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Micromechanical model of the single fiber fragmentation test

Bent F. Sørensen

Section of Composites and Materials Mechanics, DTU Wind Energy, Risø Campus, The Technical University of Denmark, DK-4000 Roskilde, Denmark

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ABSTRACT

A shear-lag model is developed for the analysis of single fiber fragmentation tests for the characterization of the mechanical properties of the fiber/matrix interface in composite materials. The model utilizes the relation for the loss in potential energy of Budiansky, Hutchinson and Evans. The model characterizes the interface in terms of an interfacial fracture energy and a frictional sliding shear stress. Results are obtained in closed analytical form. An experimental approach is proposed for the determination of the interfacial fracture energy and the frictional shear stress from simultaneously obtained data for the applied strain, the opening of a broken fiber and the associated debond length. The residual stresses are obtained as a part of the approach and enables the determination of in-situ fiber strength.

1. Background

It is well-recognized that the overall mechanical properties of composite materials, such as strength, toughness and delamination resistance, depend strongly on the mechanical properties of the fiber/matrix interface (Curtin, 1991; Hutchinson and Jensen, 1990; Feih et al., 2005; Sørensen et al., 2008). The idea to characterize the fiber/matrix interface in terms of a critical shear stress determined from the saturated lengths of broken fiber fragments originated from the classical work by Kelly and Tyson (1965). More detailed stress analysis has shown that the elastic shear stress ahead of a fiber break is highly non-uniform (Graciani et al., 2009). Nevertheless, the single fiber fragmentation test remains widely used to characterize polymer matrix composites due to its simplicity, since breakage of fibers and thus the spacing between fiber breaks can easily be determined by conventional optical microscopy for test specimens consisting of transparent matrix materials (Tripathi and Jones, 1998).

The description of the interface in terms of a single strength value has been challenged. Outwater and Murphy (1969) proposes to characterize the mechanics of the fiber/matrix interface in terms of an interfacial fracture energy and a frictional shear stress acting along the debonded surface. They also developed a model to determine the interfacial fracture energy from measurements of the applied stress and the debond length of a broken or cut fiber. Since then, more advanced fracture mechanics model have been developed. Many of these models also include a more accurate description of the stress state, include residual stresses and account for Poisson's effects of the fibers and matrix and describe the mechanics of the debonded interface by Coulomb friction. As a result, most of these models appear complicated (Wagner et al., 1995; Wu et al., 2000; Graciani et al., 2009); some models only exists as numerical models so that a parameter study must be conducted for each test series to determine interface parameters; this is obviously not a very efficient approach for the analysis of data from single fiber fragmentation tests. In other cases, additional parameters, such as the residual stresses and/or the friction coefficient (in models using Coulomb friction) must be calculated or determined from independent experiments (Nairn, 2000; Ramirez et al., 2009).

In addition, Varna et al. (1996) noted that the fiber breakage and fiber/matrix debonding are two independent features and that debonding may not always occur immediately after fiber breakage but may require a substantial higher strain.

Kim and Nairn (2002a) provided a detailed description, documented by micrographs, of the evolution of damage in single filament specimens subjected to increasing applied strain. They used polarized light to visualize the shear stress field around a broken fiber. They found that an initial debonding developed during the fiber breakage. The debond length and the fiber break gap were found to increase with increasing applied strain, whereas the fiber gap decreased during unloading. The maximum debond length was 16–17 times the fiber diameter (224 µm). Images showed that some fiber break gaps were several times the fiber diameters (up to 30–50 µm). Such observations clearly show that for these material systems, a model based on interfacial fracture energy and sliding friction provides a better description of the fiber/matrix interface than a model based on a constant shear stress.

Kim and Nairn (2002a) reported both the "whole debond" length (the average value of all debond length of all locations

E-mail address: bsqr@dtu.dk

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of fiber break of a specimen) and “instantaneous debond length” (the debond length associated with new fiber breaks, i.e. fiber breaks that occurred between the present and previous load step) as a function of applied strain. For glass/epoxy, Kim and Nairn (2002a) found that the data for “whole debonds” and “instantaneous debonds” were identical for small applied strain (indicating little or no interaction between the fiber breaks, i.e., isolated fiber breaks) but deviate for strains larger than 2.75%, indicating interaction between the locations of fibre break.

Kim and Nairn (2002a) analyzed their experimental data using the analytical model of Nairn (2000), a mathematical model that incorporates Poisson’s effects in an approximate way and models the mechanics of the interface in terms of an interfacial fracture energy and Coulomb friction. The model predicts an initial non-linear relationship (progressive increase in debond length) between applied strain and debond length, followed by a linear relationship (isolated fiber breaks) and finally a non-linear relationship (decreasing debond growth rate) for high strains, as fiber breaks interact. In an accompanying study (Kim and Nairn, 2002b), debond data were presented for “instantaneous debonds” only, and only up to the strain value up to 3.0%, i.e. strain values where there were little interaction between fiber breaks. Kim and Nairn (2002b) concluded that to get correct parameter values, the debonding experiments should be combined with other experiments that can measure residual stresses and friction. Nevertheless, they identified the interfacial fracture energy to be 120 J/m^2 and the frictional parameter to be 0.01.

