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Effect of thermal residual stresses on matrix failure under transverse tension at micromechanical level: A numerical and experimental analysis

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ABSTRACT

In the present work the influence at micromechanical scale of thermal residual stresses, originated in the cooling down associated to the curing process of fibrous composites, on inter-fibre failure under transverse tension is studied. In particular, the effect of the presence of thermal residual stresses on the appearance of the first debonds is discussed analytically, whereas later steps of the mechanism of damage, i.e. the growth of interface cracks and their kinking towards the matrix, are analysed by means of a single fibre model and making use of the Boundary Element Method (BEM). The results are evaluated applying Interfacial Fracture Mechanics concepts. The conclusions obtained predict, at least in the case of dilute fibre packing, a protective effect of thermal residual stresses against failure initiation, the morphology of the damage not being significantly affected in comparison with the case in which these stresses are not considered. Experimental tests are carried out, the results agreeing with the conclusions of the numerical analysis.

1. Introduction

The final stage of the manufacturing process of fibrous composites materials is the curing of the material. The differences in free contraction between the fibres and the matrix cause, during this stage of the process, the appearance of thermal residual stresses. These residual stresses are generated at micromechanical level for unidirectional and multidirectional laminates, and also at macro/meso-mechanical level for multidirectional laminates. Additionally, extra residual stresses may arise in thermosetting matrix composites from chemical shrinkage of the matrix as it cures. The presence of these stresses may affect the strength of the laminate and also have influence on the development of failure mechanisms in the material.

The study of residual stresses at macro- and meso-mechanical level is widely developed, there being several methods able to quantify them, Andersson et al. [1]. By contrast, at micromechanical level, the measurement and prediction of residual stresses presents more difficulties, due to the high complexity of the material at this scale. If knowledge of the mechanisms of failure at micromechanical level is considered to be fundamental for the development of failure criteria able to perform a more complete diagnosis of the appearance of these mechanisms, París [2], the analysis of the influence of curing stresses at this scale then becomes highly relevant.

Many authors have tried to quantify the effect of residual curing stresses of fibre reinforced composites leading to relevant conclusions. Particularly, Crasto and Kim [3] measured the differences in free expansion of 0°/90° laminates cured at different temperatures, and later in [4] analysed, for the case of unidirectional laminates, the influence of curing time on the generation of residual stresses. Huang and Young [5] carried out several fragmentation tests comparing interfacial shear strength between materials cured at 80 °C and at room temperature, finding higher values of interfacial shear strength for the material cured at 80 °C. De Kok and Meijer [6] performed transverse loading tests at temperature different from the room one, showing that residual stresses have a protective effect against failure, this effect increasing with fibre content (according to [7] these results were already presented by De Kok in his doctoral dissertation in 1995).

The particular case of inter-fibre failure (also known as matrix failure) under transverse tension has already been the object of several micromechanical studies by the authors, París et al. [8,9], for single fibre case or dilute packing. These studies have made it possible to understand the initiation of failure at the micromechanical scale as well as its later progress, which leads to the macro-failure of the material, without considering the presence of residual curing stresses. The results obtained assumed that crack nucleation is controlled by the radial stress generated between fibre and matrix and showed that the maximum values are placed, in the single fibre case (or dilute packing), at the angles 0° and

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180° with respect to the tension applied, Fig. 1a. Once a small debonding crack is supposed to appear (in particular, one of 10° length centred at 0° was assumed, which later proved to be in accordance with the range predicted by Mantič [10]), single-fibre BEM models, similar to that shown in Fig. 2a, were employed for the characterisation of crack growth. The results produced by the BEM model, analysed following the energetic approach of Interfacial Fracture Mechanics, predicted an unstable growth of the interface crack up to a position characterized by debonding angle θ_d = 60–70°, Fig. 1b. The study also showed that the end of unstable growth coincides with the development of a physically relevant contact zone at the crack tip. The third step of the analysis, Fig. 1c, ascertained the condition under which the interface crack would find it easier to kink into the matrix than to continue growing along the interface, a problem studied with the BEM model showed in Fig. 2b. The coalescence of these kinked cracks caused the appearance of a macromechanical failure which, as expected and confirmed from the experiments [9], was oriented perpendicularly to the external load.

Some authors have employed FEM models to numerically analyse the role of residual stresses in transverse failure. In this sense, Asp et al. [7] performed FEM analyses to study the transverse failure, finding that the presence of residual stresses delays the initiation of failure in composites with a high fibre content. Fiedler et al. [11] concluded that thermal residual stresses lead to an increase in transverse strength with the local fibre-volume fraction. Zhao et al. [12] claimed that for tension dominated transverse loading, residual stress could be detrimental or beneficial depending on the material strength. Specifically, residual stresses seem to be detrimental for relatively low resin strength and beneficial for relatively high resin strength. Hojo et al. [13] performed FEM analyses for two dimensional image-based models, concluding that microscopic thermal residual stresses contribute greatly to the increase in transverse strength. Maligno et al. [14] studied the effect of residual stresses on uniaxial transverse failure using a non-uniform cell model, finding that they provide a general beneficial effect.

