Computationally efficient method of tracking fibres in composite materials using digital image correlation

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# Abstract

A computationally efficient method based on digital image correlation (DIC) has been introduced in this paper for fast and accurate characterisation of fibre orientation fields from a series of optical mosaics of a continuous fibre-reinforced composite (CFRC) specimen, which were obtained using a well-established automated serial sectioning technique. The newly developed method has the capability of determining fibre paths from the sequence of mosaics in scenarios where the serial section spacing between the adjacent mosaics is atypically large, resulting in shifts in the fibre locations on the order of 90 pixels or twelve fibre diameters. The performance of the proposed method was quantitatively compared with a state-of-the-art fibre-tracking algorithm based on a Kalman filter, by applying them to the mosaic sequences from two CFRC material specimens. It was demonstrated from the fibre-tracking results that the proposed DIC-based method outperformed the Kalman filter algorithm in terms of both reliability and speed.

# Keywords

A. Ceramic fibres; A. Carbon fibres; C. Microstructures; D. Optical microscopy

# Introduction

The use of traditional alloys in modern aerospace structures is being phasing out by the emergence of advanced composite and hybrid materials. Continuous fibre reinforced composite (CFRC) materials, in particular, are being used extensively in the manufacture of load-bearing components due to their high stiffness, increased strength-to-weight ratio and enhanced fatigue performance. Recently-developed toughened ceramic based CFRCs, which are capable of withstanding temperatures in excess of 1500°C, are being viewed as a potential replacement for the nickel-based alloys in high temperature applications[1](#_ENREF_1). The enhanced mechanical properties of CFRC materials are typically achieved through the complexity in their tailored, heterogeneous, microstructure. Hence, the damage mechanisms in such materials are highly sensitive to the defects or anomalies in their microstructures, such as misalignment of fibres, which might be introduced during the processing stage. It is therefore important to be able to identify and characterize these anomalies, not only for the purpose of quality control, but also to link them to the processing techniques in order to accelerate the development of stronger and more consistent microstructures for next generation CFRCs.

Light microscopy is one of the most common tools used for analysing microstructures; however, it can only be used on two-dimensional (2D) cross-sections for opaque materials such as CFRCs. Automated mechanical polishing-based serial sectioning is an extension of conventional materialographic preparation used to produce a polished specimen surface. Recently, it has emerged as a well-established destructive technique to obtain a reconstruction of three-dimensional (3D) microstructure in a wide variety of materials[2](#_ENREF_2) due to a combination of advancements in automation and control, and the development of high-resolution digital sensors. At the same time, the availability of high intensity X-ray beams from synchrotron radiation sources has made X-ray computed tomography (CT) a powerful technique to visualise 3D microstructure, non-destructively, in composites. Despite the working principles being entirely different for the two microstructure characterisation techniques, the outcome from both the techniques is similar in the form of a series of images of a specimen’s cross-section at various depths, which collectively represent the 3D microstructure of the specimen. Hence, image analysis is required to extract the microstructural features such as fibre misalignment, fibre coating variation or voids from image data. This paper focuses on the development of a robust and computationally-efficient method for the extraction of 3D fibre profiles from a sequence of greyscale images of a CFRC specimen, which can be used to identify misalignment of fibres. The extraction of fibre profiles is generally a two-step process. In the first step, image segmentation is performed to identify individual fibre cross-sections in each of the images in the sequence. The second step involves the linking of individual fibre cross-sections through the sequence of images in order to construct profiles of individual fibres through the depth of the specimen.

Over the past couple of years, a number of notable studies have been carried out in which cross-sectional images of CFRC specimens were acquired either using automated serial-sectioning[3-5](#_ENREF_3) or X-ray CT[6-10](#_ENREF_6) in order to determine fibre orientations. In some of the studies[3](#_ENREF_3), [7](#_ENREF_7), [10](#_ENREF_10), fibre cross-sections were tracked in the image stack using a neighbourhood search. This simple approach projects the position of the fibre in the next image, based on its previous orientation, and searches for the fibre cross-section with the smallest Euclidean distance to the projected location. Czabaj and his co-workers[8](#_ENREF_8) proposed the use of the Kalman filter for tracking fibres in a unidirectional graphite fibre-reinforced polymer composite specimen, which is a commonly used framework in machine-vision for tracking multiple targets such as vehicles or people in an image sequence. In this algorithm, the positions of fibre cross-sections were projected in the next image using a linear extrapolation model and the detected fibre cross-sections were assigned to the projections using a global nearest neighbour scheme[11](#_ENREF_11). In their later study[12](#_ENREF_12), the same algorithm was successfully employed to track fibres in a multi-directional graphite fibre-reinforced polymer specimen in which fibres were orientated at +45° and ±60° from the cross-section plane. More recently, Sencu et al[9](#_ENREF_9) developed a similar fibre-tracking algorithm by employing a Bayesian filter. In their method, global fibre shifts between the adjacent images in the stack were first determined using cross-covariance. These global fibre shifts were then used to track individual fibres by using them as predictions for fibre locations in a Bayesian inference model.