Graciani et al. (2009) developed a numerical model using the boundary-element method (BEM). The interface was modelled in terms of a fracture energy and Coulomb friction and the model included residual stresses. The model predicts that the debond crack tip singularity becomes weaker (i.e. a power less than 1/2) in the presence of friction. The model predicts that the relationship between debond length and applied strain is non-linear (debond length increasing progressing with increasing strain) for debond length smaller than about five fiber radii, and a linear relationship with a finite, constant slope for larger debond lengths. Apparently, the non-linear relationship between strain and debond length (for small debonds length) is due to a variation in the energy release rate with debond length for fixed overall strain; the energy release rate starts very high and decreases rapidly with increasing debond crack length attaining a steady-state value when the debond crack length exceed about five fiber radii.

Graciani et al. (2011) analyzed the experimental data of Kim and Nairn (2002b) using the numerical BEM model. They obtained best agreement with the experimental data with a Coulomb friction coefficient of 1.0 and an interfacial fracture energy of 12 J/m^2 . Recall that Kim and Nairn (2002b) determined the interfacial fracture energy to be 120 J/m^2 for the same data. It is remarkable that analyzing the same data, the two advanced models (that of Nairn (2000) and that of Graciani et al. (2011)) identify parameters that are widely different, despite both incorporate residual stresses, Coulomb friction and Poisson’s effects. There is thus a need for a clearer approach for parameter identification. A drawback of the advance models is that they are a bit complicated to use - parameters are not determined in a straight forward manner - and it is not possible - due to model complexity - to see the sensitivity of each parameter on model predictions. The simple shear-lag model that is developed in the present paper enables a clearer parameter identification from experiments data.

The accuracy of analytical shear-lag models can be assessed by comparing their predictions with predictions from more accurate numerical models. Such comparisons were made by Hutchinson and Jensen (1990) who developed closed form analytical shear lag models for fibre debonding and pull-out. The fiber/matrix interface was modelled in terms of an interfacial fracture energy and a constant interfacial frictional shear stress or by Coulomb friction. The model also includes Poisson’s effects and residual stresses. They compared results from the analytical model with accurate numerical results. They found that the energy release rate of the numerical model approaches that of the analytical model when the debond length is larger than about one fiber radius. They also compared the displacement difference between the lower end of fiber and matrix and found that the analytical model become increasing accurate as the debond length grows. According to Hutchinson and Jensen (1990), the difference should not be of much significance when the debond length is longer than about five times the fiber radius.

The proper way of mechanical characterization of frictional sliding remains an open issue. Mackin et al. (1992) and Liang and Hutchinson (1993) have proposed an interfacial friction sliding law of the form

$$\tau_s = \tau_0 - \mu\sigma_{rr} \qquad for \;\; \sigma_{rr} \le 0 \tag{1}$$

where τ_s is the frictional sliding shear stress, τ_0 represents friction introduced by roughness, μ the Coulomb friction coefficient and σ_{rr} is the radial normal stress at the debonded fiber/matrix interface. Connell and Zok (1997) found that such a description could represent the sliding behavior of a ceramic fiber composite well. They found that a constant sliding shear stress could described the sliding behavior well at one temperature; the second term in (1) allows the description of different frictional sliding stresses at various other temperatures (via changes in the radial normal stress, σ_{rr}).

The motivation for the present study is thus to develop an analytical model and an approach for the determination of the interfacial fracture energy and the frictional sliding shear stress from a tensile specimen consisting of a single filament embedded in a matrix specimen subjected to uniaxial tension. More specifically, we wish to develop a practical approach for the determination of the frictional shear stress, τ_s, and the interfacial fracture energy, $\mathscr{G}_c^i$ from experiments, accounting for the residual stresses.

In the present paper, we propose to use data for the broken fiber gap as an additional experimental parameter to measure - building on the conclusion of Kim and Nairn (2002b) that additional experimental data are needed. Moreover, we propose a new 1-D model that is simpler that the models of Wu et al. (2000) and Nairn (2000). An advantage of the new, simpler model is that it gives a clearer relationship between interface parameters and measure properties so that it becomes easier to assess the effect of interfacial parameters from experimental data. Being a shear-lag model, it only applies for debond lengths larger than about five fiber radii.

Obviously, the hope is that the model enables the determination of interface parameters which can be considers being material properties and thus be used in micromechanical models of composites with much higher fiber volume fraction (typically, 40–60% in engineering composites). This would enable tests of single filament composites to be used as the primary tool for characterization of mechanical properties of fiber/matrix interface. Investigations of how changes in fiber surface treatments, composite processing conditions alters the mechanical properties of the fiber/matrix interface (e.g., van der Waals or covalent bonds) will then help the development of composite materials with improved properties. This assumption will be discussed in more details in Section 7.

2. Problem description

The problem to be analyzed is a single fiber embedded in a tensile test specimen made of the matrix material as shown in Fig. 1. We consider a situation where the applied stress level is $\bar{\sigma}$, the