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Development and Testing of an Image Analysis Procedure for Quantification of Fibre Misalignment in Composites Materials

K.K. Kratmann[1,3], M.P.F. Sutcliffe[2], L.T. Lilleheden[3]
O.T. Thomsen[1] and R. Pyrz[1]

Summary

This paper concerns the quantification of fibre misalignment in unidirectional carbon fibre reinforced polymer composites (UD CFRP). The motivation for determining the fibre misalignment is described and existing applicable methods are presented. The concept of a newly developed image analysis procedure is described and the test procedures used to verify the robustness and precision of the method are presented along with selected results.

Introduction

The compressive strength of most commercial unidirectional fibre reinforced polymers (FRP) is often below 60% of their tensile strength [1]. This often makes the compressive strength the limiting design factor in large composite structures. Therefore it is necessary to develop an understanding of the failure mechanisms of composites loaded in compression and the dependency of fibre misalignment. In addition it is necessary to develop and adapt predictive tools to be used in future developments of high performance composite materials. The first step in this procedure is the development of a methodology for the quantification of fibre misalignment. A brief review of the theoretical background and the significance of fibre misalignment in composites is given in the following.

Localized microbuckling is widely accepted as being the dominant failure mechanism governing the compressive strength of unidirectional polymer-matrix fibre reinforced composites [1-2]. The first analytical model by Rosen [3] described micro-buckling as an elastic instability event assuming perfectly aligned fibres. Later Argon [4] argued that commercial composites always have regions of misaligned fibres. Argon modelled initial fibre misalignment as being uniformly distributed in an infinite kink band and developed a rigid perfectly plastic model. This was further developed into an elastic perfectly plastic model by Budiansky [5]. Still considering uniform initial misalignment of an infinite kink band, Budiansky identified the initial fibre misalignment as one of the governing parameters along with

[1]Department of Mechanical Engineering, Aalborg University, Pontoppidanstræde 101, DK-9220 Aalborg, Denmark
[2]Department of Engineering, University of Cambridge, Trumpington Street, Cambridge, CB2 1PZ, UK
[3]Research & Development, Fiberline Composites A/S, Barmstedt Allé 5, DK-5500 Middelfart, Denmark

the in-plane shear modulus and the shear yield strain of the composite. Since then the elastic perfectly plastic model has been extended to take into account effects such as fibre bending resistance and strain hardening [1-2]. Other contributions [6-9] have conducted numerical studies to investigate how the geometrical properties of the misaligned regions influence the compressive strength.

Existing Methods

Only a few methods are available to measure fibre misalignment in UD CFRPs. The method by Yurgartis [10] analyses planes sectioned at a small angle of approximately 5° to the nominal fibre direction. This results in fibres with circular cross sections appearing as ellipsoids in the section plane. The fibre orientation can then be derived by measuring the major and minor axes on micrographs captured at 500–1000x magnification with an optical microscope. Another method is the Multiple Field Image Analysis method, MFIA [11]. This method analyses planes parallel to the fibre direction in which fibres appear as elongated white features. With the MFIA method image analysis software is used on micrographs taken at 50–100x magnification.

One major drawback of both the Yurgartis and the MFIA methods is the processing/analysis time. The fastest method is the MFIA method, which originally used about 3 hours on a typical analysis [11] conducted on a powerful computer. This has been reduced to a few minutes in a modified version developed by the first author in collaboration with the University of Cambridge.

Proposed Method

The method proposed in this paper analyses planes parallel to the nominal fibre orientation in which the fibres appear as elongated features. Digital 8-bit greyscale micrographs are captured with an optical microscope at 50x-100x magnification, and if necessary scaled to a resolution of approximately 1μm/pixel. The first step in the procedure is to divide the digital micrograph into several evenly spaced square domains. The proposed method works with domains of 200 by 200 pixels, but other domain sizes can easily be accommodated. These are then fully analysed one at a time. Two-dimensional fast Fourier transformation is then performed, transforming the image domain into the frequency domain. To visualize the frequency domain the logarithmic power spectrum is computed and centred for subsequent direction analyses. These steps are illustrated in Fig. 1. The line identified by an encircling ellipse in the centred power spectrum in Fig. 1 represents the mean orientation of the fibres in the image domain. The orientation of this line is determined and then used to build a domain-specific Fourier filter with the same size as the domain.

