

NOVEL IMAGE ANALYSIS PROCEDURE FOR MEASURING FIBRE MISALIGNMENT IN UNIDIRECTIONAL FIBRE COMPOSITES

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ABSTRACT

This paper is a brief description of a novel method named Fourier transform misalignment analysis (FTMA) designed for measuring fibre misalignment in unidirectional (UD) carbon fibre reinforced plastic (CFRP). Existing methods are briefly illustrated and evaluated. The FTMA-method is presented describing how 2D Fourier transformation is applied to compute single fibre orientations. Verification of the method robustness is briefly described and followed up by precision estimations where the proposed FTMA-method is compared against the existing multiple field image analysis (MFIA) method. To exemplify the usage of the FTMA-method it is used to analyse the fibre misalignment of two different CFRP materials. Overall, the proposed FTMA-method is found to be a robust and precise tool for estimation of fibre misalignment in unidirectional fibre composites.

1. INTRODUCTION

The compressive strength of unidirectional (UD) carbon fibre reinforced plastic (CFRP) is often less than 60% of the tensile strength [1-2kyrr], when considering commercial CFRP. In large composites structures loaded in compression or bending the compressive strength thereby often becomes the limiting design factor. With the increased usage of CFRP in industrial applications during the last decade; manufacturer's capability of producing UD CFRP with high compressive strength thereby becomes a competitive factor.

In UD CFRP the fibre misalignment is used to express the fibres deviation from being perfectly parallel aligned. Fibre misalignment is a production related imperfection and one of the material properties governing the compressive strength of unidirectional composites. More specific fibre misalignment is one of the properties governing the compressive failure mechanism called localised plastic microbuckling. This failure mechanism is today widely accepted as the dominant failure mode in most commercial unidirectional polymer-matrix fibre composites [1-3].

This paper concerns a newly developed method for measuring the fibre misalignment describing robustness, precision and computational efficiency. Such a method will be of value to composites manufactures wanting to evaluate their production techniques; in quality control and for engineering scientists wanting to improve compressive strength models.

2. ANALYSIS METHODS

2.1 Modelling compressive failure

Microbuckling was originally described as an elastic event [4 Rosen] where perfectly aligned fibres buckled in or out of phase as illustrated in Figure 1.

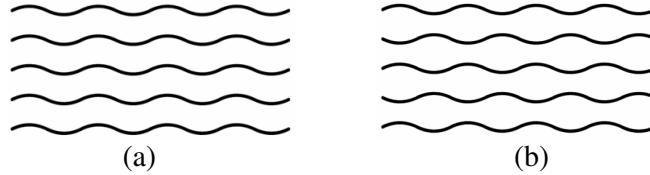


Figure 1: Elastic microbuckling of perfectly aligned fibres.(a) Elastic in-phase microbuckling, matrix undergoes shear. (b) Elastic out-of-phase microbuckling, matrix undergoes tension-compression. [4]

Such elastic failure was observed in carefully designed experiments, with perfectly aligned fibres. Later it was argued that composites manufactured with normal production techniques always have regions with misaligned fibres. The strength of these misaligned regions was modelled as microbuckling of an infinite kink band [5] as shown in Figure 2.

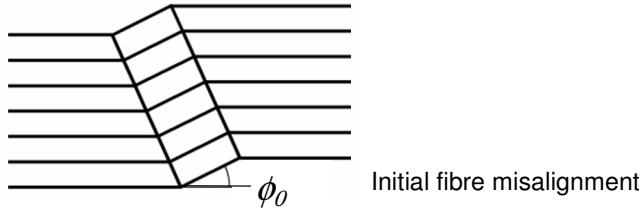


Figure 2: Infinite kink band with initial fibre misalignment [5]

Microbuckling of an infinite kink band was first modelled as a rigid-perfectly plastic event [5], but was later extended to an elastic perfectly plastic model, where the critical compressive stress [6]

$$\sigma_c = \frac{G}{1 + \phi_0/\gamma_Y}$$

is governed by the composite shear modulus G , the shear yield strain γ_Y and the initial fibre misalignment ϕ_0 .

