Etude comparative des méthodes de quantification des orientations de fibres dans les renforts des composites

Comparative Study of Methods for the Quantification of Fiber Orientations of Composite Reinforcements

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Résumé

Les propriétés macroscopiques des composites dépendent fortement des caractéristiques et de la distribution des fibres. Ainsi connaitre la distribution des orientations des fibres est nécessaire pour prédire les performances mécaniques de la pièce finale. Différentes techniques de traitement d'image ont été développées pour la quantification des orientations des fibres à partir des images de la microscopie optique, de la microtomographie aux rayons X. Cependant ces méthodes de quantification ne sont pas appropriées pour tous les types d'architecture des renforts fibreux : fibres coupées droites ou mèches courbées dans les SMCs, fibres continues dans les stratifiés. Cette étude identifie les paramètres clefs des différentes méthodes qui peuvent contrôler des sources d'erreur possible dans la quantification. La méthode du tenseur de structure, la méthode basée sur la transformée de Fourier rapide, la méthode stéréologique et la méthode de la projection à travers une fente sont comparées. Les avantages et inconvénients des méthodes sont discutés vis-à-vis de leur facilité d'utilisation, leur application aux structures 2D ou 3D, la sensibilité au bruit présent dans l'image et d'autres critères. Les recommandations sont données pour le choix de la méthode en fonction du type du renfort fibreux et la qualité d'image.

Abstract

Macroscopic properties of composites are highly dependent on the properties and distribution of fibers. Thus, knowing the distribution of fiber orientations is necessary to predict the mechanical performance of the final part. Various image processing techniques have been developed for the quantification of fiber orientations from optical microscopy, X-ray tomography images. However, these quantification methods are not appropriate for all types of fiber reinforcement architecture: chopped straight fibers or curved tows in the SMCs, continuous fibers in laminates. This study identifies the guiding parameters for different methods that can control possible sources of error in the quantification. The structure tensor method, Fast Fourier Transform based method, stereological method, and single-slit projection method are analyzed and compared. The advantages and limitations of the methods are discussed with respect to the ease of use, their application to 2D or 3D structures, sensitivity to the image noise and other criteria. Recommendations are given for the choice of method according to the type of fibrous reinforcement and image quality.

Mots Clés : renforts des composites, orientation de fibres, distribution, analyse d'image, désalignement
Keywords: composite reinforcement, fiber orientation, distribution, image processing, misalignment

1. Introduction

Mechanical, thermal and electric properties of composite materials at the scale of the part strongly depend on the orientation and distribution of fibers. Hence the knowledge of local fiber orientations is important for the derivation of descriptors of the microstructure that are necessary for the prediction of the macroscopic behavior of a composite.

Numerous techniques of observation of the microstructure, such as optical microscopy, SEM, X-ray microtomography etc., are now available to characterize 2D and 3D images of real materials without being restricted only to their idealized virtual prototypes. To this purpose, after the image acquisition stage different image processing methods of extraction of quantities of interest (fiber orientations in this case) have started to play a major role. Each method of orientation quantification has its advantages and drawbacks with respect to its application to different fibrous microstructures. In the case of short fiber reinforced polymers, the fiber orientation results from the flow of the suspension; in the case of the continuous fiber reinforcements, the orientation is defined by the deformability of the textile. Thus the distribution of local fiber orientations has its peculiarities in each class of composite, and the method employed to extract the local orientations should be capable to address these peculiarities.

The objective of this study is to compare the capabilities of different methods in terms of: i) ease of use (preparation of images); ii) computation effort; iii) applicability to fibrous structures with different morphologies:

- chopped straight fibers in SMCs (Sheet Molding Compounds),
- continuous fibers in laminates,
- assembled in bundles fibers in SMCs that can be curved (Tab.1),
- undulated fibers within the textiles.

