Composites Science and Technology 108 (2015) 16–22

Contents lists available at ScienceDirect

Composites Science and Technology

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

Matrix cracks around fibre breaks and their effect on stress redistribution and failure development in unidirectional composites

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A R T I C L E I N F O

Article history:
Received 1 July 2014
Received in revised form 23 December 2014
Accepted 3 January 2015
Available online 9 January 2015

Keywords:
A. Polymer-matrix composites (PMCs)
B. Matrix cracking
C. Stress concentrations
C. Probabilistic methods

A B S T R A C T

Despite the crucial significance of failure prediction in composites, such an objective remains challenging, even in unidirectional (UD) systems. A strength model for UD composites was used that has great versatility in handling various matrix and fibre behaviours. This model includes a simplified superposition principle that was found to be reliable in predicting stress concentration factors irrespective of the presence of matrix cracks. The model revealed the negligible influence of matrix cracks on stress concentrations, ineffective length, cluster development and failure strain. The presence of matrix cracks can therefore be safely neglected in models for UD composites. This information is important for experimental validations and for advancing the state of the art in strength models for UD composites.

1. Introduction

Failure of fibre-reinforced composites often occurs suddenly and without any visible signs of damage serving as a warning. This feature is caused by the gradual development of microscopic damage. Predicting such damage is challenging, especially in multidirectional composites. In most cases, however, the failure of multidirectional composites coincides with the failure of the fibres oriented in the loading direction. Hence, understanding the 0° tensile failure of unidirectional (UD) composites is vital.

Monotonic loading of a UD composite results in stochastic fibre failure [1], with their failure strength typically obeying a Weibull distribution. Each break locally causes the fibre to lose its load transfer capability and shed its load to nearby fibres [2,3]. The fibres nearby are hence subjected to stress concentrations, and their failure probability increases. As the matrix surrounding the fibre break is loaded in shear, stress is transferred back into the broken fibre. At a characteristic distance from the fibre break plane, the stresses in both the broken and intact fibres return to their nominal value. The increased failure probability of the nearby fibres causes the development of break clusters [4]. These clusters grow with increasing strain, until one of them reaches the critical cluster size. This cluster then propagates unstably and leads to the final failure of the composite.

Failure development is dominated by two features: (1) the Weibull distribution of fibre strength and (2) the stress redistribution around a fibre break. The Weibull strength distribution determines the stochastic sequence of fibre failure. Many Weibull strength distributions have been characterised experimentally, but the results can be quite different, even for a given fibre type. For example, this is the case for T300 fibres [5,6] and T800 carbon fibres [7,8].

Stress redistributions around single fibre breaks have been investigated extensively by shear-lag analysis [9–12] and by the finite element (FE) method [13–18]. The two vital parameters in UD composite strength predictions are the stress concentration factors (SCF) in the intact fibres and the ineffective length in the broken fibre. Both parameters are strongly influenced by the modelling assumptions. The importance of the matrix, both for normal and shear stress transfer and through its inelastic behaviour, has been demonstrated by many authors [16,19–22]. In addition, random fibre packings introduce variations in the SCFs, whereas they are deterministic for regular packings [13,23–25].

Another vital assumption concerns the stress singularity around a fibre break. Stress concentrations in the matrix around a fibre break are infinite for elastic, well-bonded materials. The matrix and interface are thus unlikely to be able to cope with this, yet many models assume perfect bonding and an intact matrix [15,26,27].

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http://dx.doi.org/10.1016/j.compscitech.2015.01.002
0266-3538/

Three scenarios or combinations thereof can occur: (1) the matrix yields [16,19–22], (2) the fibre–matrix interface debonds [21,24,28], or (3) the matrix cracks in the fibre break plane [29–32]. Matrix yielding is typical in thermoplastic polymer matrix composites, and can also occur in thermosets. Fibre–matrix debonding typically occurs for weak interfacial bonds, and is common in ceramic matrix composites. Matrix yielding and fibre–matrix debonding have been extensively investigated [16,19–22,24,28], but studies on matrix cracking remain scarce.

Matrix cracks are commonplace in ceramic matrix composites [33], but mainly as a phenomenon occurring prior to fibre failure. In polymer matrix composites however, both phenomena are interlinked. Several authors have observed matrix cracking around fibre breaks during single fibre fragmentation tests [29–32]. This occurred typically in material systems with a strong fibre/matrix interfacial bond and a low stiffness [32]. Including matrix cracking in strength models for polymer matrix composites has lagged behind. Li et al. [34] and Mishnaevsky and Brøndsted [35] developed models involving matrix cracks around fibre breaks, but the influence of these cracks on stress redistribution and strength of the composite was not investigated yet.

