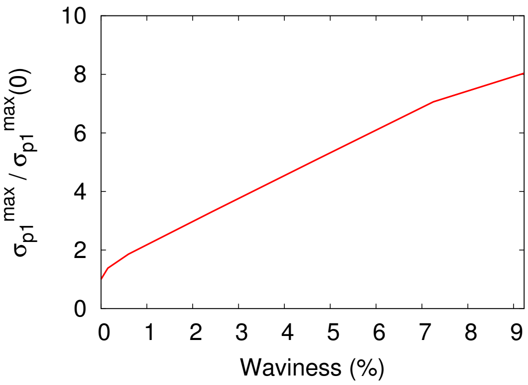

Figure 5. Waviness influence on σ_{p1}^{max}.

- Matrix and yarns Young's modulii ratio (E_{matrix}/E_{yarn})

FE simulations were performed with identical waviness and yarn volume ratio. Fig. 6 shows a significant increase of the largest principal stress σ_{p1} when the E_{matrix}/E_{yarn} ratio tends to 0. Several yarn volume ratios were tested with the same trend. For the present 2.5D angle interlocked fabric, the Young's modulii ratio equals 0.015.

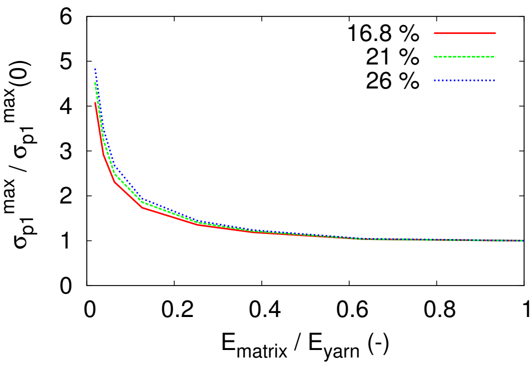

Figure 6. Young's modulus influence on σ_{p1}^{max}.

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- Minimum inter-yarns distance

Calculations conducted on several minimum inter-yarns distances showed variations in the matrix constraint thereby causing, for a decrease of yarns inter-distance d (Fig. 7 (a)), an increase of the maximum of the largest principal stress σ_{p1}^{max} (Fig. 7 (b)). The present 2.5D angle interlocked fabric exhibits a average value of 0.15 mm for the minimum inter-yarns distance.

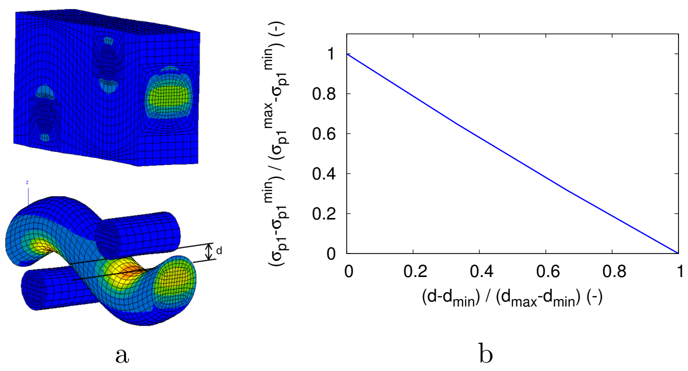

Figure 7. Yarns inter-distance periodic cell (a) and influence on the σ_{p1}^{max} (b).

4. Conclusion

A numerical simulation of the yarns' breakage was presented and applied to a 3D woven composite. Based on an erosion procedure of broken elements, the failure mechanisms were modelled on 3D periodic cells by FE calculations. The element break was determined with a failure criterion using the largest principal stress σ_{p1}. The use of this parameter has been justified by that all yarns were subjected to uniaxial stress state and the yarn failure appears without necking. By using a failure criterion based on the yarn stress at break σ_R, FE simulations were in good agreement with the experimental data as well as the observed failure mechanisms. Namely, the crack surfaces were perpendicular to the yarns axis and located at the peak and troughs positions respectovely. With the concept of interzone, the failure kinetics have also been revealed for two kind of macroscopic loading. A sudden death failure was identified for a woven composite loaded in tension whereas only a partial failure was found for a combined tensile/bending loading.

The influence of three architectural parameters on the largest principal stress σ_{p1} was further analyzed. It was shown that these parameters could be advantageously used for the optimization of the design of any 3D architecture of woven composites.

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