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Stochastic framework for quantifying the geometrical variability of laminated textile composites using micro-computed tomography

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ABSTRACT

Reference period collation, a method recently proposed for analysing the stochastic nature of a nominally periodic textile reinforcement, is extended to allow application to a laminate of stacked, nested plies. The method decomposes the characteristics of the fibre reinforcement into non-stochastic periodic (or systematic) trends and non-periodic stochastic fluctuations. The stochastic character of every tow is analysed in terms of the centroid position, aspect ratio, area, and orientation of its cross-section. The collation method is tested using X-ray micro-computed tomography data for a seven-ply 2/2 twill woven carbon-epoxy composite produced by resin transfer moulding.

All tow characteristics, with exception of the in-plane centroid position, exhibit systematic trends that show only mild differences between plies. They correlate most strongly with cross-over points within a single ply. Of the various parameters, the in-plane centroid position is subject to the largest tow-to-tow variability, with deviations correlated over distances exceeding the unit cell size.

1. Introduction

The variability of reinforced polymer composites can be substantial, especially when the reinforcement is a textile product. With the sources of variability poorly understood, methods are lacking for its control or the accurate prediction of the effects of variability on the quality and reliability of composite structures. This is particularly important for safety critical components used in aerospace and for lifetime estimation of various applications, e.g. wind turbine blades.

Uncertainty quantification for composite materials is getting more attention lately [1–3]. The definitions of uncertainty and variability are taken from Oberkampf et al. [4] and Moens et al. [5]. The magnitude of variability in performance, resulting from imperfections generated at various stages of production, has been partially reported with contributions considering elastic mechanical properties [6], formability [7], permeability [8,9] and damage propagation [10,11]. However, the inadequacy of experimental data [1] and realistic numerical models of composites for establishing Virtual Tests [12] are still obstacles. Almost all published work deals with randomness of local properties, without considering the correlation of properties between different positions in a component. Yet, experimental work [13] has already proven that spatial variation must be taken into account to achieve a correct representation of the material. Significant advances in realistic material modelling can only be achieved by [1] (i) collecting enough experimental data on the spatially correlated random fluctuations of uncertain material parameters for short and long range deviations, and (ii) forming a probabilistic link between macroscopic mechanical properties and the lower scale mechanical characteristics. This paper reports and analyses data for short range deviations, i.e. deviations correlated over distances less than or compared to the size of the unit cell, while the collection of long range deviations and the relation of microstructural deviations to macroscopic properties will be addressed in future publications.

The spatial geometrical variability over scales of 1–15 mm is characterised using three-dimensional (3-D) images acquired via X-ray microfocus computed tomography (micro-CT). This non-destructive technique is nowadays used in composite materials to characterise the geometry for modelling purposes [14,15] or to analyse damage initiation [16–18]. The use of micro-CT for quantifying geometrical variability [6,19] offers advantages over the optical imaging processes when spatial information needs to be analysed over the extent of a structure. Unlike optical imaging, which yields data on discrete, separated cross-sections [20,21], micro-CT images every voxel throughout a scanned volume.

Variability quantification of geometry using micro-CT has already been performed with different approaches but with the same objective: quantifying the scatter in geometry introduced during

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the textile manufacturing. Desplentere et al. [6] quantified variability in the structure of four different 3-D glass warp-interlaced fabrics. Local tow parameters such as tow dimension and spacing are statistically quantified in terms of the mean value and standard deviation. The measures are performed from cross-sectional images taken at an arbitrary location in the textile. Bale et al. [19] statistically quantified the entire tow path by introducing the *reference period collation* procedure which maximises the information derived from a small specimen and exploits the nominal periodicity of the textile. This method was introduced to distinguish non-stochastic periodic variations from non-periodic stochastic deviations. Two ceramic textile samples are investigated using synchrotron micro-CT to quantify the tow centroid locations stochasticity with variations in the aspect ratio, area and orientation of tow cross-sections in terms of its standard deviation and correlation length. This correlation length is essential to determine the spatial dependencies between parameters on the same tow and between tows.

The current paper extends the characterisation procedure of Bale et al. [19] to polymer textiles with different topology and arranged in a laminate. The objectives are to (i) present a stochastic framework to derive a spatially statistical description of an arbitrary textile composite using micro-CT at the laboratory scale, (ii) apply this methodology to a seven ply carbon-epoxy 2/2 twill woven textile sample produced by resin transfer moulding (RTM) and (iii) discuss the variability in geometry within one ply and between plies.

