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Micromechanical study on the influence of scale effect in the first stage of damage in composites

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ABSTRACT

The variation in the apparent strength of a lamina in a laminate depending on the stacking sequence and thicknesses of the laminas of the laminate has been a matter of interest since the initiation of the extension of the applicability of composites. This fact led to the concept of in-situ strength, the problem itself being covered as a scale effect. In this paper this question is revisited moving towards the level where the damage appears, that is the micromechanical level. As the origin of the effect under consideration, the variation of thickness, takes place at a different level (mesomechanical), a multi-scale model is developed. It is possible in this model to vary the thickness of the lamina under consideration and to observe its effect on the damage. In this paper, only the first stage of damage, which appears in form of debondings between fibres and matrix, is taken into consideration. The analysis carried out shows that there is no scale effect at this first stage of the damage, which is corroborated by experimental evidences.

1. Introduction

From almost the beginning of the explosion of application of composites, a phenomenon associated with the strength of laminas placed in a laminate was experimentally identified. Thus, Parvizzi et al. [1] and Flaggs and Kural [2], among others, found that the appearance of damage in the 90° lamina of a $[0,90_n]_S$ laminate was a function of the value of n, the delay in the appearance of the first transversal damage in the 90° lamina being associated with the lowest values of n used. This fact, not easy to be understood, was associated with the different role that the restriction of the 0° lamina may play in the behaviour of the 90° lamina, not covered by the Classical Laminate Theory. This phenomenon gave rise to identify the term “in situ strength”, which indicates that the actual strength was not only a property of the material but a function of the configuration of the laminate where the lamina was, the total phenomenon being known as a “scale effect”.

When analysing the scale effect, the emphasis may be put either in the value of n in a $[0, 90_n]_S$ laminate (see for instance [2]) or in the value of the thickness of the 90° lamina (see for instance [1]). There exists a link, but not a complete and biunique connection, between the two approaches. Notice that with the definition of the laminate given, the thickness of the 0° plies is taken as a reference and the value of n defines the thickness of the 90° lamina in relation to the 0° lamina. All of this lead to the fact that many different laminates have been historically studied and tested (with different procedures to detect the appearance of first damage in the 90° lamina). The results might neither always be comparable nor leading to a unique view of the matter.

There have been many trials to give an explanation to this phenomenon, those of Dvorak and Laws [3] and Li and Wisnom [4], being widely recognized, among others. Both approaches, while different conceptually speaking, have in common that are based on the fact that the laminas are considered as equivalent homogeneous materials. Again in this context and more recently, García et al. [5] have given a new insight into the problem by using a double stress and energy criterion, based on Finite Fracture Mechanics, which adds a convincing explanation on the scale effect identified by Parvizzi et al. [1]. It is also worth to mention that the challenges of dealing with in-situ strength of embedded laminae through different approaches have been highlighted in Kaddour et al. [6].

In contrast with the previous approaches that consider an homogenized view of the laminas, it is reasonable to accept that the

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most plausible explanation for the initiation of the damage indicates that it appears in a 90° lamina as debondings between fibre and matrix. By coalescence, these debondings, may give rise to a mesomechanical crack that propagates across the thickness of the lamina stopping near the interface with the 0° lamina. When approaching this interface, the cracks provoke damage at micromechanical level that could be viewed, at mesomechanical level, as an incipient delamination, able to grow giving rise to an apparent and noticeable delamination between 0° and 90° laminas París et al. [7,8].

The appearance of ultra thin plies has alerted on the possibility of having now an extra increase of the apparent strength of these 90° laminas, significantly delaying the appearance of the first identified damage in the laminate. This would allow a longer period of behaviour without damage, what for a designer of actual composite structures would compensate the extra work in manufacturing which derives from the use of ultra thin plies. Several attempts have been recently made to deal with a view of the scale effect at micromechanical level. Saito et al. [9] performed an experimental study complemented later with a numerical simulation at micromechanical level, Saito et al. [10], allowing debondings between fibres and matrix as the mechanism of damage. More recently, Arteiro et al. [11] and Herráez et al. [12] have used finite element models, both at micromechanical level involving cohesive approaches, to try to give an explanation to the scale effect. In the first study the authors claim to have performed a numerical study that support the scale effect, whereas in the second one they claim that the numerical model developed does not support the presence of the scale effect. All these models require the use of several material and interfaces properties that are not identified in the literature, and thus must be fitted using the models themselves. Additionally the use of many fibres in the model may partially hide the actual nature of the damage and the causes that control their onset and propagation.

