Composites: Part A 76 (2015) 262–271

Contents lists available at ScienceDirect

Composites: Part A

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

Stochastic reconstruction of filament paths in fibre bundles based on two-dimensional input data

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ARTICLE INFO

Article history:
Received 11 March 2015
Received in revised form 19 May 2015
Accepted 22 May 2015
Available online 9 June 2015

Keywords:
A. Carbon fibre
B. Microstructures
C. Analytical modelling
D. Optical microscopy

ABSTRACT

Conventional optical microscopy is an inexpensive technique to analyse fibre bundle micro-structures. Compared to micro-computed tomography, the resolution is higher and larger samples sizes can be analysed. This provides, for example, detailed information of filament spacing which will affect subsequent properties. This paper proposes a probabilistic method to reconstruct paths of individual filaments from a series of two-dimensional micrographs. This allows three-dimensional filament arrangements to be reconstructed and the effects of local arrangements on properties to be quantified. For example, for the small sample analysed in this work, a 15% difference in strength values was found.

1. Introduction

Textile fibre reinforcements used in composites are usually made from filaments bundled into tows. The fibre bundles within fabrics are not straight but exhibit in- [1] and out-of-plane waviness [2]. It was shown that such waviness can significantly affect the resulting properties of a composite [3,4]. In addition to the waviness of an entire fibre bundle, the filaments within bundles also exhibit undulation and twist [5]. These filaments do not necessarily follow the path of the bundle exactly and adjacent filaments are not necessarily parallel to each other. These additional misalignments on the micro-scale will affect the composite properties locally, for example promoting void formation during impregnating flow [6], which will have an adverse effect on the mechanical properties [7]. Local effects can lead to filament fracture which may cause crack growth and failure [8].

For numerical predictions of composite properties, the filaments in fibre bundles are usually assumed to be straight parallel rods, arranged in a periodic [9] or random [10] pattern. This allows simplification of model domains to two-dimensions. The assumption of parallel alignment of filaments may be applicable to small sections of a fibre bundle. In reality, the filaments exhibit random waviness which will gradually change the filament arrangement along the path of a fibre bundle [5]. This causes distances between neighbouring filaments to vary, which in turn affects local flow [11] or mechanical [12] properties.

It is possible to use micro-computed-tomography (micro-CT) to visualise the random three-dimensional filament arrangement (Fig. 1); however, these studies are limited to small areas only [5,13]. As a rule of thumb for current 'off-the-shelf' systems, the maximum sample size to be scanned in mm is equivalent to the achievable scan resolution in μm. Tiling of volume images and movable detectors allow larger samples to be analysed at high resolution. The scan times do, however, increase significantly (up to days). In addition, thicker samples will also increase the problem of artefacts occurring during the scan [14]. The current achievable resolution of commercially available micro-CT systems is limited to a maximum of about 0.5 μm and can be improved to an order of about 0.1 μm for laboratory systems [15]. This makes determination of exact positions and shapes of individual filaments difficult. Hence, it is not possible to measure small gaps between closest filaments, which are often below this resolution limit [16]. In the case of carbon fibre reinforced composites, the resulting volume images do not exhibit good contrast due to the low X-ray absorption of the fibres [17] and image analysis is therefore often limited to manual identification of features [2,18]. Automated analysis methods using anisotropy filters can overcome this problem [19,20].

Traditional techniques such as optical microscopy [21] or scanning electron microscopy (SEM) [22] can be used to achieve images of cross-sections at a higher resolution. Image tiling and automated image analysis also make it feasible to study larger areas of a

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http://dx.doi.org/10.1016/j.compositesa.2015.05.022
1359-835X/

