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# Effect of thermal residual stresses on the matrix failure under transverse compression at micromechanical level – A numerical and experimental study

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ABSTRACT

The influence at micromechanical scale of thermal residual stresses, originating in the cooling down associated to the curing process of fibrous composites, on inter-fibre failure under transverse compression is studied. In particular, the effect of these stresses on the appearance of the first debonds is discussed analytically; later steps of the damage mechanism are analysed by means of a single fibre model, making use of the Boundary Element Method. The results are evaluated applying Interfacial Fracture Mechanics concepts. The conclusions obtained show, at least in the case of dilute fibre packing, the effect of thermal residual stresses on the appearance and initiation of growth to be negligible, and the morphology of the damage not to be 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 derived from the numerical analysis.



## 1. Introduction

There exists a final stage in the manufacturing process of fibrous composite materials in which the curing of the material takes place. 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-/mesomechanical 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 residual stresses may affect the strength of the laminate and also have an influence on the development of failure mechanisms in the material.

The study of residual stresses at macro- and mesomechanical level is widely developed, there being several methods capable of quantifying them, Andersson et al. [1]. By contrast, at micromechanical level, due to the high complexity of the material at this scale, the measurement and prediction of residual stresses presents more difficulties. 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 thermal residual stresses on fibre reinforced composites, leading to relevant conclusions. A brief revision of these published works can be found in Correa et al. [3].

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, first without considering the presence of residual stresses, París et al. [4–6], and also analysing the effect of the thermal stresses generated during the cooling down of the curing process [3,7]. The results included in these previous studies [7] show that the presence of thermal residual stresses does not significantly affect the morphology of the inter-fibre failure under tension, though, quantitatively, it increases the strength of the laminate. The case of inter-fibre failure under compression, without considering the presence of residual stresses, has also been examined, Correa 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. The inter-fibre failure under compression, typically appearing in impact problems and caused by a dominant compression acting transversely to the fibres, starts with the appearance of small debonds at the fibre–matrix interfaces. The initial defects present, in accordance with Interfacial Fracture Mechanics theory, a non-symmetric morphology (deformed shape): a small 'bubble' at the lower crack tip and a contact zone at the upper crack tip, see Fig. 1a, and, in an initial period, grow unstably along the interfaces (interface cracks) following the lower crack tip. This period ends when these cracks reach a certain length at the interface, which coincides with the closing of the 'bubble' existing at the lower crack tip, Fig. 1b. From that moment

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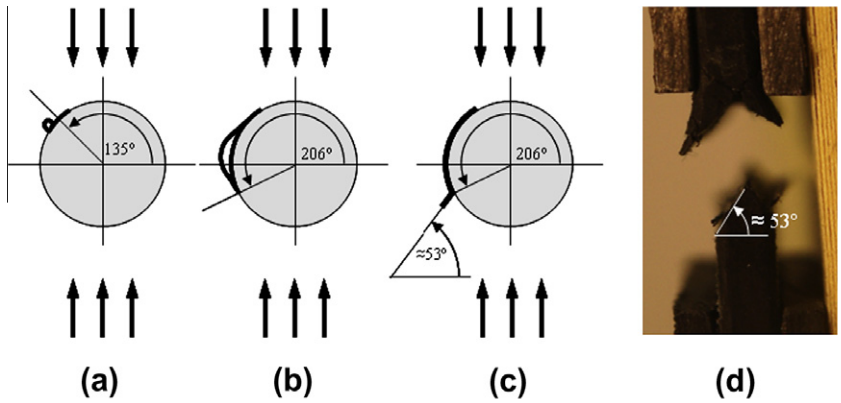


**Fig. 1.** Micromechanical phases of inter-fibre failure under unidirectional compression.

on, the growth of the interface crack becomes stable, which favours the occurrence of a different stage of the mechanism of failure: the propagation of the crack through the matrix. Thus, the interface crack suddenly changes its direction of propagation, kinking into the matrix following an orientation angle around 53° from the direction perpendicular to the load, Fig. 1c. These numerical predictions agree with the experimental results obtained from broken specimens, Fig. 1d. Note that, in that case, the numerical studies were performed without considering the presence of thermal residual stresses whereas, obviously, the specimens tested included them. In any case the comparison between numerical and experimental analysis was reduced to the orientation of the plane of failure and not to quantitative values of fracture parameters.

