CHARACTERIZATION OF INDENTATION DAMAGE ON CARBON/EPOXY LAMINATES BY MEANS OF ACOUSTIC EMISSION

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1. INTRODUCTION

Static indentation tests on carbon fibre reinforced laminates have been frequently used in literature to predict the value of penetration energy for the laminate. The mechanical set-up most commonly employed involves the use of indentors of diameter comparable with that of the impactors prescribed from standards for falling weight impact, such as ASTM D3763. The specimen is simply supported using a steel plate, so to leave a variable opening for the indentor to strike the laminate [1]. From indentation tests, empirical relations have been obtained, correlating the penetration energy with the total fibre areal weight (FAW) and indentor diameter [2]. During static indentation tests, the concentration of loading in a small area of the laminate, similarly to what is done during falling weight tests, reduces the flexure of the specimen, especially close to failure. It is to be verified, however, if this gives accurate values of the linear stiffness, a significant parameter in impact tests on composites [3]. Linear stiffness is defined as the slope of the force vs. deflection curve, usually well approximated through a linear regression: physically this corresponds to the elastic fraction of the contact energy between the impactor and the laminate [4].

With this aim, static indentation tests on carbon/epoxy laminates have been performed in a bending rig, using two different test configurations: in the former, the specimens were simply supported using a steel plate, whilst in the latter the specimens were left free to bend between the flexural rig supports. The comparison of the results obtained with the two configurations would allow clarifying the reliability of simulating falling weight impact test results using static indentation tests. All the tests were monitored by acoustic emission (AE) with the aim of analysing the presence of volume damage at the different load levels and for the different configurations [5]. In addition, damage of laminates impacted to penetration was also imaged using IR pulse thermography, a technique that proved useful in characterising impact-damaged areas in composite laminates [6].

2. MATERIALS AND METHODS

The specimens tested in this work were obtained from square carbon/epoxy panels (250 x 250 mm) made using RC200T fibres and a SP106 resin. The FAW of the fabric, a 2x2 twill, was 195 g/m^2. The samples were manufactured by hand lay-up in a closed mould using ten layers of fabric. The thickness of the cured laminates was 3.5 ± 0.05 mm and the fibre volume fraction was 0.33 ± 0.02. From the panels, square specimens (70 mm side) were removed and subjected to static indentation tests. These were carried out using two different test configurations: in the former, the specimens were simply supported using a steel plate with a circular opening of 30 mm in diameter (type A), whilst in the latter the specimens were left free to bend between the flexural rig supports (type B). The samples were loaded at their centre by a hemispherical steel indentor (10 mm diameter) in displacement control with cross-head speed of 1 mm/min. The average maximum displacement reached during the tests using both indentation configurations was measured, as being equal to 6.8 mm for type A and 7.6 mm for type B indentation: based on these values, tests at 50, and 75% of the maximum displacement have also been performed with both configurations.

During indentation tests, AE activity was recorded using a Vallen AMSY-5 system equipped with four 150 kHz resonant sensors, to allow planar localization of AE sources. The sensors were placed as forming a square array (side 85 mm) rotated by 90° with respect to the position of the samples, on bonded steel waveguides.

The flexural tests were carried out in accordance with ASTM D-790 (3-point loading) on carbon fibre/epoxy specimens (type F) having a length of 240 mm, a width of 25 mm and a thickness of 3.5 ± 0.05 mm (V_f = 0.33 ± 0.02). These tests were performed in a universal testing machine (Instron 5584), at a constant cross-head speed of 1 mm/min. The AE activity was recoded using two 150 kHz resonant sensors. The sensors were placed on the surface of the specimens at both ends to allow linear localization of AE sources (sensor-to-sensor distance = 140 mm). The AE acquisition settings used throughout this experimental work were as follows: threshold = 40 dB, RT (Rearm Time) = 0.4 ms, DDT (Duration Discrimination Time) = 0.2 ms and total gain = 34 dB.

After impact, the damaged area was observed using an Avio/Hughes Probeye TVS 200 thermal video system. The heating was obtained using a 500W lamp: a 5 seconds pulse was applied, positioning the lamp at approximately 200 mm from the sample, so that a maximum temperature of 50ºC was obtained on the sample surface. The thermograms were acquired between 0-30 seconds during cooling down of the material. The emissivity was set at 1 (black body), a value which offered the image with the best contrast with the background: to obtain an image suitable for analysis a minimum difference of temperature between the non-impacted and impacted regions on the surface of approximately 2ºC.