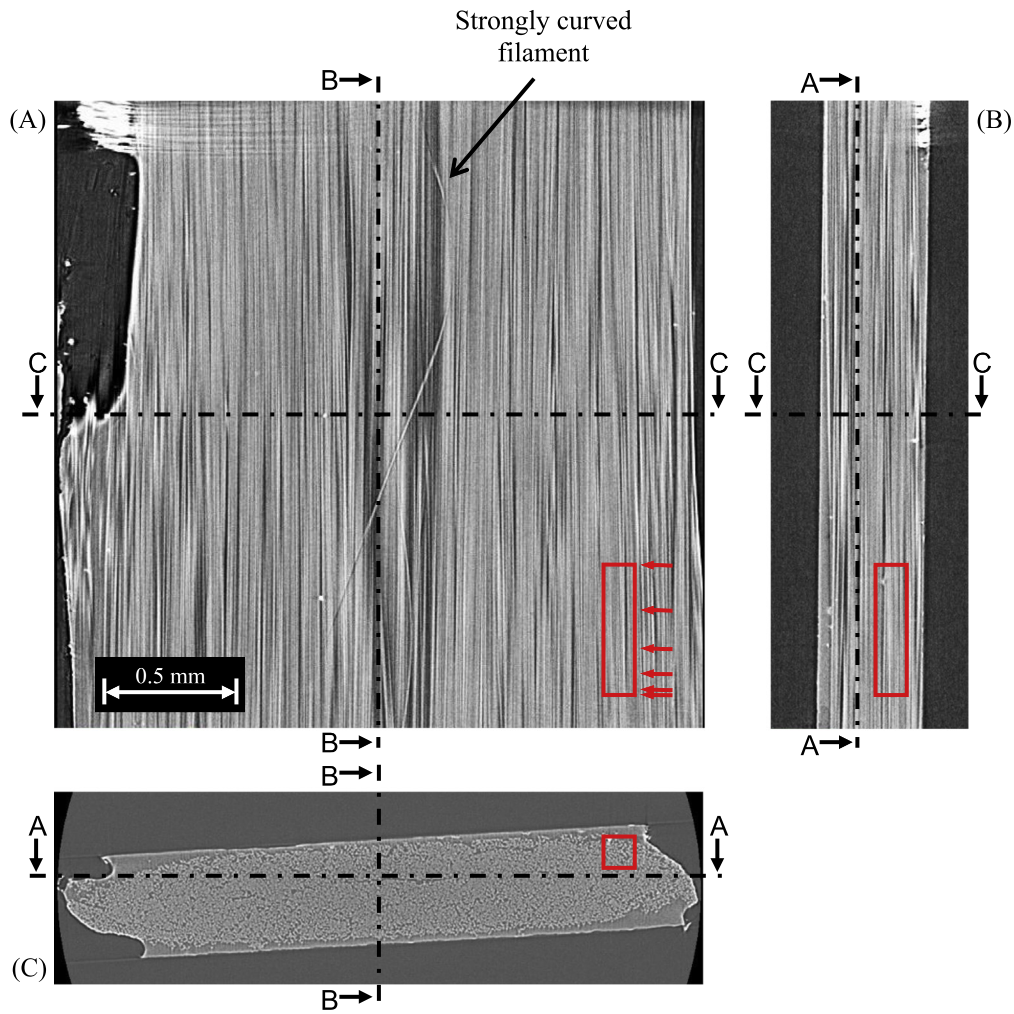

Fig. 1. Three sections of a micro-CT image of a 12K carbon fibre bundle imaged at a 2.5 μm voxel resolution. A schematic of the area analysed by Mansfield et al. [25] is indicated with red rectangles, and slice positions with red arrows in the image. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

material [23]. For example, to scan an entire fibre bundle cross-section, approximately 1–45 min are needed depending on the resolution and sample quality. However, as these techniques analyse surfaces only, a larger amount of sample preparation is required which increases the risk of damage compared to micro-CT. In addition artefacts due to, for example, lens distortions need be considered and, if necessary, be corrected.

This paper proposes a probabilistic methodology based on the Hungarian (or Munkres) algorithm [24], which allows reconstruction of filament paths from two-dimensional micrographs of slices of a material. A more simplistic approach using very small distances between individual slices and direct mapping of points has, for example, been used to reconstruct the shape of a fibre bundle [25] or the filament arrangement in a small sample [26]. In this work, a series of micrographs of a carbon fibre bundle cross-section presented by Mansfield et al. [27], cut perpendicular to the nominal filament direction and taken after repeatedly removing small amounts of material at the surface, is analysed. Determined cross-sectional centre points of the filaments in different micrographs allow prediction of which points are connected in different slices. The open source software TexGen [28] is then used to fit a spline through the different measurement points which enables reconstruction of three-dimensional filament paths. The stochastic approach used in this work is expected be more robust than simple assignment of closest points in micrographs which requires very small distances, e.g. 20 μm, between slices [26]. The disadvantage of this reconstruction method being destructive is compensated by the higher image resolution and the larger sample surface which can be studied at a significantly lower cost. This measurement technique will allow larger amounts of material to be studied which in turn will help to better understand the mechanics within fibre bundles using standard inexpensive analysis techniques. Using higher magnification images in the future will also allow interpolation of exact filament shapes in, for example, a 12k fibre bundle (Fig. 2).

2. Materials and data acquisition

The data used in this work were acquired from Mansfield's publication [27]. A small section of carbon fibre reinforced composite of approximately 100 μm × 140 μm, cut perpendicular to the nominal fibre path (Fig. 3), was analysed by means of Scanning Electron Microscopy (SEM). The average filament diameter, d, in this material was estimated to be about 8 μm. Subsequently, small amounts of material (25, 60, 100, 150, 180 μm) were removed by abrasion and the sample surfaces were repeatedly examined. This made it feasible to analyse the cross-sectional positions of fibres throughout the material. Based on a fixed reference point inside the sample and the shape of selected single fibre cross-sections, Mansfield was able