The above-mentioned tracking algorithms assume fibre profiles to be predominantly straight with no significant curvature since the majority of them employ linear extrapolation to estimate the fibre location between two adjacent images in the stack. Hence, they are applicable to scenarios where there are no significant shifts in the locations of fibre cross-sections between the adjacent images. Zhou et al[5](#_ENREF_5) proposed a more sophisticated Kalman filter based fibre-tracking method, which was employed to track fibres in a sparsely sampled image sequence of a composite specimen with a ceramic fibre-reinforced ceramic matrix. The fibres in their specimen were orientated nominally at ±45° from the cross-section plane and the maximum gap between the adjacent images in their sparsely-sampled sequence was 20 µm, which caused shifts in the fibre positions exceeding 20 µm or 10 pixels based on their image spatial resolution of 0.5µm/pixel. Their algorithm performs tracking by first projecting the fibre position, based on a linear extrapolation model similar to the one employed in the Kalman filter method by Czabaj et al[8](#_ENREF_8). The detected fibre cross-sections are then assigned to their corresponding projections using a novel group-wise association algorithm which leverages the fact that the fibres are typically implanted in bundles, and hence, their profiles are expected to be highly aligned within the bundle. Their association algorithm divides the projected fibre locations, using K-means clustering, and then assigns the projected fibre locations (predictions) in each cluster with the detected fibre locations (observations) using non-rigid thin plate splines[13](#_ENREF_13). The performance of the proposed algorithm, referred to, by the authors, as the Kalman-Groupwise method, was quantitatively compared with a neighbourhood search method[3](#_ENREF_3), two baseline Kalman filter methods[13](#_ENREF_13), [14](#_ENREF_14) and four other state-of-the-art multi-target tracking algorithms[15-18](#_ENREF_15); and it was demonstrated that the Kalman-Groupwise method outperformed the previously published tracking methods.

In this paper, a faster and reliable method for tracking fibres based on digital image correlation (DIC) is proposed that does not rely on a prediction model and hence is capable of tracking fibres in scenarios where fibres have twisted profiles and the spacing between adjacent images is variable, which can occur during automated serial sectioning. Since it was established by Zhou et al[5](#_ENREF_5) that their novel Kalman-Groupwise algorithm clearly outperforms the existing state-of-the-art multi-target tracking methods, their algorithm was selected to compare its performance against the proposed DIC-based method. The process chart of the Kalman-Groupwise method is provided in Figure 1.

This paper is structured in the following manner: the next section describes the proposed fibre-tracking method. The two CFRC specimens analysed in this work, i.e., ceramic fibre-reinforced ceramic matrix composite (CMC) and a carbon fibre-reinforced polymer matrix composite laminate (PMC) and the serial sectioning technique used for acquiring their cross-sectional images are described in the third section. The fourth section presents the results of the quantitative comparison between the fibre-tracking performances of the proposed method and the Kalman-Groupwise method. The potential application of the proposed method to the X-ray CT images is also discussed in this section. The key findings of this study and concluding remarks are provided in the final section. To avoid ambiguity, it is important at this stage to define the terms “mosaics”, “images”, “tiles” and “micrographs” which will be used frequently in the following sections to describe the data acquired from the serial sectioning technique. The word “image” in this paper is used as a generic term for a mosaic, micrograph or a tile primarily to describe the proposed fibre-tracking method in the next section. The mosaics were constructed by digitally stitching together a grid of micrographs of the specimen’s surface captured using an optical microscope. Tiles refer to smaller sub regions that are cropped from the mosaics, for performance comparison of the proposed method with the Kalman-Groupwise method.

# Proposed fibre-tracking method

The proposed method can be divided into two parts. The first part involves the steps for acquiring the prerequisite data for fibre-tracking. The second part contains the set of steps for tracking individual fibres through a sequence of images. The two parts of the methods are described in this section. The process chart of the proposed method is shown in Figure 2 and the flow diagram detailing all the steps is provided in Figure 3 for those readers who are interested in implementing this method.

## Prerequisite data for fibre-tracking

Prerequisite data for fibre-tracking is obtained in three steps. In the first step, bulk fibre shifts between the images of the stack are determined utilising DIC. Segmentation is then performed on the first image of the stack to identify individual fibre cross-sections to be tracked in the second part of the proposed method. The third step involves assigning the detected fibre cross-sections to the pointwise DIC measurements

### Measurement of bulk fibre shifts using DIC

DIC is an optical technique which employs image registration concepts to track local grey-level intensity patterns in the images. A typical DIC algorithm discretises the first (reference) image in the image series into a grid of small square-shaped regions called facets. Each facet in the reference image is then matched to its corresponding location in the subsequent image to determine the displacement vector. For a DIC algorithm to work effectively, the facets should be different from each other in terms of their grey-level intensity distribution, and hence, the image must possess a high contrast random pattern. When DIC is used to measure full-field deformation from a component’s surface, the component is usually painted by spraying black or white droplets on to its surface in order to create a random speckle pattern. In the case of a cross-sectional image of a CFRC specimen, the distribution of fibre cross-sections, which appear in the image as ellipses, provide a sufficiently random pattern to employ DIC in order to evaluate bulk fibre shifts between the adjacent images in the sequence. The choice for the size of the facet depends on the speckle size, and in this case, the nominal size of the fibre cross-sections. To ensure that each facet is unique, Sutton et al[19](#_ENREF_19) have suggested that the facet size should be such that it nominally contains 9 speckles within it. Fibre cross-sections act as speckles in the case of cross-sectional images of a CFRC specimen. The suggested facet size is sufficient for successful correlation provided the displacements or bulk fibre shifts to be determined between adjacent images is significantly less than a fibre-diameter. In scenarios where the displacements to be resolved are greater than a fibre-diameter, the facet needs to be much larger than the size recommended by Sutton et al[19](#_ENREF_19) in order to maintain a low displacement-to-facet size ratio.