In this paper, it is assumed that the mechanism of damage starts with micromechanical fibre-matrix debondings that may coalesce by giving rise to a mesomechanical transverse crack. The first stage of this damage mechanism (that associated to the debonding between fibre and matrix) is going to be analysed in this paper in light of the scale effect. To this end, a multi-scale model is developed using the Boundary Element Method (BEM) and the concepts derived from Interfacial Fracture Mechanics (IFM), as the damage consists of an interface crack running between fibres and matrix in a lamina of a laminate. The model developed does not require any property other than those of the stiffness of the materials, fibre, matrix and lamina, as it has no predictive objectives in terms of damage and load associated. This model has only the objective of understanding the relation, at micromechanical level, between the first stage of damage and the scale effect, which only requires predictions on the stress state.

The effect of the presence of additional fibres surrounding the damaged fibre under consideration will be studied following the previous studies by Sandino et al. [13,14]. Damaged fibre refers in what follows to a fibre with a damaged interface. Finally, experimental evidence supporting the predictions obtained with the numerical methods is presented.

2. Tools and materials

As debonding between fibre and matrix is going to be the focus of attention in this study, Interfacial Fracture Mechanics (IFM) is the adequate tool to characterize the behaviour of these interface cracks. The background of IFM and its application to the problem under consideration can be found in París et al. [15,16]. The variable to be used as representative of the behaviour of this damage is the Energy Release Rate G of the debonding crack. Both the case of the open crack model, Rice [17], and the case of contact crack model, Comninou [18], require very accurate values of displacements of the faces of the crack as well as the stress state in its neighbourhood. It is significant to remark that both models need to be applied when modelling the different lengths of the debonding to simulate the growth of a debonding crack. Thus, for small values of the debonding it will be oriented almost normal to the load applied, mode I being dominant and the open model being of application. On the contrary, when the debonding reaches a certain value, a contact zone between the faces of the debonding crack appears, mode II being the unique existent, and consequently, the contact model being of application. In the transition between these two extreme situations, a mixed mode appears evolving from mode I to mode II, the open model being of application along this period of growth, París et al. [16].

All matters associated with IFM, for both models, lead to the necessity of having a very fine discretization in the neighbourhood of the crack tip. The Boundary Element Method (BEM), París and Cañas [19], has been selected as the adequate tool to deal with the multi-scale problem under consideration. The level of accuracy at which the solution in the neighbourhood of the debonding crack tip must be obtained to get accurate values of the Energy Release Rate (ERR), without having the associated refined domain discretization, can be only reached by BEM. A program for multi-body modelling considering contact between the boundaries of the bodies involved in the model will be used, Graciani et al. [20]. The main difficulties derived from this approach come from the necessity of having extremely fine discretizations near the crack debonding tip. This leads to have very similar integral equations involved in the final system of equations to be solved, see Velasco et al. [21].

As a summary, the analysis carried out presents the following features: is based on linear elastic behaviour and no thermal stresses are considered, the fibres are assumed to have perfect bonding out of the damaged zone, no interphase layer has been used between fibres and surrounding matrix, and no failure is aimed to be predicted, as previously stated.

Table 1 shows the properties of the carbon-epoxy material taken as reference for this study, which corresponds to that employed in Soden et al. [22], to facilitate comparisons with previous studies. Table 2 gives the properties of a glass-epoxy system also used in this study.

3. Multi-scale model

Fig. 1 describes the multi-scale model used in this study of a $[0,90_n]_S$ laminate with a cell involving fibre and matrix. The thickness of each 0° ply is t_0 and the total thickness of the 90° ply is $2t_{90}$.

Table 1
Carbon-epoxy system used: AS4/3501-6, Soden et al. [22].

Material	Properties
0° ply (orthotropic)	$E_{11} = 135$ GPa, $E_{22} = 8.75$ GPa, $E_{33} = 8.75$ GPa, $\nu_{12} = 0.3$, $\nu_{13} = 0.3$, $\nu_{23} = 0.4$, $G_{12} = 4.75$ GPa
90° ply (isotropic)	E ($E_{22} = E_{33}$) = 8.75 GPa, ν (ν_{23}) = 0.4
Matrix (epoxy, isotropic)	$E = 4.2$ GPa, $\nu = 0.32$
Fibre (carbon, transversely isotropic)	E ($E_{22} = E_{33}$) = 15 GPa, ν (ν_{23}) = 0.2