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Effect of a secondary transverse load on the inter-fibre failure under compression

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ABSTRACT

At present, the progress in the failure criteria of unidirectional reinforced laminates requires the study of the evolution of the mechanisms of damage at micromechanical level. The objective of this paper is the study of the influence (at micromechanical scale) of a secondary transverse load (tension or compression), perpendicular to the transverse compression nominally responsible for the failure, on the inter-fibre failure under compression. The Boundary Elements Method and Interfacial Fracture Mechanics concepts are employed. It is shown that a secondary tension accelerates the generation of failure whereas a secondary compression inhibits it.

1. Introduction

The inter-fibre failure under uniaxial compression has already been the subject of several studies by the authors [1,2]. These studies identified the first stages of the mechanism of damage at micromechanical level that starts with the appearance of small debonds at the fibre–matrix interfaces. The initial defects present, in accordance with Interfacial Fracture Mechanics [3], a non-symmetric morphology: a small ‘bubble’ at the lower crack tip and a contact zone at the upper one, see Fig. 1(a). At an early stage, these initial cracks grow unstably along the interfaces from their lower crack tips. This period ends when these cracks reach a certain length at the interface, which coincides with the closing of the ‘bubble’, Fig. 1(b). From that moment on the growth becomes stable, favouring the occurrence of crack kinking towards the matrix and following an orientation angle around 53° from the direction perpendicular to the load, Fig. 1(c). These numerical predictions agree with the experimental macromechanical results [2].

Many of the existing proposals for the prediction of the inter-fibre failure at lamina level are based on the hypothesis that the failure taking place at a plane is governed by the components of the stress vector associated to that plane. In the present work this assumption is revised for the compression dominated matrix failure by means of single-fibre Boundary Element models. An analysis of the influence of an out of failure plane stress component (tension or compression), secondary external load in what follows, on the generation of the damage dominated by a transverse compression is carried out. A similar study for the matrix failure under tension was performed by the authors in [4] leading to the conclusion that this failure is much more affected by a compressive secondary external load than a tensile one.

2. Numerical model

The numerical study has been carried out using a tool based on BEM [5,6] that makes it possible to perform the numerical analysis of plane elastic problems considering contact and interface cracks. Two single-fibre BEM models are used in this analysis. The size of the cell is large enough for the fibre to be considered as isolated. The basic model employed is shown in Fig. 2(a) and represents the case of a crack which, under the plane strain hypothesis, grows along the interface.

To characterise the problem from the Fracture Mechanics point of view, the Energy Release Rate (ERR), G, is used. The expression employed, based on VCCT [3], for a circular crack that propagates from a certain debonding angle, α, Fig. 2a, to $\alpha + \Delta\alpha$ ($\Delta\alpha \ll \alpha$), is:

$$G(\alpha, \Delta\alpha) = \frac{1}{2\Delta\alpha}\int_0^{\Delta\alpha} [\sigma_{rr}(\alpha+\theta)\Delta u_r(\alpha-\Delta\alpha+\theta) + \sigma_{r\theta}(\alpha+\theta)\Delta u_\theta(\alpha-\Delta\alpha+\theta)]d\theta \quad (1)$$

where θ is the circumferential coordinate with reference to the crack tip. σ_{rr} and $\sigma_{r\theta}$ represent, respectively, radial and shear stresses along the interface, and Δu_r and Δu_θ represent the relative displacements of the crack faces. Both modes of fracture, I (associated to σ_{rr})

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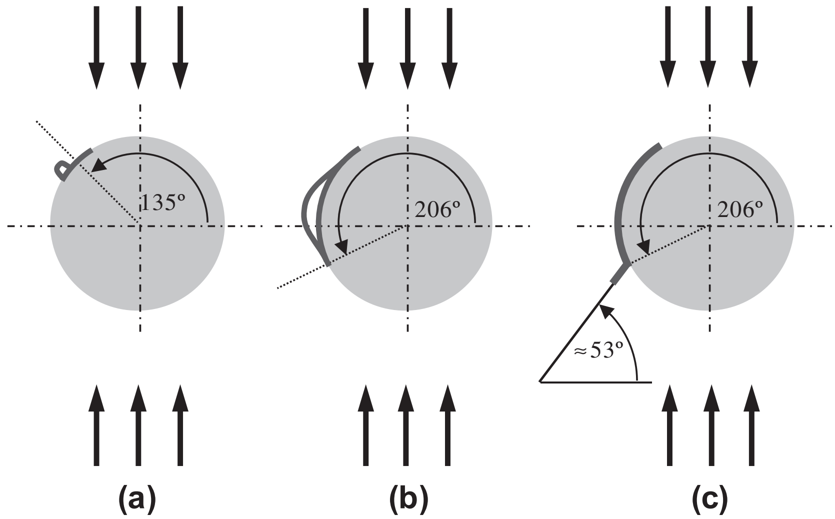

Fig. 1. Micromechanical phases of inter-fibre failure under uniaxial compression.

