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Effect of fiber arrangement on mechanical properties of short fiber reinforced composites

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ABSTRACT

The present paper developed a three-dimensional (3D) "tension–shear chain" theoretical model to predict the mechanical properties of unidirectional short fiber reinforced composites, and especially to investigate the distribution effect of short fibers. The accuracy of its predictions on effective modulus, strength, failure strain and energy storage capacity of composites with different distributions of fibers are validated by simulations of finite element method (FEM). It is found that besides the volume fraction, shape, and orientation of the reinforcements, the distribution of fibers also plays a significant role in the mechanical properties of unidirectional composites. Two stiffness distribution factors and two strength distribution factors are identified to completely characterize this influence. It is also noted that stairwise staggering (including regular staggering), which is adopted by the nature, could achieve overall excellent performance. The proposed 3D tension–shear chain model may provide guidance to the design of short fiber reinforced composites.

1. Introduction

Biological materials such as bone and nacre are made of mineral and protein. While the mineral is as stiff as chalk with relatively low fracture toughness and the protein is as compliant as skin with relatively high ductility, many studies [1–3] have indicated that the stiffness and toughness of these biocomposites are comparable to their stiff and tough constituents, respectively. Further studies [1,2,4–8] found that these biological materials have very similar nano-structures: the hard platelets or fibers are staggered within the soft matrix, as shown in Fig. 1. These structures are considered as crux [9–11] of the superior mechanical properties of the biological materials.

Several studies on biocomposites with staggered platelets have been conducted. Jager and Fratzl [11] proposed a model with staggered array of platelets, which successfully reproduced the fact that both the elastic modulus and rupture stress are increased with the amount of mineral. Ji and Gao [12] assumed the load in the longitudinal direction is mainly transferred via shear in matrix and developed a tension–shear chain model, for regular staggering situation (platelets overlap with half of their length) to illustrate how biocomposites achieve high stiffness and toughness, which can be used to interpret many mechanisms of the behaviors of biocomposites. Nonetheless, there also exist some distributions of reinforcement phase other than regular staggering, such as the stairwise staggering of bone shown in Fig. 1b. Moreover, with the progress of micro/nano-scale manipulation, Tang et al. [13] and Bonderer et al. [14] successfully fabricated biomimetic materials with non-uniform or even random platelets alignment. The studies of Zhang et al. [15] further developed the tension–shear chain model by investigating the effect of arbitrary distributions of reinforced platelets on the mechanical properties of biocomposites.

On the other hand, short fiber reinforced composites have been widely used and studied for a long time [16–19,31,32]. Especially in recent years, carbon nanotube is considered to be an ideal reinforcement phase [20–29] for new generation of high-performance composites. Similar to platelet reinforced composites stated above, introducing bio-inspired alignment of reinforcements into short fiber reinforced composites is also expected to produce better mechanical properties. Zhang and Liu [30] extended the tension–shear chain model to predict the axial Young's modulus of bio-mimetic composites with discontinuous fibers aligned in a regularly staggered pattern. However, the cases with other staggered patterns have not been systematically studied.

The purpose of this paper is to investigate the effects of non-uniform or random distribution of unidirectional short fibers on the mechanical properties of composites through a theoretical

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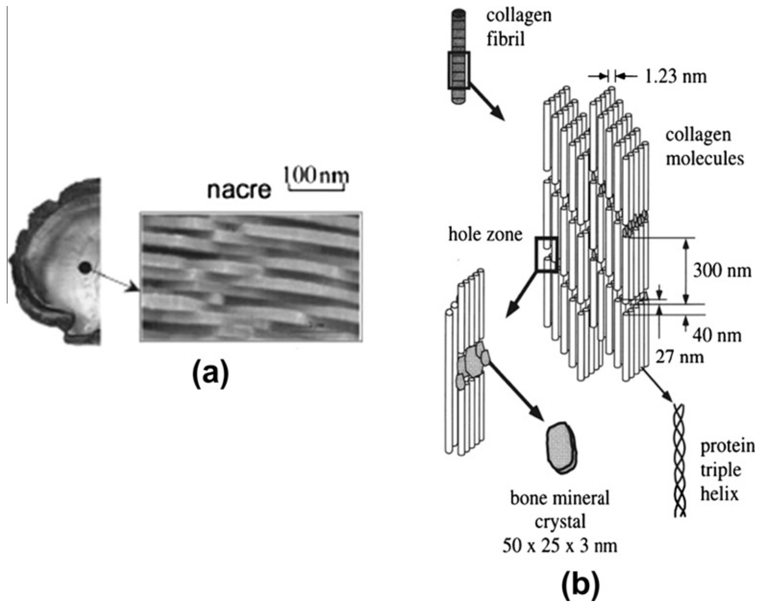

Fig. 1. Nanostructures of (a) nacre (Reprinted with permission from [9]) and (b) bone (Reprinted with permission from [8]).

model and FEM calculations. The paper is outlined as follows. In Section 2, the analytical model for short fiber reinforced composites is developed, and corresponding FEM model is also presented. The effects of various parameters, especially fiber distribution, on the mechanical properties of composites are investigated in Section 3. Main conclusions are summarized in Section 4.

