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3D numerical simulation for the elastic properties of random fiber composites with a wide range of fiber aspect ratios

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ABSTRACT

A new automatic searching & coupling (ASC) technique is proposed to generate the 3D representative volume element (RVE) to analyze the random fiber composite (RaFC) with a wide range of fiber aspect ratios (FAR), particularly the RaFC with a high FAR. Compared with the conventional model, the present model is easier to generate and more time-saving as it eliminates the drawback of free meshing. In addition, the ASC technique can remove the additional stiffness introduced by the embedded element technique (EET), and hence can improve precision and convergence. Moreover, our technique facilitates the direct application of the 3D periodic boundary conditions (PBC) to the RVE. Using the finite element (FE) method, the elastic properties of RVE are calculated, and the critical RVE size is determined. Furthermore, the 3D elastic properties of RaFC are predicted, which accord well with experimental data. Besides, the RVE is employed to explore the influences of FAR, fiber volume fraction (FVF) and the fiber incline angle on the elastic properties of RaFC, and a comparison with theoretical results is also presented.

1. Introduction

Random fiber composites (RaFCs) are widely employed for the production of load bearing parts in many industrial fields due to the significant weight savings as well as the development of new manufacturing technologies and processes [1]. In recent years, there is a growing need for RaFCs with high-aspect-ratio fibers as they possess both higher performance and mass processability. However, RaFCs do not need very high FVFs, since the stiffness and strength criteria can be met when the FVFs reach 20% or less [2,3]. To expand the use, two factors are required: first, reliable estimates of the overall material properties following a homogenization process that allows for efficient analysis of large scale structures; second, good predictions of micro-level properties for predefined macro-scale loadings. However, it is difficult to establish a model that can explore the capabilities of RaFCs, particularly RaFCs with high FAR and FVF [4].

Mean field methods are employed to estimate material properties based on Eshelby's [5] field solution for single ellipsoidal inclusion in an infinite medium (matrix). The extension to such family of methods based on the original work by Mori and Tanaka [6] has enjoyed much attention, especially after the method has been applied to composite materials [7]. Weng [8] provided the generalization of the Mori–Tanaka (MT) method and the solution for the complete set of elastic constants, which guaranteed the method's popularity for the analysis of RaFCs. Hence the overall elastic properties are obtained using the orientation distribution function [9] to average the stiffness tensor [10]. Giordano [11] analyzed the effect of the orientation of the reinforcements on the electrical and elastic characterization of composites, by using the MT method based on integrating up the orientation distribution function.

A more mechanistic set of methods—the laminate approximation approach (LAA) [12]—have been employed to create an analogous model for the RaFC. By idealizing the material as a set of parallel layers of in-plane randomly oriented fibers, a classical laminated plane theory [13] is performed to compute the composite "global" stiffness matrices. These methods employed the famous shear-lag model [14] or the semi-empirical Halpin–Tsai equations [15] to evaluate the macro-properties for the composite with uniform fiber orientation and length. Thus they have provided the means for a rather inexpensive engineering type of analysis when the FVF of the RaFC is not very high. The model proposed by Huang [16] also combines a laminate analogy approach with the MT method at the level of the individual lamina. Furthermore, Ionita and Weitsman [17] proposed the 'laminated random strand' model, using a 'moving window approach' to analyze the high FVF carbon fiber/urethane composites.

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However, few considerations are given to the micro-mechanical stress–strain state in the aforementioned theoretical methods and semi-empirical theories, thus finite element analysis (FEA) is widely employed to model the RaFC. Based on Hill's theory [18], applying the concept of RVE has become a common practice. By using direct 3D FEA, Gusev [19] evaluated the effective modulus and electric properties of the composite reinforced by different shapes of inclusion. Böhm et al. [20] studied a metal matrix composite (MMC) reinforced by approximately planar random short fibers with FAR of 5. Kari et al. [21] employed FEA to investigate the effects of FVF and FAR on a MMC reinforced by random short SiC-fiber where the FAR is not very high (smaller than 15). In order to generate the complex geometry of RaFCs, a modified random sequential adsorption (RSA) algorithm has been developed [4,22,23]. Using the RSA algorithm, Iorga et al. [22] investigated the effects of FAR and FVF on the overall elastic properties of a RaFC. Based on their work, Pan et al. [23] further studied the effect of the interaction between two over-crossing fibers on the overall elastic properties. In addition, Pan et al. developed the RVE generation using both straight and curved fibers so as to achieve a higher FVF.

