Evaluation of fiber orientation in a composite and its effect on material behavior

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Abstract
The reinforcement of concrete with polymer fibers provides resistance to crack formation. The orientation distribution of these fibers has a significant influence on the mechanical behavior of the material. To optimize material performance, micromechanical models that are capable of making accurate predictions of the mechanical behavior of composite materials are needed. These models must be calibrated using experimental results from mechanical testing and microstructural characterization. For the fiber orientation distribution analysis in the present study, computed tomography (CT) data was used to evaluate the properties of a fiber-reinforced cement mortar. The results have indicated that there is a clear tendency for the polymer fibers to agglomerate during mixing and casting. The incorporation of this experimental data into micromechanical models will significantly increase the accuracy of those models for material simulation and optimization.

Keywords: Orientation Distribution, Fiber-Reinforced Concrete, Computed Tomography.

Introduction
The orientation distribution of inhomogeneities is one of the major factors affecting the mechanical performance of composite materials. To collect information about fiber orientation distribution in a material, either non-destructive testing (inductivity-based assessment and resistivity-based assessment, CT, etc.) or destructive testing (metallography, microscopy, etc.) methods can be used [1]. However, only CT provides 3D information on fiber distribution without difficult sample preparation as it requires only a difference in the linear X-ray attenuation coefficients of the matrix and reinforcement, disregarding other physical properties. The most popular theoretical scheme for the calculation of fiber orientation distributions is the so-called orientation distribution function (ODF) [2]. However, critical to the optimization and implementation of fiber-reinforced concretes is the experimental evaluation of the ODF and its incorporation into an analytical formula which can be used for micromechanical modeling [3].

Experiments
A cylindrical sample of fiber-reinforced cement mortar with a length of 40 mm and diameter of 10 mm was extracted from a mortar prism with dimensions 4 cm × 4 cm × 16 cm using a core-drill bit. This mortar prism, which was produced for mechanical testing, contained 0.5% vol. polyacrylonitrile fibers with an average fiber diameter of 15 µm and an average fiber length of 4 mm. The material was impregnated with epoxy resin before drilling in order to prevent disintegration of the sample. To obtain a better statistical sample of the orientation distribution of fibers within the sample, six CT scans at different locations along the sample’s height were performed, each with a spatial resolution of 6.65 µm.

Results
Image analysis of the reconstructed volumes was performed using Amira ZIB Edition from Konrad-Zuse-Zentrum Berlin (ZIB) [4]. Due to the low difference in contrast between the fibers and matrix material, as well as the small diameter of the fibers (15 µm), identification of fibers by intensity segmentation was not possible. However, it was possible to trace fibers by using the template matching algorithm implemented in Amira. This tool calculates fiber distribution and orientation properties by comparing the reconstructed volume with a tube-like fiber template defined by the user. This approach helps to trace fibers even in noisy data. However, in the present study, the implementation of such an algorithm had some limitations. The crossing of low-density fibers with pores and aggregate, as well as the cutting of some fibers during sample extraction resulted in difficulties in estimating fiber length. Observations indicated that the bending of the fibers was not significant in this material. Therefore, reliable fiber orientation information could be extracted even from partial fibers. The improper identification of material interface zones (such as the surface of aggregate particles) as fibers was be minimized by implementing additional software parameters such as fiber length controls.

Two orientation angles (φ, θ) in a spherical coordinate system were obtained for each fiber from the Amira fiber-tracking algorithm. With subsequent data processing, these values were used to produce orientation distribution histograms (Fig. 1). Another data representation possibility is a surface plot of fibers colored according to their orientation angles. Figure 2 shows a depiction of fiber orientations for one part (a 7 mm × 7 mm × 6 mm prism) of the measured sample for angles φ (Fig. 2a) and θ (Fig. 2b). The reference coordinate system is also shown in the Figure 2a.
Polymer fibers in concrete are difficult to distribute with defined orientation during material production due to the tendency of the fibers to agglomerate. Characterizing the effect of parameters like volume fraction, fiber dimensions or special fiber surface treatments on the orientation distribution of fibers is important for estimating mechanical properties of the material and accurately modeling its behavior. In the specimen, some regions of agglomerated fibers were observed, indicating that the overall distribution of fibers was significantly inhomogeneous. From the orientation distribution histogram (Fig. 1), it was clear that a disproportionate number of fibers were oriented roughly parallel to the X-Z plane ($\phi$ near 0° or 180°) (Fig. 1a) with orientation angle $\theta$ larger than 45° (Fig. 1b).

The fiber orientation distribution results, together with those of three-point bending tests performed on mortar prisms, were used as an experimental input for modeling the mechanical behavior of the material. CT results have indicated that there is a clear tendency of the polymer fibers to agglomerate during mixing and casting. This tendency could form planes of weakness parallel to the primary orientation angle of the fibers. Such planes of weakness result from the weak bond between mortar and polymer material and could lead to premature failure of structural components. Future research will focus on the development of new fiber coatings and concrete casting techniques to minimize agglomeration of fibers.

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References