PARAMETRIC STUDY ON FIBER DEBONDING IN FIBER-REINFORCED POLYMERIC COMPOSITES

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ABSTRACT
This paper presents the results of our previous numerical studies (e.g., Lee, 2001) on damage evolution in chopped fiber-reinforced composites. It was intended to investigate the effects of the dominant debonding parameter $S_0$ on the evolution of fiber debonding. Progressive interfacial fiber debonding was considered in accordance with a statistical function to describe the probability of damage. The progressive damage model was implemented into the finite element program DYNA3D to simulate the progressive damage of the composites. Numerical simulations for a biaxial loading test were performed to examine whether the implemented computational model was able to predict the experimentally obtained results. Finally, a parametric analysis was carried out to systematically investigate the influence of Weibull parameter $S_0$ on the damage evolution in composites.

KEYWORDS
Parametric study, numerical simulations, progressive damage model, fiber-reinforced polymeric composites, probabilistic micromechanics.

INTRODUCTION
It is well known that fiber-reinforced composites are very susceptible to impact damages, especially at low velocities. Such damage is difficult to detect and may cause significant reduction in the strength and stiffness of the materials (Lee 2001). Hence, the predictive analytical and numerical tools are required to accurately evaluate and design fiber-reinforced composite structures for impact damage. In order to successfully develop these tools, a damage constitutive model (Lee and Simunovic, 2002) incorporating various damage mechanisms of fiber-reinforced composites is employed in the present study. In particular, a progressive interfacial fiber debonding model is considered in accordance with a statistical function to describe the varying probabilities of fiber debonding. The progressive damage model is then implemented into the finite element (FE) code DYNA3D to simulate the dynamic behavior and the progressive damage of the composites. Numerical simulations for a biaxial loading test are carried out to examine whether the implemented computational model is able to predict the experimentally obtained results. Finally, a parametric analysis is carried out to investigate the influence of Weibull parameter $S_0$ on the damage evolution in composites.

PROBABILISTIC MICROMECHANICS FOR PROGRESSIVE FIBER DEBONDING
The progressive, interfacial debonding between fibers and the matrix may occur under increasing deformations and influence the overall stress-strain behavior of composites. After the interfacial debonding, the debonded fibers may lose the load-carrying capacity in the debonded direction (Zhao and Weng 1996, 1997). However, they are still able to transmit internal stresses into the matrix through the bonded portion and are regarded as partially debonded fibers (Zhao and Weng 1996, 1997). It is assumed that the debonding of fibers is controlled by the stress of the fibers and the statistical behavior of the fiber-matrix interfacial strength (Lee et al. 2005). In the present study, the Weibull distribution is chosen to model the cumulative probability of the interfacial debonding (Lee 2001; Tohgo and Weng 1994; Zhao and Weng 1996, 1997).

The cumulative probability distribution function of fiber debonding at the level of hydrostatic tensile stress can be expressed as (Weibull, 1951)
\[ P_d[(\sigma_f)_m] = \int_0^{(\sigma_f)_m} p(\sigma_f)_m d(\sigma_f)_m = 1 - \exp \left\{ - \left[ \frac{(\sigma_f)_m}{S_0} \right]^M \right\} \] (1)

where \( S_0 \) and \( M \) are scale and shape parameters of the Weibull function, respectively; and \((\sigma_f)_m = [(\sigma_{f1}) + (\sigma_{f2}) + (\sigma_{f3})]/3\) are the hydrostatic tensile stresses of the fibers. Therefore, the current partially debonded (damaged) fiber volume fraction \( \phi_2 \) at a given level of \((\sigma_f)_m\) is given by

\[ \phi_2 = \phi_0 P_d[(\sigma_f)_m] = \phi_0 \left\{ 1 - \exp \left[ - \left( \frac{(\sigma_f)_m}{S_0} \right)^M \right] \right\} \] (2)

where \( \phi_0 \) is the original fiber volume fraction. The evolution of volume fraction of debonded fibers versus strains and the influence of Weibull modulus on the extent of damage are illustrated in Figure 1.

Furthermore, the relationship between average interfacial bond strength and Weibull modulus \( S_0 \) can be obtained through the Weibull statistical function. \((M=5)\)

\[ \tilde{\sigma}_f = S_0 \Gamma \left( 1 + \frac{1}{M} \right) = S_0 \int_0^{\infty} x^{\left( \frac{1}{M} - 1 \right)} \exp(-x)dx = \frac{S_0}{1.09} \] (3)

where \( \tilde{\sigma}_f \) is the quality of the interfacial bond strength between fibers and the matrix; and the Gamma function is defined as \( \Gamma(t) = \int_0^{\infty} y^{t-1} \exp(-y)dy \).