The filter contains two elongated "windows" symmetrically placed with respect to the centre of the image as shown in Fig. 2 (a). The transition from white to black is smoothed using a Butterworth equation [12] to avoid so-called ringing effects.

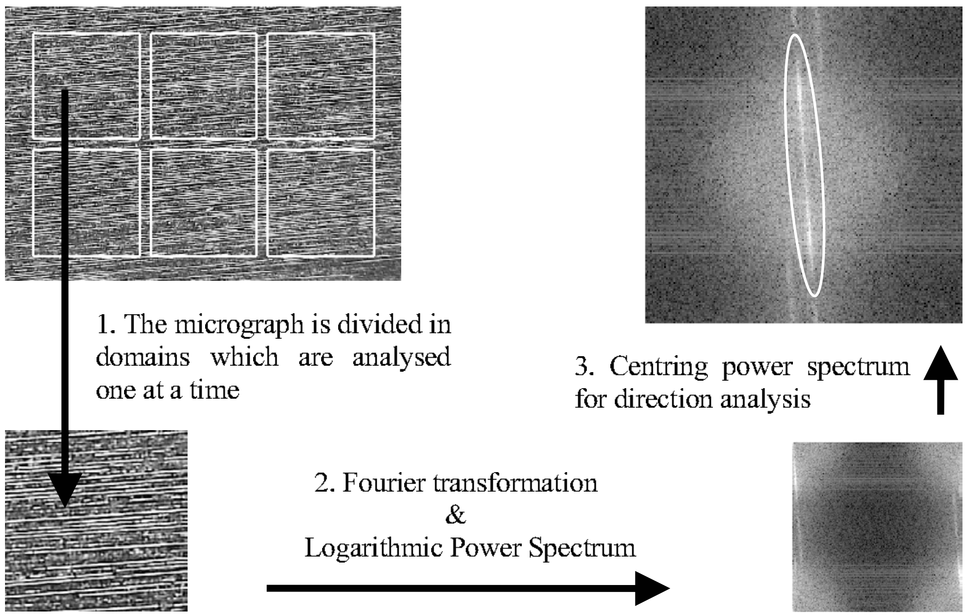
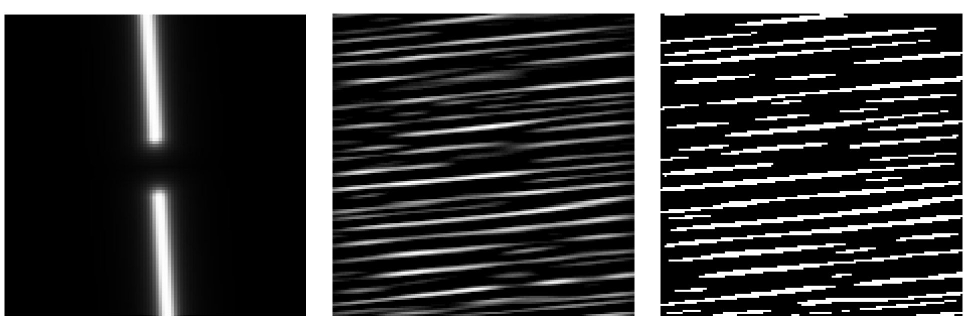


Figure 1: The three operations used to obtain a centred logarithmic power spectrum from a squared micrograph domain.

Here three input parameters are introduced, namely the filter radius, the cut off width and the filter order. These parameters control the distance from the centre of the image to the tip of the "windows", the width of the "windows" and the transition gradient, respectively. The filter is then rotated such that the "windows" are aligned with the line in the power spectrum and then multiplied onto the frequency domain.



(a) (b) (c)

Figure 2: (a) Domain specific Fourier filter. (b) Result of inverse Fourier transformation after Fourier filtering. (c) Binary image obtained with a threshold value and thereby isolating individual fibres as elongated objects.