In this study, a commercially-available DIC package, Istra-4D (Dantec Dynamics GmbH) was used to determine the bulk fibre shifts. The Istra-4D software overlays a grid of square facets on the reference image using two parameters, i.e., facet size and grid spacing, which is simply the distance between the two adjacent facet centres. It utilises a second-order shape function to map each reference image facet to its displaced location in the next image and the coefficients of the shape function are determined by minimising the sum-squared difference (SSD) between the intensity patterns of the two images[20](#_ENREF_20). In this study, bulk fibre shifts between adjacent images were determined by defining the preceding image in the stack as the reference image whilst correlating each image.

### Detection of fibre cross-sections

Otsu’s method[21](#_ENREF_21) was applied to the first image in the sequence using the Matlab function, “multithresh” to determine the grey-level intensity thresholds to separate the three microstructure features, i.e., matrix, fibres and voids. A binary image was created by converting the grey-level values of pixels identified as the fibre phase to one and the remainder to zero. The touching fibres were separated using a marker-controlled watershed segmentation method. In this approach, the identified fibre regions were first converted into local minima or so-called ‘catchment basins’ by taking a distance transform of the binary image complement using the Matlab function, “bwdist”. The catchment basins with insignificant depths were filtered out and the ones with considerable depths are marked by applying a combination of two Matlab functions, “imextendedmin” and “imimposemin”. This was done to avoid over-segmentation which is a well-known issue with the watershed segmentation approach. Finally, the touching regions were segmented along the watershed lines using the Matlab function, “watershed”. The segmented fibre regions were labelled using the Matlab function, “bwlabel”. The segmentation results obtained using the above-mentioned segmentation strategy are shown in Figure 4 for an exemplar tile defined in one of the mosaics of the CMC specimen. Each labelled fibre region was fitted with an ellipse using an open-access Matlab function developed by Simonovsky[22](#_ENREF_22" \o "Simonovsky, 2013  #52), which implements the ellipse detection method proposed by Xie and Ji[23](#_ENREF_23). The parameters of the fitted ellipses such as the major and minor axes and the centre coordinates were recorded.

### Assignment of detected fibres to DIC facets

In the previously published methods[3](#_ENREF_3), [5](#_ENREF_5), [8](#_ENREF_8), the location of fibres in the next image were predicted by linearly extrapolating their profiles based on their orientation in the previous image. In the proposed method, the nominal fibre shifts between the adjacent images, measured using DIC, were used to project the location of individual fibres in the next image. This was implemented by assigning the fibres detected in the first image of the sequence to the nearest DIC facet based on their Euclidean distance.

## Tracking of individual fibres

To track each detected fibre cross-section, a square-shaped template was defined in the first image, referred as the ‘reference template’, with its centre at the coordinate centre of the fibre cross-section. The location of this template was projected in the next image using the displacement of the DIC facet lying closest to the centre of the reference template in the first image. The projected reference template was then traced within a square-shaped search window by employing the Matlab function, “normcorr2”. This function computes the normalised cross-correlation (ncc) coefficient between the reference template and the underlying region of the search window at every pixel location within it and returns a map of ncc coefficients ranging between -1 and 1. The ncc coefficients of -1 and 1 correspond to perfect anti-correlation and correlation, respectively. The location of the identified template was considered to be the location of the peak value in the map of ncc coefficients. Finally, the identified template was segmented using the segmentation strategy described earlier and the centre coordinate of the fibre lying closest to the identified centre of the template was considered to be the position of the fibre cross-section being tracked. As the tracking progressed through the sequence of images, the reference template was updated automatically whenever the peak of ncc coefficients was found to be above a threshold value of 0.8. The size of the templates and the search windows used in this study were three and five times the average major axis of the detected fibres in the first image, respectively. This procedure for tracking fibre cross-sections is illustrated in the flow-chart in Figure 3. The plots of ncc coefficient peaks for the two exemplar templates tracked through the sequence of mosaics of the CMC and the PMC specimens are shown in Figure 5. The insets show the templates detected at different instances through the sequence of mosaics (see supplementary material for the video of detected templates). The fibre cross-section being tracked is located at the centre of these templates and is highlighted with a star-shaped marker in Figure 5. The two neighbouring fibres are also marked using the circle- and diamond-shaped markers to illustrate the relative shift of the surrounding fibres, particularly in the PMC templates, which is indicative of nonlinearity in the fibre profiles through the depth of the specimen. This further implies that the proposed DIC-based method is capable of tracking fibres with non-linear profiles through the depth of the specimen; however, in scenarios where the fibres are significantly entangled, the proposed method could potentially breakdown unless the spacing between the adjacent images is less than a fibre diameter.

