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Determination of the 3D failure envelope of a composite based on a modified Arcan test device

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ABSTRACT

This paper describes a 3D failure criterion identified through Arcan tests, to analyze the behavior of a laminate composite subjected to out-of-plane loadings. The proposed criterion is based on the Hashin's hypothesis and the interactions between tensile and shear out-of-plane loadings are taken into account. The out-of-plane stresses generated in the composite subjected to an Arcan test are studied using 3D Finite Element calculations in order to determine the stack sequence influence. Using different angles of the loading and different stacking sequences allows the ply to be subjected to complex 3D stress state. Using the experimental results and an inverse identification procedure, it is possible to identify the out-of-plane failure envelope. It is shown that a quadratic failure envelope, which takes into account a decrease of the apparent shear strength in the presence of out-of-plane tensile stress, permits the model to describe in a correct manner the experimental results.

1. Introduction

In the last few years, the use of composite laminates and their assemblies has drastically increased in almost all engineering applications, e.g. automotive, aerospace, medical prosthetics and sport devices. In these applications complex 3D loadings are often generated. It could be the case due to the shape of the specimen (for instance curved beam specimen subjected to bending), due to the thickness or to the edge effects [1]. Thus, the analysis of the failure of composite laminates under out-of-plane loadings is necessary in order to ensure the design requirements. It has been shown that a coupled strength and toughness initiation criterion [2] must be used to attain this goal. This approach has recently been used to model the failure of open-hole specimens or the initiation of delamination from the edges [1].

Different tests exist in the literature to identify the toughness: Double Cantilever Beam for the mode I [3], End-Notched Flexure for the mode II [4] and Mixed Mode Bending test for the mixed-mode (mode I + mode II) [5]. These tests make it possible to determine the toughness as a function of the mode mixity and thus to identify a propagation law such as the power-law [6] or the semi-empirical model proposed in [7] (usually known as BK model).

If the methodology to determine the evolution of the toughness as a function of the mode mixity is now well established, it is not the case for the strength. Indeed, some standards exist in the literature to identify the out-of-plane strength. For example, the four-point bending test on curved beam for the tensile out-of-plane strength [8–10] and the 3-point bending test on short beam for the out-of-plane shear strength [11]. A complete review of the different tests can be found in [12]. However, there is no consensus among researchers regarding the identification of the out-of-plane strengths under multiaxial loadings. Some authors propose to use a cylindrical specimen subjected to tensile and torsional loadings. The main drawback lies in the manufacturing of the specimens and their representativity as compared with the final application [12]. Other authors propose to use the Arcan test device to subject the butterfly-shaped specimen to multiaxial loadings (with a given ratio of tensile/shear loadings) [13,14]. The main drawback of this approach lies on the manufacturing of the specimen machined from high thickness composite plates that could lead to a high scattering of the results [15]. To overcome this difficulty, Cognard and co-workers [16] have developed a modified Arcan test device. It is based on the use of specimen manufactured from thin composite plates bonded to metallic substrates. It has already been shown that this method allows us to obtain reliable results [17]. In these previous works, the results were presented in terms of macroscopic failure envelope of the laminates. This is the reason why this article is aimed at developing a methodology

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to identify the failure criterion of a UD fiber reinforced polymer matrix composite.

2. Experimental and numerical background

2.1. Material and experimental setup

The material under investigation is a carbon/epoxy material whose elastic properties are give in Table 1.

The out-of-plane properties are investigated thanks to the modified Arcan test device developed a few years ago by Cognard and co-workers [16]. The principle of this device is given in Fig. 1(a). The specimen is constituted of a composite plate bonded to two metallic substrates (see Fig. 1(b)). The bonded surface measured 50 mm in length and 9.5 mm in width. This specimen is fixed to the Arcan device which allows the analysis of the influence of a wide range of tensile/compression-shear proportional loads using a classic tensile testing machine. By choosing the angle between the normal axis to the specimen and the loading direction, it is possible to subject the specimen to: an out-of-plane tensile loading (with $\gamma = 0^\circ$), an out-of-plane shear loading (with $\gamma = 90^\circ$), combined out-of-plane tensile/shear loading (for $0^\circ < \gamma < 90^\circ$) and combined out-of-plane compressive/shear loading (for $90^\circ < \gamma$). It has been shown that the geometry of the specimen and the fixture system of the Arcan device have a great influence on the stress distribution and could lead to stress concentration in the adhesive and in the composite plate. Consequently, both the specimen geometry and the set fixation must be optimized in order to reduce these stress concentration. The current specimen geometry used in this study has been proposed by Cognard et al. [17] and avoids the stress concentration in order to obtain reliable results (thanks to the grooves machined in the specimen see Fig. 1(c)).