3. RESULTS

The presence of the plate to support the specimen leads to a higher linear stiffness of the laminate, as indicated by the slope of the linear part of the load vs. displacement curves (Figure 1). This is likely to suggest that the initial damage is more severe for configuration B than for configuration A, while both configurations indicate a linear stiffness value higher than the one measured during flexural tests. It has been also noted that this is owed to the fact that in quasi-static indentation tests, before reaching the maximum load, only delamination and matrix cracking events take place [7]. In contrast, fibre breakage is likely to take place in flexural tests at loads lower than the elastic limit, as it is suggested from the quasi-linearity of the curve up to failure.

In this respect, amplitude distribution plots of acoustic emission events can successfully assist damage characterisation due to their dependence on material properties and deformation mechanisms. Amplitude distributions were recorded at different times during each test in order to show their evolution. They indicate that in correspondence with the first load drop, AE events are more numerous and generally of higher amplitude for configuration B than for configuration A (Figure 2).

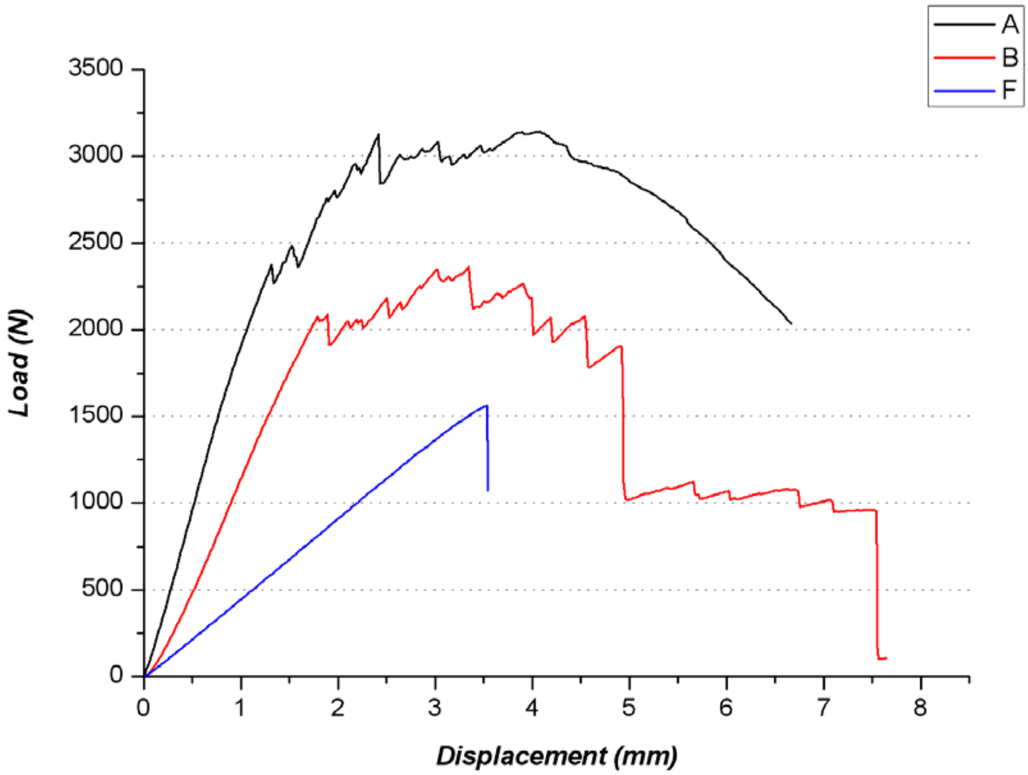

Figure 1: Load vs. Displacement curves up to penetration for types A (indentation supported with steel plate), B (indentation not supported with steel plate) and F (three-point flexural loading).

