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Stress transfer analysis of unidirectional composites with randomly distributed fibers using finite element method

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ABSTRACT

A three-dimensional representative volume element (RVE) of unidirectional composites with both randomly distributed fibers and periodic geometry was generated using DIGIMAT-FE software. Finite element analysis of the stress transfer mechanisms around a fiber break in the RVE was performed via ABAQUS/Standard. The influences of distance to the broken fiber, fiber/matrix stiffness ratio and fiber volume fraction on the stress transfer process of intact fibers were discussed for the case of perfect fiber/matrix adhesion. The study shows that the nearest fibers and the second nearest fibers share the stress released from the broken fiber. The stress transfer coefficient and the ineffective stress transfer length of the nearest fibers was found to increase with the increasing distance to the broken fiber and the stiffness ratio, while decrease with the increasing fiber volume fraction. However, the trends in the two stress transfer parameters of the second nearest fibers are slightly different from those of the nearest fibers due to the random distribution of other intact fibers.

1. Introduction

Fiber-reinforced composites are increasingly used as structural parts in the fields of civil engineering, aviation and aerospace for their excellent mechanical properties [1–3]. In a unidirectional (UD) composite, stress transfer around a fiber break is vital to the fiber failure process [4–6]. According to the Weakest Link Theory, the cumulative failure probability of the element along a fiber follows Weibull distribution. With the increase of tensile stress the fiber segment with a lower strength breaks first. Consequently the fiber is deprived of the ability to carry load at the break location and the stress progressively increases along the fiber to the value in far field. Besides, the stress of the nearest fiber around the break increases because of the stress transferred by the matrix. As a result there is a stress concentration in the breakage section and the stress in the nearest fiber progressively decreases to the value in the far field [7].

Research efforts have been formed on the development of a universal model to simulate the stress redistribution in the UD composite. The analytical approaches can be divided into two categories: local load sharing (LLS) models and global load sharing (GLS) models [8]. The shear lag model (SLM) is a common LLS model. It was firstly proposed by Cox [9], and further improved by Hedgepeth [10] and van Dyke [11] for the two-dimensional case and three-dimensional case, respectively. The SLMs established so far neglect the shear stress across the finite fiber dimensions, and are only accurate for systems with a high fiber/matrix stiffness ratio and high fiber volume fraction [12]. Another famous analytical approach based on LLS theory is the Green's function model (GFM) [13–15]. GFM has some advantages over the SLM such as better computational efficiency and adaption of a broader range of damage phenomena. However, the input variables need be obtained from other micromechanical solution in this method [15]. Fiber Bundle Model (FBM) developed by Daniels [16] was reported as a typical GLS models [17–19]. But with the increase of fiber number there would be a large increase in computing time and a decrease in calculating efficiency [8].

Numerical modeling approach provides an effective alternative for stress transfer analysis after a fiber break. It was found that most limitations introduced by the assumptions in analytical models could be overcome by numerical models. Moreover, it is appropriate for the composites with high fiber volume fraction, and the parameter acquisition in this method is independent of that in other approaches [12]. Van den Heuvel et al. [20] proposed a simple finite element model (FEM) consisting of a planar array of five carbon fibers positioned in the center of an epoxy tensile bar. Xia et al. [12] developed a three-dimensional FEM of a unidirectional composite with hexagonally distributed fibers. Further studies

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were conducted by Blassiau et al. [21] for a representative volume element (RVE) with square distributed fibers. It should be noticed that most of the numerical models assume the network of fibers as hexagonal or square distribution, which is deviated from the real fiber network. Recently Swolfs et al. [22] raised the awareness of the influence of different fiber distributions and established a FEM with random fiber packing. The geometry of this model was chosen as cylinder for symmetry. Consequently this model cannot be called "RVE" because its nonperiodic boundary conditions make the model unable to represent the whole composite structure. Therefore, it is of great necessity to develop a RVE containing randomly distributed fibers for the analysis of stress transfer mechanisms due to fiber failure.

In the present paper the stress transfer mechanisms after a fiber break in a UD composite were analyzed via a three-dimensional periodic FEM with randomly distributed fibers. Apart from the fibers nearest to the broken fiber, the stress release of the second nearest fibers was also investigated. After convergence analysis, the relationship between stress transfer coefficient and distance to the broken fiber of the two types of fibers were established. Finally, stress transfer parameters obtained from models with different fiber volume fractions and fiber/matrix stiffness ratios were discussed.