The tensorial representation of fiber orientations as a geometric descriptor of the representative volume microstructure was proposed in [1]. This orientation tensor together with the identified principal directions of anisotropy of a structure can be the quantities for the comparison of different orientation quantification methods. However, for the fibrous structures that are more complex than a population of isolated straight fibers, for which the orientation tensor was initially proposed as a descriptor, the concept of orientation tensor becomes inappropriate. An example of such complex structures can be illustrated in SMCs with fibers assembled in bundles (tows), but with simultaneous presence of a second population of fibers that got detached from the bundles and became isolated (Tab.1, Fig. 3a). Moreover, these 25 mm long fiber bundles are not necessarily straight; they can be curved as a consequence of complex rheological mechanisms. In such a case orientation distribution functions are more appropriate quantities than orientation tensor.

In this study the influence of different parameters on the quantification of fiber orientations is analyzed for the following methods: structure tensor approach (see e.g. [2-4]), Fast Fourier Transform based method (FFT) (see e.g. [5-9]), single-slit projection method [10-11], and stereological approach (also known as the method of ellipses) [12-16]. The impact of the morphological features of the structure itself is analyzed as well.

2. Methods

2.1 Stereological method

The stereological method of quantifying 3D fiber orientations from 2D images of cross-cuts generally made perpendicular to the plane of the mean fiber orientation is also known as a *method of ellipses* due to its principle [12-16]. Depending on the fiber orientation, its circular cross-section projects on the cutting plane either in the form of a circle, or in the form of an ellipse that can have different major to minor axis ratio. The fiber orientation angle is then determined from this ratio following the stereological rules. Hence this method requires highly resolved images, namely with the pixel size of at least $r/5$ as was deduced, where r is the fiber radius. Besides, if the images are acquired with the optical or scanning electron microscopy (as opposed to the X-ray microtomography), a high quality of sample polishing has to be ensured since the method is sensitive to the irregularity of fiber cross-sections.

The drawback of this method is that the location of the cutting plane should be carefully chosen preliminarily in order to avoid a possible fiber orientation ambiguity when differently oriented fibers project into equal ellipses. Indeed, such situation occurs if two fibers are symmetric with respect to the cutting plane. Thus to overcome this, several choices of cutting plane were proposed in the literature [13], [15]. For instance, if all fibers are nearly orthogonal to one “normal” direction, a section that forms an angle of about 30° with this normal direction can be used as a cutting plane [13]. Another disadvantage of the method of ellipses is its low accuracy in the case if fibers are nearly perpendicular to the cutting plane. Once a proper cutting plane is selected and the image is acquired, further steps of the method are quite straightforward. Due to the abovementioned numerous limitations and distinct character of images needed for the method compared to other methods, the quantification of fiber orientations by this method is not reevaluated in this study.

2.2 FFT-based method

The principle of the Fast Fourier Transform method (FFT) applied to the quantification of fiber orientations [5-9] is to use the information of the optical diffraction pattern of the image that has a certain fibers distribution. The spatial domain of the image matrix with gray levels $f(x,y)$ should be transformed by the 2D FFT to the frequency domain $F(u,v)$. Then its power spectrum is computed as

$$P(u,v) = abs\big(F(u,v)\big) = [R^2(u,v) + I^2(u,v)]^{1/2} \qquad \text{(Eq. 1)}$$

where $I(u,v)$ and $R(u,v)$ are the imaginary and real parts of the Fourier coefficients respectively. Since the power spectrum range is often very large compared to the grayscale range of pixel intensities, the power spectrum is scaled then by the logarithmic transformation: $P_{ln}(u,v) = ln(1+P(u,v))$. Due to the periodic character of the Fourier transformation the highest intensities of the power spectrum are located in the corners of the created 2D domain (Fig. 1). Thus for further determination of the mean fiber orientation within the domain the power spectrum should be centered by shifting the 4-quarters as depicted in Fig.1. The obtained domain will contain a pattern with a dominating oriented white area in the center, whose direction will indicate the mean fiber orientation in the domain rotated by 90°.

