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Comparative experimental analysis of the effect caused by artificial and real induced damage in composite laminates

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ABSTRACT

This paper presents the results of an extensive experimental campaign aimed to examine the effect upon the vibration response and on the residual load-bearing capacity caused by both: isolated artificially induced interlaminar damage and low-velocity impact induced damage in composite laminates. The experimental programme included modal testing, drop-weight impact testing, ultrasonic inspection, transverse quasi-static loading testing and compression testing conducted on a set of 72 carbon fibre-reinforced composite laminated coupons. Both types of damage caused measurable changes in laminate performance, however marked divergent trends were observed. The results allowed for conclusions to be drawn regarding the adequacy of the artificial damage approach and highlighted the importance and role of other forms of degradation upon damage tolerance of laminated composites containing damage.

1. Introduction

With the increasing use of composite materials in industry comes an increasing need of a better understanding of their behaviour and improving their performance. Over the years, a tremendous amount of activity has been devoted to developing accurate and fast non-destructive evaluation techniques as well as numerical methodologies, which can quantitatively predict the performance and durability of composite structures. This is due to the fact that composite materials represent a departure from the way that conventional materials are used, and, consequently, they require unconventional approaches to dealing with them.

During the last decades, a significant research effort has been particularly devoted to the study of impact and post-impact behaviour of laminate composite structures, since this is a phenomenon which has greatly hindered their widespread application. Experimental studies consistently indicate that impact induced damage is a mixture of three main failure modes: matrix cracking, delamination and fibre breakage, among which delamination the most severe because it may severely degrade the stiffness and strength of composite structures Reid and Zho [1], Hodgkinson [2]. Consequently, several studies assessed and quantified composite damage resistance and damage tolerance in terms of delaminated area.

Numerous contributions have been made to numerically model the damage in composite materials Orifici et al. [3]. Continuum damage mechanics approaches, which are based on material degradation models, have proved to be successful to predict different composite failure modes, including matrix cracking, delamination and fibre breakage Hinton et al. [4]. However, major efforts have been focused on the treatment of delamination Pagano and Schoeppner [5]: two common approaches are the virtual crack closure technique (VCCT) Krueger [6] and the cohesive zone models (CZMs) Camanho et al. [7], Lopes et al. [8]. In parallel, numerous experimental studies dealing with composite damage detection have also been published. It is notable that a large number of experimental works were based on the analysis of the influence of an isolated artificially induced damage Ooijevaar et al. [9], Wei et al. [10], Kessler et al. [11], Yam [12]. It is common practice to induce delamination by inserting a polyimide film before consolidating a composite specimen in an autoclave.

As shown, the importance of delamination is well recognized. However, for the particular case of an impact, delamination does not occur in isolation. While numerous studies on the relationship between delamination and damage tolerance have been reported, little has been found in the literature concerning the role of other forms of damage, such as fibre breakage or indentation, in the residual load-bearing capacity. This issue could be addressed

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through numerical modelling. On the other hand, problems can arise when using an experimental approach since different damages are not always accounted for separately. One approach that may be worthy of consideration is the use an artificially embedded delamination, which allows the delamination-type of failure to be decoupled from the other ones.

Bearing this in mind, the purpose of the present study was to deeply examine in-depth the effect upon the vibration response and on the residual load-bearing capacity caused by both: isolated artificially induced interlaminar damage and low-velocity impact induced damage in composite laminates. According to the authors' knowledge, this topic has not been fully studied hitherto. This work enters in the continuity of the work conducted by the authors Pérez et al. [13]. This paper mainly presents the results of an extensive experimental campaign carried out on a set of 72 carbon fibre-reinforced composite laminated coupons. The experimental programme included modal testing, drop-weight impact testing, ultrasonic inspection, transverse quasi-static loading testing and compression testing. The results showed that both types of damage caused measurable changes in composite laminate performance. However, markedly divergent trends between experimental results of two types of damage were observed. The results allowed for conclusions to be drawn regarding the adequacy of the artificial approach and highlighted the importance and role of other forms of damage induced during the impact event.

In the following section, the methodology is described and details and requirements of the experimental test procedures are given. Subsequently, test results are presented, compared and discussed in Section 3. Finally, the conclusions of the study are presented.

