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Numerical analysis of debond propagation in the single fibre fragmentation test

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ABSTRACT

A numerical analysis, using the Boundary Element Method, of the stress state within the specimen in the single fibre fragmentation test is presented first. Thermal residual stresses and fibre–matrix interfacial friction along the debonding crack faces have been considered in the study. Special attention has been paid to the axial stresses along the fibre and the interfacial tractions and relative displacements in the neighbourhood closest to the debonding crack tips. In order to analyse the debond propagation, the associated Energy Release Rate has been evaluated from the near-tip elastic solution. Numerical results show that both the effects of thermal residual stresses and of fibre–matrix interfacial friction are opposed to the debond propagation. Additionally, the effect of the debond propagation on the load transfer through the interface has been studied, showing that fibre–matrix interfacial friction has a weak influence on the distance needed to re-establish the nominal axial load within the fragment.

1. Introduction

Since it was first introduced by Kelly and Tyson [1], single fibre fragmentation test (SFFT) has been extensively used for fibre–matrix interface characterization in Fibre Reinforced Composites. In this paper, a sample made of E-glass fibre and epoxy matrix is considered. SFFT specimens consist of a long fibre embedded in a large block of resin matrix, subjected to tensile load in the fibre direction, applied as a uniform strain at the ends of the specimen. Since strain to failure in the fibre is much lower than in the matrix, after reaching a certain load, successive fragmentation of the fibre is observed. Once the fragmentation process, which reflects the statistical fibre strength distribution, starts, tensile load is transferred to the fibre fragments through shear stresses at the fibre–matrix interface, thus allowing for the appearance of new fragments.

If the failure properties of the interface are high, fragmentation continues until a critical fragment length (saturation length) is reached. At this situation, the fragments are not long enough to receive through the interface an axial load sufficient to cause subsequent fibre breakages.

In most cases the above described saturation length is not reached during the test. Instead, series of cracks appear which arise from the ends of fibre fragments and grow through the matrix or the interface (see, for example [2]). The appearance of these cracks implies further relaxation of the axial stress in the fibre, which prevents the appearance of new fragments.

The earlier results obtained from the SFFT correspond to *interface strength* measurements. These were carried out following the shear lag stress distribution model proposed by Cox [3], with different assumptions regarding the shear stress distribution along the interface, the thermal residual stresses or the statistical distribution of fragment lengths [4–9]. Therefore, the *interface strength* values obtained using the SFFT are strongly related to the assumptions made, and not easily applicable to situations in which the interface is subjected to a different stress state.

In the cases in which the matrices show low yielding, the elastic solution at the interface contains shear singular stresses in the vicinity of the crack tips, and the use of a strength criterion is questionable. For this reason, a fracture mechanics approach is considered more appropriate for the characterization of the interface failure in presence of singular stress states (see, for example, the works of Nairn [10], Varna et al. [11], Nairn and Liu [12] and Wu et al. [13–16]). The approach followed in the present work, based on energetic principles, considers that crack propagation would take place when the total energy released per unit length during the propagation (i.e., the Energy Release Rate) equals the work needed to create the new unit crack surfaces. As the propagation takes place under pure mode II, failure of the interface is characterized by the interfacial mode II *fracture toughness* (usually denoted as G_{IIc}). In this work, the Energy Release Rate is evaluated from the elastic solution in the vicinity of the crack tip.

The main objective of the present study is to obtain an accurate solution of the displacement and stresses within the specimen in

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the SFFT. To this end, a specific numerical tool based on the Boundary Element Method has been developed and employed for the numerical simulation of the problem. This numerical solution may help in the understanding of the mechanism of fibre–matrix interfacial debond propagation and may serve as a validation tool for developers of simpler and easier to apply analytical models. To this end, the effect of thermal residual stresses, fibre–matrix interfacial friction and geometrical parameters on debond propagation is discussed.

2. Numerical model

Numerical analysis has been carried out by the collocation Boundary Element Method (BEM) for elastic contact problems with axial symmetry (see Graciani et al. [17] for a description of the numerical tool developed). This approach has been chosen for the numerical analysis of the SFFT since it offers clear advantages if compared with other alternative numerical methods (for example, the Finite Element Method).

Firstly, taking into account the axial symmetry with respect to the fibre axis, only a 1D mesh is needed for the analysis of the 2D axi-symmetric problem with BEM. As a consequence, to carry out a strong refinement of the mesh in the vicinity of the crack tips, where singular solutions are expected, is a very easy task. Secondly, since the debonding crack grows along the fibre–matrix interface, the displacements and tractions needed for the study of debond propagation are the actual primary unknowns in the nodes of the BEM mesh. Finally, non-conforming meshes have been employed in the interfaces, which results in an important reduction in the number of elements needed for the numerical analysis.

Isotropic linear elastic material behaviour, repetitive solutions in the vicinity of all fragment ends and local symmetry with respect to the fibre crack have been assumed in order to simplify the BEM model. Thus, the geometry and boundary conditions employed for the analysis are those shown in Fig. 1a. Material properties, corresponding to typical E-glass fibre and epoxy matrix, are listed in Table 1. The fragment semi-length L_f and the debonded length a have been parametrically varied in the ranges: $50 < L_f\ (\mu\text{m}) < 500$ and $0.1 < a\ (\mu\text{m}) < 50$. The outer radius of the resin cylinder has been taken as $r_s = 1000\ \mu\text{m}$. A detail of the BEM mesh employed in the vicinity of the crack tip is shown in Fig. 1b, for the case with $a = 10\ \mu\text{m}$.