More recent contributions to this elastic-perfectly plastic model have included fibre bending resistance and strain hardening [1-3]. Other studies have used the finite element method to model finite kink bands and through this investigate the influence of the kink band's size and shape [2,7-8]. Finally, recent research [9] has used statistics to link the statistical distribution of compressive strength to the root mean square of the fibre misalignment.

2.1 Existing methods for measuring fibre misalignment

One method for estimating the fibre misalignment is the Yurgartis [10] method which uses classical 2D optical light microscopy at 500-1000x magnification. With the Yurgartis method the material is sectioned in an angle of approximately 5° to the nominal fibre direction as shown in Figure 3.

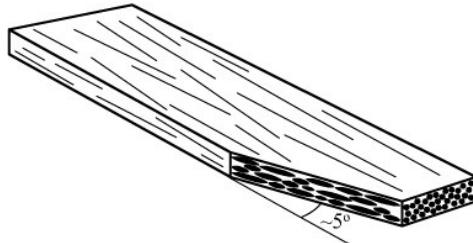


Figure 3: Sketch of unidirectional fibre composite sectioned in an angle of approximately 5° to the nominal fibre direction.

As seen in Figure 3 circular fibres will thereby appear as ellipsoids and their orientation can be derived by measuring the major and minor axis. Because of the high magnification the Yurgartis method is relatively time consuming. The measurements are sensitive to polishing artefacts which requires good polishing quality and several micrographs need to captured and analysed. Another disadvantage of the Yurgartis-method is that it is only applicable to fibres with circular cross sections. In cases where fibres are polygonal or kidney-shaped other measuring techniques are necessary.

The multiple field image analysis (MFIA) method [11-Chreighton] is a more recent developed method for measuring fibre misalignment. Also using classic 2D light microscopy digital micrographs are captured at 50-100x magnification. Here planes parallel to the nominal fibre orientation where the fibres appear as elongated white features are analysed. The micrograph is divided into several square domains, for which the average fibre orientation within the domain is found. A result plot from a MFIA-analysis is shown in Figure 4.

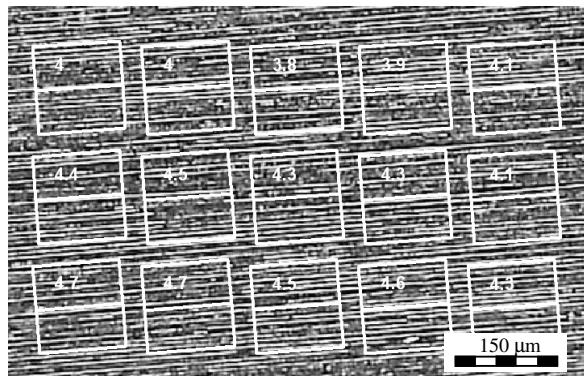


Figure 4: Result plot from an MFIA-analysis. Each domain is rotated to the computed average angle of the fibres within it.

Because of the low magnification a much lower polishing quality is sufficient reducing specimen preparation and measuring time significant. Nevertheless, a typical analysis was reported to take 3 hours [11] and the precision of the method was not fully investigated.

Non destructive methods using confocal laser scanning microscopy (CLSM) has been proposed [12-13] for the measuring of fibre misalignment. But because of the opacity of carbon fibres such methods are not applicable to CFRP.

2.2 Proposed method for measuring fibre misalignment

The proposed Fourier transform misalignment analysis (FTMA) method works on planes parallel to the nominal fibre direction. Digital 8-bit greyscale micrographs are captured at 50-100x magnification with a classical 2D optical light microscopy. The micrograph is then divided into square domains, which are analysed one at a time.

Using 2D Fourier transformation the micrograph domain is decomposed into the frequency domain. For visual interpretation of the frequency domain the intensities are logarithmically scaled; followed up by centring of the largest intensities. These steps are shown in Figure 5.