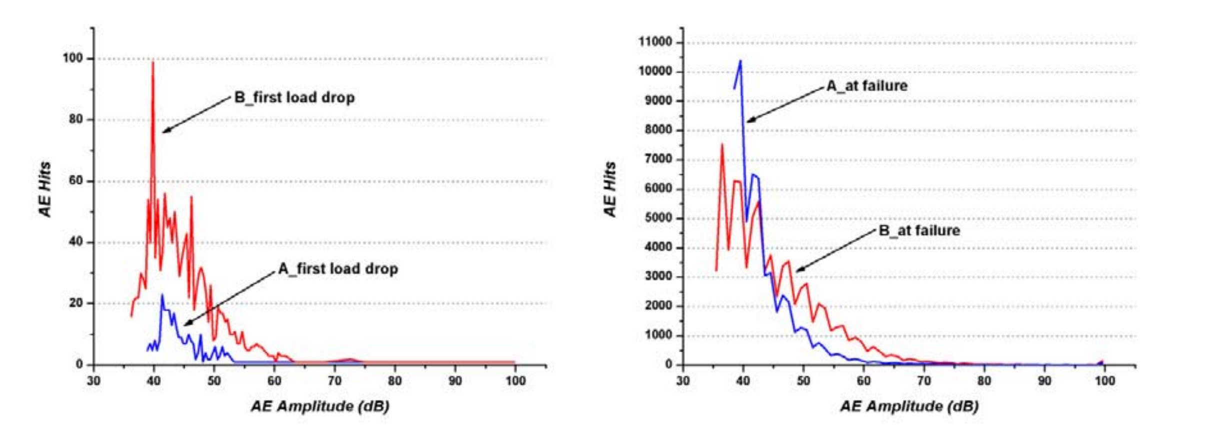

Figure 2: Typical AE amplitude distributions for the two indentation test configurations A and B at different times during the tests.

This provides evidence for the differences in the failure processes involved, since in the two configurations A and B the first load drop occurs at 75% and 88% of their maximum load, respectively. At failure, this behaviour is reversed, suggesting that damage concentrates in the area unsupported by the plate in configuration A, whilst it spreads along a preferential direction of bending in configuration B (similarly to what happens in a standard flexural test). This is confirmed also by AE localisation plots: AE events recorded during the A-type indentation tests (Figure 3a) showed no obvious preferential location, being evenly diffused on the whole surface of the plate. In contrast, for B-type indentation, in a region of the laminate surface, on a line passing through the centre of the indenter, a lower amount of AE activity can be shown, as an effect of the longitudinal cracking of the material, which led to the uplifting of the rear part of it (Figure 3b).

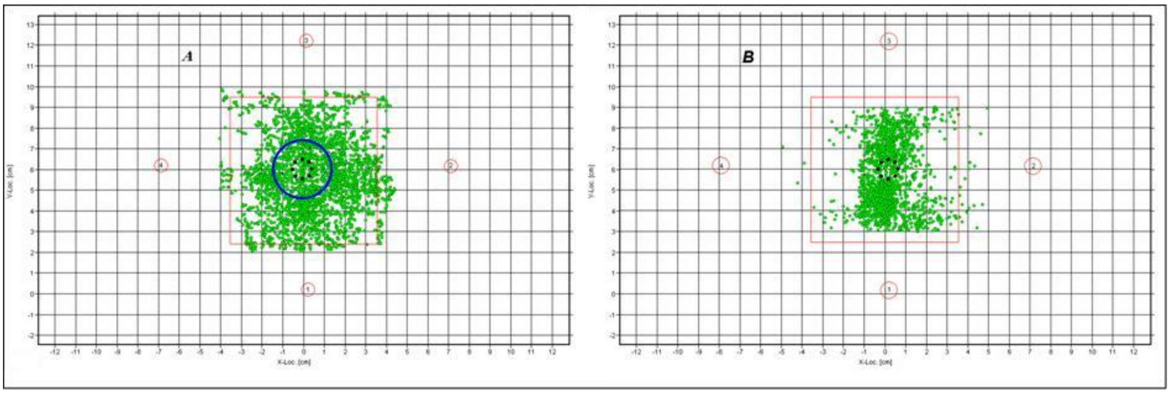

Figure 3a: Typical AE X-Y localisation diagrams for the two indentation test configurations A and B (the small red circles represent the position of the four sensors, the red squares the tested samples, the blue full line circle the hole in the supporting plate, and the dotted blue circles the indentor).