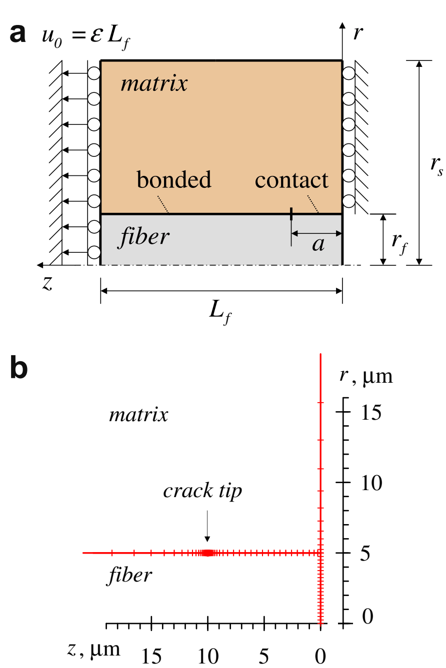

Fig. 1. (a) Sketch of BEM model and boundary conditions. (b) Detail of BEM mesh.

Table 1
Material properties, with $i = f, m$.

	Fibre	Matrix
Young modulus (E_i)	70,000 MPa	3500 MPa
Poisson ratio (ν_i)	0.2	0.3
Thermal expansion coefficient (α_i)	$7 \times 10^{-6}\ \text{K}^{-1}$	$50 \times 10^{-6}\ \text{K}^{-1}$
Outer radius (r_i)	5 μm	1000 μm

To take into account the effect of thermal residual stresses, a constant decrease in temperature $\Delta T = -80$ K has been introduced before the application of the mechanical load. Frictional contact conditions between crack faces have been imposed using Coulomb's law, with a friction coefficient $\mu = 0.3$. Since few data and great dispersion exist in the literature about the experimental measurements of glass/epoxy interfacial friction coefficient (i.e., Chua and Piggott [18] report values in a range of $0.07 < \mu < 0.76$, depending on the surface treatment), only one typical value of the friction coefficient has been employed for brevity. The influence of parametrically varying the friction coefficient will be addressed in a forthcoming work. For the sake of comparison, results neglecting fibre–matrix interfacial friction and thermal residual stresses have also been obtained.

The inclusion of fibre–matrix interfacial friction makes the problem become non-linear. However, as a result of the different material properties, the tendency for radial shrinkage, induced by the effect of cooling and by the Poisson's effect while loading in axial tension, is higher in the matrix than in the fibre. As a consequence BEM results show that the debonding cracks are always closed, compressed and sliding in their whole length.

As a consequence, in the frictionless case, the specimen will reach a stress-free state if the mechanical and thermal loads are removed once the debond crack has reached a certain length. In this state, the geometry of the specimen is identical to the initial state, the only difference being that the fibre is broken and the interface is partially debonded. Therefore, the elastic state corresponding to a certain debonded length can be linearly obtained applying mechanical and thermal loads to a model in which, initially, the fibre is broken and the interface is debonded.

This procedure is, strictly speaking, not valid in the frictional case. Friction is opposed to the relative sliding of debond crack faces both in the loading and the unloading of the specimen. Therefore, the specimen would retain some stresses once the mechanical and thermal loads have been removed, since some energy is dissipated by frictional slip. However, it can be reasonably assumed that energy dissipated by friction is negligible in comparison with the energy needed to cause debond propagation. Thus, in the frictional case, the linear solution of the problem, neglecting the effect of load history in the elastic state, can be considered a satisfactory approximation of the actual solution.

Thus, the solution for a certain average mechanical strain ε applied at specimen ends can be obtained by linear superposition of the solutions of two basic cases: one including the constant decrease in temperature $\Delta T = -80$ K and the corresponding average axial thermal shrinkage of the specimen $\varepsilon_{\Delta T}$, and another including a zero decrease in temperature and a unit average mechanically applied strain. That is:

$$\begin{aligned}\boldsymbol{u}(r,z) &= \boldsymbol{u}(r,z)_{\Delta T=-80\ \text{K},\varepsilon=\varepsilon_{\Delta T}} + \varepsilon\boldsymbol{u}(r,z)_{\Delta T=0,\varepsilon=1\%},\\ \boldsymbol{\sigma}(r,z) &= \boldsymbol{\sigma}(r,z)_{\Delta T=-80\ \text{K},\varepsilon=\varepsilon_{\Delta T}} + \varepsilon\boldsymbol{\sigma}(r,z)_{\Delta T=0,\varepsilon=1\%},\end{aligned} \tag{1}$$

where as the specimen contains one single fibre, $\varepsilon_{\Delta T} \approx \alpha_m \Delta T$. For the actual properties employed, shown in Table 1, an average axial thermal shrinkage $\varepsilon_{\Delta T} = -0.3998\%$ of the specimen is obtained.