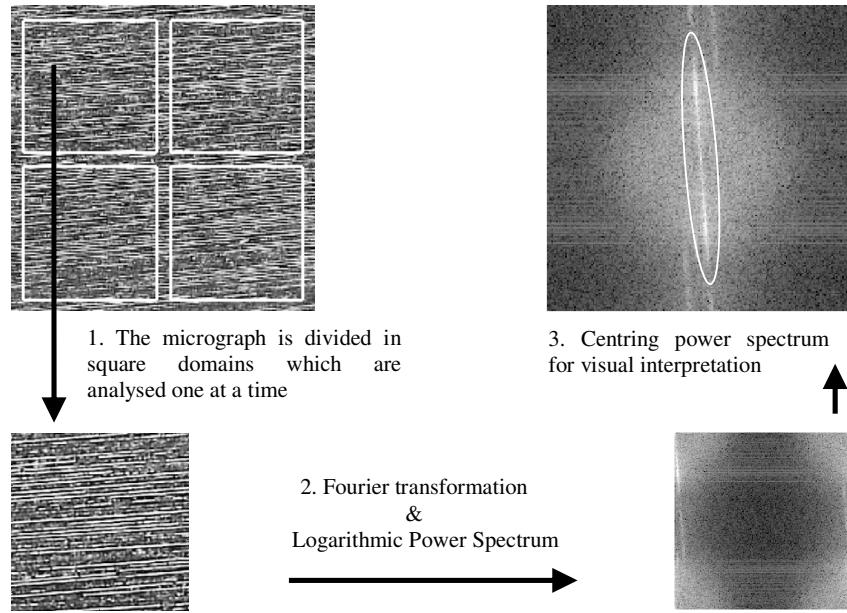


Figure 5: The three steps used to obtain a centred power spectrum for visual interpretation of the Fourier transformation [14].

In the centred power spectrum the unidirectional fibres result in a white line (encircled), which is perpendicular to the average orientation of the fibres within the domain. The average fibre orientation is determined and used to build a domain specific filter as shown in Figure 6.

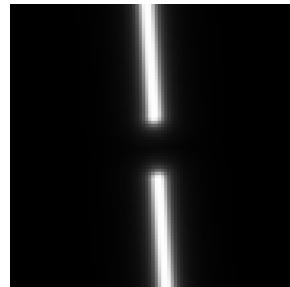


Figure 6: Domain specific Fourier filter used to enhance fibre pattern.

The purpose of the Fourier filter is to remove noise so that the individual fibres can be isolated and labelled for subsequent orientation analysis. The filter is multiplied onto the centred frequency domain element-by-element. The white regions correspond to a filter value of one, black as zero and greyscales are scalars in between. The grey transition regions are build using the Butterworth equation [15].

$$I^2(\omega) = \frac{I_0^2}{1 + \left(\frac{d}{d_c}\right)^{2n}}$$

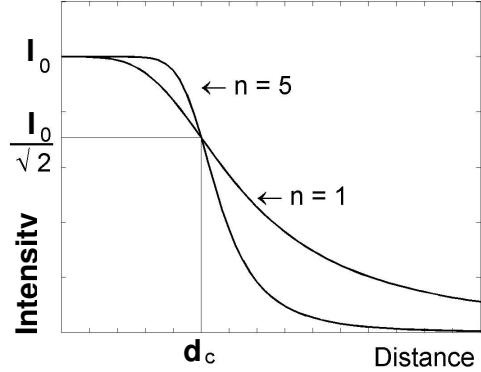


Figure 7: The Butterworth equation and a sketch illustrating its variables.

In the Butterworth equation the intensity $I(d)$ at a given distance d is a function of the intensity at zero-distance I_0 ; the Butterworth-order n and the cut-off distance d_c as illustrated in Figure 7. Together with the filter radius, which is the distance between the white regions, the Butterworth-order and the cut-off distance make up the filter parameters. The influence of the filter parameters will be described in the following robustness considerations.