While matrix cracks around fibre breaks are neglected by most strength models, experiments have indicated that they sometimes occur in UD composites [29–32]. The purpose of the present paper is to analyse the influence of matrix cracks could have on the strength and damage development in UD composites. Their influence on the stress redistribution around fibre breaks and on composite failure development is explored.

2. Stress redistributions around fibre breaks

2.1. FE model for stress redistribution

A vital aspect of every strength model for UD composites is an accurate description of the stress redistribution caused by a single fibre break. The FE model and its input parameters have been extensively described in Swolfs et al. [13,14]. The main difference is that an elasto-plastic epoxy matrix was used instead of an elastic one. The data from Okabe et al. [6] was used for this purpose.

A single fibre break is surrounded by intact fibres in a random fibre packing. A displacement is applied to the bottom surface of the model (see Fig. 1), corresponding to an applied strain of 2%. Symmetry conditions are applied to the entire top surface, but not to the middle fibre, representing the broken status of that fibre. Matrix cracks around fibre breaks are simulated in a similar fashion, by eliminating the symmetry condition from the corresponding matrix crack area. Models without matrix cracks were simulated using a baseline and an improved strategy. The difference between both strategies lies in the boundary conditions applied to nodes at the perimeter of the fibre break. The baseline strategy applied symmetry conditions to these nodes, as this most closely reflects the assumption that matrix cracks do not occur. The improved strategy however, released these nodes, which is equivalent to a tiny matrix crack with a width of just 13 nm.

The SCFs are calculated by averaging the stress over the cross-section of the fibres and dividing this average by the far field stress. The SCFs will always be expressed as the percentage by which they exceed unity.

Five FE models were made for each of the three types of boundary conditions. The models without and with a matrix crack are illustrated in Fig. 1. In the absence of experimental data on the size of the matrix crack, the matrix crack is assumed to be constrained by nearby fibres. Since that defines uniquely neither the size nor the shape of the matrix crack, a sensitivity analysis is performed to assess its influence. Three different matrix crack sizes with an area of 60 μm^2, 150 μm^2 and 205 μm^2 were implemented in one specific fibre packing. The SCFs and ineffective length were found to be fairly insensitive to the shapes and sizes of the matrix crack. A relative difference of only 12% is found for the maximum SCFs when comparing the smallest and largest crack models. The difference in ineffective length is smaller than 1%. A medium-sized matrix crack will therefore be used in the assessment of SCFs. The area of the matrix crack varies between 100 and 155 μm^2 depending on the packing. An example of such a crack was shown in Fig. 1b.

To analyse interactions among fibre breaks, FE models with multiple fibre breaks are created. These fibre breaks are located in the same plane, as this situation has the strongest amplification of the SCFs.

2.2. Non-interacting breaks

The primary influence of the matrix cracks occurs through a change in the stress redistribution around fibre breaks. This section analyses this redistribution in the broken and intact fibres, for the case of a non-interacting or single fibre break.

Fig. 2 depicts stress recovery profiles in the broken fibre. Fibre stress is plotted as a percentage of the nominal level caused by the global axial strain. The profile for the baseline solution without matrix cracks seems to start at 45%, while the two other ones start

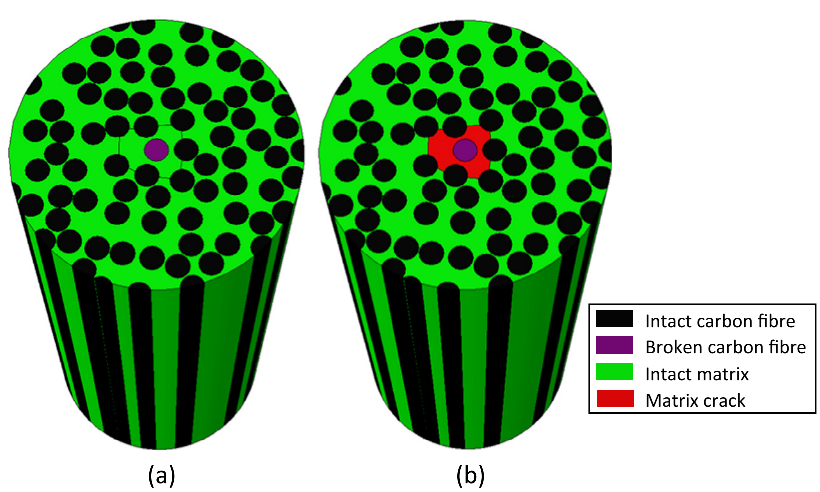

Fig. 1. A 3D view of the FE model of a single fibre break: (a) without a matrix crack, and (b) with a medium-sized matrix crack.