However, the aforementioned approaches are difficult to generate RVEs with high FAR and FVF. Besides, distorted FE meshes may intensively occur at local fiber contact points, resulting in great problems in computational efficiency and precision. By using the embedded element technique (EET), Hoffmann et al. [24] speeded up the modeling approach of RVE generation; but as they have pointed out, an additional stiffness would be introduced through this approach. More recently, Harper and co-workers [25,26] proposed a valuable idea of ignoring fiber intersections for the FE modeling of RaFCs, where fibers were meshed as 1-D line elements. In their papers, a 2D RVE was employed to analyze discontinuous carbon fiber composites; EET was used to couple fiber and matrix elements.

The convergence rate falls in the FE model because of the additional stiffness introduced by EET; additionally, the 2D RVE is insufficient to evaluate the out-plane properties of RaFCs. But the idea of meshing fibers or fiber tows as 1-D elements is valuable, and the idea has been widely used in the FEA of composites. A representative work is done by McGlockton et al. [27], who employed the Binary Model to simulate the fracture in 3D weaves. Based on the previous works, we carry on the idea of modeling fibers as 1-D elements while providing a new modeling technique that can remove the additional stiffness and generate 3D models for RaFCs with high FAR and FVF.

In the current work, a new ASC technique is presented to generate a great amount of 3D RVEs for RaFCs with a wide range of FAR (23–231) and FVF (3.70–18.72%). Statistical criterion [28] is used to determine the RVE size. The FEA results are compared with published experimental data [2,3] to support the present FE model. Finally, we employ the 3D FE model to study the influences of FAR, FVF and the fiber incline angle on the effective in-plane and out-plane Young's modulus, where the effective Young's modulus is compared with the predictions by LAA and MT methods.

2. FE model using ASC technique

2.1. Generation

3D fiber architectures are generated by a modified RSA algorithm to ensure they are geometrically periodic, wherein fibers are modeled as straight lines [23]. Fiber intersections are ignored and therefore no limitation is imposed on the FVF when generating the model. Fig. 1 shows a sketch of the geometric model and the fiber arrangement. Fig. 1(a) is an overall spatial view. The top view and side view are respectively shown in Fig. 1(b and c). In 3D space, as shown in Fig. 1(d), a fiber is described by the center point **C**, and

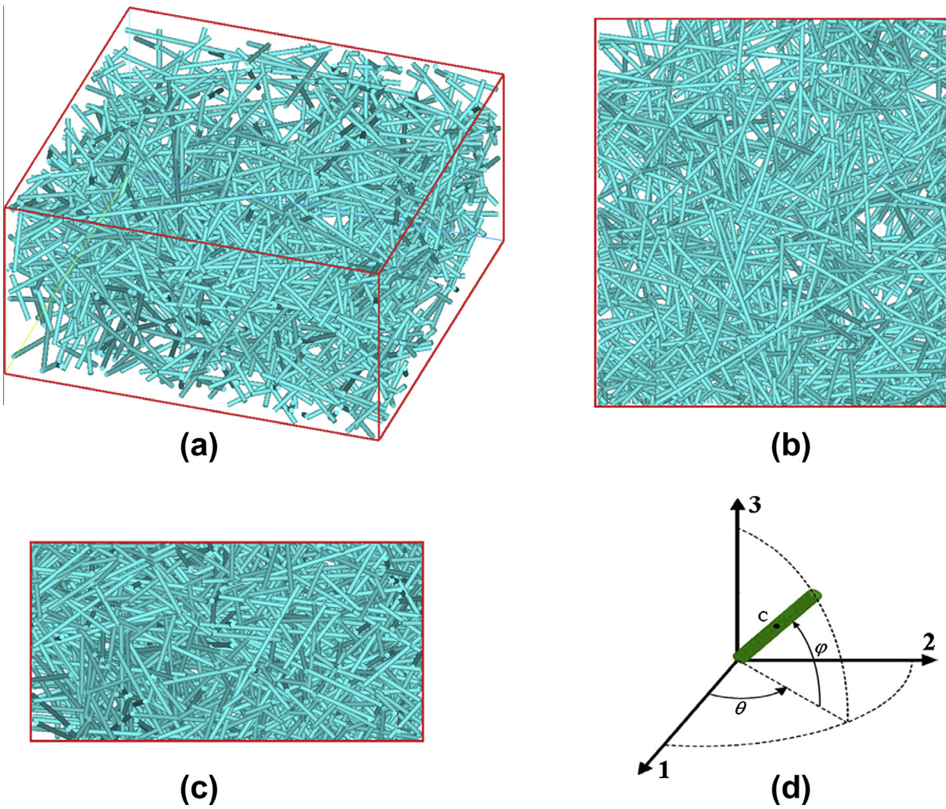

Fig. 1. The sketch for the fiber architectures in the 3D model.