Mechanics of Materials 58 (2013) 35–54

Contents lists available at SciVerse ScienceDirect

Mechanics of Materials

journal homepage: www.elsevier.com/locate/mechmat

The effect of a graded interphase on the mechanism of stress transfer in a fiber-reinforced composite

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ARTICLE INFO

Article history:
Received 3 February 2012
Received in revised form 12 September 2012
Available online 1 December 2012

Keywords:
Fiber-reinforced composites
Graded interphase
Shear-lag model
Stress transfer
Shear failure

ABSTRACT

Based on an improved shear-lag model, the effect of an inhomogeneous interphase on the mechanism of stress transfer in fiber-reinforced composites is investigated. The inhomogeneity of the interphase is represented by the graded feature of the Young's modulus varying according to a power law or a linear one in the radius direction, while the Poisson's ratio and thermal expansion coefficient are assumed to be constants. Considering the effects of the inhomogeneous interphase as well as the Poisson's contraction and thermal residual stress, closed-form solutions to the axial fiber stress and interfacial shear stress are obtained analytically. Comparing the case with a power law to that with a linear one, we find that the fiber stress increases significantly in the former case, while it decreases slightly in the latter one with an increasing interphase thickness. With the same external tensile load and interphase thickness, it is found that the fiber in the power law case is subjected to a larger tensile stress than that in the linear variation one. However, the interfacial shear stress is not sensitive to the interphase thickness in both cases, except that near the two ends of fiber. Under the same external load, the maximum shear stress in the interphase is much smaller in the latter than that in the former. All the phenomena can be characterized by one parameter, i.e., the average Young's modulus of interphase, and denote that an interphase with a power variation law is more effective for stress transfer while the linearly graded one is more advantageous to avoid shear failure. The results should be helpful for engineers to properly design the interphase in novel composites, e.g. a carbon-fiber reinforced epoxy one.

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1. Introduction

The mechanical properties of composites are affected by a number of factors, such as the volume fractions and constitutive behaviors of different constituents, some of which have been systematically reviewed in the recent papers (Fu et al., 2008; Lauke, 2006). Among the influencing factors, interphase, as one of the dominant elements, will show great significance on the composite performances (Yang and Pitchumani, 2004). During the process of manufacturing composites, physical and chemical interactions between reinforcements and matrix result in the formation of interphase encompassing the reinforcement/matrix interface (Drzal, 1986; Hughes, 1991; Theocaris, 1990; Williams et al., 1994). As an intermediate transition zone linking the reinforced fibers and matrix, the interphase plays a key role during the stress transfer between fibers and matrix (Hughes, 1991; Swain et al., 1990). Via proper design of an interphase zone in composites, the interfacial adhesion can be effectively improved, leading to a more efficient load transfer at interfaces. As a result, the overall stiffness and strength of composites can be enhanced since more external loads are sustained by the stiff reinforcements (Fu et al., 2008; Rjafiallah et al., 2010). Therefore, understanding and disclosing the micro-mechanism of stress transfer in fiber-reinforced composites with

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0167-6636/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.mechmat.2012.11.008

interphase should be of great significance for the design of advanced composite materials.

Relevant experimental studies are relatively few due to the complexity of interphase composition, although the importance of the interphase has been fully acknowledged for a long time. The formation of an interphase depends directly on the chemical, mechanical and thermo-dynamical natures of the bonding process between fibers and matrix, which leads to spatially non-uniform properties of interphase in the thickness direction (Hughes, 1991; Gao and Mader, 2002; Liu et al., 2008; Naslain, 1998; Zhang et al., 2010). The size of an interphase region is rather small (at sub-microscopic scale) and experimental tests of the interfacial characteristics should be affected by many factors, such as the specimen geometries and fiber volume fractions (Atkins, 1975; Hughes, 1991; Liu et al., 2008; Zhang et al., 2010). An unequivocally experimental method to determine the realistic distributions of interphase properties is not yet available.