By performing the inverse Fourier transformation a noise-filtered image as shown in Fig. 2 (b) is generated, and by the use of a threshold value a binary image is obtained, see Fig. 2 (c). Finally, the orientation of each individual object can be computed using the least squares method. The procedure is repeated for the remaining domains, object orientations are stored for post processing at which point the analysis is complete.

To verify the robustness of the proposed procedure a parameter study has been conducted with a focus on the influence of the filter parameters on the analysis results. Furthermore, software generated micrographs, where the orientation of each object is known, have been used to estimate the precision of the proposed method and the modified MFIA method. Finally, the computation time efficiency of the two methods has been estimated and compared.

Results

The parameter study shows that obtaining a robust analysis is highly dependent on good specimen preparation. For micrographs of good polishing quality the computed nominal orientation and standard deviation are consistent within an accuracy of $\pm 0.1^{\circ}$, independent of the filter parameters. Furthermore, a set of input parameters which always produce reliable results have been determined as default filter parameters.

The precision of the proposed method with the default parameters and the modified MFIA method has been estimated using software generated micrographs. Both methods can determine the nominal orientation to an absolute precision of $\pm 0.1^{\circ}$, for images with nominal orientations varying from 0°-50°. The new method is however significantly better at determining the standard deviation of the object orientations, as shown in Fig. 3.

As Fig. 3 shows, the modified MFIA method is relatively incapable of determining the standard deviation of the randomly distributed object orientations. The proposed method, however, displays a uniform precision of $\pm 0.1^{\circ}$ for nominal standard deviations below 3°.

Regarding computational efficiency, the computing time for a typical analysis containing 100 domains is reduced from 4.5 minutes for the modified MFIA method to one minute with the proposed method. The above tests have been performed under the same conditions on a laptop with a 1.86 GHz Pentium M processor and 1.5 GB RAM.

Conclusions

A new image analysis procedure using 2D fast Fourier transformation has been presented. A parameter study has shown that the robustness of the presented procedure is dependent on good polishing quality.

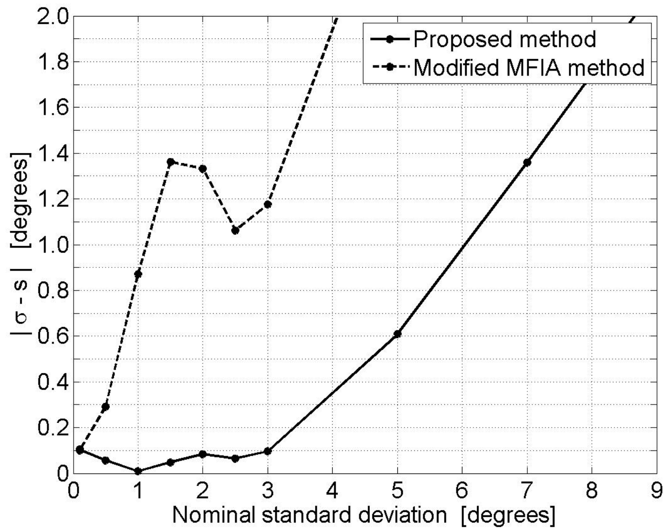


Figure 3: Precision in terms of the absolute difference between the known standard deviation σ and the computed standard deviations.

Using software generated micrographs the precision of the proposed method and the modified MFIA method has been estimated. Both methods can determine the mean orientation to an absolute precision of $\pm 0.1^\circ$. The modified MFIA methods is, however, not able to capture the fibre misalignment when it is randomly distributed. This makes the proposed method advantageous as it can estimate the standard deviation with a precision of $\pm 0.1^\circ$ for nominal standard deviations below 3°.

The time efficiency of the MFIA method has been improved significantly from about 3 hours to a few minutes, due to modifications in the MFIA algorithm. Nevertheless, the proposed method has reduced the analysis time of a typical analysis to about 1 minute making it 4-5 times faster than the modified MFIA method.

Future work will extend the documentation regarding robustness, precision and efficiency. Guidelines for specimen preparation will be established and the significance of the polishing quality further investigated.

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