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Geometrical modelling of 3D woven reinforcements for polymer composites: Prediction of fabric permeability and composite mechanical properties

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ABSTRACT

For a 3D orthogonal carbon fibre weave, geometrical parameters characterising the unit cell were quantified using micro-Computed Tomography and image analysis. Novel procedures for generation of unit cell models, reflecting systematic local variations in yarn paths and yarn cross-sections, and discretisation into voxels for numerical analysis were implemented in TexGen. Resin flow during reinforcement impregnation was simulated using Computational Fluid Dynamics to predict the in-plane permeability. With increasing degree of local refinement of the geometrical models, agreement of the predicted permeabilities with experimental data improved significantly. A significant effect of the binder configuration at the fabric surfaces on the permeability was observed. In-plane tensile properties of composites predicted using mechanical finite element analysis showed good quantitative agreement with experimental results. Accurate modelling of the fabric surface layers predicted a reduction of the composite strength, particularly in the direction of yarns with crimp caused by compression at binder cross-over points.

1. Introduction

In thick composite components, multiple thin layers of fabrics with two-dimensional (2D) architectures can be replaced by thick three-dimensional (3D) fibrous structures as reinforcements. As discussed by Mouritz et al. [1], 3D textile processes, in particular highly versatile weaving processes, allow the near net-shape manufacture of reinforcements with complex geometries. 3D woven reinforcements consist typically of layers of aligned non-crimp yarns with alternating orientation along the fabric weft and warp directions, and additional binder yarns, which follow paths through the fabric thickness and hold the non-crimp layers together.

In composites, the non-crimp yarns in each fabric layer show generally better axial mechanical properties than the crimped yarns in most 2D reinforcements. The presence of binder yarns provides toughness and resistance to delamination but tends to reduce mechanical in-plane properties compared to purely unidirectionally aligned layers. However, mechanical in-plane properties of composites were found to be higher for 3D woven reinforcements than for multi-layer plain weave reinforcement [2,3]. For the case of frequently used 3D orthogonal woven reinforcements, the mechanical properties of composites have been addressed in detail in a variety of studies. The in-plane stiffness and strength have been investigated experimentally, analytically and numerically, e.g. by Tan et al. [4,5]. Carvelli et al. [6] characterised the fatigue behaviour in tension. The response to static and impact transverse loading was studied, e.g. by Luo et al. [7]. Mohamed and Wetzel [8] described in detail the influence of the variation of fabric parameters on the properties of a component.

Regarding reinforcement processing properties, forming of an orthogonal weave was characterised by Carvelli et al. [9] in terms of in-plane biaxial tension and shear behaviour. Due to increased thickness and the through-thickness fixation of the yarns, the drapability of 3D woven reinforcements, i.e. the formability to doubly-curved surfaces, tends to be reduced compared to 2D fabrics. However, this is less relevant, since the reinforcements can be manufactured to near net-shape [1]. On the other hand, the reinforcement compressibility is highly relevant, since it determines the fibre volume fraction in the reinforcement. This affects the reinforcement impregnation with a liquid resin system in Liquid Composite Moulding (LCM) processes, which are particularly suited for the manufacture of thick components with 3D woven reinforcements, and the mechanical properties of the finished component. Some data for a 3D fabric, suggesting significantly higher stiffness in compression than for a random mat, were given by Parnas et al. [10]. Potluri and Sagar [11] studied the compaction behaviour of several fabrics with interlacing weaving patterns in more detail and applied an energy minimisation technique to

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compaction modelling, which generally showed good agreement with experimental results. Endruweit and Long [12] observed experimentally that local reduction of the gap height between the fibre bundles is significant in compression of an angle-interlock weave with offset of layers. On the other hand, the main compression mechanism for an orthogonal weave was found to be compaction of the fibre bundles. This results in higher compressibility for the angle-interlock weave than for the orthogonal weave.

The flow of liquid resin during fabric impregnation in LCM processes is more complex than in thin fibrous structures because of the presence of additional through-thickness yarns. Information on impregnation behaviour, characterised by the reinforcement permeability, is sparse for 3D reinforcements. Experimental data published by Parnas et al. [10] suggest that the in-plane and through-thickness permeabilities of 3D woven fabrics are in the same order of magnitude as those of 2D fabrics at similar fibre volume fractions. Elsewhere, it was suggested that 3D orthogonal woven fabrics have significantly higher in-plane permeability than 2D fabrics (woven and knitted) at identical fibre volume fraction [13]. Numerical predictions of the permeability of an orthogonal weave by Ngo and Tamma [14] indicated that the in-plane permeability is high compared to the through-thickness permeability, and qualitative agreement with experimental observations was found. Song et al. [15] predicted the permeability tensor for a 3D braided textile (similar to an interlacing weave). While they also found higher values for the in-plane than for the through-thickness permeability, experimental results were overestimated by significant margins. Endruweit and Long [12] modelled the influence of inter-yarn gap widths and the pattern and dimensions of binder yarns on the in-plane permeabilities of 3D woven fabrics. Experimental data suggested that in-plane permeabilities reflect the reduction of inter-yarn gap spaces during fabric compaction. Through-thickness permeabilities were found to be enhanced by through-thickness channels formed around the binder yarns.

