Influence of voids presence on mechanical properties of 3D textile composites

Y Chen 1,2, D Vasiukov 1,2*, C-H Park 1,2
1 IMT Lille Douai, Institut Mines-Télécom, France
2 Université de Lille, France
* dmytro.vasiukov@imt-lille-douai.fr

Abstract. Presence of the voids in final part made of textile reinforced materials is one of the main process-induced type of defects, which is governed by a set of manufacturing parameters. This work focuses on investigating the effect of voids on mechanical properties of the 3D textile reinforced composites. This study includes the following steps: manufacturing of composite plates with RTM process, mechanical analysis, and multi-scale material modeling. The internal structure has been characterized from µCT scans and scanning electron microscopy observations. The influences of micro- (intra-yarn) and meso- (inter-yarn) porosities are discussed. Anisotropic damage model has been implemented into Fast Fourier Transform solver for simulation of non-linear response of the 3D interlock composite. Analysis includes the averaged stresses in different material phases (warp, weft, and matrix) and local concentration of stress/damage field near voids.

1. Introduction
Resin Transfer Molding (RTM) is used in producing geometrically complex shapes made of textile composites in a cost-effective way. However, one of the possible drawbacks could be a presence of the voids induced into the final part during manufacturing. In general, voids are not expectable as they can reduce functionality of the composite structure affecting its elastic properties, strength, electrical resistivity etc. Commonly voids are considered as the origin of local stress concentrations and hence of crack initiation in the textile composites. Both elastic and damage behaviors of the composites can be affected by presence of voids. In this work, the focus is placed on the 3D interlock composites with voids induced by RTM process.

Voids can be generally separated into two groups: intra-yarn voids and inter-yarn voids. The former exist inside each yarn and usually has line-like geometries elongated in the direction of adjacent fibers; while the latter are located between yarns whose geometries are mostly spherical or ellipsoidal.

Due to the complex 3D feature of both, the textile architecture and the void defects, a reliable characterization requires a 3D observation. X-ray micro-computed tomography is one of the most powerful tools for this purpose [1,2]. Voids and fibrous architectures can be identified using some specific image processing algorithms. A mesoscopic method has been proposed by [3] to separate the yarns from the matrix. The identified mesoscopic geometry then feeds further numerical modeling of mechanical behavior of composites (see e.g. [4]).

Once the different phases are identified in a unit cell, different numerical methods can be used to simulate the local response of the composite. Finite element method (FEM) is the most commonly used, but it requires a relatively tedious preprocessing: meshing. For highly heterogeneous microstructures,
such as the textile composites herein, conformal FE meshes are difficult to be achieved and have already been the subject of many researches [5–7]. Regular meshing based on the initial image discretization is an alternative way to simplify this processing, yet it requires a large number of elements to reduce the unexpected effect due to the non-conformal discretization of the phase interfaces (see e.g. [4,8] for an illustration).

As an alternative to FEM, Fast Fourier Transform (FFT) based methods [9–14] may be used due to their simplicity of meshing and efficiency of parallel computation. The FFT methods intrinsically use regular grids to describe the microstructural geometry. In addition, through a reference material and the related Green operator, the local problem can be separately solved at each discretization point for each iteration, so the FFT models can be efficiently parallelized. Therefore, the FFT methods are very convenient for image-based modeling.

In the present work, the mesoscopic image segmentation technique [3] will be employed. Yarns with different orientations (warps and wefts) are separated. The anisotropy inside yarns will also be considered using the local orientation identified by the structure-tensor method. The microstructures will be described by regular grids generated from the initial image. The FFT based method will be coupled with a continuum damage model [4] to simulate the damage evolution in the composites.

2. Materials and experiments

2.1. Interlock textile and RTM process

The interlocks studied in this work are usually classified as 3D orthogonal interlock with layer-to-layer binding (Figure 1) in which binding warp yarns connect by two adjacent layers. These textiles were manufactured at ENSAIT (Roubaix, France). The areal density ($\rho_A$) is 0.266 g/cm$^2$. Yarns are made of E-glass fibers with density $\rho_f = 2.61$ g/cm$^3$, $E = 72$ GPa and $\nu = 0.2$. Textiles were impregnated with thermoset resin (Prime 27) which has the following properties: $\rho_m = 1.11$ g/cm$^3$, $E = 3$ GPa and $\nu = 0.3$.

