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Multi-scale modelling strategy for textile composites based on stochastic reinforcement geometry

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Abstract

The quality of high-performance composite structures is difficult to predict. Variability in the macroscopic performance is dominated by the spatial randomness in the geometrical characteristics of the reinforcement, especially for textile composites. This work provides a roadmap for generating realistic virtual textile specimens spanning multiple unit cells, which are required to perform high-fidelity simulations. First, the geometrical variability in the reinforcement structure is experimentally quantified on the meso- and macro-scale in terms of average trends, standard deviations and correlation lengths. Next, each reinforcement parameter is modelled by the sum of its average trend and its zero-mean deviations, which are both determined by analysing experiments. Virtual specimens are then created using advanced simulation techniques that match the experimental statistics. Depending on the nature of measured correlations, the simulation technique is either a Monte Carlo Markov Chain method, a cross-correlated Karhunen–Loève Series Expansion technique or a Fourier Transform method used in combination with a Markov Chain algorithm. In a last step, a virtual representation of the textile geometry is constructed in geometrical modelling software, such as the commercially available WiseTex software.

The multi-scale framework is validated using data for a carbon–epoxy 2/2 twill woven composite produced by resin transfer moulding: the simulated tow deviations trends replicate the target statistics.

Keywords: Textile composites; Multi-scale modelling; Non-determinism; Probabilistic methods

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1. Introduction

The advantages of composites structures are well known. Besides a lower weight for the same or an enhanced performance, composites enable energy efficiency for air, ground and water transport. However, the introduction of composites remains hampered by the relatively high cost of raw material and the uncertain quality of high-performance

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composite structures. The latter is especially important in the aviation industry, where process variability is indicated as one of the main reasons for the increase in development time and cost for structural components [1].

Sufficient methods are available for the characterisation of mechanical properties by experiments and numerical simulation. Yet, there is a lack of understanding of how and why the mechanical properties vary across a composite product. Due to the specific nature of each composite with its specific manufacturing process, scatter can be very pronounced which impedes a correct estimate of the quality of the composite component. This variability in the macroscopic performance is directly linked with variability in the internal structure and constituents at the lower scales.

Variability in the reinforcement structure is frequently omitted or only partially introduced in simulations [2–4]. For the specific case of textile composites, the reinforcement is adequately modelled by exploiting the hierarchical principle. Predictive models are constructed following a sequence from fibre, tow, textile, preform, to the final composite [5]. To represent its internal geometry, a periodic unit cell model is considered where tow path characteristics are computed based on deterministic inputs such as fibre mechanics, topology, tow dimensions (shape, width, height) and tow spacing. These unit cell descriptions are considered to be repetitive along the entire structure without any variation in the tow position, shape and dimension. However, physical samples do show randomness in the geometrical parameters within a single unit cell and between neighbouring unit cells; tow path descriptors are spatially distributed across the composite [6]. Realistic modelling of internal geometry must include local variations along each individual tow path.

Among the different strategies for simulating the randomness in composites using appropriate scaling techniques [7–10], those that are most likely to lead to accurate predictions of the statistical distributions of composite properties are calibrated by experimental quantification of the material variability. Charmpis et al. [4] present an excellent discussion of how the Stochastic Finite Element Method (SFEM) [11,12] might be improved if experimental data were used to define the random fields that are incorporated within element properties. The desired modelling procedure for textile composites consists of three main steps: (i) collection of material data to define the stochastic geometry of tows (the step of uncertainty quantification and characterisation), (ii) generation of virtual specimens that replicate the measured statistics of the stochastic tow geometry and (iii) formulation of a stochastic multi-scale modelling scheme by which macroscopic material properties, and the variability in those properties, are predicted from the stochastic tow properties. When the first step is missing, analysts are forced to make assumptions regarding the input required for the second and third steps, leading to questionable estimates of the limits of material properties. The more detail that is available in the characterisation of the stochastic material microstructure, such as local tow path centroid variations and scatter in cross-sectional dimension, the higher the possible fidelity of simulations of damage evolution. In particular, not only are the distributions of material characteristics at any point important, but data defining the correlations between material deviations at different points can also be essential to complete prediction of the performance of a component [4,8,13].

This article describes a multi-scale framework to generate realistic representations of the reinforcement geometry, in which the variability of fibre positioning in a textile is characterised on different scales and fused into virtual specimens that span many unit cells (typically 10^3–10^5 unit cells) while retaining details of stochastic variability of tow geometry within a single unit cell. The article starts with a general overview of existing uncertainty modelling techniques applied to composites, before proposing the multi-scale strategy in Section 3. Section 4 discusses the experimental frameworks that are defined to characterise the scatter in the internal geometry over two scales: the short-range, i.e. the unit-cell scale, and the long-range, i.e. the sub-component scale, which incorporates large numbers of unit cells. Next, random instances of tow path parameters are produced that match the experimental data using a Markov Chain [14], Series Expansion [15] or a combination of Fourier analysis and the Markov Chain algorithm [16]. In a final step, virtual models of the entire composite geometry are constructed using the WiseTex software [17], which is a geometry processor for textile fabrics (Section 6). Each step throughout the developed framework is demonstrated for a 2/2 twill woven carbon fibre reinforced epoxy composite for which experimental data are already reported in prior publications [18,19].

2. Overview of existing simulation techniques for textile composites

Methods of simulating the effects of random microstructure on composite properties can generally be classified into “non-intrusive” and “intrusive” approaches, terminology which we borrow from the field of spectral methods for uncertainty quantification, with applications in, e.g., fluid dynamics [20].