The filtering isolates the fibre pattern as shown in Figure 8b.

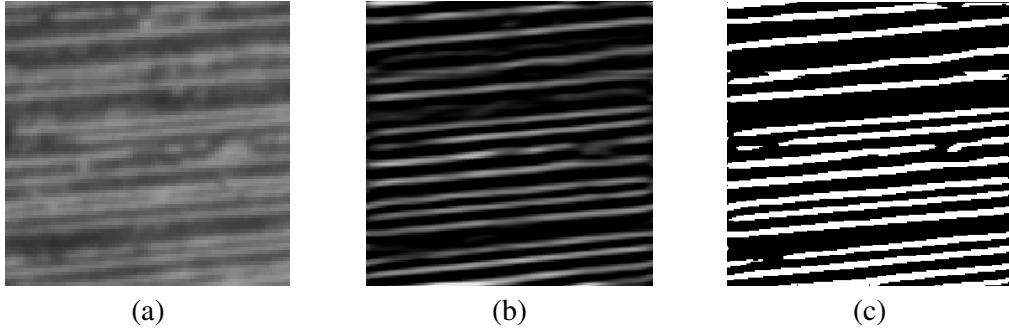


Figure 8: Steps in isolating the fibres as individual objects. (a) domain from a digital micrograph, (b) fibre pattern isolated by filtering with 2D Fourier transformation, (c) filtered image evaluated against threshold value so fibres appear as isolated white objects.

The filtered image is subsequently thresholded in order to obtain a binary image as shown in Figure 8c, where the orientation of each individual object is determined using the well-known least squares method. As a control plot the computed regression lines can be plotted on top of the original micrograph as shown in Figure 9.

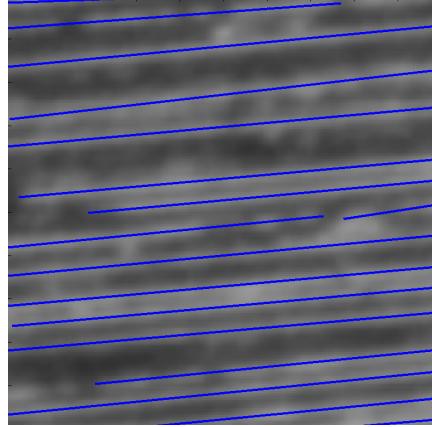


Figure 9: Optional result plot for visual control of computed regression lines.

When the orientation of each object in Figure 8c is computed they are stored for post analysis and the procedure moves on to the next domain.

In order for the method to be reliable it needs to be robust. With the FTMA-method the robustness is thought of as the influence of the filter parameters on the computed results. This has been investigated with a thorough parameter study where the three filter parameters have independently varied and the results compared against each other.

The precision of the FTMA-method has been estimated using software generated micrographs. With such micrograph replicas the orientation of each fibre is known and thereby the overall mean orientation and standard deviation. These can be compared to the results computed by the FTMA-method. For comparison precision estimation has also been applied to the MFIA-method.

3. RESULTS

3.1 Robustness and precision estimations

The FTMA-method is found to produce relatively consistent results regardless of the filter parameters. The parameter study performed to support the robustness is, however, too extensive to be accounted for in this paper. The reader is therefore kindly referred to future publications on the FTMA-method. In summary, the parameter study shows that the FTMA-method computes results that are consistent within $\pm 0.2^\circ$ independent of filter parameters. The parameter study also reveals that too little contrast in the micrograph can ruin the consistency. Polishing techniques therefore need to be further developed to ensure sufficient contrast and thereby ensure analysis robustness.

The precision of the FTMA-method is estimated on several software generated micrographs with mean orientations varying from 0° to 60° . The precision is determined as the absolute difference between the known and computed mean orientation. For comparison the precision is estimated for both the proposed FTMA-method and the existing MFIA-method. The results are shown in Figure 10.