![Figure 1. Repetitive Unit Cells of 3D interlock textile architecture.](image)

The RTM process described in this paper is assisted by constant pressure injection. Table 1 consists the manufacturing parameters for two textiles described in this paper. Figure 2 describes the adopted manufacturing scheme.

| Twill – 3D | Injection pressure | 1.5 Bar |
|------------|--------------------|---------|
| Length of injection | 26 cm |
| Time of injection | 585 s |
| Resin velocity | 0.5 mm/s |
2.2. µCT and image processing

The tomographic images were acquired on the ISIS4D platform (LML/LaMcube, France). The scanning parameters are given in Table 2. The sample was scanned with 1440 projection images over a 360° rotation. A projection image was the average of 6 frames to reduce the random noises. The spot size of about 2 µm was chosen to achieve the required voxel sizes.

Table 2. Imaging parameters used during the CT scan

| Sample | Voxel size (µm) | Tension (kV) | Current (µA) | Frame rate (f/s) | Scan time (min) | Dimension of reconstructed image (mm³) |
|--------|----------------|-------------|--------------|-----------------|----------------|----------------------------------------|
| RVEU   | 8.79           | 80          | 68           | 10              | 20             | 13.71x3.14x9.99                         |

Three-dimensional images were reconstructed using the software of RXSolution©. Due to the high density contrast between the glass fibers and epoxy matrix, beam hardening was observed within the reconstructed images (unpublished). Therefore, a beam-hardening reduction algorithm was applied during the reconstruction procedure. Physical filter (e.g. aluminum) was not used during the scans but would be another option to reduce the beam hardening effect. The finale reconstructed images (Figure 3.a) cover one RVE of the fibrous architecture.

Figure 3. (a) cross-sectional slice of the reconstructed image; (b) segmented image using the structure tensor based method.
2.3. µCT and image processing

The post-processing of the obtained images aims at generating unit cells for numerical simulations. A mesoscopic modeling strategy for textile composites using an image processing technique based on structure tensor of image gray levels [3] has proved its efficiency (for example [4]). In the present work, the same approach is implemented in MATLAB routine, which allows us to identify inter-yarn voids, matrix, warps, and wefts. In our implementation, the structure tensor is calculated at each voxel position within a small local window (7 voxels per side in the present case). Therefore, the resulted description of the microstructure (image segmentation result) has the same resolution of the initial image (Figure 3.b). Three parameters are used for the image segmentation: average gray level (AVG), anisotropy degree (β) and characteristic angle (γ). The characteristic angle is chosen as the angle between the local orientation vector and the X-axis (warp direction), so that the warps and wefts can be distinguished.

The resulted unit cell contains about 450 million elements (1407x323x987 voxels). Even though the FFT based methods have been proven to provide a great advantage for parallel computation [15], such simulations are quite expensive that require a huge number of processors. To economize the computational cost, we choose to decrease the unit cell resolution (i.e. number of elements). Unit cells with four different resolutions have been generated (Table 3).

| Name     | w21   | w11   | w5   | w3   |
|----------|-------|-------|------|------|
| Resolution (voxels) | 15x69x49 | 29x131x93 | 64x291x207 | 107x483x343 |
| Element size (µm) | 185   | 97    | 44   | 26   |

3. Numerical models

3.1. FFT based methods

Since the first conference paper of [9] (called “basic scheme”, see Table 4), the FFT based methods have been improved, extended to many nonlinear behavior (viscoelasticity, plasticity, etc) and have become more and more attractive for image-driven modeling of materials properties, thanks to their simplicity and efficiency. The variables to be solved in FFT based methods are strains or stresses, instead of displacement. Note that no tangent calculation is necessary, which is different from the FEM scheme. In fact, by introducing a polarization term ((3) of Table 4), the local problem is transformed into Lippmann-Schwinger equation, leading to a convolution product with the Green operator: $\varepsilon(x) = E - (F_0 \ast \tau)(x)$. With periodic boundary conditions, the problem can be transformed into Fourier space, turning the convolution product to a simple multiplication ((5) of Table 4). Such an algorithm is very suitable for parallel computation, because: (i) the computations of (2,3,5) in Table 4 are local and can be solved separately for each material point; (ii) the FFT and inverse FFT are not local, but various packages (e.g. parallel FFTW) are available to efficiently complete these two steps in a parallel way.

