Tension dominated inter-fibre failure under bi-directional loads. Micromechanical approach

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ABSTRACT
The growth of interface cracks corresponding to tension dominated inter-fibre failure under bi-directional loads is studied. The Boundary Element Method is employed for the analysis of the fracture process and the results evaluated by means of Interfacial Fracture Mechanics. The conclusions of the numerical analysis contribute to clarify the failure onset.

1. INTRODUCTION

The inter-fibre failure under uniaxial tension has already been the objective of several studies by the authors, París et al. (2007). These studies allowed the first stages of the mechanism of damage at micromechanical level to be identified, showing that it starts with the appearance of small debonds at the fibre-matrix interfaces. The initial defects grow unstably and symmetrically along the interfaces (interface cracks). This period ends when these cracks have reached a certain length at the interface coinciding with the appearance of a physically relevant contact zone at the tip. From that moment on the growth of the interface cracks becomes stable, which favours the occurrence of the kinking towards the matrix. The coalescence between different cracks in the matrix leads to the final macro-failure.

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 tension dominated inter-fibre failure by means of a single-fibre Boundary Element model, Fig. 1, using the same bi-material system employed in París et al. (2007). An analysis of the influence of an out of failure plane stress component (tension or compression) on the generation of the damage dominated by a transverse tension is carried out. Several aspects of this problem have already been analysed by the authors in París et al. (2003). Interfacial Fracture Mechanics has been used to analyse the numerical results.

2. ORIGIN OF FAILURE

The presence of an external secondary load, σ_{33}, acting at the same time as σ_{22} could alter the origin of the failure and, thus, the development of the interface crack. The initiation of the failure at the interface has been considered in this work to be controlled by the σ_{rr} distribution, Goodier (1933), at the undamaged interface, as was already done in París et al. (2007). Then it is fundamental to analyse the influence that the different levels of σ_{33} have on σ_{rr} of the undamaged interface. Three different values of n coefficient have been considered: 0, 0.5 and 1. Based on this the notation employed to distinguish between the different bi-directional cases follows the scheme: T-*n*C and T-*n*T (T=tension, C=compression).

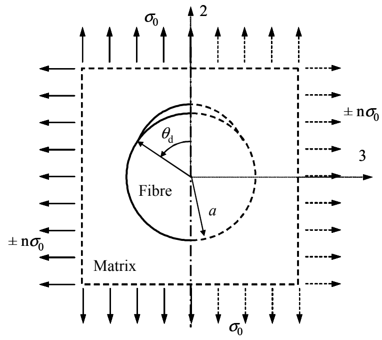

Fig. 1. Single fibre BEM model.

Curves presented in Fig. 2a (T-*n*C case) show that the presence of σ_{33} does not qualitatively alter the distribution of σ_{rr} at the interface. Quantitatively, and with reference to the T-0 case, compressive σ_{rr} significantly increases as σ_{33} does, whereas maximum tensile σ_{rr} increases only slightly. Referring to the T-*n*T case, Fig. 2b, the σ_{rr} level at the interface is maintained with reference to the T-0 case though presenting some qualitative alterations, consisting in an increase of the σ_{rr} level in those interfacial points that were less stressed in the unidirectional case. Thus the tendency generated is to level the σ_{rr} state between all interfacial points, as is shown in the limit case T-T.

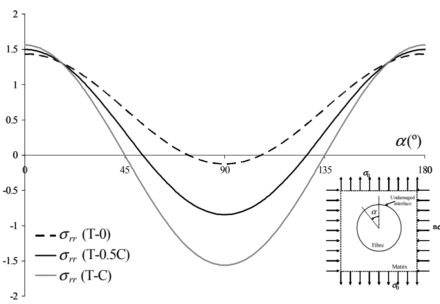

Fig. 2a. σ_{rr} **distribution. (T-*n*C case).**

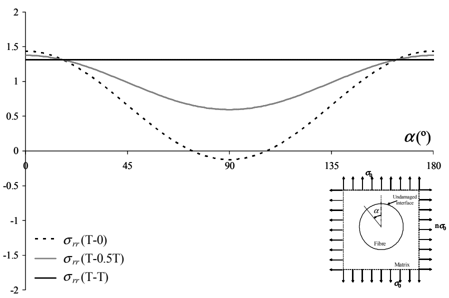

Fig. 2b. σ_{rr} **distribution. (T-*n*T case).**

Based on the former evidence, an initial debond at the interface of 10º length centred in axis 2 (position at which σ_{rr} is maximum) will be assumed for the study of the growth of the interface crack, both for the T-*n*C case and the T-*n*T case.