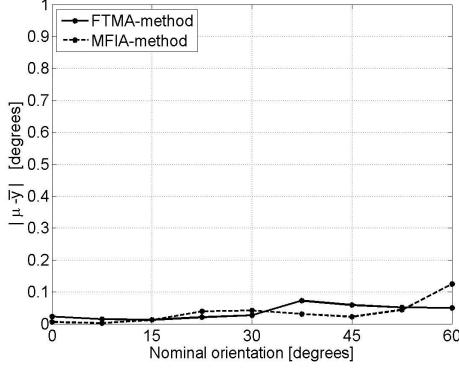


Figure 10: Precision in terms of the absolute difference between the known mean orientations and the computed mean orientations.

It is seen that both methods have a satisfying precision of $\pm 0.1^\circ$ for micrographs with mean orientations below 60° with a horizontal line representing 0° .

Another and just as important measure of the precision is the methods ability to estimates the standard deviation of the single fibre orientations. Similar software generated micrographs with varying standard deviation has been used. The precision is again defined as the absolute difference between the known and estimated standard deviation. The results are shown in Figure 11.

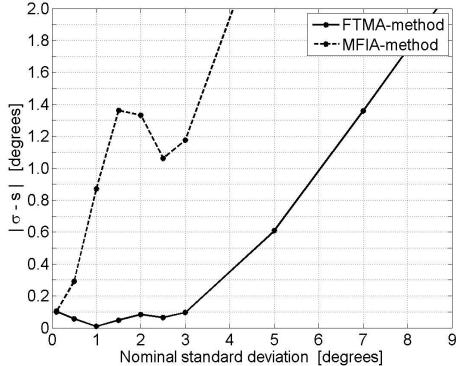


Figure 11: Precision in terms of the absolute difference between the known standard deviation and the computed standard deviation.

Regarding the methods' ability to estimate the standard the results are relatively different. It is clear that the MFIA-method is not capable of determining the standard deviation with satisfying precision. The proposed FTMA-method on the other hand can determine the standard deviation with a precision of $\pm 0.1^\circ$ for nominal standard deviations below 3° , which is considered to be satisfying.

3.2 Computational efficiency and method comparison

The computational efficiency of the proposed FTMA-method has been estimated by performing several analysis of different sizes. Similar has been done with a modified version of the existing MFIA-method. The modified MFIA-method was developed by the first author during a stay at Cambridge University, where the MFIA-method was originally developed. The difference between the original and the modified version of the MFIA-method is reduced computational time with price being increased memory

usage. A typical analysis size of 100 domains is used as basis for comparison of the FTMA-method and the modified MFIA-method. The results are summarised in Table 1.

1.86 GHz Pentium M processor 1.5 GB RAM 200 by 200 pixels domains		FTMA	Modified MFIA
Precision	Nominal orientation	$\pm 0.1^\circ$	$\pm 0.1^\circ$
	Standard deviation	$\pm 0.1^\circ$	-
Time efficiency (100 domains)		1 minute	4.5 minutes
Memory usage (100 domains)		8 MB	> 200 MB

Table 1: Comparison of precision and computational efficiency between the proposed FTMA-method and the modified MFIA-method.

3.3 Misalignment analysis of two different UD CFRPs

To exemplify the usage of the FTMA-method it is used to estimate the fibre misalignment of two different CFRP materials. The difference between the two materials lies in the manufacturing process. One of the micrographs represents CFRP manufactured by traditional open bath pultrusion and the other is manufactured by closed injection pultrusion.

The objective of this specific comparison is to investigate whether one of the manufacturing techniques is better suited for aligning the fibres than the other. The results of the FTMAs are shown in Figure 12.

