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Micromechanical analysis of composites with fibers distributed randomly over the transverse cross-section

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ABSTRACT

A new method to generate the random distribution of fibers in the transverse cross-section of fiber reinforced composites with high fiber volume fraction is presented in this paper. Based on the microscopy observation of the transverse cross-sections of unidirectional composite laminates, hexagon arrangement is set as the initial arrangement status, and the initial velocity of each fiber is arbitrary at an arbitrary direction, the micro-scale representative volume element (RVE) is established by simulating perfectly elastic collision. Combined with the proposed periodic boundary conditions which are suitable for multi-axial loading, the effective elastic properties of composite materials can be predicted. The predicted properties show reasonable agreement with experimental results. By comparing the stress field of RVE with fibers distributed randomly and RVE with fibers distributed periodically, the predicted elastic modulus of RVE with fibers distributed randomly is greater than RVE with fibers distributed periodically.

1. Introduction

Fiber-reinforced composites have been widely used in aeronautical and astronautical structures due to their supreme strength and stiffness properties along with their lightweight characteristics [1]. Since composite materials are composed of fibers and matrix, they are known as hierarchical materials with three structural levels: micro-scale, meso-scale and macro-scale. The micro-scale defines the distribution of fibers, the meso-scale generally relates to the fabric/lamina geometry, and the macro-scale refers to the engineering structures. Micro-scale approaches are usually applied to predict the effective stiffness of composites, serving as theoretical tools for engineering structure design [2].

The micromechanical analysis is usually performed on a representative volume element of the composite, and the spatial arrangement of fibers in a composite can be periodic and random. The arrangements of periodic distributions include square diagonal arrangement, square arrangement, and hexagon arrangement [3]. Periodic distributions offer great simplicity to the analysis while maintaining a reasonable extent of approximation to the reality in many aspects, such as deterministic and ordered distribution of fibers, and the exact same radius of fibers. The spatial arrangement of fibers in a composite microstructure is in fact non-uniform and this can have a significant effect on strength prediction and fatigue life prediction. Trias et al. [4] compared the stress and strain distributions between a periodic and a random model for the same carbon fiber reinforced composites. The comparison showed that the use of periodic models could lead to an underestimation of the matrix cracking and damage initiation.

To capture the non-uniform spatial arrangement of fibers within a composite microstructure, the general approach is to develop a statistically equivalent RVE by hard-core model (HCM) or the initially periodic shaking model (IPSM). The HCM considers the fibers as a set of non-overlapping disks, with their centers randomly distributed in a square region. The HCM is natural and simple, while the big disadvantage of HCM is that it can hardly generate distributions with fiber volume fractions greater than 50% [5]. To overcome the jamming limit, hard-core shaking model (HCSM) is developed. HCSM uses an initial configuration generated by HCM and then subjected the fibers to small arbitrary displacements, which creates matrix-rich regions. The presence of these areas allowed further fibers to be placed in the domain, resulting in high fiber volume fractions of 65% [6–9]. IPSM starts from an initial periodic fiber array of the desired volume fraction and then creates a non-uniform fiber distribution by shifting the fibers through a random displacement [3,10]. IPSM can generate RVEs with much higher fiber volume fraction. For square diagonal arrangement and square arrangement as the initial arrangement pattern, the jamming