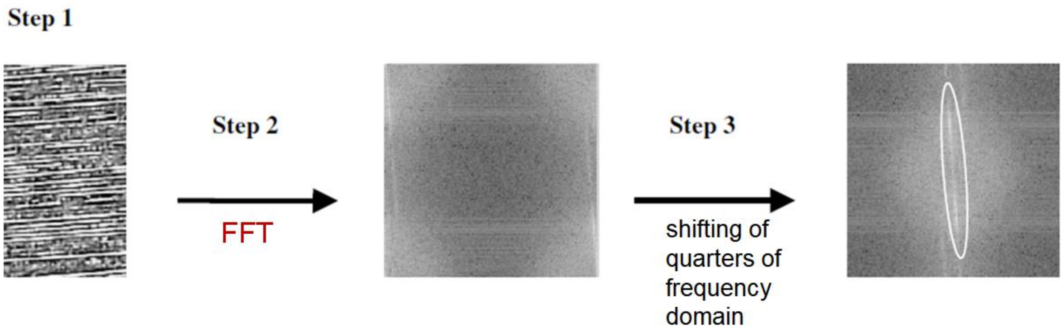
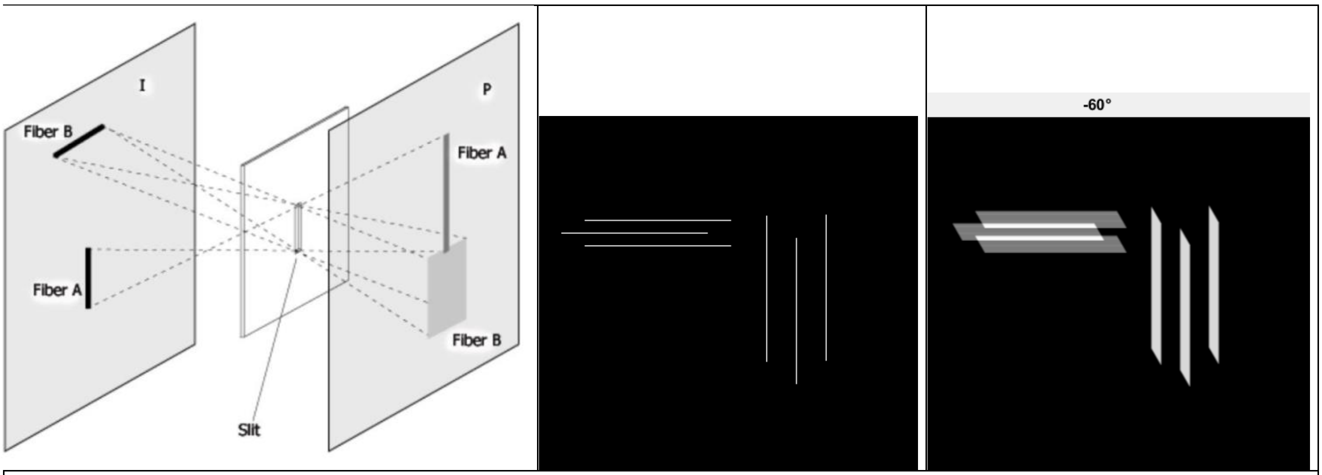


Fig. 1. FFT-based method steps to obtain a centered logarithmic power spectrum for the initial image [7].

The critical stages of the FFT-based algorithm are the thresholding of the finally obtained centered power spectrum to obtain the principal anisotropy directions, as well as the noise reduction of the latter. Since each of these stages itself can be realized via a variety of families of image processing thresholding algorithms and smoothing filters, the accuracy of the orientation quantification by the FFT-based method strongly depends on the accuracy of the mentioned algorithms in their combination. Furthermore, it is recommended to use high contrast images to be analyzed by this method.

2.3 Single-slit projection method

The quantification of the fiber orientations in the image by the single-slit projection method [10-11] is based on the principles of geometrical optics. It is known that while being projected through a narrow slit the features of the image that are aligned with the slit are accentuated in its projection, while the others obtain blur shapes with low intensities. Thus if the slit orientation is prescribed and fixed, the fibers that are aligned with the slit can be easily captured because they cast a high intensity narrow shadow on the screen, while the fibers whose orientation differs a lot from the slit, on the contrary, cast a wide low intensity shadow (projection) (Fig. 2a). The algorithm consists in rotating the slit with a certain angle discretization step in order to threshold the image projections obtained at each step. In this way only the fibers co-oriented with the slit at its fixed rotation step will be present on the thresholded projections, and their number and length can be quantified to build the orientation distribution function.



a) *b)* *c)*

Fig. 2. a) Scheme of the projection of image features through a slit [10]; b) initial validation image; c)projection of the validation image through a slit oriented at -60°.