In Eq. (3), the average interfacial bond strength in composites is related to the yield stress of composites. More information can be found in Goan and Prosen (1969), Flom and Arsenault (1986), Ochiai and Osamura (1988), and Lee (2001). Consequently, there are two methods to measure the Weibull modulus \( S_0 \): (a) experimental prediction: the value of \( S_0 \) can be estimated from Eq.(3) after direct experimental measurement of the interfacial bond strength \( \tilde{\sigma}_f \); (b) parametric evaluation: the value of \( S_0 \) can be chosen to yield some simple interfacial strength conditions in damage modeling as a parametric study (see also Lee 2001). For example,

\[ \sigma_f = \sigma_y \rightarrow S_0 = 1.09 \sigma_y ; \quad \text{weak interfacial strength} \]
\[ \sigma_f = 3 \sigma_y \rightarrow S_0 = 3.27 \sigma_y ; \quad \text{intermediate interfacial strength} \]
\[ \sigma_f = 10 \sigma_y \rightarrow S_0 = 10.9 \sigma_y ; \quad \text{strong interfacial strength} \]
NUMERICAL SIMULATIONS FOR PARAMETRIC STUDY

Numerical Simulations for a Biaxial Test

Numerical simulations for a biaxial test are carried out to examine whether the implemented computational model is able to predict the experimentally obtained results. Towards reaching this goal, the numerical simulation of the biaxial test with cruciform shaped specimen containing centrally located cutouts is carried out. A computational model of the specimen and loading conditions are shown in Figure 2.

![Figure 2. FE model to simulate the damage evolution of cruciform shaped specimen](image)

The material properties and parameters for the simulation are assumed to be: $E_0 = 3.0 \text{ GPa}$, $\nu_0 = 0.35$, $E_i = 72.0 \text{ GPa}$, $\nu_i = 0.3$, $\phi = 0.3$, $\alpha = 5.0$, $S_0 = 165 \text{ MPa}$, and $M = 4.0$. Time history plots for the current volume fraction of damaged fibers $\phi_i$ around the cutout of the composite specimen are shown in Figure 3, which corresponds with Waas and Quek’s (1999) observations. For more details, refer to Lee (2001).

![Figure 3. Time history plots for the current volume fraction of damaged fibers around the cutout](image)

Parametric Analysis of the Weibull Parameter $S_0$

A parametric analysis is carried out in order to illustrate the influence of Weibull parameter $S_0$ on the damage evolution in composite materials and to evaluate constitutive model sensitivity to Weibull parameter $S_0$. As a debonding property of the fiber-matrix interface, four sets of the Weibull parameters are used: $S_0 = 0.109 \times 150 \text{ MPa}$ and $M = 4$; $S_0 = 0.80 \times 150 \text{ MPa}$ and $M = 4$; $S_0 = 1.09 \times 150 \text{ MPa}$ and $M = 4$; $S_0 = 10.9 \times 150 \text{ MPa}$ and
M=4. For comparison, four-point bend impact simulations are conducted using the same finite element model. Figure 4 represents the time history for the volume fraction of perfectly bonded fibers $\phi_1$ for various values of Weibull parameter $S_0$ at the contact surface of the composite plate around loading noses during the four-point bend impact. As shown in Figure 4, if the interfacial strength between fibers and the matrix is low (lower $S_0$), most fibers are debonded in early stage and the material will show the nonlinear behavior. For more details, refer to Lee (2001).

![Figure 4. Time history plots for the volume fraction of the fibers for various values of Weibull parameter $S_0$](image)

**CONCLUDING REMARKS**

Evolutionary interfacial debonding model was developed in accordance with the Weibull’s probability function to characterize the varying probability of fiber debonding. Fiber debonding was considered as a primary damage mechanism under impact. The constitutive damage model for progressive fiber debonding was implemented into the FE code DYNA3D to simulate the dynamic behavior and the progressive damage of composite materials.

Numerical simulations for a biaxial loading test were carried out to validate the computational model and investigate impact damage evolution in composite structures. Furthermore, parametric analysis was performed to investigate the influence of Weibull parameter on the damage evolution in composites. It was concluded from the parametric study that the influence of Weibull parameter $S_0$ on the constitutive behavior and damage evolution of the composite is quite remarkable. Although more laboratory experimental work is needed to determine the Weibull parameters, the implementation of a constitutive model into the finite element program has resulted in a promising numerical tool for the simulation of progressive damage in composite structures.

**REFERENCES**