Some authors have employed FEM models to numerically analyse the role of residual stresses in transverse failure [3]. The main effort has been devoted to the tensile case, whereas the compressive case has been studied by only a few authors. In this respect, Zhao et al. [10] performed an FEM analysis on a unit cell to predict damage initiation under transverse failure, finding that the presence of residual stresses influences neither the site of damage initiation nor the pattern of damage evolution in the case of compressive failure.

The present work is a continuation of the previous studies by the authors related to inter-fibre failure under transverse compression [4,8] and analyses the influence of thermal residual stresses, originated by the cooling down associated to the curing process, on the conclusions obtained so far about the development of the mechanism of damage at micromechanical level. To this end a single fibre model has been generated by means of the Boundary Element Method (BEM) and its results analysed using the concepts obtained from Interfacial Fracture Mechanics. The numerical predictions derived from Boundary Element analyses are validated with macromechanical experimental tests.

In particular, in Section 2 the main features of the BEM model employed, as well as the materials properties, are presented. Sections 3–5 refer 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 compression and the temperature 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. Finally, in Section 7, a discussion on the connection between numerical and experimental results is presented.

## 2. Single fibre model

The study has been carried out using a tool based on BEM, París and Cañas [11], 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. [12] for planar problems and Graciani et al. [13] 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 that, under the plane strain hypothesis, grows along the interface.

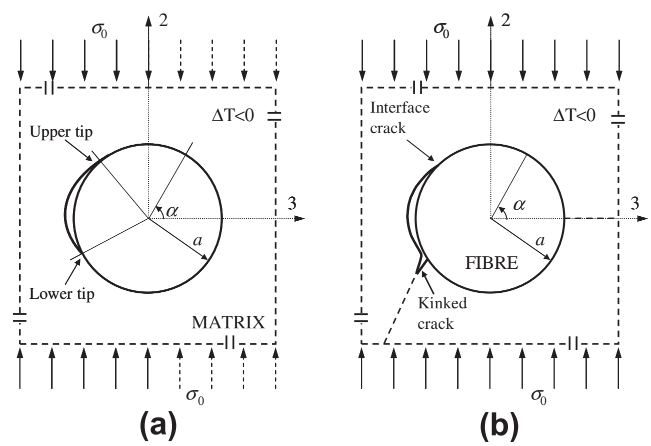


**Fig. 2.** Single fibre model with (a) interface crack and (b) kinked crack.

In order to characterize the problem from the Fracture Mechanics point of view the Energy Release Rate (ERR), $G$, will be used. The expression employed for $G$ evaluation, based on the Virtual Closure Crack Technique (VCCT), Irwin [14], for a circular crack that propagates from a certain debonding angle, $\alpha$, Fig. 2a, to $\alpha + \Delta\alpha$ ($\Delta\alpha$ being much smaller than the crack length), 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 $\sigma_{rr}$ and $\sigma_{r\theta}$ represent, respectively, radial and shear stresses along the interface, and $\Delta u_r$ and $\Delta u_\theta$ the relative displacements of the crack faces. $\theta$ is the circumferential coordinate with reference to the crack tip position. Both modes of fracture, I (associated to $\sigma_{rr}$) and II (associated to $\sigma_{r\theta}$), are obviously considered in Eq. (1).

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, once kinked into the matrix, is progressing through it, Fig. 2b. In this case Eq. (1) is appropriately adapted to a crack in a homogeneous material. The materials chosen for the analysis included in Sections 3–5