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Quality control of CFRP by means of digital image processing and statistical point pattern analysis

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Abstract

Although fiber-reinforced composite materials have often been considered as periodic materials in theoretical models, the distribution of fibers is random in real materials. This random distribution of fibers is closely related to their transverse failure behavior. This paper proposes the use of statistical functions which describe random point patterns as a quantification of the dispersion of the transverse failure properties of several carbon fibre reinforced polymers (CFRP). It is shown that the analysis of the K function is the most meaningful for this purpose.

Keywords: A. Polymer-matrix composites; B. Microstructure; C. Probabilistic methods; C. Statistics; Digital image processing

1. Introduction

At the microscopical level, the main morphological characteristics of long fibre reinforced polymers are heterogeneity and anisotropy. In spite of this, composite materials have classically been modeled by means of periodical unit cells, that is, without taking into account neither the heterogeneity nor the geometrical disorder of fibers. The periodicity hypothesis leads to simplifications which make possible the application of homogenization methods [1–3], it provides good estimations for the elastic properties [4], and it can also be employed with good results in non-linear two-scale methods [5–9]. Also, in computational mechanics, the periodicity assumption leads to lower computational costs whereas other approaches may be computationally unaffordable.

However, a simple optical microscope observation reveals that long fiber reinforced composites (i.e. carbon or glass fiber-reinforced thermoset matrices) are far from being ordered materials since the fiber is randomly distributed through the matrix, sometimes showing areas with fiber clusters and resin pockets. These heterogeneities lead to local stress values in the matrix which are higher than those obtained assuming a periodical distribution and, consequently, they are more likely to produce damage, matrix cracking, or to cause degradation phenomena [10]. For this reason, the local damage in a transverse section of the composite (that is, matrix cracking and matrix-fiber debonding) is expected to depend strongly on the random distribution of the reinforcement.

On the other hand, because of the growing importance of composite materials in mechanical and structural engineering together with the lack of knowledge about many issues related to their failure, damage and fatigue behavior, there is a demand from the industry for quality control methods. This quality control methods should provide information on the defects within the material produced during manufacturing, the tolerance to these kind of defects, the relation between the material properties and its micro-scale structure. Traditionally, volume fraction is

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used as a measure of the quality of a laminate and ultrasound devices are normally used to complement this information by detecting voids and bubbles within the matrix.

Some researchers have proposed sophisticated and highly technological procedures such as thermal imaging techniques [11,12], optical coherence tomography [13], near-infrared spectroscopy [14,15] or X-ray tomography [16] for the inspection of fiber-reinforced composites. Although these techniques are extremely precise, they usually require high technology machinery, sophisticated interpretation techniques and highly specified and qualified personnel. This makes them unusable for most industries.

The widespread use of computers in industry prompted some pioneering work, like that by Berryman [17], in data acquisition using digital image processing for heterogeneous materials. The quantitative techniques for digital image processing of composites are widely employed in metal matrix composites (MMCs) [18,19] and some research has applied Fourier transformation to detect the orientation of reinforcement in reinforced concrete [20].

In fiber-reinforced polymers, much of the work devoted to the geometrical characterization of materials via digital image processing has been focused on braided composites [21]. Summerscales and co-workers computed total perimeter and total area of inter-tow pore spaces in woven laminates produced by RTM [22,23] and applied Voronoi tessellation and fractal dimensions to quantify the microstructure of woven composites [24].

The full characterization of glass and carbon fiber reinforced composites has also been addressed by means of optical microscopy [25] and digital image processing of micrographies has been employed by Joffe and Mattsson [26].

This work is part of a line of research which tries to bridge stress and strain fields at the macroscale with damage initiation and other microstructural phenomena by considering the random distribution of the fibers within the composite. This approach provides probability distribution functions for the stress and strain components, and is therefore useful for structural reliability purposes. The methodology presented here starts from micrographies and, using image processing techniques together with spatial statistics tools, measures the homogeneity of the distribution of the fiber within the composite. Although the distribution of the fiber within the material is random, it is homogeneous – as will be shown in the next section the *statistical homogeneity* can be mathematically defined – if the fiber is correctly spread through out the material and, in this way, regions containing matrix pockets are avoided. This homogeneity can be seen as a measure of the quality of the fiber distribution since, as this paper will show, homogeneity in the material leads to lower mechanical property dispersion.

2. Spatial point patterns

This section summarizes the basics on spatial point patterns focusing on those aspects which are specially relevant for the statistical analysis of the microstructural characteristics of heterogeneous materials. Details on these topics can be found elsewhere [27–29].

A spatial pattern is a set of points which are located irregularly in a domain. The points' position is governed by some stochastic mechanism. Consider an image of area A of a fiber-reinforced composite material, with the number (N) and position ($\mathbf{x}$) of the center of the fibers being a random variable. Then, the set of the position of the centers is a spatial point pattern.

The first-order properties of a spatial point pattern can be described by the intensity function, $\lambda(\mathbf{x})$:

$$\lambda(\mathbf{x}) = \lim_{|dx| \to 0} \left\{ \frac{E[N(\mathrm{d}x)]}{|\mathrm{d}x|} \right\} \tag{1}$$

where $E[\cdot]$ is the mathematical expectance operator. The second-order intensity function, $\lambda_2(\mathbf{x}, \mathbf{y})$, can be defined as:

$$\lambda_2(\mathbf{x}, \mathbf{y}) = \lim_{|dx|,|dy| \to 0} \left\{ \frac{E[N(\mathrm{d}x)N(\mathrm{d}y)]}{|\mathrm{d}x||\mathrm{d}y|} \right\} \tag{2}$$

which corresponds to the intensity function at $\mathbf{x}$ conditional on knowing that there is a fiber located at $\mathbf{y}$. The scaled function:

$$g(\mathbf{x}, \mathbf{y}) = \lambda(\mathbf{x}, \mathbf{y})/\lambda^2 \tag{3}$$

is called the radial distribution function.

A usual assumption for the spatial point patterns found in heterogeneous materials is that they are second-order stationary. This assumption implies that their statistical properties are invariant under translation, they have a constant mean, $\lambda((x)) = \lambda$, and second-order properties can be expressed only as a function of the vector $\mathbf{r} = \mathbf{x} - \mathbf{y}$. Moreover, if a spatial point pattern can be considered isotropic, second order properties only depend on the modulus of vector $\mathbf{r}$, so we can write $\lambda_2(\mathbf{x},\mathbf{y}) = \lambda_2(r)$, $g(\mathbf{r}) = g(r)$. The point patterns given by the positions of fiber centres in fiber-reinforced composite materials can be considered isotropic second-order stationary and, consequently, the second order properties analyzed in this work only depend on r.

The usual probabilistic function which is assumed to describe the position of inclusions in a material is the Poisson point field [28,29]. This model describes complete spatial randomness (CSR) in the distribution of fibers. That means that the probability of finding N fibers in a subdomain of area A is the same for any chosen subdomain. Consequently, this model assumes that clusters of inclusions (fibers) do not take place.

The probability of finding k fibers in a window W of area $A(W)$ is given by:

$$P[N = k] = \frac{(\lambda \cdot A(W))^k}{k!} \cdot \mathrm{e}^{-\lambda \cdot A(W)} k = 0, 1, \ldots \tag{4}$$

where λ is the fiber density, that is, the number of fibers per unit area.

Nevertheless, the Poisson distribution is physically unattainable due to finite dimension of the inclusions. For this