International Journal of Engineering Science 122 (2018) 14–29

Contents lists available at ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

Evaluation of the probability density of inhomogeneous fiber orientations by computed tomography and its application to the calculation of the effective properties of a fiber-reinforced composite

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ARTICLE INFO

Article history:
Received 5 October 2017
Revised 18 October 2017
Accepted 22 October 2017

Keywords:
Computed tomography
Orientation distribution
Effective properties
Fiber-reinforced composite

ABSTRACT

This paper focuses on the experimental evaluation of one of the key microstructural parameters of a short-fiber reinforced composite – the orientation distribution of fibers. It is shown that computed tomography (CT) produces results suitable for reconstruction of the orientation distribution function. This function is used for calculation of the effective elastic properties of polymer-fiber reinforced concrete. Explicit formulas are derived for overall elastic moduli accounting for orientation distribution in the frameworks of the non-interaction approximation, the Mori–Tanaka–Benveniste scheme, and the Maxwell scheme. The approach illustrated can be applied to any kind of composite material.

1. Introduction

1.1. Contribution of fiber distribution and orientation characteristics to composite performance

Although the performance of components made from composite materials, and in particular from concrete, is still commonly simulated using macroscale models that treat these materials as homogeneous media, recent research has made it clear that in order to accurately simulate the response of concrete, models which adequately account for concrete heterogeneity will be required (Cusatis, Pelessone, & Mencarelli, 2011). This is because even at service loads, concrete cracking patterns are highly dependent on material heterogeneity (Cusatis & Nakamura, 2011). Previous research has demonstrated that both spatial arrangement and fiber orientations have a great impact on the strength of fiber-reinforced concrete members (Barnett et al., 2010; Ferrara & Meda, 2006; Pujadas, Blanco, Cavalaro, de la Fuente, and Aguado, 2014a; Oesch, 2015). These fiber orientations are often highly anisotropic in nature and are the result of material flow patterns during the casting process (di Prisco, Ferrara, & Lamperti, 2013; Pujadas et al., 2014a; Oesch, 2015).

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https://doi.org/10.1016/j.ijengsci.2017.10.002
0020-7225/

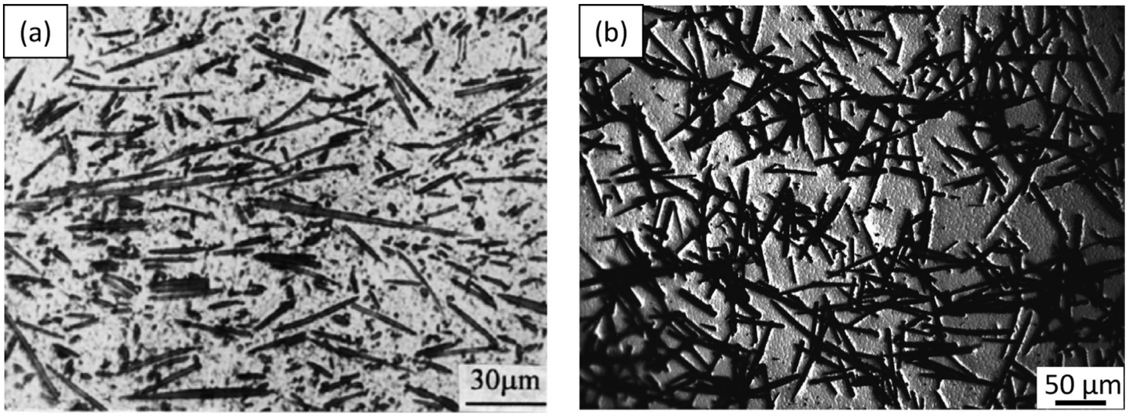

Fig. 1. Optical micrographs showing the orientation distribution of fibers in: (a) and Al2O3 fiber-reinforced aluminum alloy (from Kang, Yang, & Zhang, 2002); (b) polypyrrole-coated amorphous silica short fiber reinforced polyvinylidene fluoride matrix (from Arenhart, Barra, & Fernandes, 2015).

These anisotropic characteristics of fiber-reinforced concrete have major safety implications for its widespread use. Material anisotropy can lead to planes of weakness within structural members. When not properly controlled, these weak planes can become aligned with the primary plane of stress and cause premature failure. The analysis of these fiber orientation characteristics and their implementation into finite element analysis models will serve as an important first step towards obtaining a better understanding of how the characteristics of concrete component materials and casting methods affect material structure and performance.

1.2. Analytical methodologies proposed to account for anisotropic fiber orientation distribution

The present paper focuses on the integration of CT data into micromechanical homogenization techniques to account for orientation distribution of non-spherical inhomogeneities in heterogeneous materials. In short-fiber reinforced composites, the fibers are usually neither perfectly parallel, nor perfectly randomly oriented, but have a certain orientation distribution (Fig. 1), which is one of the primary factors affecting the overall mechanical properties (Kachanov & Sevostianov, 2005). However, non-spherical inhomogeneities in composites had typically been considered as perfectly aligned until the beginning of 1980s. The authors are not aware of analyses accounting for the random orientation of fibers prior to Chou and Nomura (1980–1981) and Takao, Chou, and Taya (1982), who applied an average induced strain approach to composites with 3D randomly oriented short fibers. The averaging procedure was later used by Benveniste (1987) and Chen, Dvorak, and Benveniste (1992) in the Mori–Tanaka scheme. Tandon and Weng (1986) considered two cases of random distribution of fibers: in-space (overall isotropy) and in-plane (overall transverse isotropy). The general case of the orientation distribution of short fibers was first discussed by Ferrari and Johnson (1989), who presented a theoretical scheme in which the fiber orientation distribution was allowed to be arbitrarily specified. These authors first introduced an orientation distribution function (ODF) defined over the full Euler space. This approach was implemented into the Mori–Tanaka scheme by Ferrari (1991) and Marzari and Ferrari (1992).

In the successive years many specific ODFs have been discussed in literature. During the analysis of a fiber-reinforced composite by Lu and Liaw (1995), independence of the orientation distribution of fibers was assumed with respect to different Euler angles $\phi, \theta, and\, \varphi$, so that:

$$P(\phi,\ \theta,\ \varphi) = P(\phi)P(\theta)P(\varphi) \quad (0 \le \phi,\ \theta,\ \varphi \le \pi) \tag{1.1}$$

They used a combination of Gaussian and trigonometric distributions which fit the distribution obtained by quantitative image analysis of SEM pictures:

$$P(\phi) = \frac{2+\cos(2\phi)}{2\pi};$$
$$P(\theta) = \sqrt{\frac{2}{\pi}}\exp\left(\frac{-(\theta-\pi/2)^2}{2}\right);$$
$$P(\varphi) = \sqrt{\frac{2}{\pi}}\exp\left(\frac{-(\varphi-\pi/2)^2}{2}\right) \tag{1.2}$$

Applicability of this function to non-random orientation distribution is, however, unclear.

Chen and Wang (1996) calculated the effective thermal conductivity of a transversely isotropic composite containing misoriented inhomogeneities. The orientation distribution was described by:

$$P(\theta) = 1 - \exp(\lambda\theta) \tag{1.3}$$