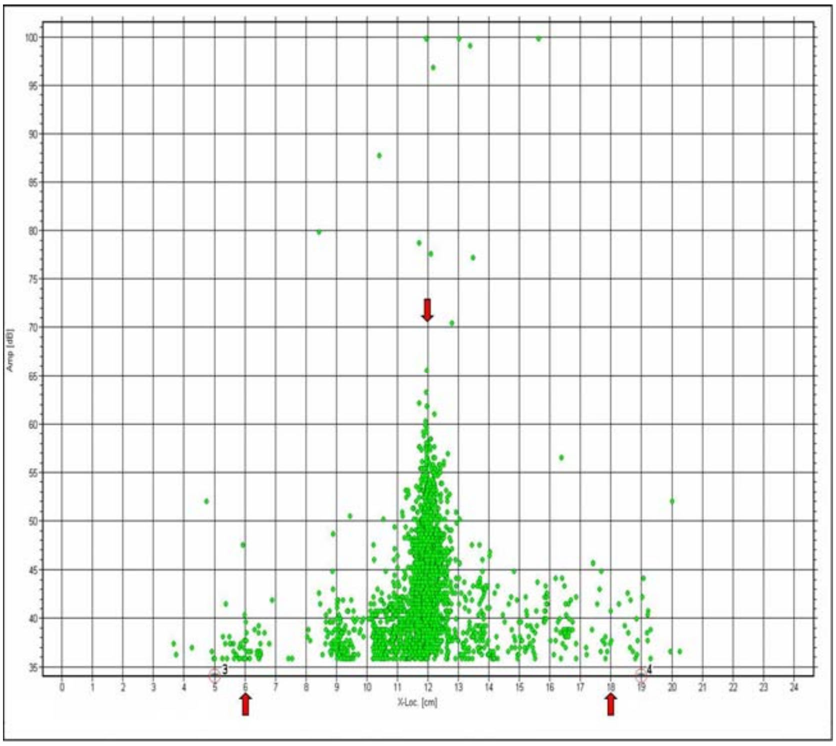

Figure 3b: Typical AE localisation vs. amplitude diagrams for the flexural tests (the small red circles represent the position of the two sensors in acquisition, the red arrows the position of the three supports of the three point bending rig).

The uplifting of rear side is also clearly observable from the thermogram of a B-type indented sample in Figure 4 (right), whilst A-type indented laminate shows (Figure 4 left) a clearer penetration-like pattern with no obvious preferential direction of damage.

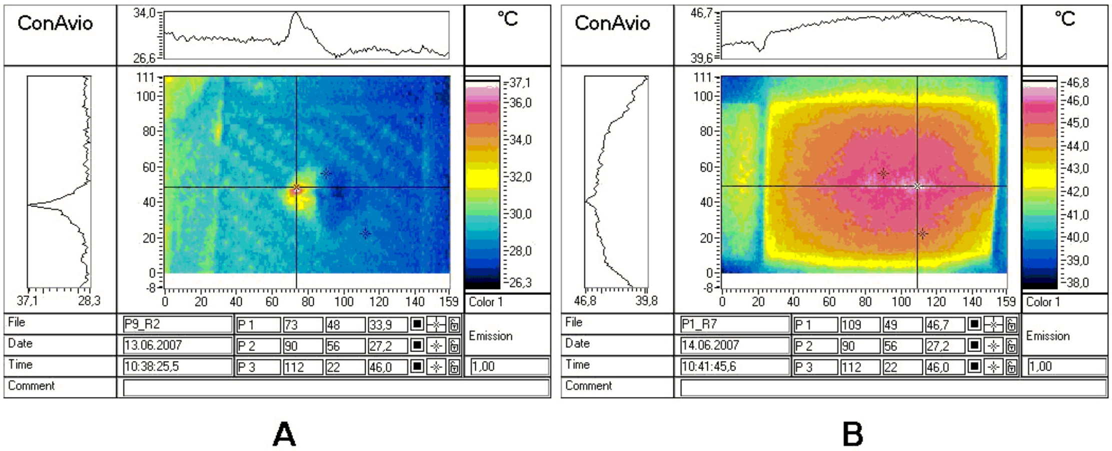

Figure 4: Thermograms of damage produced by the two indentation modes A and B at 100% displacement on the rear side of the samples.

