Composites: Part A 87 (2016) 131–137

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Quantification of micro-scale variability in fibre bundles

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ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form 7 April 2016
Accepted 19 April 2016
Available online 20 April 2016

Keywords:
A. Carbon fibres
B. Microstructures
C. Statistical properties/methods
D. Optical microscopy

ABSTRACT

Local variations in the random filament arrangement in carbon fibre bundles were determined by optical microscopy and automated image analysis. Successive steps of abrading, polishing and acquiring micrographs of the sample surface made it feasible to analyse the micro-structure over a series of cross-sections along the fibre bundle path. Random and systematic changes in local filament arrangements were determined. Systematic changes were related to the interaction of a fibre bundle with an intersecting binder thread leading to a local increase of the fibre volume fraction at the interface. Random clustering of filaments in areas of high or low fibre volume fractions within the fibre bundles were found to be unaffected by the relative position of the bundle.

1. Introduction

Textile reinforcements utilised in the manufacture of composite components are based on filaments which are usually bundled in yarns and then processed into a fabric for easier handling. Due to this structure, fibre reinforced components are usually analysed on different levels, each with its own variability. Composite parts are made from layers of textile reinforcement (macro-scale) which consist of individual fibre bundles (meso-scale). The bundles can consist of several thousand filaments (micro-scale). It was shown that the variability at each scale affects the properties of a fibre reinforced composite component [1,2]. Depending on the scale of analysis, properties at the smaller scales of the material are usually homogenised, and any variability at these scales is ignored [3]. Attempts have been made to incorporate statistical variability at the smaller scales in multi-scale modelling approaches [4]. The variabilities are, however, usually obtained from randomly generated distributions only and are uncorrelated to the actual variability in the material.

For numerical analysis, fibre reinforcements are often represented by an idealised geometry of the smallest repeat in form of a unit cell [5]. To add variability of fibre bundle paths at the meso-scale, representative volume elements can be utilised [6]. In this case, the bundle paths exhibit a defined degree of variability; however, the geometry at the boundaries is usually periodic. As composite components are made from several layers of fibre reinforcement, this can introduce additional sources of variability. The stacking process introduces variability in between layers such as nesting or fibre bundle shape changes. Attempts were made to incorporate these bundle deformations into a geometrical model [7]. For the analysis of properties at the meso-scale, the filament arrangements at the micro-scale within the fibre bundles are usually treated as uniform [8]. The properties at the micro-scale are then easily estimated from bulk parameters such as the overall fibre volume fraction, V_f [9] in the yarn. Treating the fibre bundles as homogenous material ignores, however, any information about the local arrangement [10] or waviness [11,12] of the filaments. It was demonstrated numerically that the macro- or meso-scale failure of a part may be initiated by local stress concentrations at the micro-scale [13]. The local arrangements of filaments in fibre bundles should therefore not be ignored, but a systematic description is currently not available.

This paper analyses low crimp carbon fibre bundles and local effects of the reinforcement geometry on the micro-scale filament arrangements. Non-destructive examination methods such as micro-computed tomography are only feasible on very small samples and have a limited resolution [14,15]. Conventional optical microscopy is therefore used as an inexpensive alternative technique which also allows achieving a higher resolution. Automatic image analysis of optical micrographs of cross-sections of the material allows a detailed analysis in a time efficient manner [16]. The obtained data can be employed in multi-scale modelling approaches, for example, to improve the accuracy of local properties assigned to voxels in a finite element analysis [17].

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http://dx.doi.org/10.1016/j.compositesa.2016.04.019
1359-835X/

2. Materials and methods

2.1. Fibre reinforcement and processing

Composite panels with dimensions 125 mm × 60 mm were made from a single layer of low-crimp plain weave reinforcement and a low viscosity epoxy resin system. The fabric consisted of aligned carbon fibre bundles with a filament count of 12 K (warp direction), stabilized by thin glass fibre weft yarns coated with a thermoplastic polymer (Fig. 1). The dry fabric was placed in a stiff metallic tool where the global fibre volume fraction, V_f, is determined by the cavity height and was estimated to be 0.45. The fabric was saturated with a liquid resin matrix, MVR 444 supplied by the Advanced Composites Group, by circumferential injection at 2 bar pressure. The resin was preheated to 70° before the injection pressure was applied which reduced the initial viscosity to approximately 0.025 Pa s.

2.2. Sample preparation and image processing

Micrographic analysis of cross-sections of these specimens, cut perpendicular to the nominal fibre bundle path, allowed to identify the filament distribution within the carbon fibre bundles (Fig. 2). By successively removing thin layers of material at the surface of these specimens and acquiring new images, the filament arrangement can be determined at different positions along the fibre bundle path [18].

