Composites Science and Technology 68 (2008) 2433–2440

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

# Simulation and tomography analysis of textile composite reinforcement deformation at the mesoscopic scale

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ARTICLE INFO

*Article history:*
Received 5 February 2008
Received in revised form 10 April 2008
Accepted 13 April 2008
Available online 7 May 2008

*Keywords:*
A. Textile composites
B. Mechanical properties
C. Finite element analysis (FEA)
E. Resin transfer moulding (RTM)
X-ray tomography

ABSTRACT

The preforming stage of the RTM composite manufacturing process leads to fibrous reinforcement deformations which may be very large especially for double curvature shapes. The knowledge of the mesoscopic deformed geometry is important for reinforcement permeability computations and for damage prediction analyses of the composite. A simulation method for woven composite fabric deformation at mesoscopic scale is presented in this paper. A specific continuum hypo-elastic constitutive model is proposed for the yarn behavior. The associated objective derivative is based on the fiber rotation. Spherical and deviatoric parts of the transverse behavior are uncoupled. X-ray tomography is used to obtain experimental undeformed and deformed 3D geometries of the textile reinforcements. It provides, in particular, fiber distribution within the yarn. A comparison between deformed geometries obtained by mesoscopic simulation and by tomography is presented for biaxial tension and in-plane shear deformation.



## 1. Introduction

The RTM (resin transfer moulding) process for composite material forming consists of three stages. A dry textile reinforcement is formed (preforming stage), then the resin is injected within this preform and cured to obtain the final composite part [1–3]. If the shape of the composite part is double curved, the textile reinforcement is subjected to in-plane deformation in order to reach this shape. These deformations can be significant, especially in-plane shear that can reach 40° or 50° (see Fig. 1) [4,5]. Preform deformation at the scale of the composite part (macroscopic scale) corresponds to local deformation of the fibrous network (mesoscopic scale) which can be large particularly when it is woven. This deformation modifies the mechanical properties and the permeability of the reinforcement.

The objective of this paper is to present a method for the simulation of the deformation of a woven composite reinforcement representative unit cell (i.e. at the mesoscopic scale). These simulations enable to determine the macroscopic scale mechanical behavior of composite reinforcements (without resin) at finite strain. This mechanical behavior is required in finite element simulations of the preforming stage [6–13]. Besides, knowing the deformed geometry of the woven cell enables to determine the permeability of the fibrous reinforcement via Stokes (or Stokes Brinkman) flow simulations within this deformed cell [14–18]. Finally, the geometry of the deformed reinforcement heavily influences the mechanical behavior of the final composite part. In particular, mesoscale damage prediction simulations require the knowledge of this geometry [19–23].

The local geometry of the woven reinforcement can be determined experimentally using X-ray tomography. The advantage of tomography is to give access to local 3D observations inside the sample [24,25] which is not possible with the standard microscopy techniques restrained to surface observations. X-ray tomography is used in the present paper at a mesoscopic scale (the scale of the yarns) to determine the initial and deformed geometry of fibrous composite reinforcements and at a microscopic scale (the scale of the fibers) to determine the density and distribution of fibers within the yarn. The information gathered from these experiments is used to improve and justify the hypotheses made during the development of the mechanical constitutive model and above all to validate the results obtained from simulation.

In the present paper, the yarn is assumed to be a continuum. The mechanical behavior of this continuum is very specific since the yarn is made up of thousands of fibers which can slide with respect to each other. The suggested constitutive model is hypo-elastic [26–29]. The objective derivative of this model is defined from the local fiber rotation so that it accurately tracks the fiber direction. The transverse behavior of the yarns is of a great importance because local crushing of the yarns is significant during the deformation. It will be shown in Sections 2.3 and 3.1 that the X-ray tomography observations support the fact that the behavior of the yarn can be assumed to be transversely isotropic. Spherical

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doi:10.1016/j.compscitech.2008.04.038

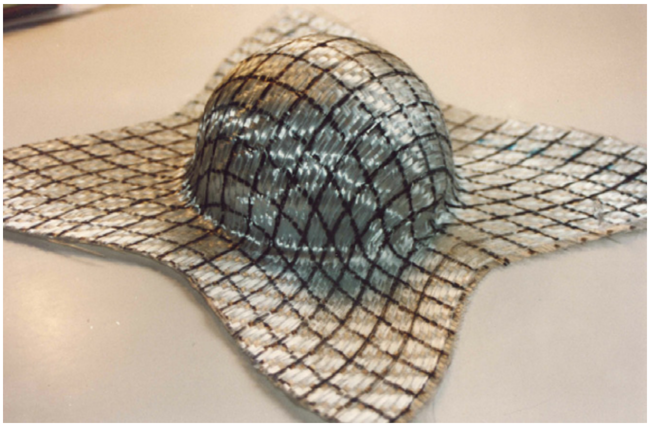

**Fig. 1.** Hemispherical preforming of a woven composite reinforcement. A network of initially straight and continuous orthogonal lines has been drawn on the initial flat reinforcement.

