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Simulation of the cross-correlated positions of in-plane tow centroids in textile composites based on experimental data

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ABSTRACT

In-plane centroids of textile composites are simulated as cross-correlated random fields. Each tow position is defined as an average trend quantified from experimental data, added with zero-mean deviations produced as a stochastic field. Realisations of these fields are generated using a framework based on the Karhunen–Loève series expansion that is calibrated with experimental information from prior work. Positional deviations are obtained that are correlated along the tow and between neighbouring tows.

The application is a 2/2 twill woven carbon fibre reinforced epoxy consisting of multiple unit cells. Generated in-plane deviations of the warp and weft tows resemble the experimental fluctuations with similar wavelengths. Simulation of thousand specimens demonstrates that the virtual in-plane positions possess the experimental standard deviation and correlation lengths on average.

1. Introduction

The reinforcement of a textile composite is susceptible to a significant amount of variability. Though, composites are often modelled without considering randomness in the tow path descriptions. Such ideal representations do not appear in physical samples and lead to unreliable results because the performance of a textile is strongly linked to its geometrical structure. Any variation in the tow path will influence the properties of the final composite. The effect of geometrical scatter on the mechanical performance is already investigated for the elastic mechanical properties [1,2], formability [3], permeability [4,5] and damage initiation and propagation [6–8]. A correct identification of the spatial geometrical fluctuations of a textile product improves the quality of numerical analyses and permits to quantify the effect of variability on the mechanical performance.

This deficiency in realistic simulations is partially attributed to the lack of experimental data with a thorough statistical analysis. Researchers who are quantifying the variation in geometry usually do not consider correlation. However, the description of dependency of a single property along its tow length or between different parameters at one location, is required to reproduce the correct geometry of the material. This is already demonstrated for several types of composites [9]. Further, modelling techniques are often inadequate to introduce local and long-range variations in the tow path and accurately simulate the desired correlation structures [10]. It is not the objective to simulate more precise representations without considering experimental data, such as in [11], but to calibrate the numerical modelling procedure with the measured variations. Realistic representations of textile composites are acquired by a two-step procedure [12]: (i) collection of sufficient experimental data on the spatially correlated short- and long-range geometrical variations, and (ii) derivation of the macroscopic mechanical properties from the lower scale geometrical characteristics. This paper describes the last step of the approach of Charmpis et al. [12] and is preceded by several other publications [13–15]. A methodology is proposed to generate the cross-correlated geometrical variability of textiles typically present at the long-range, and is demonstrated for a 2/2 twill woven carbon fibre reinforced epoxy composite.

Long-range variations are frequently omitted when modelling component-size textile samples. Generally, representative volume elements are assembled to generated any size of composite, but this is not a full replica of the real reinforcement structure. Simulation of long-range variations in textile composites is only sparsely tackled in literature. Skordos and Sutcliffe [3] investigated the in-plane behaviour of a carbon-epoxy satin weave for modelling the forming process. Tow orientations are simulated as an Ornstein–Uhlenbeck process of which the parameters are estimated by

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the likelihood function. Next, realisations of woven sheets are obtained using the Cholesky decomposition of the covariance structure of warp and weft direction in combination with normally distributed independent variables. Values of warp and weft orientation and unit cell size are generated at discrete points that compromise the warp and weft direction and size of the unit cell. Endruweit et al. [5] performed stochastic simulations of the resin injection in bi-directional non-crimp fabrics. Random fields of fibre distances are constructed using spectral representations with trigonometric functions to implement spatial correlation along the tow. The frequency and phase of each function are determined randomly on given intervals, with an upper limit for frequencies determined by the tow mobility in the transverse direction observed in actual fabrics and the phases between 0 and π. Abdiwi et al. [16] reproduced full-field variability of the tow directions across flat sheets based on measured variability of inter-tow angles. The geometry mesh is generated with a pin-jointed net kinematics code where variability is added by stretching and additional perturbations of the nodes. These perturbations are introduced using sinusoidal functions with particular wavelength and vertical amplitude to simulate the long-range correlation effects. No short-range variability is considered. This code is implemented in a genetic algorithm with objective functions that minimises the mean and standard deviation of the measured inter-tow angle to reproduce similar statistical variations as measured. Series expansion techniques are also employed by Yushanov and Bogdanovich [17] to generate a random reinforcement path characterised by its mean value and covariance matrix. The stochastic reinforcement is generated by defining a suitable position vector with a random vector function which is expanded into a deterministic component and a random component. A stochastic local basis is afterwards introduced to uniquely define the directional cosines of the arbitrary reinforcement path, specified by the position vector.