# Experimental Methods

Serial sectioning data from two CFRC specimens were utilised in this study. The first serial sectioning experiment characterised a volume of 3.6 × 2.6 × 0.1 mm, for a CMC specimen comprised of six layers of plane weave silicon-carbide fibres with a nominal diameter of 13 µm in a silicon-nitro-carbide matrix with a fibre volume fraction of 38 %. The fibres in the CMC specimen were orientated nominally at ±45° to the sectioning plane. The second serial sectioning experiment inspected a volume of 24.5 × 2.6 × 1.1 mm of a carbon fibres reinforced polymer matrix composite (PMC) that consisted of twenty plies of unidirectional carbon-fibres with a nominal diameter of 5 µm in an epoxy resin having a fibre volume fraction of 50%. Fibre tracking analysis was performed on one-quarter of the volume originally inspected by the serial sectioning system i.e. 6.1 × 2.6 × 1.1 mm. This volume contained around a hundred-thousand carbon fibres and was therefore sufficient in size to fully demonstrate the fibre-tracking capability of the proposed method; this is further explained later in the section. The unidirectional fibre plies have a symmetric [±15/+45/±75]2s layup, defined with respect to the sectioning plane. The two specimens were serially sectioned using an automated optical microscope-based mechanical polishing system that has extensive custom modifications (Robo-Met.3D ver. 2, manufactured by UES Inc., USA). The serial sectioning instrument automates the iterative removal of material from the specimen’s surface by single or multiple polishing steps, to produce a materialographic surface that enables quantitative analysis of the desired microstructure features. After each sectioning cycle, the specimen is placed on a motorized inverted microscope (Axiovert 200M, Zeiss, Germany), that allows the automated collection of hundreds of micrographs from the specimen’s surface that are digitally stitched into a mosaic after collection.

For the CMC specimen, 100 sections were acquired at uniform increments of approximately 1 µm[3](#_ENREF_3). After stitching and cropping a grid of micrographs captured over the specimen’s surface, each constructed mosaic was 7200 × 5200 pixels in size with a spatial resolution of 0.522 µm/pixel. For the PMC specimen, 212 sections were acquired and the mosaics representing these sections had dimensions of 73148 × 7653 pixels and a spatial resolution of 0.335 µm/pixel. For the first 0.4 mm of specimen depth, the polishing process was performed for a longer duration resulting in the first set of 30 mosaics having a nominal spacing of 13.2 µm. The serial sectioning rate was reduced at 0.4 mm depth and kept at a steady rate until a depth of 0.9 mm was reached which resulted in a second set of 75 mosaics with a nominal spacing of 6.2 µm. The grinding rate was further reduced for the remaining 0.2mm depth of specimen, providing a third set of 107 mosaics with a nominal spacing of 2.2 µm. During automated data acquisition of the PMC specimen, the auto focus feature of the microscope system malfunctioned resulting in a loss of image data from six sections, which caused a single gap of 55 µm between sections containing valid image data.

The mosaics of the PMC specimen were 14 times bigger than that of the CMC specimen. Hence, the PMC mosaics were split into four sections by dividing them along their longest dimension and only one quadrant of the mosaics with dimensions of 18287 × 7653 pixels (6.13 × 2.56 mm) were considered in the fibre-tracking analysis. The resolution of the mosaics for both the material samples were exceptionally high compared to images used routinely in DIC; and hence, the resolution of the CMC and the PMC mosaics were reduced from 0.522 and 0.335 μm/pixel to 1.04 and 0.67 μm/pixel, respectively, by averaging the intensity of regions consisting of two-by-two squares of pixels and replacing these regions with a single pixel. This did not result in a significant reduction in accuracy but did result in a 50% reduction in processing times for tracking fibre cross-sections. Exemplar mosaics of reduced resolution, which were used for fibre-tracking analysis, are shown in Figures 6 and 7 for the CMC and PMC specimens, respectively.

To compare the performance of the proposed DIC and the Kalman-Groupwise methods, rectangular tiles were first defined in the reduced resolution mosaics of both the CMC and the PMC samples (see Figure 6 and Figure 7). For the CMC mosaic, the size and location of the tile were selected such that it contained at least 500 fibre cross-sections distributed between at least three different fibre tows. For the PMC mosaic, the tile was positioned such that it contained fibres from two adjacent plies orientated nominally at ±75° from the sectioning plane. After extracting the sequence of tiles from the original sequence of low-resolution mosaics, all the tiles were aligned with respect to the first tile in the sequence using the Matlab image registration function, “imregister” based on the grey-level intensity. In total, four tests were performed. In the first test, both the methods were applied to the whole sequence of tiles of the CMC specimen which had the uniform serial section spacing of 1 μm. In the second test, a new sequence of CMC specimen tiles was constructed by repeatedly skipping nine tiles before selecting the next tile in the original sequence until the end of the sequence was reached. This resulted in a new sequence with a uniform serial section spacing of 10 μm. For the third test, a sequence was constructed for the CMC specimen tiles with a non-uniform serial section spacing which ranged from 1 µm to 10 μm. The fourth test was performed on the first thirteen tiles in the original sequence of tiles for the PMC specimen. The key details of the four tests are summarized in Table 1. Figures 8 and 9 show the plots of cumulative thickness of the specimen against the serial numbers of the tiles which were selected in the original sequence to construct new sequences for the four tests.