Since little information was given in [10-11] about the choice of method key parameters, it is detailed in the present study. It should be noted that the projections are casted through a slit that has an infinitesimal width and whose length should be correlated in the image pixel space to the following quantities: image dimensions, fibers diameter, and minimal distance between fibers. The bigger the slit length the more stretched and blur projections it gives. This can be risky because the superposition of low-intensity fiber projections due to the small distance between them might form local high-intensity false zones that can be erroneously interpreted after thresholding as fibers. This situation is illustrated in Fig. 2b,c. Therefore, the slit length should be chosen small enough compared to the image dimensions and distance between fibers, but bigger than the fiber diameter. Other important parameters that govern the single-slit projection are the binarization threshold applied to projections, and a discretization angle step of the slit rotation. The threshold should be selected as a globally applied to all projections value, rather than a locally adjusted for each projection magnitude. If the analysis of the fiber length distribution is also of interest the threshold value also considerably affects this evaluation.

The application of the single-slit method in its current formulation to the fully three-dimensional random fibrous structures is not possible. It can only be applied to the 3D architectures of fibers that are distributed over 2D stacks of two perpendicular planes. In this case the algorithm is applied to each 2D image of the stacks in order to obtain a fiber distribution per stack, combined afterwards to deduce the components of the second-order orientation tensor that are dependent on two spatial angles, as defined in [1].

2.4 Structure tensor method

The structure tensor method [2-4], that is the most widely used *derivative-based* or *gradients* method, allows to derive the local orientation and anisotropic properties of the depicted in a gray-scale image microstructure. It is based on the idea that the fiber direction is orthogonal to the fiber surface normal, i.e. to the gray-value gradient direction. For a 2D image the structure tensor is defined for each pixel as a 2 x 2 symmetric positive matrix $\boldsymbol{J}$:

$$\boldsymbol{J} = \begin{bmatrix} \langle f_x, f_x \rangle_w & \langle f_x, f_y \rangle_w \\ \langle f_x, f_y \rangle_w & \langle f_y, f_y \rangle_w \end{bmatrix} \quad \text{(Eq. 2)}$$

where f_x and f_y are the spatial partial derivatives of the image $f(x,y)$ along the principal directions x and y, and where the weighted inner product between two arbitrary functions g and h is defined as:

$$\langle g, h \rangle_w = \iint_{R^2} w(x,y) g(x,y) h(x,y) dxdy \quad \text{(Eq. 3)}$$

where $w(x,y)$ is a Gaussian weighting function with a specified size σ that defines the local neighborhood. The local predominant orientation θ can be determined from the calculated structure tensor as the direction of the eigenvector corresponding to the smallest eigenvalue λ_{min} of the tensor:

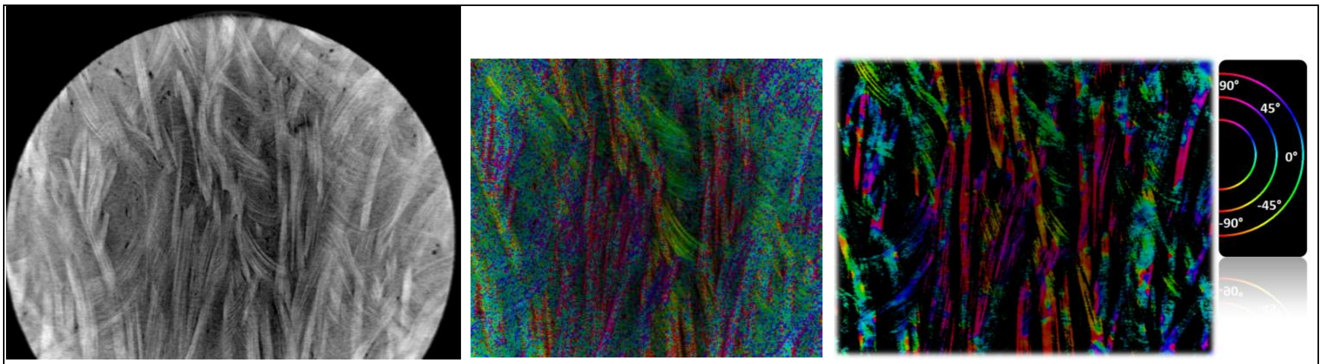
$$\theta = \frac{1}{2} arctan\left(2 \frac{\langle f_x, f_y \rangle_w}{\langle f_y, f_y \rangle_w - \langle f_x, f_x \rangle_w}\right) \quad \text{(Eq. 4)}$$

