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Stochastic multi-scale modelling of textile composites based on internal geometry variability

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ABSTRACT

A stochastic model of an experimentally measured unit cell structure is computed using the multi-scale textile software WiseTex. The statistical characteristics of a sample, derived in prior work, are used to calibrate the recently proposed Markov Chain algorithm for textile fabrics. The generated variable tow reinforcements are transformed in the WiseTex format that is compatible with tools for micromechanical analysis and permeability simulation.

The application is a seven ply polymer textile composite, with each ply consisting of a twill 2/2 woven carbon fabric in an epoxy matrix. The developed model possesses random tow centroid paths with nominal cross-sectional properties.

1. Introduction

The variability in the internal geometry of textile reinforced polymer composites can be substantial. It is important to quantify the effect on the mechanical performance to improve the quality and reliability of numerical analysis for composite structures. Mapping the variation in material properties will support material design and certification of structural composites for e.g. aerospace applications [1,2].

Within the field of uncertainty quantification, the overall uncertainty is differentiated in *aleatory uncertainty* and *epistemic uncertainty* [3,4]. The former uncertainty is due to inherent randomness of the structure, while epistemic uncertainty is due to a lack of knowledge and has an unknown source. The objective in this study is to reduce the epistemic uncertainty in the geometrical parameter distributions and the variation in the mechanical properties of textile composites. Uncertainty quantification in composite materials is attaining more attention lately [5,6]. Introducing variability at different scales in computational models is found to be essential or even critical. Zohdi and coworkers [7,8] demonstrate that the macroscopic failure behaviour of ballistic fabrics changes from abrupt to gradual failure when variation in the filament alignment within a tow is considered. Variation in the geometrical model of composite materials must be included to obtain random media models [9,10] that can be used to investigate the effect of random design parameters on e.g. the effective elastic properties.

When performing uncertainty analysis, it is important to verify the assumptions made throughout the procedure. The sources of variability in composites remain poorly understood and the inadequacy of experimental data [5,11] results in assumptions for the input probability density functions of numerical modelling methods. Further, only a few tools are available to partially model the geometrical variation of textile reinforcements [12]. Almost all published work considers randomness of local properties without correlation. However, recent experimental work [13] has proven that spatial variation of the stiffness properties is present over the extent of a composite structure. Significant advances in realistic material modelling can be achieved by Charmpis et al. [5] (i) collecting sufficient experimental data on the spatially correlated random fluctuations of uncertain material properties for short and long range deviations, and (ii) deriving probabilistic information for macroscopic properties from the lower scale mechanical characteristics of the material. In prior work [14], statistical information is collected on the short range deviations of a woven textile composite, i.e. deviations correlated over distances less than or compared to the size of the unit cell. This data is used as input for a multi-scale modelling technique to generate virtual specimens.

The developed virtual specimen will differ from computational models where the geometry is transformed to be more useful for numerical analysis. For these models, the reader is referred to

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the work of Kaminiski [9] and Ostoja-Starzewksi [10]. In this study, virtual specimens are generated that are replicas of the actual samples i.e. the random tow reinforcement is fully modelled. The availability of the full structure permits performing micromechanical analysis, permeability calculations or even creating a finite element model for stress–strain analysis, using the same random model. Modelling of random textile reinforcements for evaluation of performance has already been analysed with different approaches [15–18]. In a recent work of Abdiwi et al. [15], full-field variability of the tow directions across flat sheets is modelled. First, the variability of the inter-tow angles is determined for a range of woven fabrics. Second, a geometry mesh is generated with a pin-jointed net kinematics code where variability is added by introducing (i) horizontal stretching or contraction of elements along the horizontal centreline of the mesh and (ii) additional perturbations of the nodes based on functions over the horizontal and vertical centreline. This code is combined into a genetic algorithm controlling six parameters to ensure that the generated full-field geometric mesh reproduces the variability of the measurements. Yushanov and Bogdanovich [16] presented a generic theory to generate a random reinforcement path. The input information is limited to the mean and standard deviation of measured tow paths. 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. The elastic characteristics are evaluated using a stochastic generalisation of the orientation averaging approach. Sejnoha and Zeman [17] use the concept of statistical equivalent periodic unit cell by considering a two-layer idealised unit cell to be constructed with seven independent parameters, including the tow spacing and thickness. Numerical values are accordingly chosen such that the resulting macroscopic behaviour of the unit cell compares with that of a measured material. The correct values are found by a minimisation procedure of a set of equations of experimentally obtained two-point probability functions and lineal path functions. Blacklock et al. [18] define a Markov Chain algorithm to generate virtual specimens in which each tow is represented by a one-dimensional (1-D) locus in the three-dimensional (3-D) space. Fluctuations in the coordinates are generated by marching systematically along the tow's length and deviations depend only on the deviation of the previous point. The transition matrix for moving from one point in a single tow to the next is calibrated with the standard deviation and the correlation length measured for that type of tow. The dominant correlations must be those along a tow, with correlations between tows being relatively weak, to satisfy the Markovian procedure. If one of these conditions is not met, a variant of the proposed algorithm needs to be developed. A virtual specimen is built by combining the systematic variations of each parameter along the tow length, which is defined by experimental data, with the generated deviations by the Markov Chain procedure.