For fibre-tracking using the DIC method, the tile sequences were processed with a DIC package, Istra-4D (Dantec Dynamics GmbH). As explained in the previous section, the choice for the facet size depends on the nominal diameter of the fibre cross-section as well as the magnitude of the displacements between two adjacent tiles. The maximum displacements in the fibre positions between the adjacent tiles in the sequences of CMC and PMC tiles were approximately 10 and 4 μm respectively, which means that the CMC tiles require a bigger facet size compared to the PMC tiles. Hence, the sequence of CMC and PMC tiles were processed using the facet sizes of 69 and 39 pixels, respectively. The Kalman-Groupwise method processes the centre coordinate data for the fibre cross-sections in order to determine the fibre profiles through the sequence of tiles. The centre coordinates of the fibre cross-sections were first determined for each tile in the sequence using the segmentation strategy described in the previous section. A text file was generated for each tile which contained the centre coordinates for all the fibre cross-sections which were detected in a given tile. The sequence of text files were then used as an input for the publicly available Matlab code[24](#_ENREF_24) which implements the Kalman-Groupwise method. The fibre-tracking analysis was performed on a workstation with an Intel Xeon E5-1620 v4 processor with 32GB of RAM. The computational times required by the two methods to process the tile sequences in the four tests are provided in Table 2.

# Results and Discussion

The comparison between the fibres profiles determined using the DIC and the Kalman-Groupwise method for the first three tests, performed on the CMC tile sequences, is shown in Figure 10 and for the fourth test, performed on the PMC tile sequence, it is shown in Figure 11. The fibres present in the CMC data were distributed between three fibre tows and were orientated predominately in the X-Z plane, i.e., the plane of the weave at nominally ±45° to the sectioning (X-Y) plane, whereas the fibres in the PMC tiles belong to the two unidirectional fibre plies which were orientated at nominally ±75° to the sectioning plane. The plot on the left in Figures 10 and 11 clearly show that DIC has correctly determined the global orientation of the fibres in both the specimens. The Kalman-Groupwise method, on the other hand, worked only in the first two tests which involved sequences of CMC tiles with uniform serial section spacing of 1 and 10 μm respectively. It is pertinent to mention here that the open access Matlab code for the Kalman-Groupwise method[24](#_ENREF_24) assumes a constant spacing between the adjacent tiles. Hence, it fails to predict the global orientation of the fibres in Tests 3 and 4, which involved tile sequences with non-uniform serial section spacing. To further investigate the influence of serial section spacing on the fibre tracking performance of both the methods, the global orientation of the fibres in 3D space was evaluated in the first three tests. The fibres in the CMC specimen were assumed to be predominantly straight since the specimen depth of 100 µm was not sufficient to resolve the curved profile of the woven fibres. The direction vectors representing the global orientation of the CMC fibres were determined from their respective Cartesian coordinate data using principal component analysis by employing the Matlab function, “pca”. The schematic in Figure 12 shows the two angles of the direction vector i.e. θxy (global) and θxz (global), defined with respect to the X-Y (sectioning) and the X-Z (weave) planes respectively, which were used to define the 3D orientation of the fibres in the CMC specimen.

The maps of global fibre angles, θxy (global) and θxz (global), acquired using the DIC and the Kalman-Groupwise method for the first three tests are shown in Figures 13 and 14, respectively. The maps obtained from the DIC-based method appear to be identical implying that the tracking performance of the proposed method is not significantly influenced by the serial section spacing. In contrast, the Kalman-Groupwise method correctly predicted the overall orientation of the fibres only in the first two tests; however, the maps for the second test are significantly noisier in comparison to ones for the first test (see maps on the right in the first two rows in Figures 13 and 14). To explore the likely cause for the deterioration in performance of the Kalman-Groupwise method in the second test, the variation in the localised fibre angles, θxy (local) through the depth of the specimen were determined for each of the three fibre tows in the sequence of CMC tiles, using the coordinate data acquired from DIC-based method in Test 1. The localised fibre angle was evaluated at a given depth by performing principal component analysis on the coordinate data representing a fibre segment of approximately 10 µm in length. The bar plots provided in Figure 15 shows the variation in the mean absolute values for θxy (local) through the depth of the specimen for the three fibre tows. The error margins on the bars indicate the variation in θxy (local) for individual fibres within a fibre tow and are represented as one standard deviation from the mean value. The maximum difference in the mean values for θxy (local) was found to be 10° in these bar plots, which translates to a gap of approximately ±5 pixels (≈ 5 µm) between the observed and the linearly-extrapolated location of the fibre when the serial section spacing was 10 µm. This gap in the observed and projected fibre location is almost equal to the nominal radius of the fibres in the CMC specimen. Hence, the deterioration in performance of the Kalman-Groupwise method in Test 2 was likely due to a significant gap between the observed and projected fibre locations resulting in an increased number of false associations. The results in Figures 13 - 14, therefore, provide compelling evidence to suggest that the previously published fibre-tracking methods, which rely on a linear extrapolation model to predict the location of fibre centres, are not capable of identifying anomalous behaviour in the fibres, such as curvature or localized waviness, in particular, when the serial section spacing is large relative to the scale of the fibres, resulting in significant shifting in the fibre positions between adjacent sections. The processing times required by the two methods to track the fibres in Tests 1 to 4 are provided in Table 2. The DIC-based method was found to be at least 30 times faster than the Kalman-Groupwise method.

