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A periodic unit-cell simulation of fiber arrangement dependence on the transverse tensile failure in unidirectional carbon fiber reinforced composites

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ABSTRACT

The effect of fiber arrangement on transverse tensile failure in unidirectional carbon fiber reinforced composites with a strong fiber-matrix interface was studied using a unit-cell model that includes a continuum damage mechanics model. The simulated results indicated that tensile strength is lower when neighboring fibers are arrayed parallel to the loading direction than with other fiber arrangements. A shear band occurs between neighboring fibers, and the damage in the matrix propagates around the shear band when the interfacial normal stress (INS) is sufficiently high. Moreover, based on the observation of Hobbiebrunken et al., we reproduced the damage process in actual composites with a nonuniform fiber arrangement. The simulated results clarified that the region where neighboring fibers are arrayed parallel to the loading direction becomes the origin of the transverse failure in the composites. The cracking sites observed in the simulation are consistent with experimental results. Therefore, the matrix damage in the region where the fiber is arrayed parallel to the loading direction is a key factor in understanding transverse failure in unidirectional carbon fiber reinforced composites with a strong fiber/matrix interface.

1. Introduction

Carbon fiber reinforced plastics (CFRP) are widely used in aerospace industries due to their superior mechanical properties. In those applications, unidirectional layers composed of long carbon fibers and polymer matrix are stacked to obtain multidirectional mechanical properties. These composite laminates are used most commonly. In general, when an external load is applied to composite laminates, cracks are initially generated in the transverse plies, where the fibers are aligned transversely to the loading direction (Garrett and Bailey, 1977). Those cracks become the origin of subsequent damage and cause transverse tensile failure (Takeda and Ogihara, 1994; Boniface et al., 1997; Okabe et al., 2008). Therefore, understanding the mechanism underlying cracking behavior is very important for the safe design of composite structures.

Transverse tensile failure in unidirectional carbon fiber reinforced composites has already been studied for over forty years. These studies indicated that cracks tend to form at the interface between the fibers and the matrix when the interface is weak. In contrast, if the fiber-matrix interface is sufficiently strong, cracks occur due to the matrix plasticity instead of the interface decohesion. In a previous study, Hobbiebrunken et al. (2006) conducted a bending test of CFRP under a scanning electron microscope and observed the initiation of cracks generated in a transverse ply of the laminate. They confirmed that a crack was generated in the matrix around the interface when the fiber-matrix interface was sufficiently strong. Moreover, they calculated the stress distribution in the transverse ply with the finite-element homogenization method and found a strong correlation between the cracking position and the interfacial normal stress (INS). In their succeeding paper (Hojo et al., 2009), they concluded that the variation of INS from one interface to another is controlled by the irregularity of fiber arrangement. Thus, it is important to clarify the effect of fiber arrangement on transverse tensile failure. However, they did not discuss the damage or crack growth generated in the matrix and/or the interface. In another work, Canal et al. (2009) analyzed the damage process in a transverse ply under a combined stress state (tension and shear). To address the damage due to the matrix plasticity and the interface decohesion, they utilized the constitutive law proposed by Jeong (2002), which considers the void growth in the matrix. They found that shear cracks due to matrix plasticity are generated and connected along interfaces when the fiber-matrix interface is sufficiently strong. Therefore, the relationship between fiber arrangement and the cracks due to matrix plasticity should be studied to clarify the mechanism of transverse tensile failure.

Recently, we proposed a continuum damage mechanics model addressing the damage growth in epoxy resin, by reproducing cracking behavior in the matrix at the stress concentration area

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