In contrast to a few experimental studies, a large number of theoretical and numerical investigations have been carried out in order to figure out how the interphase properties influence the overall mechanical behaviors of a fiber-reinforced composite. For simplicity, the interphase in many micromechanical models is assumed to be a homogeneous material (Christensen and Lo, 1979; Hashin, 1990; Hayes et al., 2001; Qiu and Weng, 1991; Rjafiallah et al., 2010; Tsai et al., 1990), or divided into many homogeneous sub-layers with different properties (Jiang et al., 2008; Mogilevskaya and Crouch, 2004; Wang et al., 2006). More realistic and accurate models regard the interphase as an inhomogeneous region with mechanical properties varying continuously in the thickness direction (Huang and Rokhlin, 1996; Jayaraman and Reifsnider, 1992, 1993; Kiritsi and Anifantis, 2001; Low et al., 1995; Lutz and Zimmerman, 2005; Romanowicz, 2010; Shen and Li, 2003), in which several empirical laws, such as power, linear and exponential ones, are used to describe the variations of the elastic modulus, Poisson's ratio or thermal expansion coefficient. Based on these models, the influences of an inhomogeneous interphase on the mechanical performances of composites, e.g. the thermal stress distribution and overall stiffness, can be qualitatively investigated.

Though a lot of attention has been paid to the effects of interphase properties on the stress transfer in a fiber-reinforced composite, most of them are numerical studies (Hayes et al., 2001; Kiritsi and Anifantis, 2001; Needleman et al., 2010; Wu et al., 1997). As for theoretical researches, the shear-lag model (Cox, 1952) is always chosen as a simple and effective approach, based on which a three-dimensional cylindrical or three-phase shear-lag model was often adopted (Afonso and Ranalli, 2005; Fu et al., 2000a,b; Monette et al., 1993; Tsai et al., 1990; Zhang and He, 2008). However, the interphase was also always modeled as a homogeneous material in these works. Few researchers used the shear-lag model to analyze the stress transfer in a fiber-reinforced composite with an inhomogeneous interphase.

In the present paper, an improved three-phase shear-lag model is established, in which an inhomogeneous interphase is taken into account. The inhomogeneity of the interphase is represented by a non-uniform Young's modulus, which varies according to a specially graded law, i.e., a power law and a linear one, while the Poisson's ratio and thermal expansion coefficient are assumed to be constants. An average interphase modulus, denoted as the integration of Young's modulus over the thickness divided by the interphase thickness, is introduced as a value to evaluate the effective stiffness of the inhomogeneous interphase. Then, the shear-lag governing equations for the two cases with differently graded laws are derived, in which the effects of Poisson's contraction and thermal residual stress are included too. Finally, the effects of interphase properties on the stress transfer in uni-directionally fiber-reinforced composites are explored. Comparisons are made for the two cases with different graded variations of interphase. The analytical solutions are also compared to the numerical ones in order to validate the constant assumptions of Poisson's ratio and thermal expansion coefficient in our model. The results in this paper should be helpful for optimal designs of an interfacial region in some novel composites with a thermosetting matrix and stiff fibers, e.g. carbon fiber-reinforced and carbon nanotube (CNT)-reinforced epoxy composites.

2. Basic model and general formulae

A three-phase concentrically cylindrical unit cell for a unidirectional fiber-reinforced composite is shown in Fig. 1, in which the cell is subjected to a uniform tensile load σ_0 at two ends and the lateral surfaces are traction free. The radius of the fiber cylinder is r_f and the length is L_f, surrounding which is a coaxially inhomogeneous interphase with the thickness t and radius r_i. Here $r_i = r_f + t$ as shown in Fig. 1. The radius of the matrix is r_m and the length is L_m. Thus, the volume fraction of fibers V_f in the fiber-reinforced composite can be expressed as

$$V_f = \frac{\pi r_f^2 L_f}{\pi r_m^2 L_m} = \frac{r_f^2 L_f}{r_m^2 L_m} \tag{1}$$

There are two interfaces in the three-phase model, i.e. the fiber/interphase interface and the interphase/matrix one, both of which are assumed to be perfect bonding. All the fiber, matrix and interphase are regarded as linear elastic and isotropic materials with E_f, ν_f, κ_f, E_m, ν_m, κ_m, E_i, ν_i, κ_i being their Young's moduli, Poisson's ratios and thermal expansion coefficients, respectively. The subscripts f, m and i represent the fiber, matrix and interphase. For simplicity, only the Young's modulus of the interphase is assumed to be spatially non-uniform in the radial direction, i.e., $E_i = E_i(r)$, while the Poisson's ratio and thermal expansion coefficient of the interphase are constants, as treated in Jayaraman and Reifsnider (1992) and Yang and Pitchumani (2004). In the following text, the constant assumptions of Poisson's ratio and thermal expansion coefficient will be proved to be reasonable. Then, an average modulus of the interphase can be defined as

$$\bar{E}_i = \frac{1}{r_i - r_f}\int_{r_f}^{r_i} E_i(r)dr = \frac{1}{t}\int_{r_f}^{r_i} E_i(r)dr, \tag{2}$$

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