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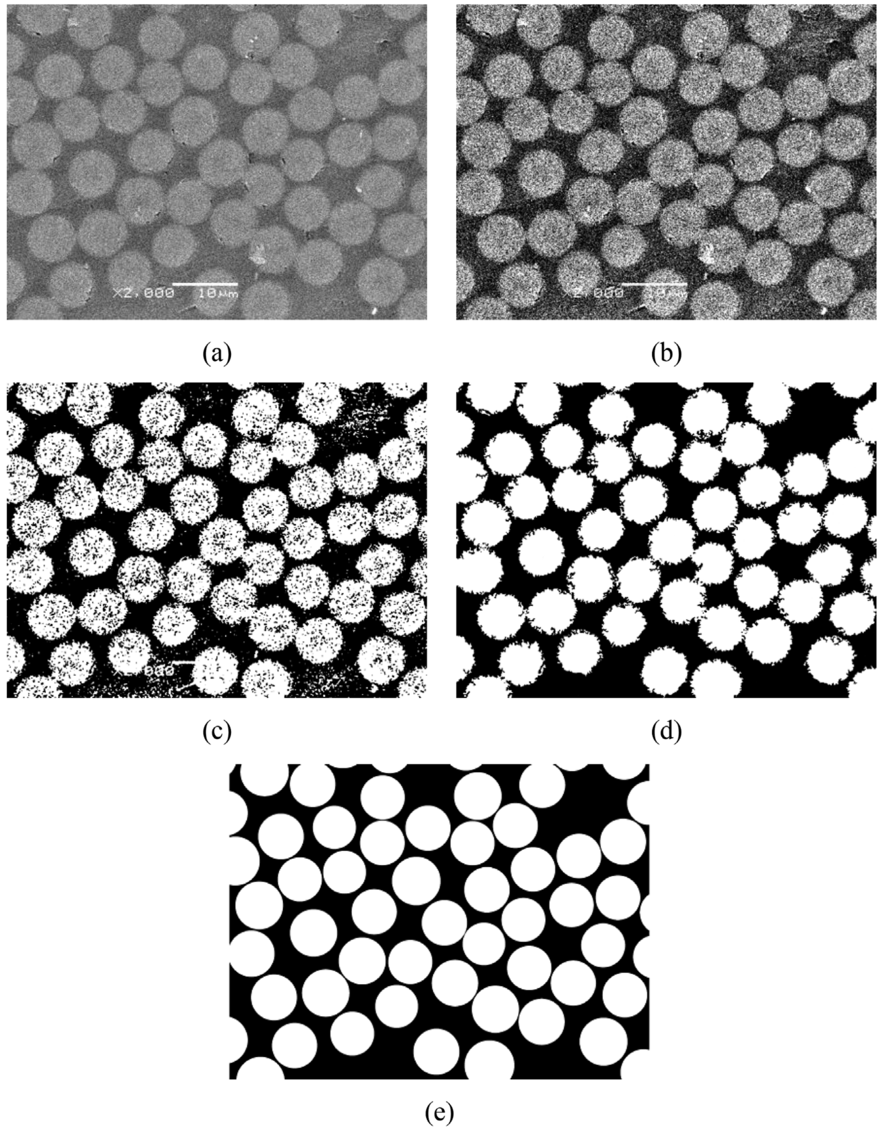

Fig. 1. (a) The original micrograph of fiber-reinforced composite material; (b) binarization processing applied; (c) Eq. (1) applied; (d) Adobe Photoshop CS5 applied; (e) Nano Measurer 1.2 applied.

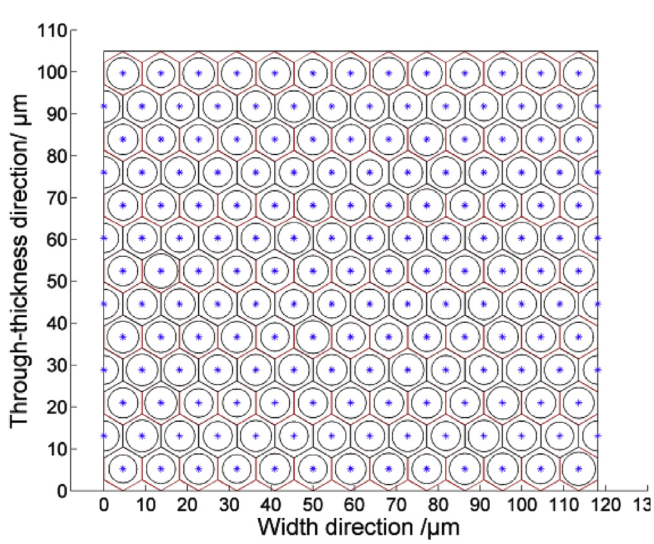

Fig. 2. Initial hexagonal arrangement of fibers.

limit is 78.54%; for hexagon arrangement as the initial arrangement pattern, the jamming limit is 90.69%.

There are two ways to deal with the fibers around the borders: the fibers can cross the borders of the RVE, and the fibers cannot cross the borders of the RVE. For the RVE with the fibers can cross the borders, in Refs. [8,9], the fibers on opposing borders satisfy the periodic condition; while in Refs. [3,10–12], the fibers on opposing borders does not satisfy the periodic condition. For the RVE with the fibers cannot cross the borders [12–14], there are matrix-rich regions around the borders.

Since unidirectional composites and composite laminates are both made of unidirectional prepreg, the thickness of the RVE in this paper is set as the thickness of the unidirectional prepreg. In order to generate a statistically equivalent RVE for a composite microstructure of high fiber volume fraction, a new algorithm is developed based on completely elastic collisions. Statistical analysis is performed on the generated microstructures and compared to experimental samples to demonstrate the randomness of fiber distributions. And the newly developed algorithm uses the diameter distribution to assign fiber diameters. Finite element analysis is then implemented to predict the effective elastic properties of a carbon/epoxy composite and a glass/epoxy composite.