The current paper develops a stochastic virtual specimen in the deterministic WiseTex software [19] by applying the Markov Chain algorithm [18]. Virtual samples are generated that possess the same statistical information of an experimentally measured carbon-epoxy 2/2 twill woven textile laminate produced by resin transfer moulding (RTM) [14]. The systematic, periodic (or mean) patterns are first constructed from WiseTex according to a predefined grid along each tow length. Second, the Markov Chain algorithm, with specific input parameters for the material under consideration, generates deviations for the centroid coordinates for each particular tow type. The addition of these deviations to the systematic centroid values at each grid location results in a random structure that can be used for mechanical property evaluation. The objectives of the paper are summarised as (i) the generation of the centroid deviations of each tow type for the particular 2/2 twill woven material with verification of the Markov Chain assumptions, and (ii) the construction of the stochastic virtual specimen in the WiseTex software.

2. Statistical data of the material

2.1. Stochastic characterisation of the woven material

The subject material is a seven ply polymer textile composite. Each ply has a 2/2 twill woven carbon fabric from Hexcel (G0986 injectex) [20], with areal density 285 g/m^2 and ends/picks count of 3.5. The seven ply dry reinforcement is impregnated with epoxy resin using RTM as production process. The unit cell representation of the fabric is given in Fig. 1 with λ_x and λ_y respectively the period in the *x*- and *y*-direction. One unit cell includes four equally spaced warp tows and four equally spaced weft tows with nominal unit cell dimensions of 11.43 mm by 11.43 mm.

In prior work [14], statistical information of this material is collected using 3-D images acquired via laboratory micro-CT. Use of micro-CT offers advantages over the optical imaging processes when spatial information needs to be analysed over the extent of a structure. A sample of unit cell dimensions is positioned in a GE Nanotom with X-ray source parameters set to 33 kV and 295 μA to acquire high resolution images with a voxel size of (6.75 μm)^3. From the 3-D volume representation, two-dimensional (2-D) slices are extracted in warp and weft directions. The warp cross-sections are characterised from slices normal to the weft direction and vice versa for the weft tow cross-sections. Nineteen slices are analysed for each tow direction, yielding information at 0.75 mm intervals, so that each tow cross-over contact is populated by three data slices. The tow cross-sections along the path are afterwards fitted with ellipses (see Fig. 2), which is a valid assumption for the tow shape of the current topology as discussed in Olave et al. [21]. This procedure yields information about the tow path centroid coordinates (x,y,z), tow aspect ratio *AR*, tow area *A* and tow orientation θ in its cross-section.

Each ply is further analysed individually. First, geometrical information of the plies is derived with as most important outcome the mean of the unit cell periods: $\lambda_x = 11.55$ mm and $\lambda_y = 11.48$ mm. Second, the tow paths in each ply are statistically characterised using the method of *reference period collation* where each tow parameter is projected on a defined grid along the tow length [22]. This process exploits the nominal periodicity of the textile to maximise the information derived from a small specimen. Data is collected for tows assigned to the same *genus*, i.e. tows that should be identical given the nominal periodicity of the textile. The particular 2/2 twill woven fabric can be represented by two different genuses: one for the warp tows and one for the weft tows.

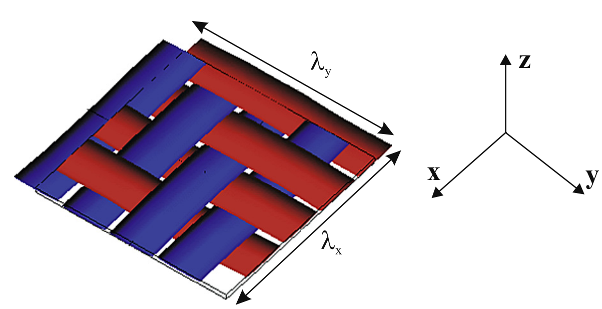

Fig. 1. WiseTex model of a 2/2 twill woven reinforcement. The *x*-axis and *y*-axis of the coordinate system are respectively parallel to the warp and weft direction.