2. Finite element modeling

2.1. RVE with randomly distributed fibers

The micromechanisms of load transfer in a UD composite can be well described using RVE. The optical microscopic observation (Fig. 1) of the cross-section of the UD composite reveals that the fiber distribution in the matrix is random. Thus the fiber network of the RVE in this study was chosen as random distribution with periodic geometry. The DIGIMAT-FE is employed to generate the RVE with random fiber arrangements.

The ratio of fiber diameter to fiber length in the RVE ought to be equal to or slightly greater than 14 according to previous surveys [20–22]. If the ratio is smaller than 14, the longitudinal stress in both the broken fiber and the intact fibers nearby cannot recover to the value in far field along the fiber direction. If the ratio is far greater than 14, larger numbers of meshes generated would result in a decrease of computing efficiency. Therefore, the RVE size was determined as 25 μm × 25 μm × 100 μm. A broken fiber was placed in the geometric center of RVE to represent the damage of the composites. The fiber and matrix were both assumed to be isotropic, homogenous and linearly elastic, and the interface between the broken fiber and matrix was considered bonded perfectly. The material parameters of the fiber and matrix for modeling are shown in Table 1.

2.2. Boundary conditions and applied load

The boundary conditions and applied load of RVE should represent the macroscopic stress state of the UD composite under uniaxial tension load. The breakage of the central fiber was described by the DOF release of their nodes in the plane $z = 100$. Other nodes in the same section were geometrically symmetrical with respect to the plane $z = 100$. The nodes in the plane $x = 0$, $x = 25$ had the same displacements along X direction respectively, and the nodes in the plane $y = 0$, $y = 25$ had the same displacements along Y direction respectively as well, which was used to represent the periodic characteristics of the microscopic strain field. A strain load denoting the uniaxial stress on macroscale was applied to the nodes in the plane $z = 0$.

2.3. Mesh and convergence analysis

Convergence study was carried out in order to determine the appropriate mesh size. The element type of this analysis was linear parallelepiped, which has 8-node linear brick, reduced integration with hourglass control (C3D8R). Initially, the calculation accuracy of load transfer at the interface of the RVE was confirmed by optimizing the node number around fiber adjacent to the broken fiber. The refinement of mesh was verified by comparing the tensile stress in the broken section with different node numbers. The meshes contained 16 nodes, 24 nodes, 32 nodes and 64 nodes respectively. Fig. 2(a) shows the convergence of fiber/matrix interface for the four different meshes. The longitudinal stress became stable for 32 nodes, which corresponds to a mesh size of 0.5 μm. In addition, the calculation accuracy of load transfer of the RVE along the fiber direction was confirmed by optimizing the element lengths of the fiber adjacent to the broken fiber along Z direction. The four meshes were set as 15 nodes, 20 nodes, 25 nodes and 30 nodes. The calculation result was stable for 25 nodes (see Fig. 2(b)), which is equivalent to a mesh size of 4 μm. Therefore, all numerical analyses were conducted with an approximate size of 0.5 μm × 0.5 μm × 4 μm.

2.4. Definition of the key parameters

There are two key parameters for the stress transfer evaluation in literature [10,21,22]. The stress transfer coefficient (*STC*) reflects the stress increasing along the nearest fiber owing to the fiber break. It is defined as the ratio of the average fiber stress in the failure section and that in the section far away from the failure location,

$$STC = \frac{\overline{\sigma_N}(z = z^*)}{\overline{\sigma_N}(z = 0)} \quad (1)$$

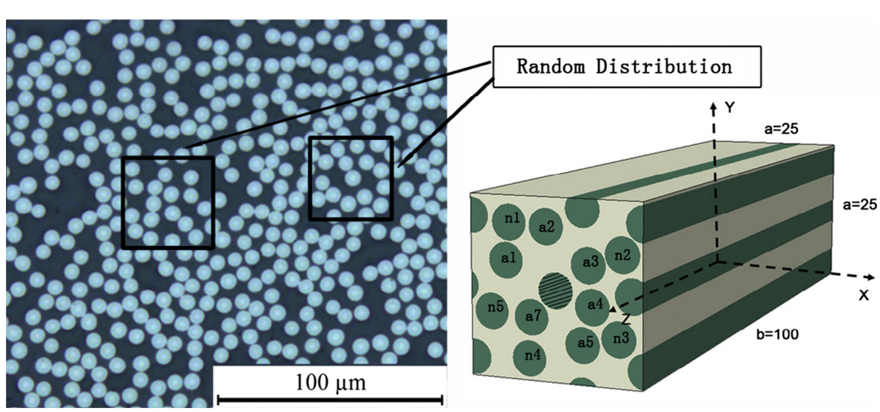

Fig. 1. Random fiber distribution observed from the real composites.