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Stochastic characterisation methodology for 3-D textiles based on micro-tomography

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ABSTRACT

A recently developed framework to quantify variability of common textile reinforcements of unit cell size is extended to allow for a stochastic description of complex three-dimensional (3-D) textile architectures spanning multiple unit cells. The reinforcement geometry is characterised from synchrotron micro-tomography images in terms of centroid coordinates and tow cross-section. The statistical information includes an average trend, standard deviation and correlation information. A general representation of correlation information is proposed to account for the different tow correlations depending on the location inside the 3-D architecture.

The methodology is applied to the characterisation of a 3-D carbon fabric considered for NASA's Adaptive Deployable Entry Placement Technology (ADEPT) system. Determining geometrical variability in the weave is of importance during the process of setting design margins and risk analysis. Statistical analysis demonstrates strong dependency on the crossover positions for the average trends and correlation data, with a substantially higher variation for the Z-interconnecting tows.

1. Introduction

Reinforced composite materials are subjected to substantial variability in the fibre architecture that is introduced by the different phases of the manufacturing and production process. Spatial geometrical variability is characterised by inspecting the scatter of individual tow path parameters across the entire reinforcement. Fluctuations at the micro-level, such as fibre distribution and resin content inside a single tow, are not considered in this paper. Geometrical variations in a textile architecture are associated with differences in:

- *Tow positions* which are described by the centroid coordinates (x, y, z) [1,2]. These fluctuations are also related to the variation in tow spacing with a Coefficient of Variation (COV), the ratio of standard deviation on the mean value, ranging from 1 to 9% [3–6].
- *Tow orientations* that can be regarded as the mean orientation of a ply or bundles of tows within a composite, usually vary with standard deviations around 1 degree, but maxima till 5 degrees also occur depending on the textile structure [3,7].
- *Tow dimensions* (thickness, width and shape). Irrespective of the type of textile, the largest variation is observed in the tow thickness with COV's in the range of 6–17%, while this is 2–10% for the tow width. Tow area and aspect ratio have scatter in the range of 5–12% [3,4,2,8,6].

However, variability in the reinforcement structure is still frequently omitted or only partially introduced in simulations [9,10]. By investigating the scatter in geometry and constituents, the variability in the mechanical response can be characterised more precisely which may lead to an adaptation (reduction or increase) of design margins. A more accurate estimation of the

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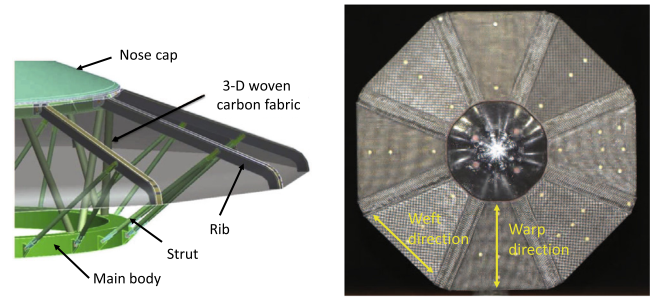
mechanical response translates to a more accurate design that could lead to cheaper and lighter structures. For the specific case of textile composites, the reinforcement is adequately modelled by exploiting the hierarchical principle. The internal geometry of a textile is represented by a periodic unit cell based on deterministic input values for fibre tow spacing, dimensions (shape, width, height) and fibre mechanics. These unit cell descriptions are considered to be repetitive along the entire structure without any variation in the tow position, shape and dimension. This is in sharp contrast with experimental observations demonstrating randomness within a single unit cell and between neighbouring unit cells [11]. Among different strategies for simulating the randomness in composites using appropriate scaling techniques [12,13], those that are most likely to lead to accurate predictions of composite properties are calibrated by experimental data.