The focus of recent studies[8](#_ENREF_8), [9](#_ENREF_9) on reconstruction of fibre profiles from cross-sectional images of CFRC specimens was to generate finite element meshes, which can be used for performing realistic simulations of micro-scale deformation in such materials. These studies present an important milestone towards the virtual testing of CFRC specimens at the micro-scale; however, owing to very high computational costs associated with the numerical modelling of CFRC specimens containing thousands of fibres, the specimen volumes analysed in these studies were limited to less than 0.5 mm3 in size. One of the objectives of the current work was to develop a computationally-efficient fibre-tracking method capable of performing fast and reliable characterisation of fibre orientations in relatively large (>10mm3) specimens, which can be considered as statistically representative samples of the bulk composite material. For instance, thevolume of the PMC specimen characterised in this study was 17mm3, which is around a thousand times larger than the minimum sample size[25](#_ENREF_25) believed to be representative of the bulk PMC material.

To further demonstrate the fibre-tracking capability of the proposed method, it was applied to the whole sequences of mosaics from both the CMC and the PMC specimens. The bulk fibre shifts between mosaics of the CMC specimen were determined using DIC with a facet size of 39 pixels. The plot of fibre profiles determined from the CMC mosaic sequence is shown in Figure 16. As mentioned earlier, the PMC specimen contained in total twenty unidirectional plies with three distinct orientations i.e. nominally ±15°, +45° and ±75° with respect to the X-Y plane. It was not possible to track fibres in those plies which were orientated at a shallow angle of ±15°. As a consequence of this shallow angle, the maximum displacement in the fibre positions between the adjacent mosaics was on the order of 300 pixels or forty fibre diameters. For the plies orientated at +45° and ±75°, the maximum displacements in the fibre positions between adjacent mosaics were approximately 90 and 25 pixels, which is equal to about twelve and three fibre diameters, respectively; hence, the fibres in these two types of plies were tracked using a facet size of 141 and 69 pixels, respectively. The fibre profiles determined in the PMC mosaic sequence are presented in Figure 17.

CT images typically suffer from limited contrast and potential artefacts, resulting from tomographic reconstruction, compared to bright-field reflection images acquired using an optical microscope. On the other hand, images from an automated serial sectioning system, despite having a better contrast, can be subject to a range of preparation and imaging artefacts from polishing scratches, dirt or debris obscuring the imaging surface, or out-of-focus images due to failure of the autofocus feature of the imaging system. The proposed method is capable of tracking fibres through an image sequence even if blurred regions exist in some of the images (see top plot in Figure 5). Over recent years, the contrast of CT images have drastically improved due to the availability of high-energy X-ray sources and advancements in the associated instrumentation. In some of the recent investigations[8](#_ENREF_8), [10](#_ENREF_10), [26](#_ENREF_26), the individual fibres are clearly observable from the raw CT images. In fact, Czabaj et al[8](#_ENREF_8) employed a segmentation approach based on 2D cross-correlation to identify individual fibre cross-sections from the CT images of a graphite fibre-reinforced polymer. This implies that there was sufficient contrast between the fibre and matrix phase in their CT images. Modern DIC algorithms are much more robust than the simple cross-correlation between two image facets; and, almost all commercial DIC packages utilise higher-order shape functions to allow for the translation, stretch, shear and/or distortion of the image facet and are unlikely to be influenced by slight variations in brightness or contrast between the corresponding image facets. It is, therefore, postulated that DIC will work effectively on the CT images similar to ones analysed by Czabaj et al[8](#_ENREF_8) and Emerson et al[10](#_ENREF_10), [26](#_ENREF_26) to track local grey-level intensity patterns for the purpose of fibre tracking.

# Conclusions

A computationally-efficient fibre-tracking method based on digital image correlation (DIC) has been proposed in this paper, which is capable of performing reliable characterisation of fibre orientations from the optical mosaics of relatively large specimens of continuous fibre-reinforced composites (CFRC), with volumes greater than 10 mm3, within a timespan of a few hours. Unlike the previously published tracking methods, the proposed method does not rely on a predictive model to estimate the fibre trajectories, instead it utilises DIC to evaluate bulk fibre shifts between the adjacent mosaics which are then used as predictions to further trace the location of individual fibres. This allows it to successfully determine fibre paths from a mosaic sequence in scenarios where the spacing between the adjacent mosaics is wide and causes shifts in the fibre locations as high as twelve fibre diameters. The performance of the DIC-based method was compared with a state-of-the-art Kalman filter based tracking method by applying them to the mosaic sequences of two CFRC specimens, i.e. a ceramic fibre-reinforced ceramic matrix composite (CMC) and a carbon fibre-reinforced polymer matrix composite laminate (PMC). The fibre-tracking results clearly demonstrate that the proposed DIC-based method completely outperformed the Kalman filter algorithm in terms of reliability and speed being at least 30 times faster.

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# References

1. Naslain R. Design, preparation and properties of non-oxide CMCs for application in engines and nuclear reactors: an overview. *Composites Science and Technology* 2004; 64 (2):155-70.

