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Residual impact strength of carbon/epoxy laminates after flexural loadings

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ABSTRACT

Very few studies can be found in the literature about the impact strength of laminates containing pre-damages promoted by loads susceptible to occur in-service. Therefore, this work intends to study the impact strength of carbon/epoxy laminates containing pre-damages promoted by flexural loadings. For this purpose, laminates were submitted to bending loads about 36%, 47%, 65% and 94% of the ultimate flexural strength. To evaluate the presence of the damages, acoustic emission and C-Scan techniques were used. The magnitude of the initial damage has a significant influence on the impact parameter values and, on the other hand, the impact strength of laminates subjected to repeated low velocity impact loads is also strongly dependent on the damages promoted by the different bending loads.

1. Introduction

Composite materials have been increasingly used but, as consequence of their poor tolerance to damage, there are some application problems. In fact, strength, stiffness and global performance of those materials are significantly affected by geometrical and material defects resulting from an imperfect manufacturing process or from external loads actuating during the operational life [1].

In terms of external loads, low-velocity impact events can occur in-service or during the maintenance activities and they are considered one of the most dangerous loads for composite materials. The impact energy is absorbed by internal damage mechanisms promoting the interaction of several damage types without exterior signs [2,3]. Matrix cracking, fibre fracture and fibre–matrix debonding are typical damages, but delaminations are the most important damages, because they affect dramatically the performance of composite materials and, simultaneously, they are difficult to detect visually [4,5]. Delaminations are prone to occur at interfaces between different oriented layers due to mismatch bending that lead to development of interlaminar shear stresses at those interfaces [6].

Several studies can be found along the literature about the delaminations' effect on the residual properties. For example, Reis et al. [7] found reductions of ultimate tensile strength about 16% in carbon/epoxy laminates containing delaminations, however, their sizes do not influence significantly the value of tensile strength. According to Mosallam et al. [8], for cross-ply laminated composites, a decrease of about 25% was observed on the ultimate tensile strength after an impact energy of 6.8 J. This reduction detected on the tensile strength can be explained by the degradation of the fibre/matrix interface and by the stress concentration promoted by the delaminations [9,10]. Relatively to the flexural properties, reductions around 34% for $[0, 90, 0, 90]_{2s}$ and 78% for $[0, 90]_8$ carbon/epoxy laminates were found by Amaro et al. [11]. Authors explained these differences due to the lower flexural stiffness of the antisymmetric layup relatively to the symmetric one. On the other hand, the delamination position along thickness shows to be also important, because the most critical situation corresponds to the delamination located at the mid-thickness of the specimen in consequence of the alterations induced on the shear stress profile [12]. Finally, compressive strength is significantly lower than the tensile mode, as consequence of the failure mechanisms [9,13–17], but, after impact loading, reductions about 60% can be reached [4,18,19]. According to Suemasu et al. [20], the main cause is related with the existence of multiple delaminations that interact during compression, but, for Lee and Park [21], delaminations tend to grow rapidly under post-buckling loads, causing further reductions in structural strength and leading to critical structural failure. According to Amaro et al. [22] the load carrying capacity of composite laminates decreases due to the presence of delamination independently of the layup or type of delamination. The same

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authors concluded that the compressive strength is strongly affected by the delamination size. It was verified that the number and the size of delaminations plays an important role on the compression after impact behaviour of composite materials. Three types of delaminations, embedded, through-the-width and partial, were analysed. They observed that, according to the type of delamination, different buckling modes appear. The local buckling mode, which is caused by embedded and through-the-width delaminations, is highly influenced by the layup. The stacking sequence determines the deflection response to the applied load, principally when there are multiple superposed delaminations.

If the mechanical performance of composites after low-velocity impact loads is conveniently reported along the open literature, few studies can be found about the impact strength in laminates containing pre-damages. In fact, composites can encounter large out-of-plane displacements and/or loadings (such as hydrostatic force) during storage or service, which creates flexural loads on the panels. Therefore, the aim of the present work is to study the impact strength of carbon/epoxy laminates, previously submitted to bending loads. The results are discussed in terms of load-time, load–displacement and energy-time curves. Finally, the damage is evaluated by the impact bending stiffness.

2. Materials and experimental procedure

Composite laminates were prepared in the laboratory from high strength unidirectional carbon pre-preg (Texipreg HS 160 RM from SEAL®) and processed in agreement with the manufacturer recommendations, using the autoclave/vacuum-bag molding process. The processing setup consisted of several steps: make the bag and apply 0.05 MPa vacuum; heat up to 125 °C at a 3–5 °C/min rate; apply a pressure of 0.5 MPa when a temperature of 120–125 °C is reached; maintaining pressure and temperature for 60 min; cool down to room temperature maintaining pressure, and finally get the part out from the mold.

