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The fiber break evolution process in a 2-D epoxy/glass multi-fiber array☆

E.D. McCarthy [a, 1], J.H. Kim [a], N.A. Heckert [b], S.D. Leigh [a], J.W. Gilman [a], G.A. Holmes [a, *]

[a] *Materials Science and Engineering Division, National Institute of Standards and Technology, Gaithersburg, MD 20899-8541, United States*
[b] *Statistical Engineering Division, National Institute of Standards and Technology, Gaithersburg, MD 20899-8980, United States*

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ABSTRACT

The mechanical integrity of a structural composite is strongly affected by the strength and toughness of the fiber–matrix interface/interphase (Norwood, 1994), with interfacial shear strength (IFSS) being generally accepted as the best quantifying metric. The value of the IFSS is not directly measurable, but it can be approximated by several micromechanics based test methods with the value obtained being dependent on the choice of the model. The most popular of these test methods is the embedded single fiber fragmentation test (SFFT) which provides the experimental data needed to estimate the IFSS: (a) mean fragment length at saturation and (b) fiber strength at the critical fragment length.

Because the IFSS is used in unidirectional composite models to predict strength and failure behavior, where the interaction between fibers can be important, the validity of extrapolating from test results based upon the repeated failure of a single isolated fiber has often been questioned. In this paper, the spatial distribution of fiber breaks in a 2-D array of glass fibers is compared with break locations observed from SFFT specimens. In both cases, the break locations in each fiber were found to evolve to a uniform distribution, thereby confirming that the ordered fragment lengths from the repeated fracture process conforms for both SFFT and multi-fiber fragmentation test (MFFT) specimens to a cumulative distribution function (CDF) derived by Whitworth (1887) and cited by others (Read, 1988; Pyke, 1988; Holst, 1980). The array break density was also observed to be less than the break density in isolated fibers, and break locations across array fibers were observed to be highly coordinated and mostly aligned.

1. Introduction

The mechanical integrity of a structural composite is strongly affected by the strength and toughness of the interface/interphase that is formed between the continuous matrix phase, or resin, and the reinforcing phase, normally consisting of closely spaced carbon or glass fibers [1]. Interfacial shear strength (IFSS) is the generally accepted parameter for quantifying the strength of the matrix–fiber interface/interphase and is used to model a composite's strength and failure behavior. However, the value of the IFSS is not directly accessible by measurement and must be approximated indirectly from experimental data obtained from micromechanics test methods and a single fiber composite (SFC) model that has been modified for composite analyses.

One mechanical test that generates such data is the single fiber fragmentation test (SFFT) [2–7] which involves the repeated fracture of the embedded fiber to a point called saturation (cessation of fiber breaks). By recording the overall strain and load on the fiber at saturation, as well as the number of breaks (current practice) and associated fragment lengths, an approximate calculation for the IFSS is obtained using models derived from the 'fiber' free body diagram shown in Fig. 1. The limitations of the various micromechanical models developed to calculate the IFSS have been well documented [8–18]. The equation for calculating the IFSS, τ_i, has the following general form:

$$\tau_i = r_f f\{l_c\}\sigma_f(l_c) \tag{1}$$

where

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* Corresponding author.

E-mail address: gale.holmes@nist.gov (G.A. Holmes).

[1] Current address: University of Manchester Aerospace Research Institute, Manchester M13 9PL, UK.

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r_f is the radius of the fiber.
$\sigma_f(l_c)$ is the strength of the fiber at the critical transfer length, l_c [13,19].
$f\{l_c\}$ is a function of l_c with the explicit expression depending on model assumptions with the two most popular models being the Kelly–Tyson (K–T, Eq. (1a)) and the Cox (Eq. (1b)) models [20].

$$\text{Kelly–Tyson Model}: \; f\{l_c\} = \frac{1}{l_c} = \frac{K'}{\bar{l}_f} \tag{1a}$$

$$\text{Cox Model}: \; f\{l_c\} = \frac{\beta}{2}\frac{\sinh(\beta l_c/2)}{\cosh(\beta l_c/2) - 1} \tag{1b}$$

$$\beta = \frac{1}{r_f}\left[\frac{E_m}{(1+\nu_m)(E_f - E_m)\ln\left(r_m/r_f\right)}\right]^{\frac{1}{2}}$$

K' variability correction factor has a value of 0.75 or 0.668 [21].
E_m, E_f are the modulus of the matrix and fiber, respectively.
r_m, r_f are the radius of the matrix and fiber, respectively.
ν_m is the Poisson's ratio of the matrix.