A major challenge in predicting the processing and performance characteristics of composite materials is the complex hierarchical structure and its local variation, in particular if 3D woven reinforcements are used. This is reflected in growing research efforts for meso-scale geometry characterisation [16–19] and modelling [20–23]. This study aims at experimental quantification of representative geometrical parameters for a 3D woven fabric and generation of unit cell models at a high level of geometrical detail, including systematic local variations in yarn paths and yarn cross-sections. Based on these models, numerical methods are implemented to predict the reinforcement permeability and the mechanical performance of the finished composite.

2. Geometrical characterisation

As an example, a carbon fibre orthogonal weave with the specifications listed in Table 1 was characterised in this study. The internal geometry of the fabric was characterised at different compaction levels by X-ray micro-Computed Tomography (μ-CT) analysis. A Phoenix Nanotom (GE Sensing & Inspection Technologies GmbH) was used for μ-CT scanning of small samples, which were slightly larger than unit cell size of the 3D woven reinforcement. While the dry fabric was scanned at no compaction, composite specimens were produced to allow the deformed geometry in the compressed fabric to be captured. To obtain good image contrast for carbon fibre composites, which show low X-ray energy absorption, the power was set to a voltage of 40 keV and a current of 240 μA, and a Molybdenum target (emitting radiation at a relatively small wavelength, which is absorbed by low-density materials) was used. The image resolution is between 7 μm and 20 μm, depending on the geometrical dimensions of the scan sample.

Table 1
Specifications of 3D reinforcement characterised here.

Fabric style	Orthogonal weave
Areal density (kg/m^2)	4.775
Number of warp layers	6
Warp yarn	12 K
Warp yarn linear density (g/km)	800
Number of weft layers	7
Weft yarn	6 K × 2
Weft yarn linear density (g/km)	800
Binder yarn	1 K
Binder yarn linear density (g/km)	67

While the 3D image data can be analysed by taking measurements manually slice by slice, contrast-based image processing (as illustrated in Fig. 1) and quantitative evaluation was automated using the MatLab® Image Toolbox. To determine shapes and dimensions of yarns and inter-yarn gaps in Fig. 1E, the images are segmented into square cells, allowing focusing on individual gaps as in Fig. 1A. Filtering techniques are applied to reduce noise and suppress small-scale features (Fig. 1B). The resulting greyscale image is then converted into a binary image (Fig. 1C), implying that information on defects such as trapped air or cracks caused by thermal shrinkage may be lost. The final stage is to remove features unrelated to gaps by assessing the size, roundness, aspect ratio and position of segmented objects (Fig. 1D). The result is a black and white image showing the inter-yarn gaps in cross-section (Fig. 1F). For each identified gap, continuity throughout the entire range of slices can be tracked.

Quantitative evaluation of the images includes measurement of area, A_c, and height, h, of gaps in a cross-section, and yarn spacing, l, i.e. the distance between the centroids of two neighbouring gaps. At given filament radius, r, and number of filaments, N, in each yarn, the fibre volume fraction in each yarn cross-section can be calculated according to

$$V_f = \frac{N\pi r^2}{hl - A_c}. \quad (1)$$

To measure gaps in weft and warp directions, the 3D images are re-sliced and analysed in each direction. Data for composites at two different fibre volume fractions, i.e. thicknesses, H, are listed in Table 2.

3. Geometrical modelling

3.1. General considerations

Reliable numerical analysis of reinforcement processing properties and composite mechanical performance requires accurate description of the reinforcement geometry. Since detailed modelling of full-size fabric specimens is not realistic, the fabric architecture is represented by a unit cell, by definition the smallest repetitive (by translation) unit in a fabric. Since yarns in a fabric are not perfectly fixated but have some mobility, all textiles tend to exhibit some degree of stochastic variability. Thus, unit cell modelling always implies idealised approximation of the exact geometry. Here, image analysis indicates that the degree of geometric variability in the 3D woven reinforcement is relatively low (Table 2), at similar level as observed by Desplentere et al. [24]. Thus, unit cell modelling can be expected to give a relatively accurate approximation of the actual (local) architecture.

To take experimentally observed variabilities into account, Desplentere et al. [24] used series of unit cell models with standardised geometry and varying dimensions as input for Monte-Carlo simulations of mechanical properties. This study aims to identify