The present work is a continuation of the previous studies of the authors related to inter-fibre failure under transverse tension [8,9]. The objective now is to analyse the influence of thermal residual stresses originated by the cooling down associated to the curing process on the conclusions obtained so far about the different micromechanical phases of mechanism of damage. The numerical predictions derived from BEM analyses are validated with macromechanical experimental tests.

Particularly, in Section 2 the main features of the BEM model employed as well as the materials properties are presented. Sections 3–5 are referred to the study of the initiation and growth of a crack at the interface between a fibre and the matrix surrounding it, subjected to the combined action of an external tension and the thermal decrease associated to the cooling down of a curing process. Section 6 includes the results associated to the experimental tests carried out on specimens subjected to different curing cycles.

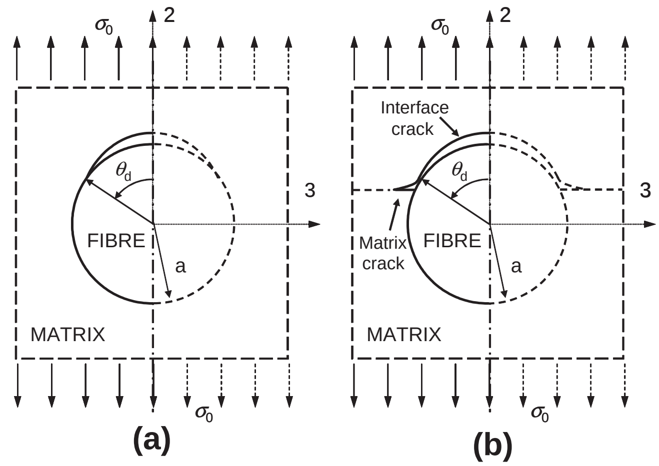

Fig. 2. Single fibre modes: (a) with interface crack only, and (b) with interface kinked crack.

Finally, in Section 7, a discussion on the connection between numerical and experimental results is presented.

2. Single fibre model

The numerical study has been carried out using a tool based on BEM, París and Cañas [15], that makes it possible to perform the numerical analysis of plane elastic problems considering contact and interface cracks, in a similar way to that described in Blázquez et al. [16] for planar problems and Graciani et al. [17] for axisymmetric problems. Two BEM models are used in this analysis. The basic model employed is shown in Fig. 2a and represents the case of a crack which, under the plain strain hypothesis, grows along the interface symmetrically to axis 2 (Section 4). Due to this symmetry it is only necessary to study one half of the problem. As an indication, the number of boundary elements modelling the fibre is 83 and that corresponding to the matrix is 115. A strongly refined BEM mesh toward the crack tip is applied. The size of the smallest element located at the crack tip is $7 \times 10^{-7}a$, a being the fibre radius, in order to achieve very high accuracy in the numerical results obtained. This small size of the elements, much smaller than the scale where a continuum theory can be applied, is used to guarantee accurate results at distances where continuum theory is applicable.

To characterize the problem from the Fracture Mechanics point of view the energy release rate, G, will be used. The expression employed, based on the VCCT, Irwin [18], for a circular crack that propagates from a certain debonding angle, θ_d, Fig. 2a, to $\theta_d + \Delta\theta_d$ ($\Delta\theta_d \ll \theta_d$), is:

$$G(\theta_d, \Delta\theta_d) = \frac{1}{2\Delta\theta_d}\int_0^{\Delta\theta_d}\begin{bmatrix}\sigma_{rr}(\theta_d+\theta)\Delta u_r(\theta_d-\Delta\theta_d+\theta)+ \\ +\sigma_{r\theta}(\theta_d+\theta)\Delta u_\theta(\theta_d-\Delta\theta_d+\theta)\end{bmatrix}d\theta \qquad (1)$$

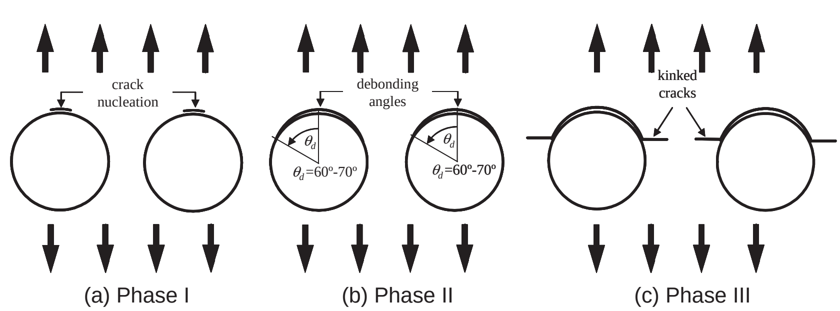

Fig. 1. Micromechanical phases of inter-fibre failure under unidirectional tension.