Characterization of indentation damage on carbon/epoxy laminates by means of acoustic emission and IR thermography

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ABSTRACT

Acoustic emission and transient IR thermography have been used to study and compare the performance of carbon/epoxy laminates, subjected to two different indentation procedures in a three-point flexural rig, one with a supporting steel plate and the other in a free bending mode.

The study of 2-D localisation plots and cumulative counts vs. time curves allowed clarifying, with the essential support of the thermograms and of optical microscopy, that both test configurations are able to represent and possibly replace a low impact testing procedure, with the main difference of having a variable flexural component into loading.

KEYWORDS: carbon/epoxy, indentation damage, stiffness prediction, acoustic emission

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 along the lines of what performed in [5]. This analysis has been carried out at the different load levels and for the different configurations, making large use of 2-D localisation plots, according to indications from a previous work done on post-impact cyclic indentation tests in [6]. In addition, damage of laminates impacted to penetration was also imaged using IR pulse thermography, a non-destructive technique that proved useful in characterising impact-damaged areas in composite laminates [7-8].

2. Experimental

Materials: Square carbon/epoxy panels (250 mm side) manufactured by 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.

Test configurations:
A: Samples simply supported using a steel plate with circular (ø 30 mm) opening
B: Samples left free to bend between the flexural rig supports

Load application: The samples were loaded at their centre by a hemispherical steel indentor (ø 10 mm) in displacement control with crosshead speed of 1 mm/min.

Acoustic Emission: 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.

IR thermography: 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 at 200 mm from the sample during 5 seconds, 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

A first observation is that during indentation tests the presence of the plate to support the laminate (case A) leads to a higher linear stiffness than in case B, much higher in both cases than flexural stiffness (F), as shown in Figure 1.

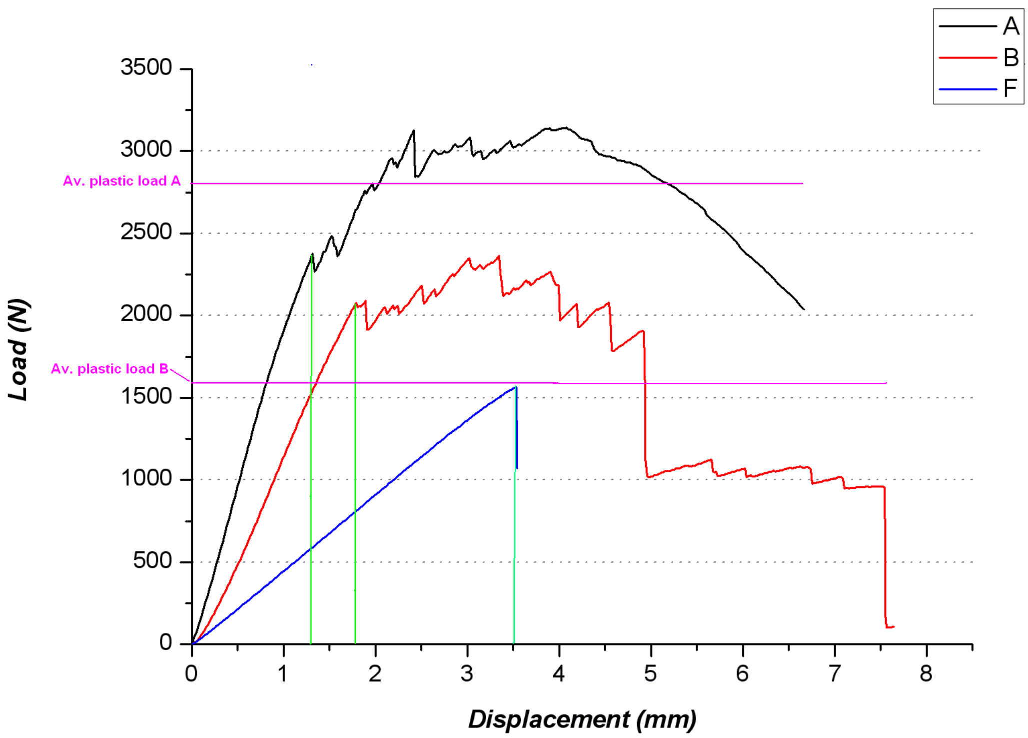

Figure 1 Typical flexural curve (F), A-type (A) and B-type indentation on carbon-epoxy laminates

Sounder considerations about the different damage progression obtained with the two indentation procedures are offered by AE amplitude distributions (Figure 2): these show 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. This provides evidence for the differences in failure processes involved, since in 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 in configuration B.