The laminates were manufactured with unidirectional carbon layers with the following stacking sequence $[0_2, 90_2]_s$. The overall dimensions of the plates were 300 × 300 × 1.2 (mm). The quality control of the plates was performed by C-Scan using a Physical Acoustics Corporation (PAC) ULTRAPAC II water immersion C-Scanner, in order to evaluate the eventual presence of defects resulting from manufacturing process. For the ultrasonic analysis a 25 MHz broadband immersion piezocomposite transducer was used in the pulse-echo mode. The same transducer received the echoes originating from multiple reflections inside the specimens from a longitudinal normal incident wave. The green color, present in all plates, is related to the backwall echoes, evidencing the absence of any damages [23].

The specimens used in the experiments were cut from these thin plates, using a diamond saw and a moving speed chosen to reduce the heat in the specimen, with dimensions of 100 × 100 × 1.2 (mm) and submitted to flexural tests. Three-point bending (3PB) tests were carried out and the procedure was adopted according to ASTM D790-10, using a Zwick universal testing machine, model 1435, equipped with a 5 kN load cell, at a displacement rate of 3 mm/min and a span of 50 mm. The flexural tests were carried out on similar specimens to those used in the impact tests, because the damage was correlated directly with the load. After obtained the ultimate flexural strength, some specific loads were selected and the specimens tested with them, in order to promote pre-damage. For this purpose, the flexural tests were monitored with the AE technique. Four loads associated to the low amplitude, middle amplitude and high amplitude events, were selected. After that, all specimens were evaluated again by C-Scan system described previously.

A Marandy acoustic emission analyser, model MR1004, was used to provide the amplitude and the number of ringdown counts for each acoustic emission (AE) event.

This equipment has a threshold voltage adjustable from 10 mV to 69.18 mV. The AE event amplitude is defined as the maximum AE signal level relative to 10 mV. The amplitude detector unit sorts the AE events into twenty-five levels, each one with a bandwidth of 2.4 dB. Level zero corresponds with the amplitude above 10 mV and below 13.18 mV. For ringdown counting, the amplitude of the signal is compared with the threshold voltage, and the total ringdown count for each event is the number of times of the signal amplitude exceeds the threshold level. More details about this equipment can be found at [24].

Finally, multi-impacts tests at low velocity were performed using a drop weight-testing machine Instron-Ceast 9340 and a 10 mm impactor diameter with a mass of 3.4 kg was used. The tests were performed on circular samples of 70 mm diameter and the impactor stroke at the center of the samples obtained by centrally supporting the 100 × 100 mm specimens. For all tests, an impact energy of 1 J was used, which corresponds to an impact velocity of 0.77 ms^{-1}. For each condition, three specimens were tested at room temperature.

3. Results and discussion

Flexural strength was studied and Fig. 1 shows the load–displacement curves obtained. An offset of 0.2 mm was used for clarity. The plot shows a nearly fragile behaviour, with a linear region up to the maximum load (P_{max}), and a significant drop of the load after P_{max} was observed. The mechanism of damage agrees with previous works developed by Amaro et al. [11] and Reis et al. [25], where the fracture of the fibres, in compression, with quite small delaminations around the broken fibres can be observed. The zigzag aspect of the curves showed in Fig. 1 results from fibres breakage. The posterior load drop is a consequence of the propagation of delaminations initiated at the regions with broken fibres. According to Reis et al. [25], the high compressive stress concentration in the pin load contact region associated with the low compressive strength of the fibres promotes compressive breakage of the longitudinal fibres in this region. In terms of ultimate flexural load, an average value around 1923 N was obtained with a standard deviation of 29 N.

In order to promote the pre-damages in the laminates, and according with the acoustic emission events obtained from the flexural tests, four loads were selected: 700 N (associated to the low amplitude events); 900 N and 1250 N (associated to the middle amplitude events); and 1800 N (associated to the high amplitude events)

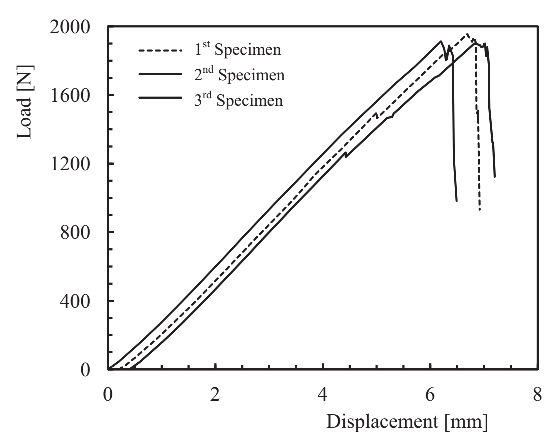

Fig. 1. Load displacement curves.