CHARACTERISATION OF WAVINESS DEFECTS IN INDUSTRIAL COMPOSITE SAMPLES

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1 Introduction

The comparatively poor uniaxial compressive strength of unidirectional (UD) composites is due to localised fibre misalignment affecting the plastic microbuckling mechanism. Established theories [1][2] for microbuckling consider idealized misalignments such as uniformly misaligned infinite bands. However fibre orientation in real composites varies with position throughout the composite. Previous published research typically considers either randomly distributed misalignment [3] or single, finite, well-defined regions of idealised fibre misalignment [4][5]. Relatively little effort has been expended in characterising the variation of fibre orientations in realistic specimens.

This paper presents characterisations of two industrial CFRP specimens – one manufactured from UD pre-preg material, and the other manufactured using a resin transfer moulding (RTM) process. Computational tomography (CT) and optical microscopy techniques have been used to obtain images of the fibre orientations at microscopic scales. A robust Multi-Field Image Analysis (MFIA) routine has been developed, building upon the work of Creighton et al [4]. The resulting characterization is presented using a variety of visualization techniques.

2 Methodology

2.1 Imaging techniques

Several composite specimens of each type of specimen (RTM and pre-preg) were sectioned, polished and digital images were acquired from an Olympus BX51 microscope. The large specimen area shown in Figure 1 was obtained by stitching several adjacent images together. 3D orientation data of a pre-preg specimen shown in Figure 2 was obtained using X-ray μCT, performed at the μVIS centre at the University of Southampton.

Note that for the optical method, the specimen is positioned such that the fibre orientation is not oriented with the pixel direction in order to improve the robustness of the data analysis algorithm.

2.2 Data analysis

Multiple field image analysis (MFIA) was used to determine the orientation of fibres at regular intervals across the image. The basic MFIA approach of Creighton et al [6] was modified by fitting a quadratic curve through the correlation data as shown in Figure 3, to improve the accuracy and robustness of the method. Particular care was needed for those images where the fibres were nearly aligned with the pixel direction to avoid error associated with the discrete pixel dimensions.

To analyse the 3D fibre orientations from CT scans, two perpendicular sets of 2D slices were extracted from the voxel data as shown in Figure 4. The MFIA method was then applied to each of these slices, and post-processed to determine the 3D orientation of each sampled region.

3 Results

3.1 Variability of fibre orientations

It is relatively straightforward to visualize 2D orientation results, by drawing local orientation directions directly over the original image (Figure 5). A histogram shows that the fibre orientations are approximately normally distributed (Figure 6).

The nominal 0° direction is taken as the mean of the calculated fibre directions in the image. The waviness is therefore characterised by the standard deviation of fibre direction from this mean. Individual results for each specimen are plotted in

Figure 7, and these results are summarised by manufacturing process and orientation in Table 1.

Process	Plane of waviness	Std deviation of fibre orientation
RTM	Out-of-plane	1.63°
	In-plane	1.37°
Pre-preg	Out-of-plane	0.67°
	In-plane	1.12°

Table 1. Standard deviation of fibre orientations from optical microscopy data

The results indicate that fibre misalignments are on average larger in the RTM component than in the pre-preg component.

Furthermore, the results show that in-plane and out-of-plane waviness is similar for the RTM component, whereas out-of plane waviness is lower than in-plane waviness for the pre-preg component. The lower out-of-plane waviness observed for the pre-preg samples may be due to the greater through thickness compression that is applied during cure of pre-preg material.

3.2 Rate of change of fibre orientation

A further interrogation of the data is performed to examine the rate at which fibre orientation changes – both in the longitudinal direction (i.e. how quickly fibre orientation changes along the length of the fibre) and the transverse direction (i.e. how quickly the fibre orientation changes between adjacent fibres). For this purpose, a characteristic length is proposed as the length over which the autocorrelation function reduces to 1/*e*.

Process	Plane	Correlation length in Longitudinal direction (mm)	Correlation length in Transverse direction (mm)
RTM	Out-of-plane	0.77	0.46
	In-plane	0.84	0.35
Pre-preg	Out-of-plane	1.23	0.50
	In-plane	1.04	0.30

Table 2. Correlation lengths in longitudinal and transverse directions

The results indicate that, for both RTM and pre-preg samples, the in-plane longitudinal correlation length is similar to the out-of-plane longitudinal correlation length. This implies that in-plane waviness has a similar wavelength to out of plane waviness.

However, the transverse correlation length is larger in the out-of-plane direction than the in-plane direction, which implies that regions of waviness are larger in the out-of-plane direction than they are in the in-plane direction. This is consistent with an application of though-thickness compression during cure – the compaction means that any waviness defects apparent in one layer will be impressed onto the adjacent layers.