In the present study, the substrates are made of aluminum (Young modulus $E_{al} = 75$ GPa, Poisson's ratio $\nu_{al} = 0.3$). In order to induce failure in the composite, it is necessary for the adhesive used to bond the composite to the substrates to have a strength greater than the out-of-plane strength of the composite. An epoxy Huntsman™ Araldite® 420 A/B adhesive has been used to join the aluminium and the composite ($E_{ad} = 2$ GPa, $\nu_{ad} = 0.3$).

Different stacking sequences with 8 plies in the composite thickness have been studied (see Table 2).

2.2. Model

In order to identify the out-of-plane strength an inverse identification procedure is used. It involves applying on a Finite Element

Table 1
Properties of the M55J/M18 UD ply measured by CNES (the elastic properties are assumed to be transverse isotropic).

Young modulus (GPa)	$E_1 = 315$ $E_2 = E_3 = 6.75$
Poisson's ratio	$\nu_{12} = \nu_{13} = 0.3$ $\nu_{23} = 0.4$
Shear modulus (GPa)	$G_{12} = G_{13} = 4.5$ $G_{23} = 2.4$
Thickness ply (mm)	0.13

Table 2
List of stacking sequences investigated in the present study.

Composite reference	Stacking sequence
A0	UD $[0^\circ{}_4]_s$
A10	$[+10^\circ + 10^\circ - 10^\circ - 10^\circ]_s$
A20	$[+20^\circ + 20^\circ - 20^\circ - 20^\circ]_s$
A30	$[+30^\circ + 30^\circ - 30^\circ - 30^\circ]_s$
A90	$[90^\circ{}_4]_s$

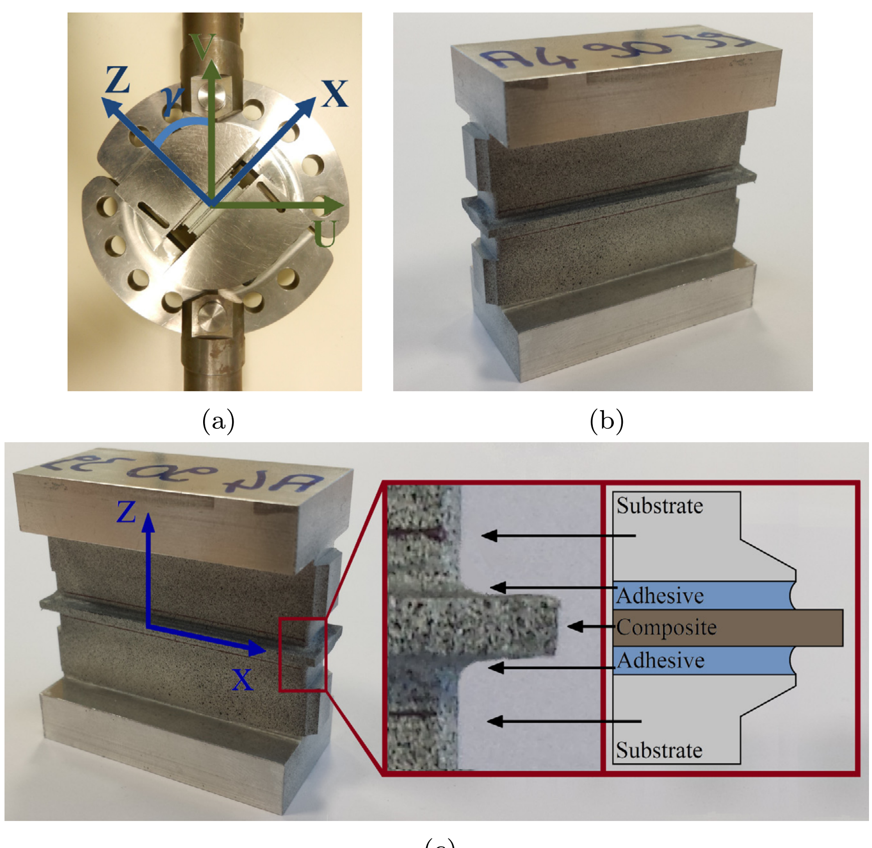

Fig. 1. Principle of the Arcan test (a). Specimen used to test the out-of-plane properties of the composite (b). Detail of the substrate design to reduce the stress concentrations close to the free edge (c).