2. Analytical and FEM model for short fiber reinforced composites

This paper is focused on studying the effective mechanical properties of composites consisting of stiff short-fibers unidirectionally distributed in the soft matrix. For simplicity, it is assumed that all fibers have the same length L and radius R, transversely distributed in a triangle lattice pattern with transverse spacing d, as shown in Fig. 2, and thus the periodicity is always guaranteed in the longitudinal direction (z direction). A representative unit cell of the composites shown in Fig. 2 has m rows and n columns of fibers, so there are $s = m \times n$ fibers in a unit cell. Denote the longitude position of the ith fiber in Fig. 2b as $z = \xi_i L$ ($0 \leqslant \xi_i < 1$, $i = 1, 2, \ldots, s$) in the global coordinate. When we study the interaction of ith fiber and its neighbors, a local coordinate $\tilde{z} = z - \xi_i L$ is introduced, thus $\tilde{z} = 0$ for the ith fiber and $\tilde{z} = \tilde{\xi}_{ij} L$ for its neighboring fibers. Briefly, ξ_i denotes the normalized coordinate of the ith fiber in the global coordinate system while $\tilde{\xi}_{ij}$ is the normalized coordinate of the jth fiber in the local coordinate system related to the subset of the ith fiber and it is completely determined by ξ_i and ξ_j:

$$\tilde{\xi}_{ij} = \begin{cases} \xi_j - \xi_i, & \text{if } \xi_j \geqslant \xi_i \\ \xi_j - \xi_i + 1, & \text{if } \xi_j < \xi_i \end{cases} \quad (1)$$

2.1. Three dimensional tension–shear chain model

To obtain simple analytical formulae, a 3D tension–shear chain model is developed under the following assumptions:

(1) The gap between the fibers is much smaller than their length and can be ignored.
(2) The diameter of fibers is one or two orders of magnitude smaller than their length, thus the deformation of the fibers can be considered as one dimensional (only depends on z).

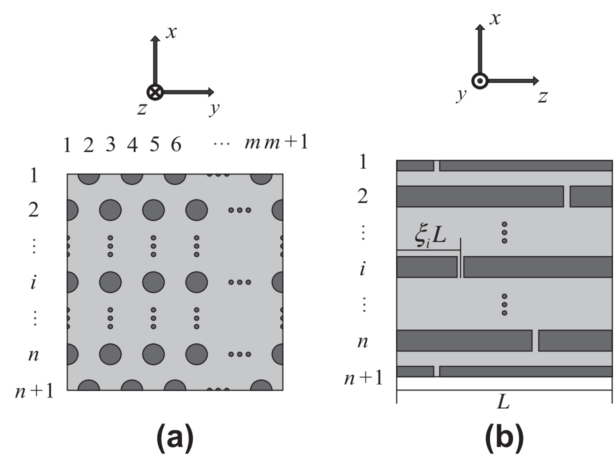

Fig. 2. Schematic of unidirectional short-fibers reinforced composites: (a) cross section view of a unit cell, (b) side view of a unit cell.

(3) The modulus of fibers is much larger than that of the matrix (at least two to three orders of magnitude), and thus the normal stress of the matrix can be ignored.
(4) Both of the fibers and matrix are assumed to be linear elasticity until failure.
(5) A piecewise uniform distribution along z is assumed for the shear stress field in the matrix between two neighboring fibers, and thus a piecewise linear profile for the normal stress in each fiber.

Note that the assumption of (5) has been shown valid for most biological and biomimetic materials by Liu et al. [33], and is also verified in this paper through comparing our theoretical predictions and FEM results. More important, the uniform shear stress assumption makes it possible for us to derive the explicit solutions of effective Young's modulus, strength, failure strain and energy storage capacity for various distributions with avoiding such complicate mathematics as occurs in elastic shear-lag theory.

Based on the above assumptions, we divide the matrix of fibers reinforced composites into two regions, the shear region and the