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Microscopical observations of interface cracks from inter-fibre failure under compression in composite laminates

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A B S T R A C T

Matrix/inter-fibre failure is characterized by the appearance at the fibre–matrix interfaces of small debonds that can progress along them until reaching a certain extension, then changing their orientation to kink towards the matrix and, finally, growing through it. The particular case of compressive loading is specially interesting, given the morphology of the interface cracks and the specific angle that the macro-cracks form in the matrix.

To date, the analysis of this problem at micro-mechanical level has been carried out mainly by means of Finite Element or Boundary Element models. In this work, the problem is approached from the experimental point of view, observing under optical microscope those coupons previously tested at different loading levels. Several aspects such as the identification of the stages of the failure mechanism, the kinking angle, the extension of the interface cracks and the presence of damage as a function of the loading level are studied.

1. Introduction

The study of the initiation of failure mechanisms in composite materials at micro-mechanical level is essential for the improvement of the existing criteria that predicts their appearance; the connection of the knowledge generated at this level with the macro-mechanical scale would contribute to a more accurate and efficient design of components made of composites.

The particular case of matrix/inter-fibre failure under compression, which corresponds, at the macro-mechanical level, to transverse failure under compression (i.e. failure occurring in 90° plies of multidirectional laminates or in unidirectional laminates subjected to transverse loads) has been analysed by several authors using numerical tools, see for instance Correa et al. [1–4], González and Llorca [5], Vaughan and McCarthy [6], Yang et al. [7] and Arteiro et al. [8]. In particular, the work by Correa et al. [1–4] identified the initial stages of the damage mechanism, and showed the importance of some key parameters on the progression of damage.

Specifically, as Fig. 1 shows, the damage is assumed to initiate at the fibre-matrix interfaces as small (10° length) debonds (interface cracks) centred at 135°; these initial debonds (Stage I, Fig. 1a) present an interesting morphology characterized by an almost closed (contact) configuration with a small 'bubble' in their lower tip [1]. The debond growth along the interface (Stage II, Fig. 1b) seems to be unstable until reaching a certain extension at the interface that coincides with the closing of the 'bubble'; this final amplitude of the crack at the interface is approximately 76° (corresponding to a position of the lower crack tip of 206°).

After this moment, the interface crack growth turns stable, giving rise to Stage III of the damage mechanism, i.e. the kinking of the crack towards the matrix (Fig. 1c). A very remarkable feature is that the crack does not kink into the matrix following an arbitrary orientation but an approximate angle of 53° with reference to the external load, coinciding with the macro-mechanical fracture angle detected experimentally (Fig. 1d) and presumably formed by the coalescence of the aforementioned kinked cracks (named as Stage IV). This characteristic macro-mechanical failure angle has already been brought to light by other authors (see for instance Puck and Schürmann [9] and Christensen and De Teresa [10]).

Previous works from different authors focusing on the experimental micro-mechanical observation of the matrix failure can be found in the literature, see for instance Zhang et al. [11], Gamstedt and Sjögren [12], Saito et al. [13], Baral et al. [14], Hobbiebrunken et al. [15], or Genz et al. [16], although micro-mechanical experimental investigations specifically devoted to transverse compression are not easily found.

Based on the numerical studies performed by Correa et al. [1–4] on the behaviour of composites subjected to compressive transverse loads, this work focuses on the experimental identification of the different stages of the damage mechanism arising in coupons from 90°

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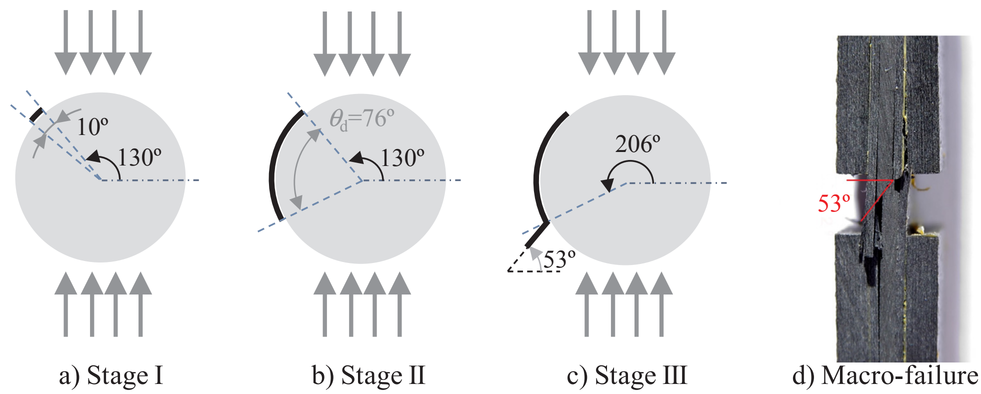

Fig. 1. Stages of the inter-fibre failure under compression (Correa et al. [2]).

unidirectional and symmetrical cross-ply laminates subjected to compression.