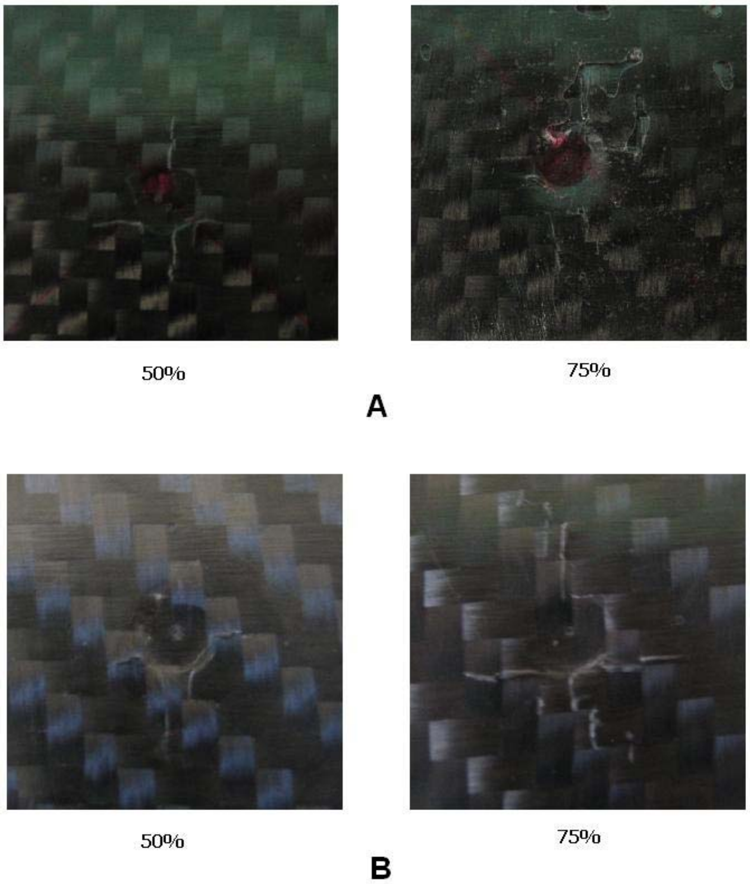

Figure 5: Typical damage produced at 50 and 75% of total displacement in the indentation modes A and B

The damage pattern can be easily summarised as more easily extending beyond the indented region in the case (B-type) no plate support is provided, as shown in Figure 5. This may indicate that both types of indentation tests can be suggestive of low-velocity impact procedures, A-type being closer to the typical impact procedure, as standardised e.g., in BS EN 2782 part 3, while B-type would rather account for the occurrence of flexural impact, with samples tested in a bending rig. The close correspondence of A-type indentation to low-speed impact with the same energy, albeit with larger permanent indentation, is a well-known occurrence [8]. Corresponding elastic impact energy can be empirically determined from the indentation curves by multiplying the average value of linear stiffness for every indentation procedure for one half of the elastic displacement. To this value needs to be added the plastic impact energy, negligible in the case of flexural loading, as can be observed in Figure 1. This can be obtained by multiplying the average value of the load by the displacement during the plateau that follows the departure of the material from linearity. The average values yielded by these calculations are summarised in Table 1. It can be observed that the total value of impact energy, as obtained from the two indentation methods, do not differ very much. In this way, it is possible that, if confirmed, both values of the energy may represent a suitable approximation for the penetration energy measured in an impact loading situation.

Loading mode	Avg. linear stiffness (N/mm)	Avg. elastic energy (J)	Avg. plastic energy (J)	Total loading energy (J)
A	1740	1.6	14.7	16.3
B	1140	1.9	14.1	16
F	445	5.4	-	5.4

Table 1: Avg. mechanical results depending on loading mode.

4. CONCLUSIONS

The indentation technique, both with and without plate support, has been confirmed to represent a suitable method for approximating the effect of low-velocity impact loading on carbon fibre reinforced laminates. The much longer time frame that indentation loading involves represents an interesting feature for the most effective application of the acoustic emission technique for damage characterisation. In particular, amplitude distribution and localisation of events were able to offer promising results on indentation damage propagation in the laminates. Further work would need to involve extending this method to other composite materials.

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