The evaluation of such properties as *anisotropic index* (also called *coherency*) and *gradient energy* allows to pre-segment the locally isotropic (homogeneous) zones of the image that may represent pores, resin, or non-fibrous inclusions in a composite. The gradient energy parameter E, which is the trace of the tensor matrix: $E = \mathrm{Tr}\,(\boldsymbol{J}) = < f_x, f_x >_w + < f_y, f_y >_w$, is close to zero when the zone is homogeneous (constant). The anisotropic index AI is also equal to zero for homogeneous (isotropic) zones, and it tends to 1 for highly oriented zones since it is defined as:

$$AI = \frac{\lambda_{max} - \lambda_{min}}{\lambda_{max} + \lambda_{min}} \quad \text{(Eq. 5)}$$

where λ_{max} and λ_{min} are the largest and the smallest eigenvalues of $\boldsymbol{J}$, respectively, following tensor diagonalization of $\boldsymbol{J}$.

The influence of the selected size for the Gaussian window on the evaluation of orientation of a population of fiber bundles (tows) of an SMC is illustrated in Fig. 3. Since the thickness of an elementary structural element – fiber – is around 6 pixels for this image, the Gaussian window size $\sigma = 1$ is too small, as can be seen in Fig. 3b, because it captures additional eventual inhomogeneities (noise) within the tows/fibers. However, when the window size is increased up to the characteristic fiber diameter (Fig. 3c) the fiber tows orientations are quantified quite accurately. It should also be noted that the image in Fig. 3c shows more accurate results because the orientation analysis has taken into account only the zones with the thresholded energy and anisotropic index values that allowed to eliminate the uniform zones of porosities and pure resin.



a) *b)* *c)*

Fig. 3. a) µCT image of an SMC sample; b) orientations of fibers in the center of the sample identified by the structure tensor method with the Gaussian window size σ = 1; c) and with the Gaussian window size σ = 6.

The extension of the structure tensor approach to three-dimensional images is straightforward. The structure tensor has the form of a 3 x 3 symmetric positive matrix in this case. In general the method's complexity can be estimated as $O(n)$, where n is the number of image pixels/voxels, independently of the prescribed neighborhood dimensions σ.

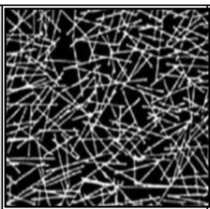
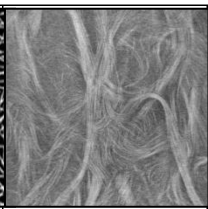
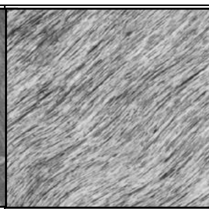
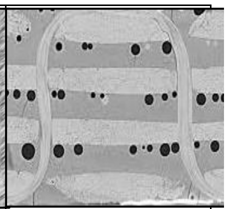
3. Discussion and conclusions

For 2D quantification of fiber orientations distribution all studied methods, except the stereological one, use 2D images in the mean plane of fiber orientations, and do not demand such high image resolution as the stereological method does. The single-slit projection method is quite sensitive to the image noise and artifacts, and thus to the image resolution as well. Furthermore, in stereological method the choice of the transverse cross-section plane for the image is not a trivial task, as explained in the previous section. These key points define in general the ease of use of a method in terms of the preparation of images.

