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Experimentally validated stochastic geometry description for textile composite reinforcements

Andy Vanaerschot [a,*], Brian N. Cox [b], Stepan V. Lomov [c], Dirk Vandepitte [a]

[a] KU Leuven, Department of Mechanical Engineering, Leuven, Belgium
[b] Teledyne Scientific Co. LLC, Thousand Oaks, CA, USA
[c] KU Leuven, Department of Materials Engineering, Leuven, Belgium

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ABSTRACT

The uncertain quality of composites, due to variability in the mechanical response, forces design engineers to employ high safety margins to ensure that the design requirements are met. Especially for textile composites, an improved assessment of the quality of any composite material is achieved by identification and simulation of the inherent uncertainty in the reinforcement geometry. This paper presents such a comprehensive multi-scale strategy to develop realistic stochastic replicas of a composite material, with emphasis on the identification step. First, the scatter in the tow reinforcement is characterised on the short-range (meso-scale) and long-range (macro-scale) from high-resolution images. Next, a probabilistic uncertainty quantification method is proposed to analyse the variability of each path parameter in terms of average trend, standard deviation and correlation information. This set of statistical information is essential to reproduce the random textile geometry in a numerical simulation approach. The multi-scale framework delivers representative models in the WiseTex format and is demonstrated for a carbon-epoxy 2/2 twill woven composite produced by resin transfer moulding.

1. Introduction

The advantages of using composites in structural applications are well known. The combination of a high strength and stiffness with a low weight offers advantages in energy efficiency for air, ground and water transport. Other benefits to conventional materials among others are the durability and favourable fatigue properties. Though, the introduction of composites is hampered by the relatively high cost of fibre material and the large scatter of performance characteristics [1,2]. In order to assure the design requirements, high safety factors and strict manufacturing tolerances are enforced. An improved assessment of the quality of any composite part is achieved by identifying the scatter in the tow reinforcement, which forms a direct link with the variability in the macroscopic performance. The effect of geometrical imperfections on the magnitude of variability in performance has already been reported with contributions considering elastic mechanical properties [3,4], formability [5] and permeability [6,7]. However, a complete statistical characterisation of the geometrical variation is still missing for many types of textile composites, while modelling approaches of textile geometry frequently omit or only partially introduce variation in the reinforcement path [8–10].

Specifically for textile composites, variation in the reinforcement structure is characterised at multiple scales. The micro-scale represents local features with reference lengths of 10^{-6} m $-$ 10^{-4} m. This is the scale of individual fibres that are bundled within a single tow. For larger reference lengths of $10^{-4} - 10^{-2}$ m, determined as the meso-scale, individual fibres cannot be distinguished anymore but appear in groups that correspond to the tows. The macro-scale averages out the small effects of the heterogeneous structure at tow level and permits to quantify any long-range variations with lengths of 10^{-2} m $-$ 10^{-0} m. Most types of composites are built using an ideal, periodic unit cell that can be identified at the meso-scale based on deterministic inputs. Such numerical models are an idealised representation of the textile composite since real physical samples consist of spatially distributed unit cells that differ from neighbour to neighbour, affecting the mechanical response.

A realistic modelling approach requires the introduction of scatter at the different levels and calibration with experimental

* Corresponding author. Department of Mechanical Engineering, KU Leuven, Celestijnenlaan 300, 3001 Leuven, Belgium.
E-mail address: Andy.Vanaerschot@kuleuven.be (A. Vanaerschot).

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work. This paper describes such a generic modelling approach for woven textile composites that can consist of multiple unit cells. The examined procedures are also applicable to characterise and simulate any other textile structure considering only minor adjustments. In general, the most suitable approach to obtain realistic representations of any composite material is by (i) collecting experimental data on the spatially correlated random geometrical fluctuations on the short-range, i.e. within the unit cell size, and long-range, and (ii) employing simulation techniques to represent the spatial variability using this statistical data as input information. In a next step, the variability in the macroscopic material properties can be predicted from these stochastic reinforcement descriptions.

The aim of the proposed multi-scale procedure is to reproduce the full internal structure of composite specimens that match the statistical information of a characterised composite sample in its final form. Virtual woven textiles spanning multiple unit cells are constructed using the concept of a periodic unit cell for generating the average reinforcement path over the extent of the entire composite. Next, zero-mean deviations are added to this average behaviour using techniques and results from preceded publications [11–14]. The representative unit cell, unique and the same all over the composite volume, is replaced by a representation of spatially distributed unit cells where each unit cell is different.