2. Spowart JE. Automated serial sectioning for 3-D analysis of microstructures. *Scripta Materialia* 2006; 55 (1): 5-10.

3. Bricker S, Simmons JP, Przybyla C and Hardie RC. Anomaly detection of microstructural defects in continuous fiber reinforced composites. *In: Proceedings of SPIE 9401, Computational Imaging XIII*, 2015.

4. Christian WJR, Dvurecenska K, Amjad K, Przybyla C and Patterson EA. Machine vision characterisation of the 3D microstructure of ceramic matrix composites. *Journal of Composite Materials* 2019: 0021998319826355.

5. Zhou Y, Yu H, Simmons J, Przybyla CP and Wang S. Large-scale fiber tracking through sparsely sampled image sequences of composite materials. *IEEE Transactions on Image Processing* 2016; 25 (10): 4931-42.

6. Martin-Herrero J and Germain C. Microstructure reconstruction of fibrous C/C composites from X-ray microtomography. *Carbon* 2007; 45 (6): 1242-53.

7. Requena G, Fiedler G, Seiser B, Degischer P, Michiel M and Buslaps T. 3D-Quantification of the distribution of continuous fibres in unidirectionally reinforced composites. *Composites Part A: Applied Science and Manufacturing* 2009; 40 (2):152-63.

8. Czabaj MW, Riccio ML and Whitacre WW. Numerical reconstruction of graphite/epoxy composite microstructure based on sub-micron resolution X-ray computed tomography. *Composites Science and Technology* 2014; 105: 174-82.

9. Sencu R, Yang Z, Wang YC, Withers PJ, Rau C, Parson A and Soutis C. Generation of micro-scale finite element models from synchrotron X-ray CT images for multidirectional carbon fibre reinforced composites. *Composites Part A: Applied Science and Manufacturing* 2016; 91: 85-95.

10. Emerson MJ, Jespersen KM, Dahl AB, Conradsen K and Mikkelsen LP. Individual fibre segmentation from 3D X-ray computed tomography for characterising the fibre orientation in unidirectional composite materials. *Composites Part A: Applied Science and Manufacturing* 2017; 97: 83-92.

11. Blackman S and Popoli R. Design and Analysis of Modern Tracking Systems *Norwood, MA: Artech House*, 1999.

12. Whitacre W and Czabaj M. Extension of Automated 3D Digital Reconstruction to Multi-Directional Fiber Reinforced Composite Microstructures. *In: 57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 2016

13. Chui H and Rangarajan A. A new point matching algorithm for non-rigid registration. *Computer Vision and Image Understanding* 2003; 89 (2-3):114-41.

14. Kuhn HW. The Hungarian method for the assignment problem. *Naval research logistics quarterly* 1955; 2(1-2): 83-97.

15. Dicle C, Camps OI and Sznaier M. The way they Move: Tracking multiple Targets with Similar Appearance. *In: Proceedings of the IEEE international conference on computer vision*, 2013

16. Magnusson KE, Jaldén J, Gilbert PM and Blau HM. Global linking of cell tracks using the Viterbi algorithm. *IEEE transactions on medical imaging* 2015; 34 (4): 911-29.

17. Milan A, Roth S and Schindler K. Continuous energy minimization for multitarget tracking. *IEEE transactions on pattern analysis and machine intelligence* 2014; 36 (1): 58-72.

18. Pirsiavash H, Ramanan D and Fowlkes CC. Globally-optimal greedy algorithms for tracking a variable number of objects. *In IEEE Computer Vision and Pattern Recognition (CVPR) Conference*, 2011

19. Sutton MA, Orteu JJ and Schreier H. Image correlation for shape, motion and deformation measurements: basic concepts, theory and applications. *Springer Science & Business Media*, 2009.

20. Becker T, Splitthof K, Siebert T and Kletting P. *In: Proceedings of the SPIE: Speckle06*, *2006*

21. Otsu N. A threshold selection method from gray-level histograms. *IEEE transactions on systems, man, and cybernetics* 1979; 9(1): 62-6.

22. Simonovsky M. *An efficient ellipse detector based on Hough voting*. 2013. Available from: https://uk.mathworks.com/matlabcentral/fileexchange/33970-ellipse-detection-using-1d-hough-transform.

23. Xie Y and Ji Q. A new efficient ellipse detection method. *In: IEEE 16th International Conference on Pattern Recognition*, 2002.

24. Yu H, Zhou Y, Simmons J, Przybyla C, Lin Y, Fan X, Mi Y and Wang S. *Groupwise Tracking of Crowded Similar-Appearance Targets from Low-Continuity Image Sequences,* 2016. Available from: https://cvl.cse.sc.edu/project/cvpr2016.html

25. Trias D, Costa J, Turon A and Hurtado J. Determination of the critical size of a statistical representative volume element (SRVE) for carbon reinforced polymers. *Acta materialia* 2006; 54 (13): 3471-84.

26. Emerson MJ, Wang Y, Withers PJ, Conradsen K, Dahl AB and Dahl VA. Quantifying fibre reorientation during axial compression of a composite through time-lapse X-ray imaging and individual fibre tracking. *Composites Science and Technology* 2018;168: 47-54.