Recent work by Cox et al. [9] and Vanaerschot et al. [14] propose a strategy to obtain a more realistic representation of the internal geometry of textiles based on experimentally obtained stochastic data. Procedures are developed to quantify and simulate tow reinforcement stochasticity, but these were only applied to composites with standard weave topologies: two-dimensional (2-D) weaves and a three-dimensional (3-D) interlock weave. This particular paper extends this approach to complex 3-D reinforcements with following main novelties: (1) A more comprehensive statistical analysis is presented in terms of tow genuses, i.e. representative tows, based on the framework outlined in [2,15]. These publications deal with a simple 2-D and 3-D unit cell, presented by 2 [15] or 4 genuses [2] respectively, and suggest that the methodology is valid for any textile topology without modification. This is the first demonstration of the strategy in the literature for a real complex engineering structure for which 15 genuses can be distinguished. (2) An improved experimental approach based on X-ray micro-CT that allows a larger region of interest to be inspected from a single scanning campaign compared to [2,15]. A low voxel size is preserved and the methodology is complemented with efficient steps and tools to perform image analysis. This approach differs from optical techniques for multiple unit cell samples described in [16,17] which only captures topological features. Although these latter features can be sufficient if only tow path positional variations are to be accounted for, micro-CT images provide a complete description of the 3-D architecture including tow cross-sectional and inner ply positional data. (3) Several correlation functions are proposed, which can describe correlations along and between the tow paths in the 3-D architecture. The first attempt to define correlation functions of a textile architecture are described in [17] and now generalised to 3-D textiles. Such descriptions feed statistical generators for textile architectures, summarised in [18].

The methodology is demonstrated for a 6-ply 3-D woven textile from Bally Ribbon Mills which is selected as candidate material for the Adaptive Deployable Entry Placement Technology (ADEPT). ADEPT is a deployable Thermal Protection System (TPS) using a 3-D woven carbon cloth as the heat shield material for the downstream skirt. The woven fabric is interfaced with a rigid nose cap, made of a conventional TPS material such as the Phenolic Impregnated Carbon Ablator (PICA). Figs. 1(a) and (b) shows the ADEPT concept. The carbon fabric is attached to lightweight ribs, functioning as structural elements, and tensioning the woven cloth in the deployed configuration. This umbrella-like configuration has a large deployable surface area enabling smaller deceleration forces and lower heating during entry compared to conventional rigid body systems.

Detailed uncertainty quantification in the as-manufactured weave allows for us to develop more detailed understanding of the utilization of woven 3-D fabrics in both the dry and resin infused states. This is especially important considering the operational environment that the heat shield is designed for. Fig. 2(a) shows a scaled down version (0.35 m diameter) of the ADEPT system being tested at conditions relevant for entry into the Martian atmosphere. Surface temperatures on the fabric reached 1600 C under a pressure of 4 kPa induced by the arc heat flow exiting from the nozzle at the left. Pre and post-test photos are shown in Fig. 2(b). ADEPT has been developed at NASA Ames Research Center (ARC) and is envisaged for scientific missions to Venus and human transportation missions to Mars.



(a) (b)

Fig. 1. Overview of the ADEPT structure: (a) detailed view on the structure of ADEPT [26], (b) view on the 3-D carbon fabric and indications of tow directions.

2. Statistical approach

Randomness in textile geometry is investigated at the meso-scale (or tow scale); scatter in the fibre material properties is not considered here. The variability of each tow path is defined in terms of centroid coordinates (x, y, z), tow aspect ratio AR, tow area A and orientation in cross-section θ. Previous studies proved that this set of parameters provides a sufficiently complete description of a woven reinforcement [15,2].

Following the generic stochastic framework from [15,14], summarised in Fig. 3, three analysis steps can be distinguished:

1. Collection of 3-D images using micro-computed tomography (micro-CT).
2. Data processing and analysis of the experimental tow path information.
3. Statistical characterisation of the tow path parameters.

Within each of these steps, new approaches are presented to be able to handle complex 3-D textile data which are complemented with efficient techniques while keeping in mind the generality of the proposed strategy. The methodology leads to a complete statistical description for all tow path parameters in terms of average trends, standard deviation and correlation information. These data are essential to reproduce the geometrical variability in a reconstruction algorithm that generates stochastic virtual specimens. The present work describes the measurement and characterisation of variability in the reinforcement structure. The reconstruction algorithm for virtual fabric specimens is based on techniques from [9,14]; the reader is referred to these publications for details.

3. Material description

The 3-D woven reinforcement for the ADEPT entry system is designed and manufactured by Bally Ribbon Mills. Both the warp and weft tows are of type Hexcel IM-7, each consisting of 6000 ex-PAN carbon fibres. The weft direction is oriented in the circumferential direction from rib to rib (perpendicular to the flow), while