**Table 1**
Plain weave and 2 × 2 twill and G1151 specifications

| Weaving | Glass plain weave | Carbon 2 × 2 twill | G1151 (interlock) |
|---|---|---|---|
| Yarn width (mm) | Warp: 3.4<br>Weft: 3.4 | Warp: 2.4<br>Weft: 2.4 | Warp: 1.9<br>Weft: 2.2 |
| Densities (Yarn/mm) | Warp: 0.25<br>Weft: 0,25 | Warp: 0.35<br>Weft: 0.35 | Warp: 0.75<br>Weft: 0.6 |
| Crimp (%) | Warp: 0.55<br>Weft: 0.55 | Warp: 0.3<br>Weft: 0.35 | Warp: 1.2<br>Weft: 0.5 |
| Yarn stiffness (N) | 47,000 | 54,000 | |

and deviatoric parts are separated in the transverse constitutive model. In Section 4, the mesoscopic deformed geometries of the unit cell under biaxial tension and large in-plane shear (46°) are compared to the experimental geometries obtained by tomography. The agreement is good.

## 2. X-ray tomography of the studied composite reinforcements

### 2.1. Principle of the technique

The principle of X-ray tomography is explained in details in [24]. This technique is analogous to the medical scanner and allows from X-ray radiography reconstructing non-destructively the internal structure of an opaque material. The reconstruction involves a computed step and the final image is a 3D map of the local X-ray attenuation coefficient. The fibers absorbing much more the X-rays than air, the attenuation contrast allows a straightforward subsequent thresholding of the images.

The laboratory tomograph used in the present study is a commercial model [30] located in the Mateis Laboratory at Université de Lyon. It includes a nanofocus transmission X-ray tube (W target). The size of the focus (and thus the resolution) is tunable from 1 to 5 μm. The detector used is a 1500 × 1900 array of amorphous silicon sensible elements each of a lateral size of 127 × 127 μm. The beam has been operated at 90 keV and 170 μA with no filtering for the observations made in this study. The setup used exhibiting a cone beam geometry, it is easy to obtain images at different values of the magnification. For this purpose, the sample is simply placed at different distances from the source leading to a possible voxel size of 1.5–80 μm in the resulting reconstruction. The highest resolution achieved in this study is 2.85 μm because of the trade-off between the resolution and the maximum specimen dimension (i.e. yarn width). The complete sample must be contained indeed within the cone beam, i.e. in the field of view of the detector.

The uncertainty of the measures made by tomography can be estimated to ±1 voxel.

### 2.2. Samples, resolution and experimental results

Thanks to the above mentioned flexibility, the woven composite fabrics have been analysed at two different scales namely the mesoscopic scale and the microscopic scale. Undeformed geometries but also deformed geometries of interest in this study can be ana-

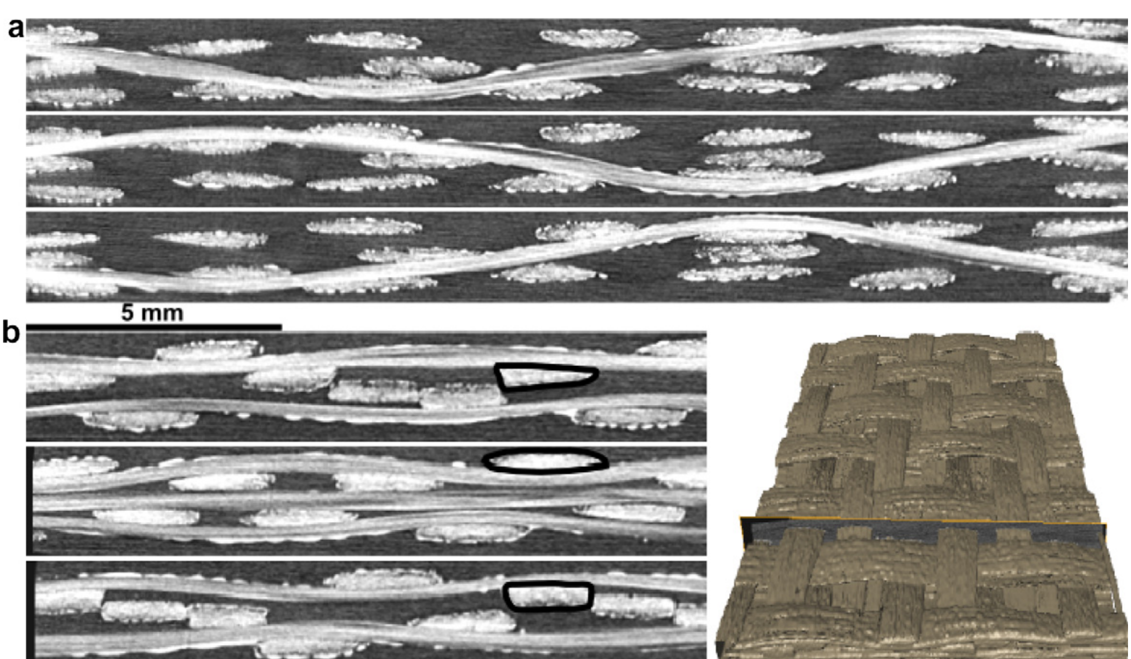


**Fig. 2.** Unloaded interlock reinforcement G1151 (20 μm resolution, rescaled). (a) Three successive slices within warp yarn planes and (b) three successive slices within weft planes. Three cross sections of the same yarn are underlined in black.