2. Multi-scale framework

Realistic woven specimens are acquired that are replicas of the experimental samples following the multi-scale framework schematically presented in Fig. 1. The variability of each tow path is defined for the centroid coordinates (x,y,z), tow aspect ratio AR, tow area A and tow orientation in cross-section θ which fully describe a woven reinforcement; scatter in the matrix and fibre properties are not considered. Three successive steps can be distinguished to obtain such random representations:

1. Collection of experimental data and statistical analysis
2. Generating instantiations of stochastic textile reinforcement using multi-scale modelling
3. Construction of virtual specimens in a geometrical modelling software

This article describes the measurement and characterization of variability in the reinforcement structure of textile composites, described in Section 3, and briefly discusses the use of such data to generate stochastic virtual specimens in Sections 4 and 5. These latter steps require much more mathematical developments, which are of a completely different nature than step 1, and will be published in another publication which deals rather with mathematical modelling concepts. All steps are demonstrated on a carbon-epoxy 2/2 twill woven composite produced by Resin Transfer Moulding (RTM).

3. Collection of experimental data and statistical analysis (step 1)

3.1. Experimental framework

Different experimental techniques are selected to effectively investigate the geometrical variability present within the unit cell and propagating over several unit cells.

In a first step, it is recommended to acquire three-dimensional (3-D) images of the internal geometry of the sample via laboratory X-ray micro-computed tomography (micro-CT). This technique is efficient to quantify the short-range spatial information of the entire reinforcement in a single experiment. From the 3-D volume

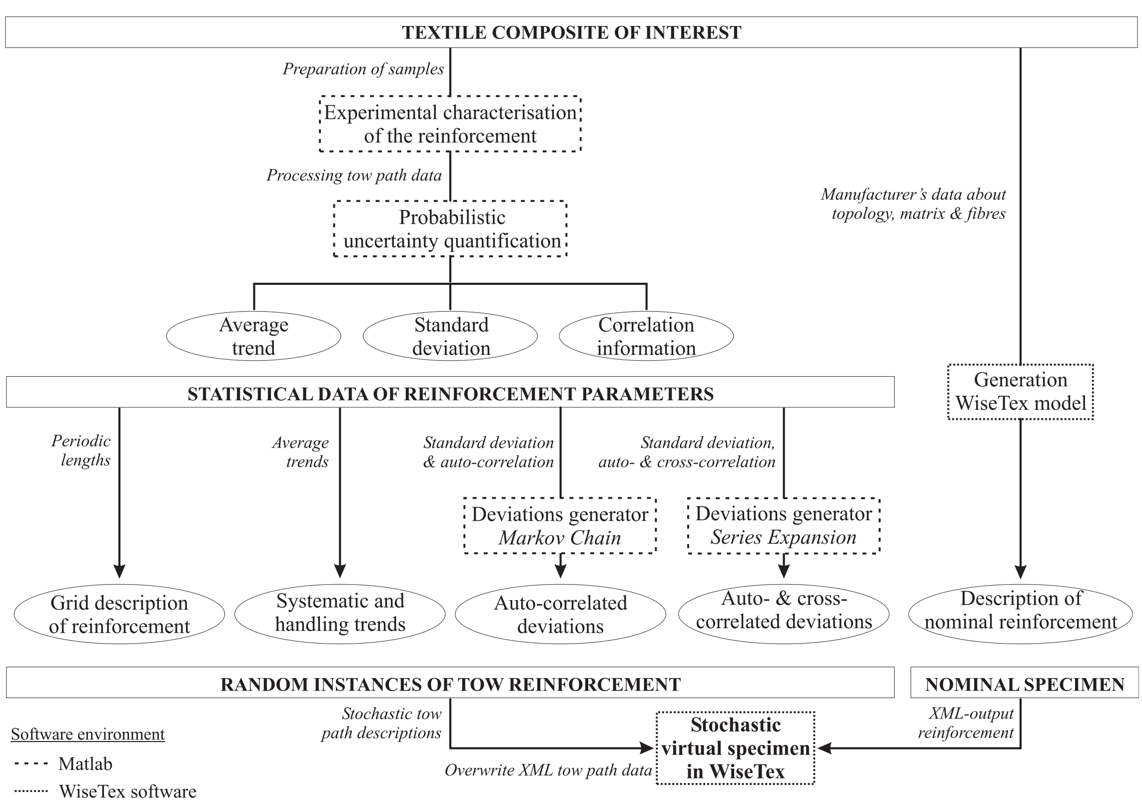

Fig. 1. Multi-scale framework.