A code (AMITEX, [16]) developed in CEA France is employed in the present work. This code provides a possibility to massively parallelize the computation in a large number of processors. AMITEX is based on the basic scheme [10]. In addition, it incorporates a convergence acceleration procedure, inspired from the FEM code CAST3M [17], as well as a modified Green operator, same as that proposed by [18]. As a result, the convergence in AMITEX is faster than the original basic scheme and much less sensitive to the choice of reference material. For instance, the computation with the
The highest unit-cell resolution (~18 million elements for w3 in Table 4) has been completed within 60 hours using 12 processors.

### Table 4. The basic scheme of the FFT method proposed by [10].

| Initialization | $\varepsilon^0(x) = E$ | (1) |
|----------------|--------------------------|-----|
| Loop           |                          |     |
| $t = k$        | Compute the stress through a constitutive law in real space (UMAT) | $\sigma^k = \sigma(\varepsilon^k(x))$ | (2) |
|                | Convergence test         |     |
|                | Compute the polarization tensor | $\tau^k(x) = \sigma^k(x) - C_0 : \varepsilon^k(x)$ | (3) |
| $t = k + 1$    | FFT transform            |     |
|                | Solve the problem via the Green operator in Fourier space | $\hat{\varepsilon}^{k+1}(\xi) = - (\mathbf{G}^0 \cdot \hat{\varepsilon}^k)(\xi)$ | (5) |
|                | Inverse FFT transform    |     |

3.2. Local constitutive laws

The composite microstructure is discretized into three types of elements, whose behaviors follow different local constitutive laws: inter-yarn voids with no stiffness, matrix as isotropic damageable, and yarns (warsps and wefts) as anisotropic damageable. As a first attempt, the influence of intra-yarn is neglected. The yarns are considered as homogeneous media, whose anisotropic properties are estimated by: simplified micromechanical models [20,21] for elastic and longitudinal strength in tension ($X_L$), experimental for longitudinal strength in compression ($X_C$), and numerical simulation based on micro-mechanical analysis for transversal and in-plane shear ($X_T$) as shown in [24]. This model has been readily used by several authors [4,15,21]. It requires the volume fraction of fibers in the yarn to be evaluated, which is approximately estimated to be 60% from SEM observations in the present study. The results are given in Table 5. The fracture toughness are chosen to be 11 kJ/m$^2$ and 0.2 kJ/m$^2$ for the tensile failure in longitudinal and transverse directions respectively.

### Table 5. Properties of the homogenized yarns (unit in MPa):

| $E_{11}$ | $E_{22} = E_{33}$ | $v_{12} = v_{13}$ | $v_{23}$ | $G_{12} = G_{13}$ | $X_L$ | $X_C$ | $X_T$ | $X_{TC}$ | $X_S$ |
|----------|-------------------|-------------------|---------|-------------------|-------|-------|-------|-------|-------|
| 44400    | 11640             | 0.26              | 0.33    | 4480              | 1500  | 1000  | 60    | 150   | 50    |

The CDM model used by [4] is employed to simulate the initiation and propagation of damage in the composite. This model is implemented in a user subroutine UMAT supported by AMITEX. Recently, a similar FFT model was also proposed by [21] to simulate the damage evolution in virtual/idealized composites. Yet, a different iterative scheme was used in their work, which is based on a variational formulation of the FFT method [13].

3.3. Loading and boundary conditions

The boundary conditions in FFT methods are intrinsically imposed as periodic. However, the unit cells of real microstructures are never perfectly periodic, which will inevitably induce artifacts on the simulated stress/strain field. Particularly in the case of damage modeling, this edge effect must be treated with more attention, because the geometrical discontinuity of microstructure at unit cell boundaries lead to unrealistic stress concentrations hence damage initiation. In order to reduce the edge effect, we add marginal layers around the unit cells, as shown in Figure 4. These marginal layers are assigned with different elastic (non-damageable) properties according to the loading direction: for loading in X-axis
(weft direction), the elastic modulus of margin Y will be set to zero, while that of margin X larger than zero; inversely for loading in Y-axis (warp direction).

**Figure 4.** 3D rendering of the unit cell with the resolution of 15x69x49 voxels (w21), the matrix is not shown in the figure.

The marginal layers with non-zero elastic properties can be understood as intermedia to uniformly transmit the load (stress in the present case) over the boundary surfaces. Therefore, their stiffness should be as high as possible. However, too high stiffness of the marginal layers induces difficulties to the convergence of the calculation (reason unclear for now). The effect of this stiffness of the marginal layers will be discussed in the following section.

The unit cells will be subjected to incremental strains with 100 time steps up to 1.5% in either X-axis or Y-axis.