3.3 3D voxel data from CT images

The analysis of 3D voxel data is achieved by taking perpendicular 2D slices from the 3D voxel region and analysing each of these with the MFIA algorithm. The standard deviation of fibre orientation for the CT data of a pre-preg sample is presented in Table 3. These data are in reasonable agreement with the values estimated from optical micrographs, being slightly lower due to a larger averaging area being used for the CT imaging.

Process	Plane of waviness	Std deviation of fibre orientation
Pre-preg	Out-of-plane	0.45°
	In-plane	0.88°

Table 3. Standard deviation of fibre orientations from CT data

Because the in-plane and out-of-plane CT results are based on a single volume, the CT data can be used to investigate the relative positioning of in-plane and out-of plane waviness and thus determine whether there is a correlation between the locations of in-plane and out-of-plane waviness in the composite. Piat et al [7] presented 3D orientation data for a carbon carbon composite by plotting probability of fibre distribution upon the surface of a sphere which represents all possible orientations in 3D space. The resulting distribution of fibre orientations from the CT data is shown in Figure 8. Since all the calculated fibre orientations for the pre-preg specimen are clustered within a few degrees of the nominal fibre direction, the area of interest has been enlarged.

The CT data shown in Figure 8 confirms the microscopy work. The elongation of the probability function in the in-plane direction – confirms that the variability of fibre orientation is lower in the out-of-plane direction than in the in-plane direction, i.e. in-plane waviness exhibits larger angles than out-of-plane waviness. Furthermore, the ellipsoidal shape of the probability function shows that there is no direct correlation between out of plane waviness and in-plane waviness, i.e. in-plane and out-of plane waviness are both normally distributed, and the presence (or magnitude) of in-plane waviness at any given location has no apparent effect upon the presence (or magnitude) of out-of-plane waviness at that location.

4 Summary

A robust methodology has been developed for characterising and quantifying the orientation of fibres within nominally UD composites, and applied to two industrial components.

The standard deviation of fibre orientation is greater for the RTM component than for the pre-preg component.

Additionally, it is seen that fibre orientation varies more quickly between adjacent fibres than it does along the fibre direction.

Fibre orientation results taken from CT images are in good agreement with the optical images of samples taken from the same component.

This work is being used to enable more representative finite element modelling of compressively loaded UD composites, in which regions fibre waviness initiate microbuckling leading to material failure.

Acknowledgements

The authors would like to thank EPSRC (EP/G012938/1 and EP/H01506X) and the MoD for their support of this work, and to thank industrial partners and our colleagues at Cambridge, Southampton and Bristol for their input and comments.

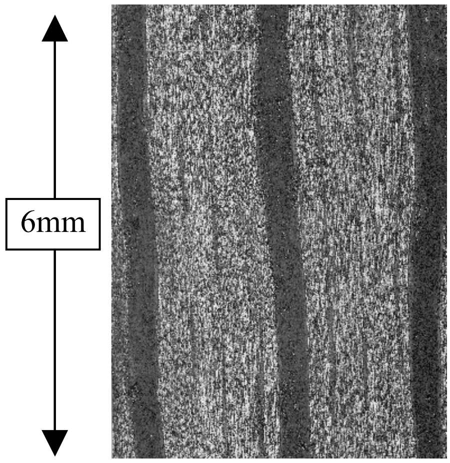

Fig.1. Micrograph of RTM specimen.