Thus, in this study, the following four stages of the damage mechanism will be experimentally distinguished:

- Stage I: Damage initiation at the interface.
- Stage II: Interface crack growth.
- Stage III: Interface crack kinking towards the matrix.
- Stage IV: Formation of a macro-crack.

The approach conceived for the investigation presented here has consisted on the manufacturing of coupons of two different types (unidirectional and cross-ply) (Section 2.1), their testing under compression at different loading levels lower than the strength of the corresponding laminates (Section 2.2), the preparation of samples (Section 3), and their inspection by means of an optical microscope (Section 4), analyzing the damage encountered and searching for an experimental base to validate the predictions of the previous numerical models. Specifically, key aspects of the stages such as the extension of Stage I debonds (Section 4.3), the amplitude of the interface crack that gives rise to Stage III (Section 4.4) and the kinking angle (Section 4.5) are studied.

2. Coupons manufacturing and testing

2.1. Coupons manufacturing

The coupons for compressive tests (Fig. 2) were manufactured based on ASTM D695-02a [17] and using a carbon/epoxy (*Hexply AS4/8552)* pre-preg. This material contains a 34% resin content and 194 g of fibre per unit area. The corresponding reinforcing tabs were bonded using a standard epoxy film adhesive with a polyamide base (*AF-163-2-K.06)* from 3 M.

Two different sets of coupons were manufactured: a first set from unidirectional 90° panels with 10 plies (and using the same laminate to build the tabs), Fig. 3a; a second set from cross-ply symmetrical panels $[0_3, 90_3]_s$ with tabs from a $[0_{12}]$ laminate, Fig. 3b. Coupons tested at different loading levels belong to different panels.

2.2. Transverse compressive tests

Transverse compressive tests were performed using the set-up presented in Fig. 4.

2.2.1. Unidirectional coupons

A first set of 5 unidirectional (UD) coupons was selected for testing under compression. The results obtained for the compressive strength (Y_c) showed a mean value of 279.8 MPa, a standard deviation of 4.8 MPa and a coefficient of variation of 1.7%, therefore implying an excellent result in terms of dispersion.

Subsequent testing campaigns were performed under maximum loads lower than the previously measured Y_c, in order to generate damage without reaching the catastrophic failure. In particular, the loads applied can be grouped in 4 levels: 25%Y_c, 50%Y_c, 75%Y_c and 80%Y_c, using 6 coupons for each group. The reason for the selection of these specific loading levels will be explained in Section 4.1.

2.2.2. Cross-ply coupons

A similar procedure was employed in this case. A first set of 5 coupons was selected for testing under compression. The results obtained for the compressive strength of the laminate (X) showed a mean value of 883.7 MPa, a standard deviation of 23.9 MPa and a coefficient of variation of 2.7%, again implying and excellent result in terms of dispersion.

Subsequent testing campaigns were performed under maximum

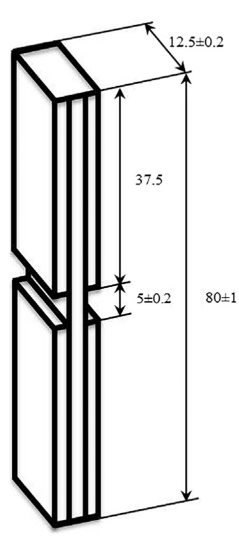

Fig. 2. Coupons geometry (dimensions in mm).

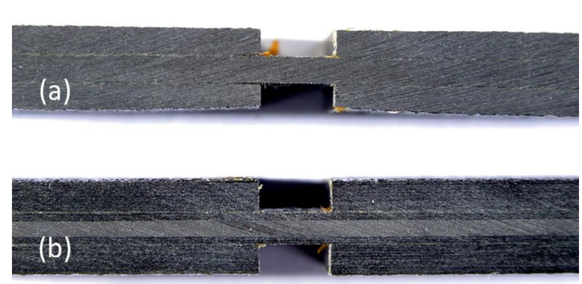

Fig. 3. (a) Unidirectional coupon, (b) cross-ply coupon.