2. Stochastic framework

A statistical description of the internal geometry of a textile composite is experimentally acquired following three general steps:

1. *Perform micro-CT scan of a composite specimen*
   (a) Preparation of samples consisting of several unit cells (at least one).
   (b) Definition of the radiation source parameters.
   (c) Acquisition of reconstructed 3-D volume of the composite specimen.
2. *Data processing and analysis of cross-sections*
   (a) Image segmentation (identification of distinct material domains) for a number of equally spaced cross-sections.
   (b) Ellipse fitting to each tow in transverse section.
   (c) Transformation of data into a new coordinate system with correction for sample alignment during micro-CT scan.
3. *Statistical characterisation of the tow paths within each ply*
   (a) Definition of a reference period.
   (b) Determination of the systematic trend for each tow component.
   (c) Determination of stochastic deviations from this systematic trend with definition and quantification of standard deviation and correlation length.

The sample material does not require any special treatment for the CT analysis, which is an important advantage of this framework. Samples cut from different plates are so recorded, because variability can arise both within one plate, *intra-plate variability* and also between plates, *inter-plate variability* [22].

3. Experimental procedure (step 1)

The dimension of each sample is chosen as a trade-off, given the fixed total number of voxels, between the desired degree of detail in the images (smaller voxel size preferred) and the number of tows that can be analysed from one scan (larger voxel size preferred with specimen volume at least one unit cell). The sample material in this work is a seven-ply polymer textile composite. Each ply consists of a twill 2/2 woven carbon fabric from Hexcel (G0986 injectex) [23], with areal density 285 g/m^2 and nominal unit cell dimensions of 11.4 by 11.4 mm. The seven ply dry reinforcement is impregnated with epoxy resin in a RTM process, achieving a fibre volume fraction of 55.3%. Fig. 1 shows the WiseTex virtual model of this fabric. One unit cell consists of 4 warp tows which are all equally spaced by $\lambda_y/4$ over the period in the y-direction λ_y, and 4 weft tows which are equally spaced with period $\lambda_x/4$ in the x-direction λ_x.

The X-ray source parameters (voltage and current of the beam) and acquisition parameters of the micro-CT inspection technique are chosen based on differences in absorption of X-rays through the material [24]. One sample of 12.5 by 12.5 mm with above material properties is mounted in a GE Nanotom. The equipment has a 180 kV/15 W nanofocus X-ray tube and can obtain minimum voxel sizes of 500 nm. For the current type of material with the given sample size, X-ray source parameters are set to 33 kV and 295 μA to acquire high quality images with voxel size of (6.75 μm)^3.

4. Data processing and analysis of cross-sections (step 2)

4.1. Image segmentation and ellipse fitting

The micro-CT scan provides a 3-D volume representation of a composite sample. Equally spaced 2-D slices are extracted from this volume in each weave direction. The warp tow cross-sections are characterised from slices normal to the weft direction and weft tow cross-sections from slices normal to the warp direction.

The steps used in image analysis are dictated partly by the imperfect quality of images. The carbon fibres and epoxy matrix material have a similar material density and tend to give poor contrast between the tows of different fibre orientation if the image voxel size is not small compared to the fibre diameter. Contrast enhancement techniques are available for characterising carbon-epoxy materials in micro-CT equipment [25,26], but require additives used to coat tows during production. The image quality of the current sample is optimised by subsequent post-processing steps in the image analysis software VG Studio MAX 2.1 to reduce the noise in the images with median filters, enhance contrast with filters, and accentuate edges with edge-preserving smoothing algorithms. A processed cross-sectional image is presented in Fig. 2a, where the marked areas indicate locations where the boundary between warp and weft tows are still hard to distinguish. Manual input for image segmentation is required, which limits the amount of slices used to analyse the internal structure of the sample in a reasonable time (set to around 6 h). Nineteen slices were analysed for

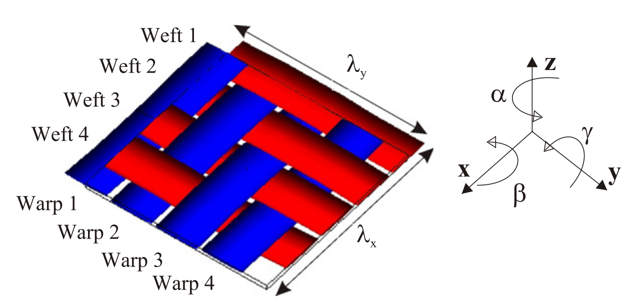

Fig. 1. WiseTex model of a 2/2 twill woven fabric. The coordinate axis system is chosen to have the x-axis and y-axis respectively parallel to the warp tows and weft tows.