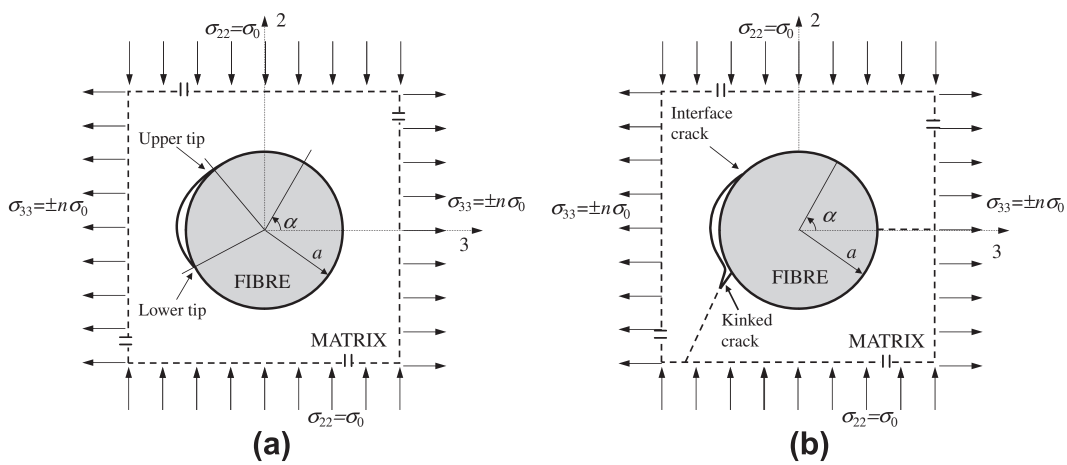

Fig. 2. Single fibre BEM models: (a) interface crack and (b) kinked crack.

and II (associated to $\sigma_{r\theta}$), are obviously considered in Eq. (1). For this study, $\Delta\alpha$ has been taken equal to 0.5°.

When the presence of an incipient crack in the matrix is considered, the previous model is altered to represent the case of a crack that has first grown along the interface and, having kinked into the matrix, is progressing through it, Fig. 2(b). The materials chosen for the analysis correspond to a typical configuration among fibre reinforced materials: a glass fibre–epoxy matrix system, whose elastic properties are included in Table 1. The fibre radius considered has been $a = 7.5 \times 10^{-6}$ m.

Dimensionless results for G will be presented. These values are obtained, following [7,8], by dividing the values of G by $G_0 = (1 + \kappa^m/8\mu^m)\sigma_0^2 a\pi$, where $\kappa^m = 3 - 4\nu^m$, μ^m is the shear modulus of the matrix and σ_0 is the external applied compression.

Table 1
Elastic properties of the materials.

Material	Poisson coefficient, ν	Young modulus, E
Matrix (epoxy)	$\nu^m = 0.33$	$E^m = 2.79 \times 10^9$ Pa
Fibre (glass)	$\nu^f = 0.22$	$E^f = 7.08 \times 10^{10}$ Pa

3. Compression–tension biaxial case

3.1. Failure initiation

The presence of a secondary external tension, $\sigma_{33} > 0$, acting at the same time as $\sigma_{22} < 0$ could alter the origin of the failure and thus the development of the interface crack. The initiation of the failure at the interface is considered in this work to be controlled by the stress distribution [9] at the undamaged interface (i.e. perfect interface with displacement continuity across the interface), as was already done in [1]. It is therefore fundamental to analyse the influence that the different levels of σ_{33} have on both σ_{rr} and $\sigma_{r\theta}$ at the undamaged interface. In this sense, the notation employed to distinguish between the different biaxial cases follows the scheme: C–nT, where C represents the compression nominally responsible for the failure applied parallel to the 2-axis (i.e. σ_{22}), n ($0 \leqslant n \leqslant 1$), see Fig. 2, is the coefficient that specifies the value of σ_{33} with reference to σ_{22}, and T represents the sign of the secondary load (T = tension). Three different values of n coefficient have been considered in this section: 0, 0.5 and 1. A simplified notation is used for the specific cases $n = 0$, pure compression C-0, and $n = 1$, C–T.