Except for the contribution of Skordos and Sutcliffe, all described publications consider an approximated correlation function along the tow direction which is not validated with experimental data. The presence of cross-correlation between neighbouring tows is also not tackled or is indirectly introduced. Experimental validation of the input data and correct introduction of all correlation structures are however mandatory to replicate the internal geometry. To precisely model the long-range tow path parameters, a methodology developed by Vořechovský [18] is chosen which is not yet applied in the field of composites. Vořechovský proposed a framework for generating cross-correlated random fields based on Karhunen–Loève series expansion. Each random field must share an identical auto-correlation, while the cross-correlation structure between each pair of fields can be described by a simple coefficient.

This paper discusses the implementation of the procedure of Vořechovský for generating Gaussian random fields of the in-plane centreline of the tow path, called *centroid*. Each stochastic field corresponds to a single tow. The methodology is calibrated with the experimental data of [15]. In summary, the paper discusses the (i) collection of statistical information from experimental samples and (ii) the application of the method of Vořechovský [18] in the field of textile composites to simulate the in-plane centroid positions. A comparison is made between the experimental and simulated statistical information to demonstrate the accuracy of the generation procedure.

2. Experimental data

The developed methodology is demonstrated for a 2/2 twill woven Hexcel fabric (G0986) [19] impregnated with epoxy resin.

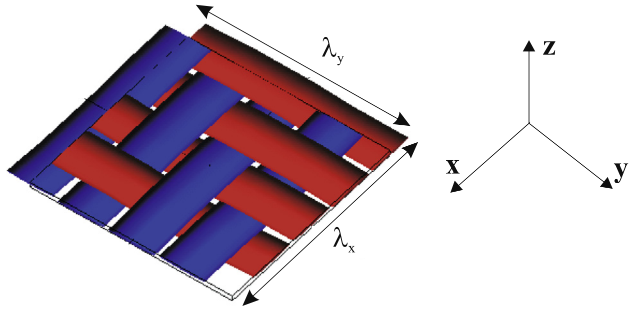

Fig. 1. WiseTex model of a 2/2 twill woven reinforcement. The *x*-axis and *y*-axis of the coordinate system are respectively parallel to the warp and weft direction.

Each reinforcement unit cell is built with four equally spaced warp and weft tows consisting of 6 K carbon fibres, with a nominal areal density of 285 g/m^2. The idealised unit cell topology is given in Fig. 1 with λ_x = 11.43 mm and λ_y = 11.43 mm, respectively the periodic lengths of warp (x-axis) and weft (y-axis) tows as specified by the manufacturer.

Data of the in-plane centroids are collected in [15] from two single-ply carbon fabrics impregnated with epoxy in a resin transfer moulding (RTM) process. The in-plane dimension of both samples (sample 1 and 2) is quantified using optical imaging over a square region of thirteen by thirteen unit cells to investigate the long-range effect. In-plane coordinates of forty warp and forty weft tows are derived that represent a total of hundred unit cells by manually marking the boundaries of tows for prescribed grid spacings. Centroid locations are subsequently defined as half the tow width at each grid location. A single tow in-plane centroid is afterwards defined by connecting these locations along the entire grid. All coordinates are given as input to Matlab where they are transformed to a global axis system and verified if a possible shift in the sample data should be removed due to the manual placement of the composite in the scanning device [15].

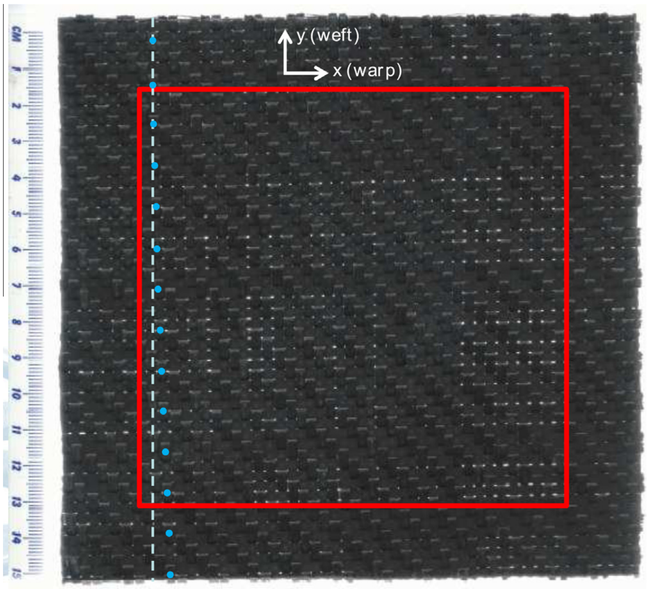

Fig. 2. Optical scan of a one-ply 2/2 twill woven carbon fibre fabric impregnated with epoxy resin. Warp tows are oriented horizontally, while weft tows are positioned in vertical direction. The red square indicates the region where the in-plane position of the centroid is characterised. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)