In reviewing the fragmentation test protocol, Curtin [22] indicated the need to record break locations along the fiber axis within the gauge length of interest, thereby allowing the actual fragment length distribution to be recorded and modeled. Drzal et al. [7] followed this approach and generated a fragment length distribution for two different fibers (sized and unsized) in an epoxy/carbon fiber system. They reported good fits of their fragment length data to a Weibull distribution. However, the Weibull distribution function has not always been successful in modeling fragment length data. Bascom and Jensen [23] reported that their fragment length data collected from ten separate carbon fibers in epoxy matrices, were not well modeled by a Weibull distribution, which suggested that an alternative statistical approach might be more accurate in representing such data. Others [13,24] have advocated the use of a log normal distribution. In 2009, a possible alternative to using Weibull statistics for fragment length data was proposed by Kim et al. [5], who demonstrated that a uniform distribution could be very successfully applied to describe the spatial arrangement of break centroids along a fiber axis. The application of Uniform Spacings theory gives an explicit equation for the ordered fragment *length* distribution due to Whitworth [25–28].

In 1995, a multi-fiber fragmentation study using 2-D Nicalon fiber arrays showed that the mean fragment length in an array is typically larger than the mean fragment length obtained from the repeated fragmentation of a single fiber [29]. The fragment length was shown to increase with smaller inter-fiber separation and/or more embedded fibers. Li et al. [29] observed that the Cox-type shear-lag theories, which are the basis for composite models, predict the opposite effect. These results led the researchers to

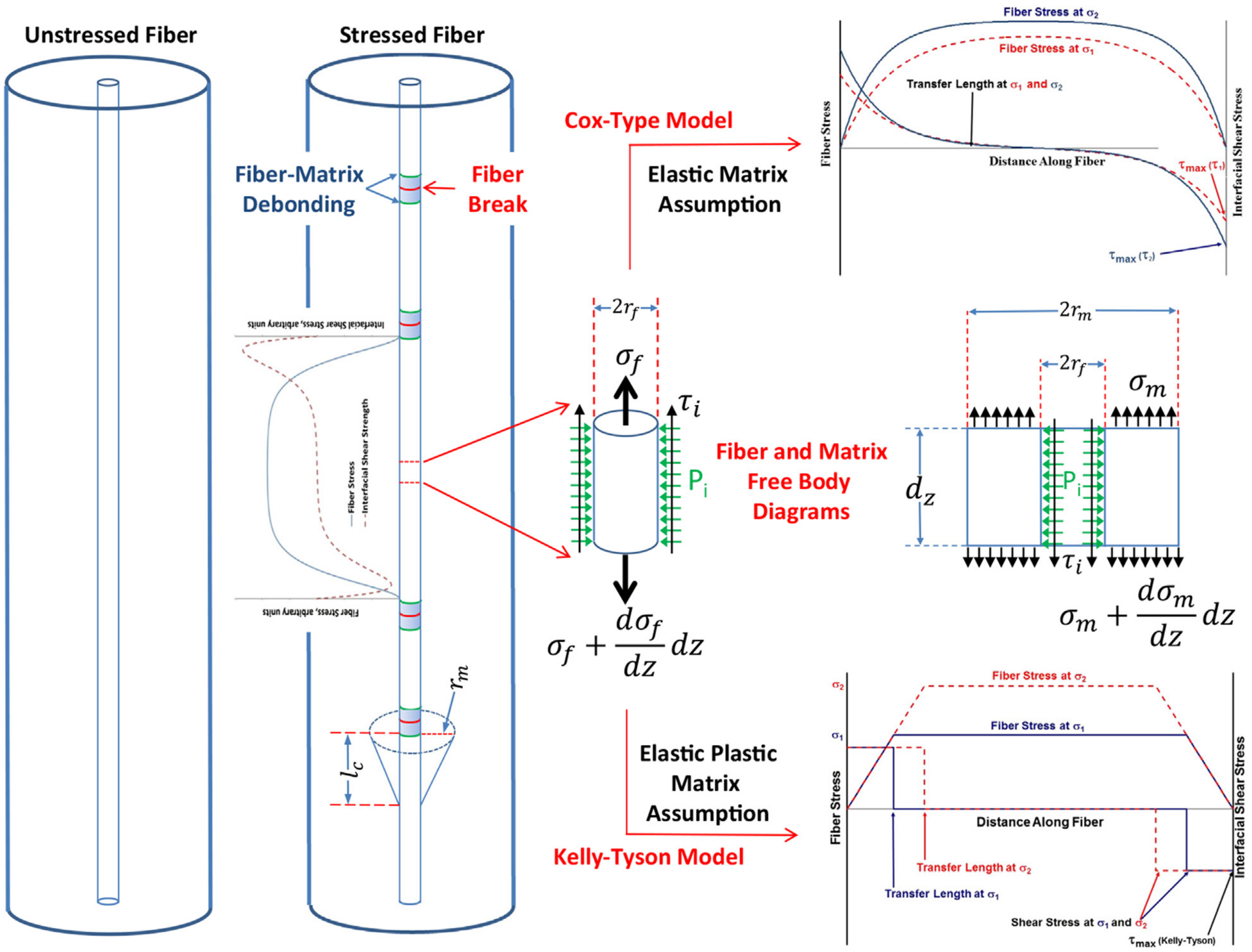

Fig. 1. Principle of the fragmentation test. Free body diagrams for developing models of the fiber–matrix interface stress-transfer process and the magnitude of the shearing forces that emanate radially into the matrix (*adapted from* [48]).