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Micromechanical simulation of tensile failure of discontinuous fiber-reinforced polymer matrix composites using Spring Element Model

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ABSTRACT

The micromechanical damage and strength of discontinuous fiber-reinforced polymer matrix composites was simulated by the Spring Element Model (SEM), and SEM was compared with Periodic Unit-Cell (PUC) simulation to clarify the potential of SEM. Tensile failure simulations indicate that SEM can be effectively used to predict the strength of long discontinuous fiber reinforced composites. The transition between matrix cracking mode and fiber breaking mode is also discussed to clarify the fiber length at which SEM can be used to predict strength. In addition, the strengths predicted with SEM are compared with the results of experiments on long discontinuous fiber-reinforced thermoplastic composites.

1. Introduction

Discontinuous fiber-reinforced polymer matrix composites have been utilized for automobile components more often than continuous fiber-reinforced polymer matrix composites because of manufacturing costs. However, discontinuous fiber-reinforced polymer matrix composites are weaker than continuous fiber-reinforced polymer matrix composites [1]. To improve the strength of discontinuous fiber-reinforced polymer matrix composites, the fibers must be as long as possible. Therefore, long discontinuous fiber-reinforced composites have recently been developed for automobile applications [2]. Strength predictions are required to design structures using long discontinuous fiber-reinforced polymer matrix composites.

The failure mode of discontinuous fiber-reinforced polymer matrix composites differs from that of continuous fiber-reinforced polymer matrix composites. Okabe and Takeda [3] demonstrated that failure of continuous fiber-reinforced polymer (Epoxy) matrix composites is dominated by fiber breaks. In contrast, Sato et al. [4] demonstrated that failure of short discontinuous fiber-reinforced polymer matrix composites is caused by crack propagation through the matrix. This failure mode can be simulated by Periodic Unit-Cell (PUC) simulation [5]. This model verified the relationship between fiber length and failure mode. In these analyses, matrix failures are modeled based on continuum damage mechanics, and fiber failures are modeled based on Weibull statistics. This analysis can comprehensively simulate damage growth, including failure mode transition, as the fiber length varies.

However, the PUC approach has limitations including computational cost, size scale, and dimensionality. The number of fibers in the PUC model is limited due to its high computational costs. Therefore, the simulated model was much smaller than the real specimen. No studies have simulated a large, complicated model of discontinuous fiber-reinforced polymer matrix composite up to failure. It is thus unclear whether PUC predicts strength well if the size effect is appropriately considered. In addition, PUC employs a 2D finite element model. Curtin [6] demonstrated that 2D models are quantitatively less accurate than 3D models when analyzing the strength of continuous fiber-reinforced polymer matrix composites.

Shear-lag model (SLM) is often used and has much lower computational costs than PUC. Young et al. [7] measured the strain distribution along a fiber during a fiber fragmentation test using Raman spectroscopy and found that SLM reproduced a strain distribution similar to that of the experiment unless fragmentation reached saturation. Many studies have modified conventional SLM [8–11]. For example, Ochiai et al. [8] took into account the normal axial stress of the matrix. In particular, several 3D SLMs were proposed after the 1990s to predict strength specifically for

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continuous fiber-reinforced polymer matrix composites [9]. Okabe et al. [10,11] proposed the Spring Element Model (SEM) to simulate failure of UD composites. This approach enabled utilization of the linear matrix solver to describe nonlinear strain fields around a fiber break and damage evolution in composites. Therefore, SEM can perform simulations more efficiently than SLM. By inserting an initial fiber break, which can be regarded as a fiber edge, SEM can perform failure analysis of a discontinuous fiber-reinforced polymer matrix composite, although it cannot deal with matrix cracks.

Ochiai and Hojo [12] applied SLM to discontinuous fiber-reinforced composites. However, their work focused on the stress distribution of fibers and was performed with a 2D model. We have never seen a 3D model that simulates tensile failure of discontinuous fiber-reinforced composites.

This study utilizes SEM for discontinuous fiber-reinforced composites and compares SEM with PUC in order to clarify the potential of SEM. We demonstrate that 3D-SEM is the most effective method for predicting the strength of long discontinuous fiber composites. Finally, for long discontinuous fiber-reinforced thermoplastic (polypropylene) composites, we compared predictions using 2D- and 3D-SEM with the experiment result of Hashimoto et al. [2].

