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Numerical simulation of matrix micro-cracking in short fiber reinforced polymer composites: Initiation and propagation

Hansong Huang, Ramesh Talreja *

Department of Aerospace Engineering, Texas A&M University, College Station, TX 77843-3141, USA

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Abstract

This paper presents a numerical simulation based analysis of micro-cracking in short fiber reinforced polymer composites. For this case, the conventional linear elastic fracture mechanics approach is shown not to be useful; instead, the Rice–Tracey ductile fracture model is shown to work well in the framework of the local approach to fracture. The model is first applied to the case of matrix cracking from the broken fiber end in a fiber fragmentation test of a single-fiber reinforced composite. The model predicts the measured conical crack path successfully, including the crack initiation angle and the kink formation as the crack propagates away from the fiber. Furthermore, the predicted dependence of the crack length on the nominal strain is found to be in qualitative agreement with measured data. Next the model is applied to micro-cracking in an aligned short fiber composite. The analysis predicts propagation of a matrix crack from the debonded fiber end towards the neighboring fiber at an oblique angle to the fiber axis. Before reaching the neighboring fiber, the crack is found to divert gradually towards the fiber axis. This behavior explains the so-called fiber-avoidance cracking mode reported in the literature. A parametric study is performed to reveal the dependence of the locally-averaged failure stress/strain on the fiber length and volume fraction.

Keywords: A. Short fiber composites; B. Matrix cracking; B. Plastic deformation; C. Damage mechanics; Ductile fracture

1. Introduction

Short fiber reinforced polymer composites have great potential to be widely used as load bearing materials, in particular in the automotive industry, for benefits such as mass reduction, corrosion resistance, and parts reduction. The enhanced use of these composites will result from the ability to reduce the design and manufacturing cost, particularly through optimizing the material properties by trade-off with manufacturing cost to realize the best performance/cost ratio. Progress has been made towards characterizing and predicting the micro-structures of as-manufactured materials from process simulation (such as injection molding simulation) and using such information to predict the elastic properties [1–3]. However, safe and reliable applications necessitate effective methods for failure and life prediction. In spite of research efforts over more than three decades, accurate tools for predicting static and fatigue failure of short fiber composite materials are still absent, mostly due to the complexity of micro-damage processes that have not been fully understood. The micro-structural features, such as fiber volume fraction and length and orientation distributions, determine the properties, especially the failure properties, of the composites through their influence on the initiation and evolution of the micro-damages. Observations have revealed the various micro-damage mechanisms involved in the failure process, including fiber/matrix interface debonding, matrix micro-cracking, and fiber breakage [4–10]. In general, the process can be described as having the following four stages. Stage 1: The matrix debonds from the fiber ends, often at an early stage of loading. It does not necessarily lead to other

* Corresponding author. Tel.: +1 979 458 3256; fax: +1 979 845 6051.
E-mail addresses: hhs@tamu.edu (H. Huang), talreja@aero.tamu.edu (R. Talreja).

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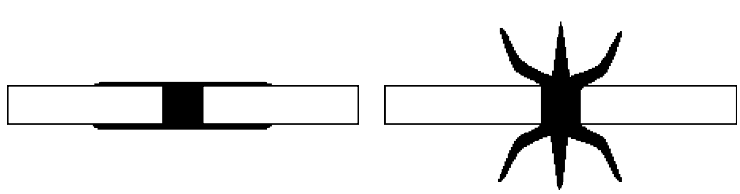
damage immediately, but rather causes localized plastic deformation. Stage 2: Matrix cracking and fiber/matrix interface debonding are induced by the stress concentration from the debonded fiber end. The interface crack and/or matrix crack propagates with increased loading. Stage 3: The discretely formed micro-cracks coalesce and form macroscopic crack. Stage 4: The macroscopic crack propagates unstably, leading to final failure. Materializing these descriptive observations into quantitative micro-mechanics models is, however, not an easy undertaking.

Tremendous efforts have been devoted to experimentally determining the relationship between the fiber micro-structures and the properties of composites, but with typically little or no understanding of the underlying mechanisms [11–14]. Besides being highly inefficient and costly, the design of experiments (DOE) approach faces the daunting task of distinguishing between influences of many possible parameters and their interactions. Compared with the experimental efforts, much less work has been done in developing models that can at least qualitatively predict the influence of the micro-structure on the failure properties [15–18]. A recent review was given by Fu et al. [18]. Due to the lack of valid methods to analyze the micro-damage mechanisms, most models have been based on simplistic empirical assumptions of uncertain validity. One such example is the widely used Kelly–Tyson model for predicting strength of discontinuous fiber composites based on the critical fiber length concept. Many researchers have pointed out that fiber breakage is not the dominant mechanism in composites that have relatively short fibers, such as in most injection-molded parts [6,8,12,19]. Another example is the somewhat arbitrarily assumed micro-crack orientations in some stiffness degradation models [15,16,20]. It is only through successful development of micro-mechanics models, which can analyze and simulate the micro-damage mechanisms, that the influence from composites micro-structures can be fully understood and predicted [21]. The purpose of the present work is to take steps in this direction.

1.1. Matrix micro-cracking

The complication in developing and verifying a micro-mechanics damage model often lies in the interaction between interface debonding and matrix micro-cracking. It is desirable to develop a model for one of them first before considering the interaction. The micro-cracking mechanism is investigated in this paper since the interface debonding can be suppressed in composites that have strong interface, especially if appropriate sizing exists. Fractography has shown that in such materials fiber surfaces are mostly covered with remnants of matrix material, indicating the undamaged interface [7,8,22,23]. Clearer evidence exists in the single fiber composite fragmentation test. With the increase of interface strength and/or decrease of matrix yielding stress, the damage mode after the fiber breakage transits from interface debonding to matrix cracking (see Fig. 1). This trend has been confirmed by many researchers in both single fiber composites and short fiber composites [8,24–28]. It can be concluded that if the interface is strong and/or the matrix is ductile, the matrix plastic deformation and the subsequent cracking near the stress concentration point, typically at the fiber end, relieve the stress so that debonding is suppressed. Under such circumstances the matrix micro-cracking becomes the governing mechanism. Yet, quantitative in situ observation of matrix micro-cracking is difficult and observation can only be made at the specimen surface. Because of the difference in the stress state, i.e., nearly plain stress on surface and nearly plain strain in the interior, the cracking process can likely be different [29]. On the other hand, the fragmentation test, in which the internal crack can be observed by transmitted polarized light, provides a "test ground" for models developed for the composites as it offers conditions in the damage initiation phase similar to those in the short fiber composites.

Two types of cracks, shown in Fig. 1 schematically, arise in fragmentation tests: penny shaped cracks that are perpendicular to the fiber axis and conical cracks that are initially oblique (reportedly 20–45°) to the fiber axis. The conical cracks kink towards the direction normal to the fiber axis as they propagate away from the fiber [26,28,30–32]. Selvadurai et al. [31] have quantitatively recorded the crack paths in a fragmentation test. The measured path of a typical conical crack is reproduced in Fig. 2. Both the oblique initial direction and the kink in the crack path are clearly seen. The two types of cracks can appear at the same time or individually. It is generally believed that the penny shaped cracks are due to the brittle dynamic fracture and naturally occur along normal to the maximum tensile stress. However, there has been no explanation of the formation of the conical cracks other than that they might have been caused by shear deformation [32]. The conical cracks have been observed in composites



a). Interface debonding b). Matrix cracking

Fig. 1. Damage modes in single fiber composite fragmentation test: (a) debonding when interface is weak; (b) matrix cracking when interface is strong [31].