It is important to evaluate the orientation quantification methods in terms of their applicability to fibrous reinforcements of different morphologies because the question of fiber orientations may be raised in different domains in order to:

- characterize the microstructure to deduce the macroscopic properties in the SMCs, platelet molding compounds, fiber mats, textiles;
- quantify the defects in a form of fiber waviness and misalignment in the laminates;

The classification of fibrous architectures according to their types of fiber orientation is given in Tab. 1. The listed fibrous morphologies, excluding the laminates by definition of their in-plane oriented structure, may require the orientations quantification not only on 2D images, but on the full 3D images of the structure. The most advantageous in this case is to use the structure tensor method because its 3D implementation is straightforward. The stereological method is only recommended for 3D architectures with straight fibers, which do not change their direction, or with fibers that can change their direction but not a lot, like 3D orthogonal interlocks, for example. In the latter case, obviously, more than one 2D cross-cut images should be used for the quantification. The single-slit method is not applicable to a general 3D fibrous architecture, as has been explained previously, only to the mentioned specific cases.

Method	**References**	 **Chopped fibers in SMCs**	 **Curved fiber bundles in SMCs**	 **Continuous fibers in laminates**	 **Undulated fibers in textiles**
Stereological method	[Yurgartis, 1987], [Mlekusch, 1999], [Eberhardt and Clarke, 2001], [Blanc et al, 2006], [Bernasconi et al, 2012]	+	–	–	–
FFT-based method	[Lovrich and Tucker, 1985], [Pourdeyhimi et al, 1997], [Kratmann et al, 2009], [Sander and Barocas, 2009], [Savva et al, 2015]	+	+ –	+	+
Single-slit projection method	[Hernandez et al, 2003], [Goris and Osswald, 2015]	+	+ –	+ –	+ –
Structure tensor method	[Rezakhaniha et al, 2012], [Straumit et al, 2015], [Püspöki et al, 2016]	+	+	+	+

Tab. 1. Classification of applicability of orientations quantification methods with respect to different fibrous reinforcements: "+" – can be efficiently applied; "+ –" – may be applied with some difficulties; "–" – of limited application.

Another criterion of the universality of application of a method to different fibrous structures is its capacity to correctly capture the fibers curvature that can be present in SMC parts, in textiles, to a lesser extent – in laminates (defective fiber waviness). Owing to its concept the stereological method is not capable of detecting a continuous fiber curvature, otherwise it would have implied to analyze fibers cross-cuts in each discretized fiber angle change step. The application of the FFT-based method to the curved fibers is direct, it can capture them well. Though it is rather sensitive to the presence of noise in the image. As regards the single-slit method, the projected images obtained by its algorithm represent the tangents to the curved fibers at each increment of the slit angle. Consequently, this generates a quite accurate continuous orientation distribution because it is a length-weighted distribution. The only difficulty is that the curved structures in fibrous reinforcements represent in the majority of cases either the fiber bundles mixed with isolated detached fibers that can be considered as a double-scale material (e.g. as in Fig. 3a), or densely arranged undulated fibers. Such structures require a protracted adjustment of key parameters of the single-slit method, explained earlier in the paper, in order to obtain an accurate estimation. In such cases the structure tensor method gives much better results, its concept contains less factors detailed before that can generate errors.

It can be concluded that depending on the type of composites and respectively fiber reinforcements architecture different orientation quantification methods can be advantageous, and their suitability of use is summarized in Tab.1. The assessment provided in Tab.1 is based on the sum of criteria mentioned previously. The highest universality of use is identified for the structure tensor method. The most restrictive employment with respect to various fibrous architectures is shown for the stereological method. However, if a specific composite application is prescribed the choice of the fiber orientation quantification method can be guided by the accuracy of the method that depends on its critical parameters that have been identified and evaluated in this study for each method. Besides, it should be mentioned that the guideline given in this study concerns the quantification on images of real materials, and not only on idealized synthetic images or prototypes.

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