2. Analytical procedure

2.1. Spring Element Model (SEM)

Okabe et al. [10] introduced an effective scheme to address plasticity around a fiber break. A Monte-Carlo simulation was performed using their Spring Element Model (SEM). The composites consisted of longitudinal and transverse springs (Fig. 1). Fig. 1a depicts the 2D model, and Fig. 1b depicts the 3D model. The calculation procedure is presented in Okabe et al. [10]. A brief introduction is provided here. In this model, longitudinal springs behave as fibers that carry only the tensile load, and transverse springs work as a matrix that carries only the shear load. The stiffnesses of longitudinal spring element $\mathbf{K}_L^e$ and transverse spring element $\mathbf{K}_T^e$ are calculated as

$$\mathbf{K}_L^e = \pi R^2 \int_0^l \mathbf{B}_L^{e^T} E \mathbf{B}_L^e dz \tag{1}$$

$$\mathbf{K}_T^e = \frac{\pi R l}{3} \int_0^d \mathbf{B}_T^{e^T} G \mathbf{B}_T^e dr \tag{2}$$

$$\mathbf{B}_L^e = \begin{bmatrix} \frac{1}{l} & -\frac{1}{l} \end{bmatrix} \tag{3}$$

$$\mathbf{B}_T^e = \begin{bmatrix} \frac{1}{d} & -\frac{1}{d} \end{bmatrix}, \tag{4}$$

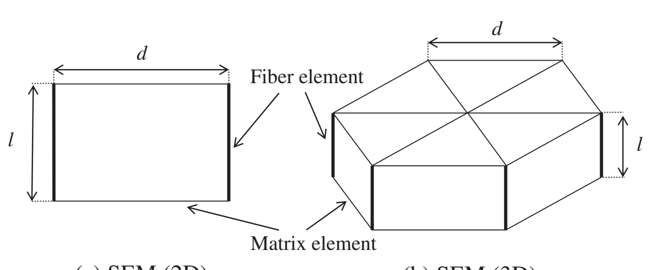

Fig. 1. Simulation models for (a) 2D-SEM, (b) 3D-SEM. In (a and b), the thick (thin) lines represent fiber (matrix) elements. The load is applied in the fiber axial direction.

where L is the longitudinal direction, T is the transverse direction, E is Young's modulus of fibers, G is the shear modulus of matrices, R is the radius of fibers, l is the length of longitudinal springs, and d is the length of transverse springs. It should be noted that 2D-SEM requires changing the stiffness of the transverse spring to

$$\mathbf{K}_T^e = \pi R l \int_0^d \mathbf{B}_T^{e^T} G \mathbf{B}_T^e dr. \tag{5}$$

In general, the stress profile of fibers varies due to plastic deformation and damage such as debonding and cracking of the matrix [13]. Since the matrix is modeled indirectly, implementing debonding and matrix cracking would be difficult. Therefore, for simplicity, this model considers only the effect of plastic deformation of the matrix. The axial stress in the broken fiber when plastic deformation occurs in the matrix around the fiber breaking point or the fiber edge is expressed as a function of distance D_s from those positions as follows:

$$\sigma^s = 2\tau_s D_s / R, \tag{6}$$

where τ_s is the interfacial shear stress and is assumed to be constant. Since τ_s is constant, the matrix behaves as an elasto-perfectly plastic body.

Thus, the equation of equilibrium is written as:

$$\left[\sum_{e=1}^{N_f - N_b - N_p} \mathbf{K}_L^e + \sum_{e=1}^{N_T} \mathbf{K}_T^e\right]\mathbf{u} + \sum_{e=1}^{N_p} \pi R^2 \int_0^l \mathbf{B}_L^{e^T} \sigma^s dz = \mathbf{f}. \tag{7}$$

Here, N_f is the number of fiber elements, N_T is the number of matrix elements, N_b is the number of broken fiber elements, and N_p is the number of fiber elements in the plastic deformation regions. The length of the plastic region (D_s) and the fiber stress in the region are preliminarily calculated using Eq. (6). This means that a non-linear problem is converted into a linear one; thus, it does not require iterative or incremental calculations.

The present numerical analysis addresses fiber failure as follows. The fiber failure criterion is assumed to be expressed as Weibull statistics [5]. The failure probability of fibers of length Δ subjected to stress σ is expressed as

$$P_f(\sigma) = 1 - \exp\left\{\left(-\frac{\Delta}{L_0}\right)\left(\frac{\sigma}{\sigma_0}\right)^{\rho}\right\}, \tag{8}$$

where ρ is the Weibull modulus and σ_0 is a representative strength for the fiber length L_0. The strength of the ith fiber segment is determined by choosing a random number R_i ranging from 0 to 1 and solving the equation $R_i = P_f(\sigma_i)$. When the fiber stress at the ith fiber segment reaches critical stress σ_i, a longitudinal element is removed from the model.

2.2. Periodic Unit-Cell (PUC) simulation

This section describes Periodic Unit-Cell (PUC) modeling. Because the scale of the material and the details of the fiber in fiber-reinforced plastics differ, it is difficult to analyze an entire model containing all fibers, due to computer limitations. We therefore use a unit-cell model that represents a characteristic cross section of fiber-reinforced plastics. By arranging the unit-cell models periodically, we can analyze fiber-reinforced plastics that contain many fibers.

Fig. 2 depicts the unit-cell modeling employed in the present study. This unit cell is assumed to deform under plane strain conditions. The fiber radius $\bar{r}_f$ in this 2D model should be half the actual radius in order to keep the stress recovery from fiber edges consistent with that in 3D. The fiber is assumed to be an isotropic elastic body and is modeled using nine-node square elements. The matrix is assumed to be an isotropic elastic–viscoplastic body intended for thermoplastic resin and is modeled using six-node