### 4. Results and discussions

#### 4.1. Effect of the stiffness of marginal layers

We use the unit cell of the lowest resolution (w21 from Table 3) to analyze the effect of the stiffness of marginal layers. Six simulations are carried out with different stiffness of marginal layers. The elastic coefficient of matrix ($E = 3 \text{ GPa}, \nu = 0.3$) is chosen as a reference for this analysis. The macroscopic stress-strain curves of the six simulations are presented in Figure 5. The strength of the material increases with the stiffness of marginal layers and trends to be stable after 60 GPa (C0x20). On the other hand, a higher marginal stiffness (> 150 GPa, C0x50) makes the computation not convergent after the damage is activated. As a compromise, we choose the elastic modulus of the marginal layers as 60 GPa for further simulations.
Figure 5. Macroscopic stress-strain curves of the simulations using different stiffness of marginal layers for tension in warp direction.

4.2. Effect of unit-cell resolution
The study of the voxel size on the macroscopic behavior is shown here. For this purpose four unit cells of different resolutions generated from the same CT image (see Table 2 in section 2). Note that the used damage model incorporates a regularization scheme based on Bazant’s crack band model [22] so that the mesh dependency on dissipated fracture energy is minimized. The macroscopic stress-strain curves are shown in Figure 6. One interesting finding is that the elastic behavior is not dependent on the image resolution, i.e. the stress-strain curves are superimposed. Both the damage initiation (the beginning of the nonlinearity of the curves) and the material strength increase with the image resolution. This effect becomes very small when the image resolution is high enough (e.g. element size of 44 µm for w5 from Table 3).

Figure 6. Macroscopic stress-strain curves of the simulations using different image resolutions under tension in weft direction.
4.3. Stress evolution and damage field

Figure 7 shows the fractured zones in matrix and transversal yarns, i.e. warps for tension in weft direction and verse-versa. Under both loads, the damage zones are less observed in matrix than in transversal yarns. The damage localized near the composite borders is linked to the geometrical discontinuity. Inside the composite volume, the transversal damage is well reproduced under both loads. For tension in warp direction, damage seems more severe between yarns (inter-yarn damage) than inside yarns (intra-yarn damage). The inter-yarn damage is mostly observed in the connecting regions between warps and wefts. On the contrary, the tension in weft direction seems to produce more intra-yarn damage than inter-yarn damage. This difference may be explained by the difference in waviness of warps and wefts. In fact, the out-of-plane undulation of warps can induce much stronger shear stress concentrations at connecting region under tension in their longitudinal direction than in their transversal direction.

Regarding inter-yarn void presence effect on the mechanical response, the following conclusions can be drown. There is no significant effect on the macroscopic elastic properties was observed under presented loading cases. The stress concentration in the adjacent yarns has been increased locally, however, the final fractured zones seems to be strongly influenced by the transverse properties and internal architecture of textile composites. On the other hand, the transverse properties of yarns are strongly affected by intra-yarn voids. To confirm this preliminary conclusion, further detailed investigations are necessary.

Figure 7. Fractured zones, whose damage parameter is larger than 0.8, in matrix (blue) and transversal yarns (red) at tension level of $\varepsilon = 1.35\%$: (a) under tension in warp direction, (b) under tension in weft direction.
5. Conclusions

An FFT based method has been employed with coupled CDM model to predict the damage evolution in 3D interlock composite including voids induced by RTM manufacturing process.

Geometric model has been reconstructed from micro CT data. In order to reduce the edge effect due to the geometrical discontinuity at the image borders, marginal layers have been added, and the effect of the stiffness on the simulation result has been studied suggesting optimal values.

Unit-cells with different resolutions have been generated from the same CT data in order to show the sensitivity of numerical solution to unit-cell resolution. It was observed that elastic response is not sensitive to unit-cell resolution, while the nonlinear (damage) behavior can be strongly affected. The efficiency of the FFT based methods is demonstrated for using high unit-cell resolution in the context of damage prediction.

A preliminary conclusion has been drawn on the influence of voids on damage evolution in the composite. The presence of the inter-yarn voids has induced stress concentrations in adjacent yarns affecting local stress field and thus the damage initiation. However, the transverse properties and out-of-plane undulation of yarns are more critical than the inter-yarn voids for the elementary properties used in the simulations. More sophisticated models at the microscopic length scale are required to study the relative importance of intra- and inter-yarn voids on damage behavior of the composite.

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