2. Experimental procedure

The experimental programme involved five main stages: modal testing performed before and after damaging the composite laminates, drop-weight impact testing in which damage was induced in a controlled manner, ultrasonic inspection which allowed determining the interlaminar damage onset and the extent of induced delaminations, and finally transverse quasi-static loading (QSL) tests and compression after impact (CAI) tests to assess the transverse and compressive residual bearing capacity of composite specimens, respectively.

2.1. Test specimens

The experimental programme was executed for a total of 72 monolithic composite plate specimens measuring $150 \times 100 \times 5.2\ \mathrm{mm}^3$. In the manufacturing process, commercially available unidirectional prepreg laminae composed of carbon fibres[1] (volume-fraction of 55.2%) embedded in a resin epoxy matrix[2] were used. The quasi-isotropic laminated plates were composed of 40 unidirectional laminae with a balanced and symmetric stacking sequence $[45^\circ/0^\circ/-45^\circ/90^\circ]_{5S}$, resulting in a nominal thickness of approximately 5.2 mm with an uniform cross-section over the entire surface. The laminated plate layup was defined such that the 0*degr* fibre orientation was aligned with the lengthwise dimension. Laminate curing was performed following a standard autoclave procedure.

Among the samples manufactured, 48 of them were pristine specimens while 24 specimens were manufactured by inserting an artificially induced delamination – a circular geometry polyimide film – before consolidating the coupons in an autoclave. Diameters of 10, 20, 30, 40, 50 or 70 mm were embedded on the layers 5, 10, 15 or 20 (see Table 1). After the curing process, pristine coupons were examined using non-destructive ultrasonic inspection to assess the grade of compaction and to discard the presence of defects, porosities or delaminations.

2.2. Modal testing

In order to obtain the modal parameters (frequencies and mode shapes) to examine the effect of the induced damage upon the vibration response, modal testing of the pristine and damaged composite laminates was performed. Tests were carried out under free boundary conditions by suspending the coupons vertically. The real-time sampled signals (excitation and response) were measured and recorded in form of time series and processed into inertance frequency response function (FRF) data. Vibration measurements were performed using a single-reference roving hammer test. A mono-axial accelerometer[3] was attached to a single degree of freedom (DoF) reference point on the top surface of the laminate, whereas the miniature transducer hammer[4] roved around, exciting the specimen at 25 measuring DoFs, 5 evenly distributed in the direction of the width and 5 evenly distributed in the direction of the length. Because the delamination mode can introduce nonlinearities Aymerich and Staszewski [14], an effort was made to minimise them by using mini hammer transducer to create a low-level input excitation. In addition to the transverse modes of vibration, in-plane modes were also estimated by exciting the specimen at 5 evenly distributed locations on each lateral side. Both the applied excitation and the measured response[5] were perpendicular to the coupon. Signals were averaged three times for each measurement point, and the test frequency band was up to 20 kHz with a resolution of 3.125 Hz.

2.3. Drop-weight impact testing

An ASTM[6] D7136 standard test ASTM-D7136 [15] was followed to determine the damage resistance of the laminated composite specimens subjected to a drop-weight impact event. The test procedure consisted in releasing a weight from a certain height, which determined the incident kinetic energy. A detailed description of the test conducted can be found in reference Pérez et al. [16].

A total of 44 coupons were impacted with incident energy levels (E_I) ranging from 6.6 to 70 J, in intervals of 5 J, with a minimum of 2 and maximum of 4 specimens tested for each impact energy. The lower limit was determined by the minimum height condition imposed by the standard test method. The upper limit was defined by considering a hypothetical energy level below both the penetration and perforation thresholds. The 4 remaining specimens were reserved to ensure the repeatability of modal testing and to determine the transverse and compressive bearing capacity of the pristine laminates.

2.4. Ultrasonic testing

The term state of damage implies knowledge of the type, extent and location of induced damage, and it is three-dimensional in nature. Ultrasonic phased array testing provides a precise through thickness damage information useful for determining the depth, size and distribution of internal delaminations. After the drop-weight impact test, the interlaminar damage onset was estimated and the extent of induced damage in impacted laminates coupons

[1] Grafil TR30S 3K.

[2] Resin epoxy HSC Epikote 4652.

[3] Accelerometer Bruel & Kjaer 4518-003.

[4] Hammer Bruel & Kjaer 8204.

[5] Data acquisition system Bruel & Kjaer 3050-B-6/0.

[6] American Society for Testing and Materials.