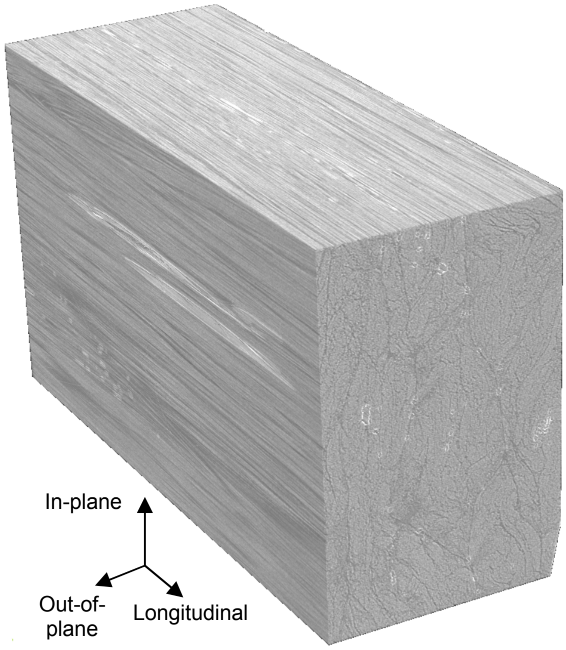

Fig.2. 3D CT data from pre-preg specimen

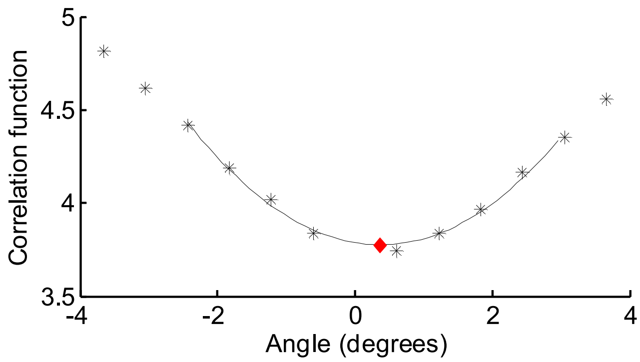

Fig.3. Quadratic curve fitted through correlation data

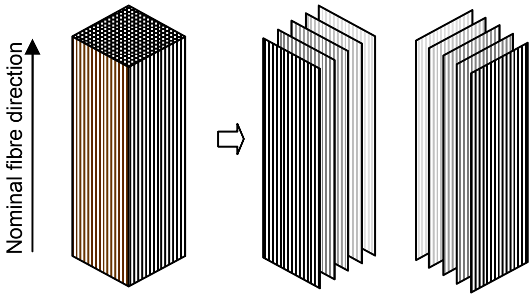

Fig.4. Perpendicular slices from 3D CT data

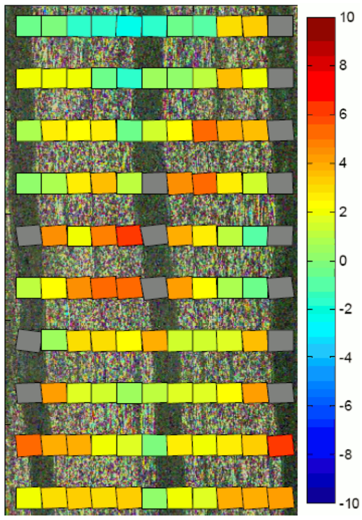

Fig.5. Fibre orientation from MFIA of micrograph image of RTM sample. Scalebar gives orientation angle in degrees. Angle is undefined in grey regions.

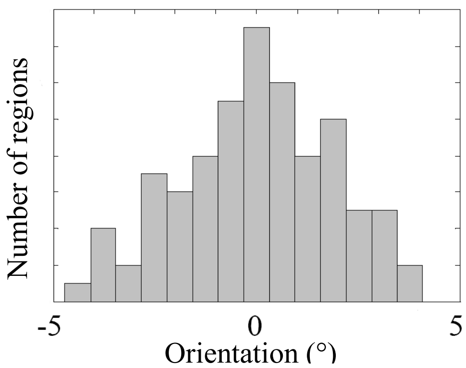

Fig.6. Distribution of fibre orientation from Fig.4.

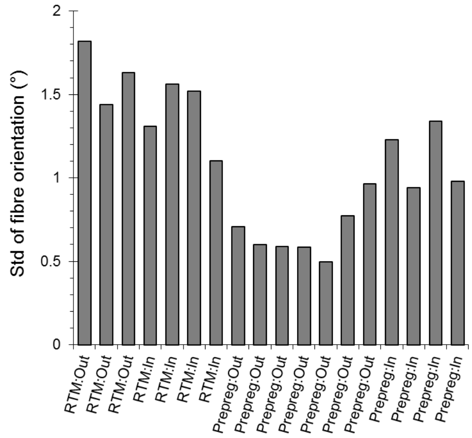

Fig.7. Standard deviation of fibre orientation for RTM and Prepreg samples from 2D microscopy

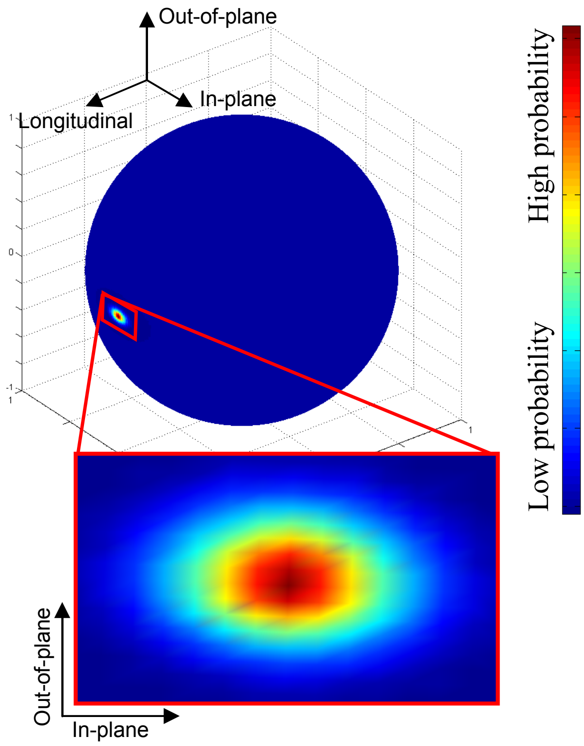

Fig.8. Probability distribution of fibre orientations

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