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Characterization and evolution of matrix and interface related damage in $[0/90]_S$ laminates under tension. Part I: Numerical predictions

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ABSTRACT

This paper considers damage development mechanisms in cross-ply laminates using an accurate numerical method that assumes a Generalized Plane Strain (GPS) state. A 2D Boundary Element Method (BEM) model is generated to investigate the two types of damage progression in a $[0/90]_S$ laminate: transverse cracks in the 90° lamina and delamination between both laminae. The model permits the contact between the surfaces of the cracks. The study is carried out in terms of the dependence of the Energy Release Rates (ERR) of the two types of crack on their respective lengths. A special emphasis is put on the mechanisms of the joining of the two aforementioned types of crack, including the study of the distribution of the stresses along the interface between the two plies when the transverse crack is approaching this interface.

1. Introduction

Composites are experiencing a massive use in primary structures of commercial aeroplanes. The associated current demand for diminishing weight requires a better knowledge of mechanisms of failure. An essential step is to generate physically based failure or damage criteria. All this leads to the necessity of revisiting classical problems of composite laminates such as the mechanism of damage in $[0/90]_S$ laminates. It is generally accepted that the damage in a $[0/90]_S$ laminate appears in accordance with the following steps. The application of load generates almost immediately the appearance of transverse microcracks in the 90° ply. The coalescence of these microcracks leads to the appearance of a transverse macrocrack that can propagate in the 90° ply towards the interface with the 0° ply. On reaching the interface, it may initiate single or double deflection at the ply interface, then propagating in the interface as a delamination crack. Many relevant contributions to the understanding of this damage mechanism have recently been reviewed in an excellent paper by Berthelot [1].

Since this review, several papers have appeared shedding more light on the understanding of this basic problem. A significant number of papers are devoted to the numerical modelling of damage and its connection with different levels of modelling [2,3]. The study of the effect of the spatial distribution of the transverse cracks [4,5] has also been a question addressed, as well as some particular questions regarding the effect of fatigue [6], the influence of mixed mode fracture [7] and the effect of residual stresses [8].

Closer to the objective of the present paper is the contribution by Lim and Li [9]. They discuss, based on a simplified analytical model for GPS conditions used by McCartney [10], the validity of the unit cell to obtain representative results for the ERR for both transverse and delamination cracks. They conclude that a point of interest for future attention is the joining of transverse and delamination cracks, which cannot be explained simply in terms of the ERR for the two types of crack.

The significant simplifying assumptions required in analytical approaches require a further validation based on a detailed numerical analysis. The problem has a 3D nature associated for instance with the fact that the initial damage, the transverse cracks in the 90° lamina, can grow in both the through-thickness and in the width directions. The vast majority of the studies carried out on this problem, concentrate effort on what happens in a longitudinal plane associated with the through-thickness direction, as will be done in this paper. Starting from this point the problem adopts a GPS formulation and it will be dealt with by means of a numerical model that does not require any additional simplifying hypotheses.

BEM has been selected, due to the nature of the problem, as the most adequate tool [11]. It is based on the fact that the important features of the problem (contact zones along cracks, Fracture Mechanics parameters, etc.) are associated directly with the boundaries of the problem under consideration. The authors devel-

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oped a special approach to treat a GPS problem with BEM, Blázquez et al. [12], and applied it to characterize the singular stress states, to study the appearance of contact zones in the delamination cracks and to evaluate Fracture Mechanics parameters, Blázquez et al. [13,14].

The present paper is a step forward towards the characterization of the mechanisms of failure of a $[0/90]_S$ laminate. Its aim is to characterize the behaviour of the two types of crack involved in the problem (transverse and delamination) by means of Fracture Mechanics, trying to connect predictions with the observed damage of specimens, which will be done in Part II, including thermal residual stress effects.

2. Description and modelling of the delamination problem in a $[0/90]_S$ laminate

The problem analysed in this work applies to a $[0/90]_S$ laminate. An indication of the final expected damage under uniaxial tensile loading is shown in Fig. 1. The first type of damage in this laminate is expected to be the nucleation and growth of a crack in the 90° ply transverse to the uniaxial load. This is in agreement with the observations of many authors, see for instance Dvorak and Laws [15] and Wang [16], and confirmed by the experimental observations of the authors described in Part II. New transverse cracks appear in the 90° ply with increasing load until the crack density reaches a saturation value. Ply cracking saturation is thought to arise from the occurrence of compressive stress states at the mid-planes between neighbouring ply cracks as the ply crack density increases [17–19]. Transverse matrix cracking in the 90° ply leads to a load redistribution in the adjacent 0° plies and induces local stress concentrations at crack tips, that can initiate significant interlaminar delamination between 0° and 90° plies [1].

The first stage of the problem, the nucleation and growth of a transverse crack, is itself a complicated 3D problem [16], with localised damage that can grow in both the width and the through-thickness directions. In this paper, due to the fact that emphasis is placed on the interaction between a transverse crack and a delamination crack, it will be assumed that the ply cracks traverse the full width of the specimen.

