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Unidirectional high fiber content composites: Automatic 3D FE model generation and damage simulation

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ABSTRACT

A new method and a software code for the automatic generation of 3D micromechanical FE models of unidirectional long-fiber-reinforced composite (LFRC) with high fiber volume fraction with random fiber arrangement are presented. The fiber arrangement in the cross-section is generated through random movements of fibers from their initial regular hexagonal arrangement. Damageable layers are introduced into the fibers to take into account the random distribution of the fiber strengths. A series of computational experiments on the glass fibers reinforced polymer epoxy matrix composite is performed to study the influence of the strength distribution of fibers on the mechanical response and strength of the composites.

1. Introduction

Lightweight fiber-reinforced composite materials find a wide application for structural applications, due to their high stiffness-to-weight and strength-to-weight ratios, and the possibility to tailor the overall anisotropic stiffness and strength of composite laminates by varying the fiber orientation and stacking sequence of the individual composite plies.

In order to analyze the effect of the microstructure and phase properties of composites on their strength and mechanical behavior, computational micromechanical models are widely used. The applications of advanced numerical simulation for the prediction of the mechanical behavior of composite structures can replace some of the mechanical tests and can significantly reduce the cost of designing with composites [1,3].

Depending on the purpose of the analysis, three basic modeling techniques for composites can be distinguished [1,2]: (1) macroscopic modeling, composite is often modeled as a single orthotropic material or a single fully anisotropic material at the laminate level; (2) mesoscopic modeling, composite is typically considered as a single transverse isotropic or orthotropic material at the lamina or ply level; (3) microscopic modeling, the matrix and reinforcement materials are both modeled separately as deformable continua at the fiber/matrix (sub-lamina) level.

The damage processes start at the nano- and microlevel, and, therefore, sub-lamina micromechanical models should be used to predict accurately the onset of damage growth in composites. For the computational (finite element) analysis of the mechanical behavior and strength of composites, taking into account its microstructures, a representative volume element (RVE) of the composite should be defined. Due to constraint of the computational tools, many researchers adopted the RVE with single fiber [4–12] by assuming that the fibers in composite are distributed periodically. However, the single-fiber model is oversimplified, and it is necessary to take into account the transverse randomness of fiber distribution for the adequate analysis of the damage evolution.

The correct representation of microstructures of composites, which can be then introduced into numerical models, can be realized with the use of the digital image technique [13–17], which requires specific software. However, for the parameter studies and computational optimization of material microstructures, algorithms for the generation of generic, typical microstructures are necessary, along with the methods of reconstruction of real microstructures. Several algorithms and models have been developed for the generation of RVE models of composites. Torquato and his colleagues [25,26] described a reconstruction algorithm which can be used to generate the general random heterogeneous media from limited morphological information. Pyrz [18] produced multi-fiber RVE using the Poisson point distribution, where the points are the centers of fibers. However, Buryachenko et al. [19] found that Pyrz's method hardly generates distributions with fiber volume fractions larger than 50%. Mishnaevsky and his colleagues [20,21] adopted the random sequential adsorption (RSA) [22] to generate 2D models of particle-reinforced composites, and then Mishnaevsky and Brøndsted [23,24] extended this method to the generation of unit cell models of 3D fiber-reinforced composites. The

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implementation of Mishnaevsky and his colleagues by the authors resulted less than of 40% of fiber volume fraction. Recently, Melro et al. [27] developed a model which can generate random distribution transverse cross-section with high fiber volume fraction. Böhm and Rammerstorfer [28], Gusev et al. [29] and Wongsto and Li [30] presented an algorithm for the generation of fiber distributions with high fiber volume content by randomly disturbing an initially square and hexagonal periodic distribution of fibers in cross-section of composite.

In this paper, we present an algorithm and program code for the automatic generation of 3D micromechanical FE models of unidirectional long-fiber-reinforced composite (LFRC) with high fiber volume fraction with random fiber arrangement. The fiber arrangement in the cross-section is generated through random movements of fibers from their initial regular hexagonal arrangement. Damageable layers are introduced into the fibers to take into account the random distribution of the fiber strengths. A series of computational experiments on the glass fibers reinforced polymer epoxy matrix composite is performed to study the influence of the strength distribution of fibers on the mechanical response and strength of the composites. In each fiber, randomly distributed damageable layers are taken into account to study the strength in fiber direction. A series of computational experiments on the epoxy matrix composite reinforced with glass fibers are performed to study the influence of 3D FE models and strength distribution of fibers on the LFRC.