Table Key details of the four tests performed to compare the performance of DIC method against the Kalman-Groupwise method.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Material | Sequence | Serial section spacing |
| Test 1 | CMC | Original | Uniform: 1 µm per section |
| Test 2 | CMC | Constructed | Uniform: 10 µm per section |
| Test 3 | CMC | Constructed | Non-uniform: 1-10 µm per section |
| Test 4 | PMC | Constructed | Non-uniform: 1.1 – 17 µm per section |

Table Processing times required by the DIC-based method and the Kalman-Groupwise method to perform fibre-tracking.

|  |  |  |  |
| --- | --- | --- | --- |
|  | Processing steps | DIC  (minutes) | Kalman-Groupwise  (minutes) |
| Test 1 | Ellipse detection  DIC  Tracking/Association | 0.2 (first tile only)  13.2  4.6 | 14.6 (whole sequence)  -  1140 |
| Total | 18 (0.3 hours) | 1155 (19.2 hours) |
| Test 2 | Ellipse detection  DIC  Tracking/Association | 0.2 (first tile only)  3  0.4 | 1.5 (whole sequence)  -  120 |
|  | Total | 3.6 (0.1 hours) | 121.5 (2 hours) |
| Test 3 | Ellipse detection  DIC  Tracking/Association | 0.2 (first tile only)  4.2  0.8 | 2.9 (whole sequence)  -  180 |
|  | Total | 5.2 (0.1 hours) | 182.9 (3 hours) |
| Test 4 | Ellipse detection  DIC  Tracking/Association | 0.2 (first tile only)  1.2  1.5 | 2.4 (whole sequence)  -  1200 |
|  | Total | 2.9 (0.1 hours) | 1202.4 (20 hours) |
| CMC mosaic | Ellipse detection  DIC  Tracking/Association | 4.3 (first mosaic only)  75  210 | -  -  - |
|  | Total | 289.3 (4.8 hours) | - |
| PMC mosaic | Ellipse detection  DIC  Tracking/Association | 20 (first mosaic only)  480  1240 | -  -  - |
|  | Total | 1740 (29 hours) | - |



Figure 1: Process chart of the Kalman-Groupwise method.



Figure 2: Process chart of the proposed DIC-based fibre-tracking method

Figure 3: Flow diagram of all the steps involved in the proposed DIC-based fibre-tracking method.



Figure 4: Top photograph shows the exemplar greyscale tile defined in a CMC mosaic. Bottom photograph shows the same tile in a binary format obtained after performing segmentation to identify individual fibre cross-sections.



Figure 5: Plot of normalised cross correlation (ncc) coefficient peak values of an exemplar template tracked through the sequence of CMC (top) and PMC (bottom) mosaics.



Figure 6: A reduced-resolution CMC mosaic (bottom) and a close-up view of the tile (top) which was selected for fibre-tracking analysis in the first three tests.



Figure 7: A reduced-resolution PMC mosaic (bottom) and a close-up view of the tile (top) which was selected for fibre-tracking analysis in the fourth test.



Figure 8: Cumulative thickness of the CMC specimen as a function of the serial number of the tiles in the order they are arranged in the original sequence (see table 1 for test details).



Figure 9: Cumulative thickness of the PMC specimen as a function of the serial number of the tiles in the order they are arranged in the original sequence. The inset shows the same plot for the first thirteen tiles in the sequence which were selected for fibre-tracking analysis in Test 4 (see Table 1 for test details).



Figure 10: A comparison between the plots of 3D fibre profiles tracked by DIC-based method (left) and Kalman-Groupwise method (right). The fibres orientated towards the left and right-hand side in the X-Z plane are represented by red and green colours, respectively.



Figure 11: A comparison between the plots of 3D fibre profiles track by DIC-based method (left) and Kalman-Groupwise method (right) in Test 4 which involved PMC specimen tiles (see Table 1 for more details). The fibres orientated towards the left and right-hand side in the X-Z plane are represented in green and red colours, respectively.



Figure 12: Middle schematic shows the profile of a reconstructed fibre (*AD*) inside the specimen volume. Top and bottom schematics show the direction vectors and representing the global orientation of the whole fibre (*AD*) and the local orientation of fibre segment (*BC*) defined at an arbitrary specimen depth, respectively.



Figure 13: A comparison between the maps of global fibre angles, representing the overall inclination of the fibres in the sample volume from X-Y plane, acquired using the DIC-based method (left) and Kalman-Groupwise method (right).



Figure 14: A comparison between the maps of global fibre angles, representing the overall inclination of the fibres in the sample volume from X-Z plane, acquired using the DIC-based method (left) and Kalman-Groupwise method (right).



Figure 15: The bar plots of local fibre angles, representing the local inclination of the fibre in the specimen volume from X-Y plane, at the specimen depth, Z for fibre tow 1 (top), fibre tow 2 (middle) and fibre tow 3 (bottom) in the CMC tile sequence.



Figure 16: A plot of 3D profiles of the fibres tracked in the sequence of CMC mosaics using the proposed DIC-based method. The fibres which are orientated nominally at ±45° from the sectioning (X-Y) plane are represented in red and green colours.



Figure 17: Plots of 3D profiles of the fibres tracked in the sequence of PMC mosaics using the proposed DIC-based method. The fibres which are orientated nominally at +45°,+75° and -75° to the sectioning (X-Y) plane are represented in grey, green and red colours, respectively. The fibre profiles are split into two plots so that the overall orientation of the fibres in each ply can be observed.