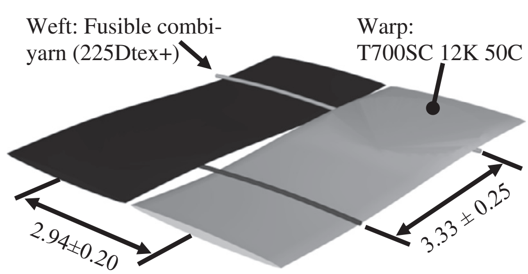

Fig. 1. Unit cell model of low-crimp plain weave, generated with the open source software TexGen available from http://texgen.sourceforge.net/. The measurements given are in mm and correspond to Ends/10 cm = 34 ± 2.5 and Picks/10 cm = 30 ± 2.5.

Stitching of overlapping images (Fig. 2C) allows large area images of fibre bundle cross-sections to be studied at high resolution [19,20]. A stitching code was implemented based on fast-Fourier correlations programmed in Matlab [21]. Micrographs were acquired at a high magnification which resulted in a pixel size of 0.09 μm (Fig. 2B). All individual filament cross-sections were determined by means of edge detection based on colour gradients in the images and fitting ellipses to the identified boundaries [16]. It was estimated that the fitted ellipse overestimates a filament cross-sectional area by about 3% on average.

Due to differences in material hardness between fibres and polymer matrix, the mechanical polishing process during sample preparation can cause filaments, located at the edge of the fibre bundle, to be abraded more than filaments in the bulk of the material. These filaments are therefore not within the limited depth of field of a conventional optical microscope imaging the bulk of the material. This results in blurred images of these filaments located at the bundle edge which can therefore not be detected with the employed image analysis method (Fig. 3). An additional false detection rate during image processing, e.g. over-/underestimation or non-detection of filament cross-sections within the bulk of the material, of approximately 2% was estimated. For these reasons, approximately only 11,500 filaments were detected during the image processing of a 12 K fibre bundle. For further interpretation of the results, the acquired micrographs and measured data of the detected filaments have been made publicly available [22].

3. Definition of fibre bundle descriptors

3.1. Fibre bundle boundary

The fibre volume fraction in a fibre bundle is defined by the combined cross-sectional area of all filaments divided by the entire area of the bundle. The cross-sectional areas of all filaments within a fibre bundle are determined during image analysis. The total bundle area is defined by a virtual boundary enclosing all filaments in the fibre bundle cross-section (Fig. 2C). To determine the envelop enclosing all filament cross-sections, the location of the top and bottom filament edge is determined over the width of the bundle. To avoid sudden changes in the estimated boundary, the filament locations are determined for a discrete step size. The

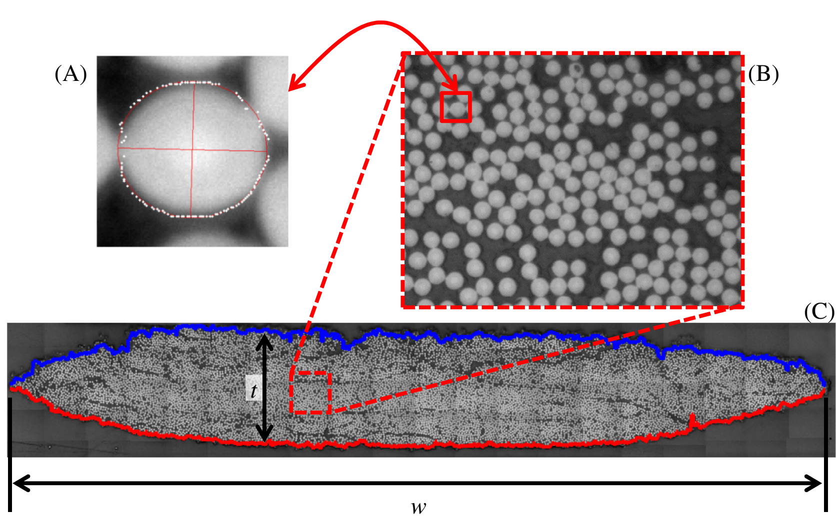

Fig. 2. (A) Filament cross-section with identified perimeter determined by image processing [16]. (B) Micrograph of carbon fibre bundle cross-section. (C) Tiling a large number of overlapping micrographs enables to analyse an entire fibre bundle. The determined fibre bundle outline is shown with solid lines and the width, w, and thickness, t, are indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)