With these assumptions, the problem is treated as a 2D problem in the plane xy shown in Fig. 1. The nature of this 2D problem corresponds to a case of GPS [12].

The two damage patterns in the specimen that will initially be considered in this paper are shown in Fig. 2, one having only a transverse crack (Fig. 2a and b) and the other having a transverse crack that has reached the interface with the 0° lamina and has deflected, nucleating a delamination (Fig. 2c). The damage pattern shown in Fig. 2d is considered later. The cases (a) and (b) have been

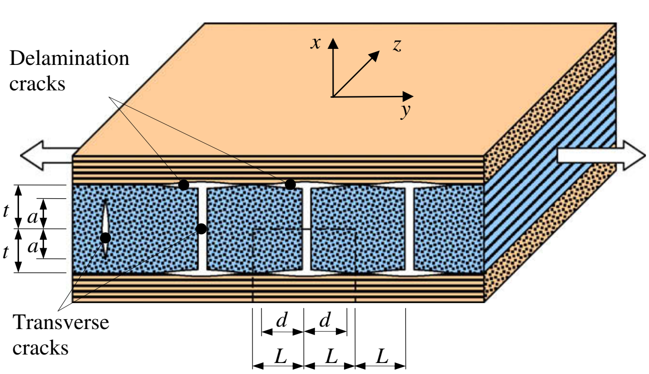

Fig. 1. Transverse and delamination cracks in a $[0/90]_S$ laminate.

separately specified for the sake of clarity, and because the nature of these two problems from a Fracture Mechanics point of view is completely different.

The cases shown in Fig. 2 exhibit symmetry (with respect to the horizontal plane in the figure), which finally leads to the study to be performed using the configuration shown in Fig. 3a. This configuration in particular corresponds to the one with a transverse crack that has reached the interface with 0° ply and also has a delamination between the 90° and 0° plies, i.e. a configuration corresponding to that represented in Fig. 2c. The boundary conditions of the problem are also specified in Fig. 3a. Fig. 3b shows the mesh used for a representative case corresponding to a delamination crack of length 0.1L.

Fracture Mechanics principles will be applied to embedded cracks within the 90° ply and to interfacial cracks. The parameter of key importance in the analysis will be the ERR calculated by means of the crack closure technique (CCT). A background to the theory used, in particular for interface cracks, can be found for a general application in [20] and with reference to the particular problem analysed here in [13].

An alternative method of estimating the ERR for the ply crack in the 90° ply is to use the following formula, for the case of uniaxial loading when thermal stresses are absent, where values of the effective axial modulus E_A for different ply crack lengths 2a are obtained using the methodology described in [21],

$$G = \frac{1}{2} Lh \frac{\partial}{\partial a}\left(\frac{1}{E_A}\right)\sigma^2, \tag{1}$$

and, where 2h is the total thickness of the laminate. The parameter σ is the effective applied uniaxial stress. The result is valid for any value of the parameter L, which affects the value of the axial modulus, so that the effects of ply crack interactions can be taken into account.

The material system considered is a carbon–epoxy (AS4/8552 Hexcel) laminate $[0_3/90_3]_S$ with the following properties: E_{11} = 141.3 GPa, $E_{22} = E_{33}$ = 9.58 GPa, $\nu_{12} = \nu_{13}$ = 0.3, ν_{23} = 0.32, $G_{12} = G_{13}$ = 5 GPa, G_{23} = 3.5 GPa, the suffix 1 denoting as usual the direction of the fibres. The thickness of each group of three laminae of both 90° and 0° is t = 0.55 mm (a value taken from the specimens that have been tested). The transverse crack separation, which defines the size of the numerical model to be solved, has been taken in most cases to be 2L = 4 mm, although other values have also been used to carry out parametric analyses. The value of the uniform transverse strain ε_z to be applied, corresponding to a state of GPS, is $\varepsilon_z = -0.000381$, a value obtained by applying undamaged laminate theory, associated with a value of a uniaxial applied strain of $\varepsilon_y = 0.01$. It is emphasised that this value of ε_z has been found by considering the GPS deformation of an *undamaged* laminate subject to uniaxial loading and in the absence of thermal residual stresses, which are neglected in Part 1 of the paper. The transverse strain is selected so that the corresponding effective transverse stress is zero. For a *damaged* laminate, as it is very difficult to select the value of the transverse strain that leads to a zero transverse effective stress, there is an implied approximation in our approach. The discrepancy is, however, thought to be insignificant.

3. Energy Release Rates for transverse and delamination cracks

3.1. Transverse crack

Fig. 4 represents the distribution of the values of the ERR of a transverse crack versus its length a. BEM curves have been obtained by means of a VCCT using a static BEM analysis for different values of the length a of the transverse crack. Curves labelled