2. Automatic generation of 3D multi-fiber microstructural FE unit cell model of high fiber content composites

In this section, a new program code, which was developed to automate the generation of 3D micromechanical finite element models of unidirectional, high fiber volume composite, is presented. The program code, developed in Compaq Visual Fortran, generates a command file for the commercial software MSC/Patran. A 3D microstructural finite element model with pre-defined parameters (including the number and volume content of fibers, mesh seeds, five random number generator seeds controlling the fiber distribution in RVE) is generated by playing the command file with MSC/Patran. The finite element meshes are generated by sweeping the corresponding 2D meshes on the top-surface of the unit cell.

2.1. Random placement of fibers in a transverse section of unit cell model of high fiber volume composites

In order to generate the multifiber unit cell with high fiber content and random fiber distribution, the following algorithm was developed. First, an ideally random arrangement of discs in a plane square in generated. Two sets of regular disc arrangements (square lattice and hexagonally packed discs) are shown in Fig. 1. Then, each disc is moved from his initial position in random direction and on the random distance, as illustrated schematically in Fig. 2. A direction angle θ of the disc movement (from 0° to 360°) is determined using the uniform random number generator. Then, a second random number k is generated, ranging from 0 to 1, and the actual distance of the disc shifting is given as $k(1-r)$. Here, r is the radius of a fiber and $(1-r)$ is the maximum distance of shift. When shifting an ith disc, the distance between the ith disc and all the existed $1\ldots(i-1)$-discs, and between the ith disc and the unit boundaries of is calculated. If any of these distances is less than a value d_0 (d_0 is determined as a length parameter of the finite elements), a next loop is performed and the new position of the disc is re-calculated again and again until it satisfies this criterion (see Fig. 2).

In order to keep the pre-defined fiber volume content, and to ensure the periodicity of the RVE, if a disc is cut by the border of the RVE, the remained part of the disc is placed into the 2D RVE unit again by it opposite boundary. For the hexagonal unit cell, the sizes of the 2D vertical section were $\sqrt{3}n_1$ and $2n_2$ units (n_1 and n_2 are the disc number in horizontal and vertical directions, respectively), and the minimal allowed distance between the disc centers was 2 units.

The maximum disc volume fraction, which can be achieved theoretically, can be calculated as follows (for regularly squared and hexagonal distributions), respectively

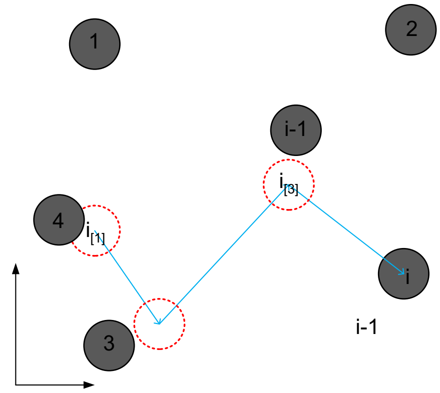

Fig. 2. Generation of the horizontal section of the unit cell by shifting the discs. The non-bracketed numbers are the disc numbers, and the bracketed numbers mean iterations.

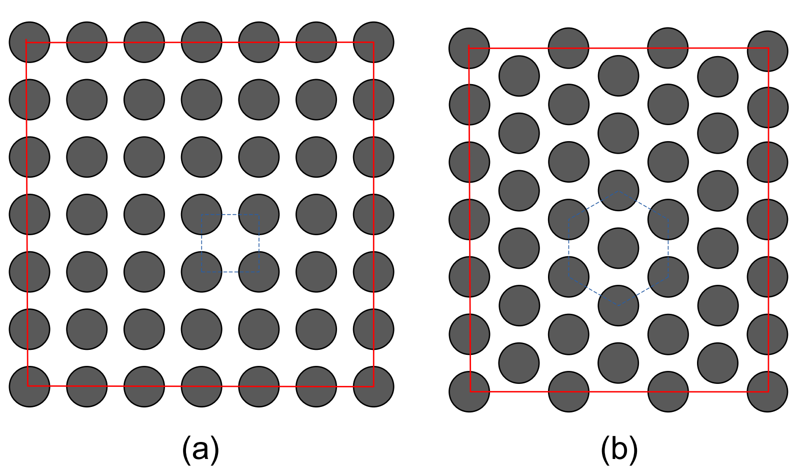

Fig. 1. Periodic distributed grids in 2D space: (a) square lattice arrangement; (b) hexagonal packing. The zone inside the red lines is the RVE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)