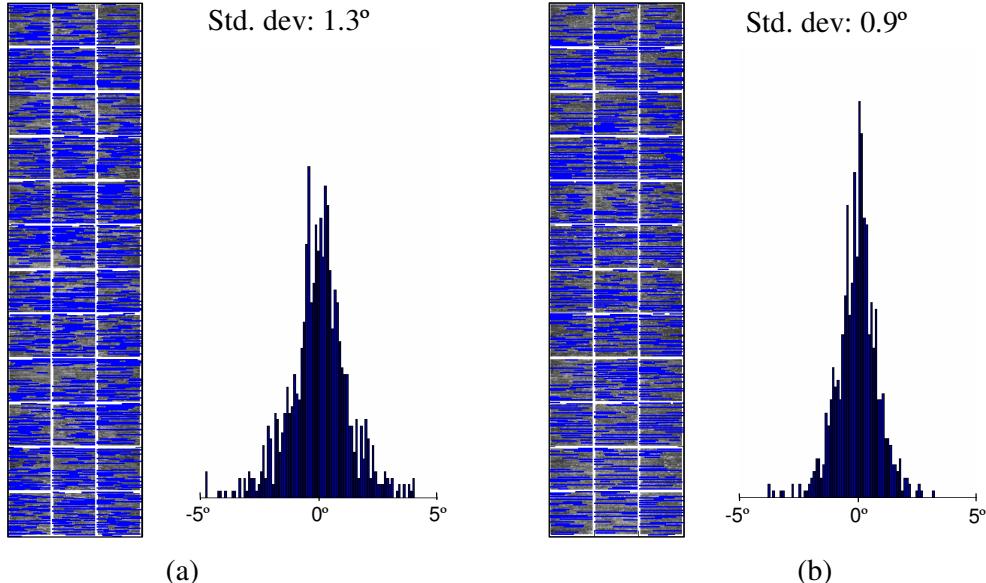


Figure 12: FTMA of UD CFRP manufactured by (a) open bath pultrusion, (b) closed injection pultrusion. The histograms represent the distribution of single fibre orientations, with the mean orientation equal to 0°. The white lines in the micrographs represent the domain borders.

The misalignment analysis in Figure 12 indicates a significant difference in the level of fibre misalignment between the two variations of pultrusion manufacturing processes. In order to reach solid conclusion regarding this difference the materials need to be more thoroughly investigated. Nevertheless, it is valuable knowledge to manufacturers aiming at producing UD CFRP material with high compression strength. Furthermore, it is possible to apply FTMA in everyday quality control, where it can be used to estimate compression strength as a substitute to actual compression tests, which is more expensive.

4. CONCLUSIONS

A new method called FTMA for measuring fibre misalignment in UD CFRP has been briefly described. The procedure used to test the robustness of the method has been described along with the procedure used to estimate the precision of the method. The results of both the robustness test and precision estimations have been summarised. For comparison the precision has also been estimated for the existing MFIA-method. Here it was found that both methods are capable of estimating the nominal fibre direction with a precision of $\pm 0.1^\circ$. Regarding the methods ability to measure the standard deviation of single fibre orientations the proposed FTMA-method is capable of doing so with a precision of $\pm 0.1^\circ$ for nominal standard deviations below 3° . The MFIA-method is, however, not capable of measuring the standard deviation of single fibre orientations at all.

The computational efficiency of the proposed FTMA-method has also been compared to a modified version of the existing MFIA-method. Here it was found that the FTMA-method could complete a typical analysis in less than a minute, where the modified MFIA-method used 4.5 minutes. Both results are a significant improvement from the three original hours, the FTMA-method, however, remains 4-5 times faster than the MFIA-method.

Finally, the proposed FTMA-method was used in an example where two manufacturing techniques were compared against each other. The purpose of the comparison was to investigate whether one technique has an advantage over the other regarding their ability to align fibres and thereby manufacturing UD CFRP with high compressive strength. From analysis of two micrographs each representing a manufacturing technique a significant difference in fibre misalignment was indicated. However, more analyses need to be carried out in order to make a solid conclusion regarding the observed difference.

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