3. INTERFACIAL GROWTH

The evolution of the first debond at the interface is studied by means of the BEM model (París and Cañas (1997), Graciani (2006)), shown in Fig. 1a and its growth evaluated in terms of the Energy Release Rate, G (Irwin (1957)).

3.1 Tension-compression biaxial case

The results obtained show that the presence of $\sigma_{33} < 0$ does not qualitatively alter the evolution of G versus θ_d, though it is found that its level increases as $\sigma_{33} < 0$ does, which means that the load level required for crack propagation is lower.
The prediction of growth of the interface crack is made by comparing G with its corresponding critical value, G_c, Hutchinson and Suo (1992). G - G_c comparisons for the cases T-0 and T-C (taken as representative of all T-*n*C cases) are plotted in Fig. 3. A value of 0.2 has been chosen for λ and G_{1c} has been taken as the value that makes G and G_c coincide for the first debonding angle, $\theta_d = 10^{\text{o}}$ in this case. This criterion for the election of G_{1c} can be implemented once a scaled representation of the G curves, that makes all curves to coincide at $\theta_d = 10^{\text{o}}$, has been considered.
The results shown in Fig. 3 predict an unstable growth of the interface crack that reaches lower debonding angles as the presence of $\sigma_{33} < 0$ increases, though the value of σ_0 needed for the initiation of the crack growth is lower as the presence of σ_{33} increases, which means that the presence of a compression superimposed on the tension nominally responsible for the failure accelerates the failure.

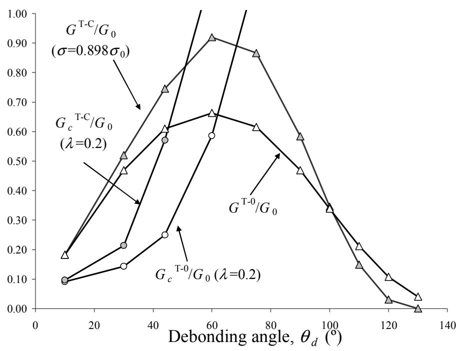

Fig. 3. G-G_c comparison. (T-*n*C case).

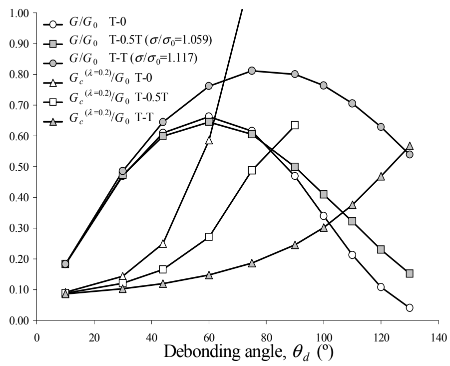

Fig. 4. G-G_c comparison. (T-*n*T case).

3.2 Tension-tension biaxial case

The results obtained for this case show that the presence of $\sigma_{33} > 0$ does not significantly alters the G level obtained in the T-0 case, though a translation of the position of the maxima has been detected. It can also be deduced that the propagation of the initial debond requires a slightly higher level of the external load as *n* increases. G and G_c curves associated to T-*n*T cases corresponding to *n*=0,0.5 and 1 are represented together in Fig. 4, having used the same scaled representation as in the T-*n*C case (Fig. 3). The results obtained predict an unstable growth of the interface crack that extends towards larger debonding angles as the presence of $\sigma_{33} > 0$ increases, though the amount of load required for the initiation of growth is also greater as this presence increases. For the T-T limit case this tendency could lead to a particularly large extension of the crack at the interface that, in conjunction with the special morphology of the crack detected in this case (consisting in the opening of the previously developed contact zone near the tip), would impede the kinking of the crack towards the matrix.

3. CONCLUSIONS

The first stages of the development of the tension dominated inter-fibre failure under bidirectional loads have been studied by means of a single fibre BEM model. A secondary external load has been considered to act simultaneously with the tension nominally responsible for the failure, and both cases (tension and compression) have been analysed. The results obtained show that the presence of a secondary load could alter several aspects of the stages already detected for the tension uniaxial case leading then to the conclusion that the presence of an out plane stress component could affect the development of the failure.

ACKNOWLEDGEMENTS

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