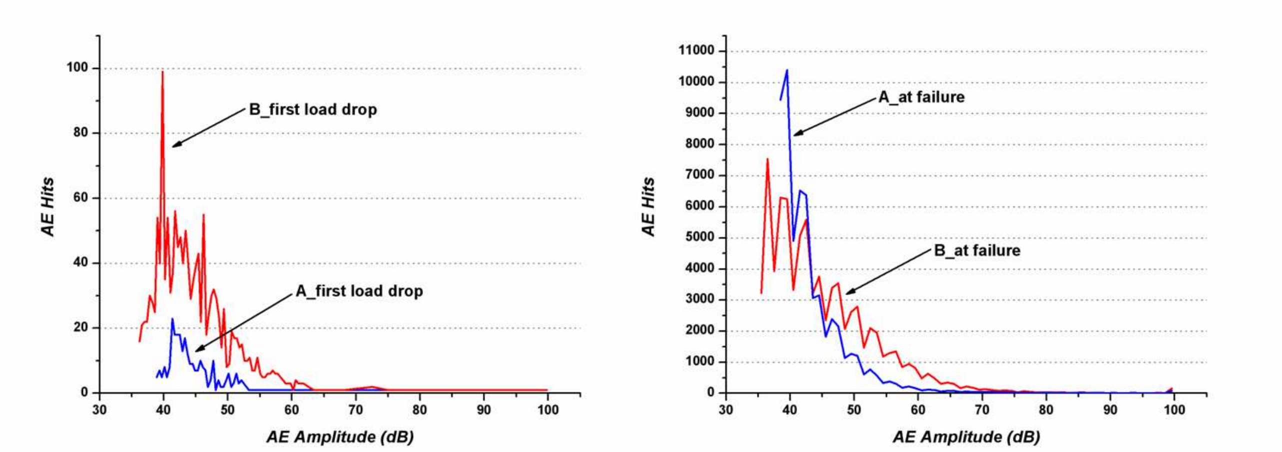

Figure 2 AE amplitude distribution curves at a stress corresponding to the first load drop (pseudo-yielding point) (left) and at failure (right): blue curves refer to A-type indentation and red curves refer to B-type indentation

In particular, AE localisation plots (Figure 3) highlight that AE events recorded during the A-type indentation tests 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.
It can be suggested that B-type indentation leads to loading patterns more similar to flexural testing than for A-type indentation. In this respect, it is noted that during three-point bending, AE events heavily concentrate around the central 10% of the rig span (Figure 4).

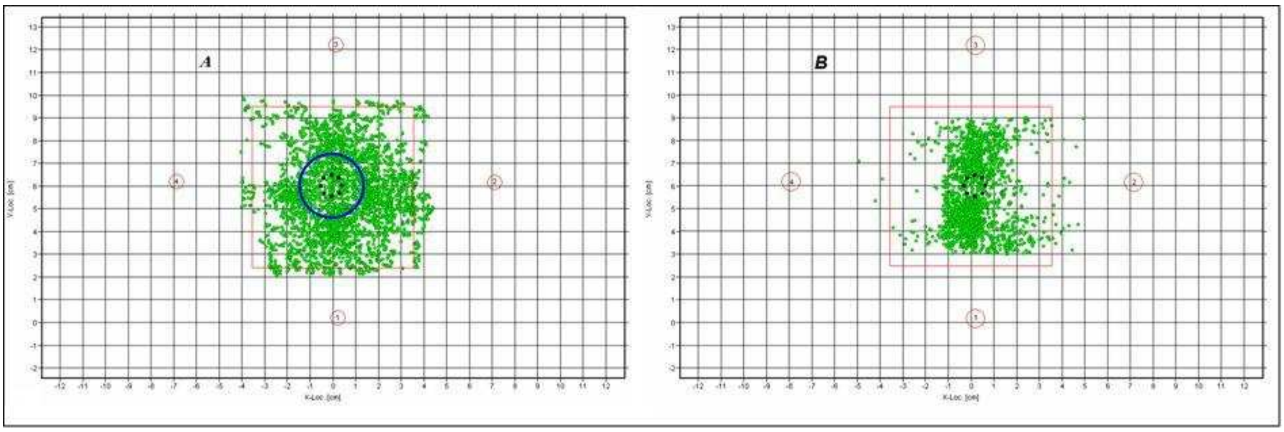

Figure 3 Typical AE 2-D localisation plots during indentation loading (A-type: left and B-type: right).
The red squares represent the edges of the plates, whilst the red circles represent the position of AE sensors.
The dotted lines represent the size of the indenter,
whilst the continuous line represents (in case A) the size of the circular hole in the steel plate.

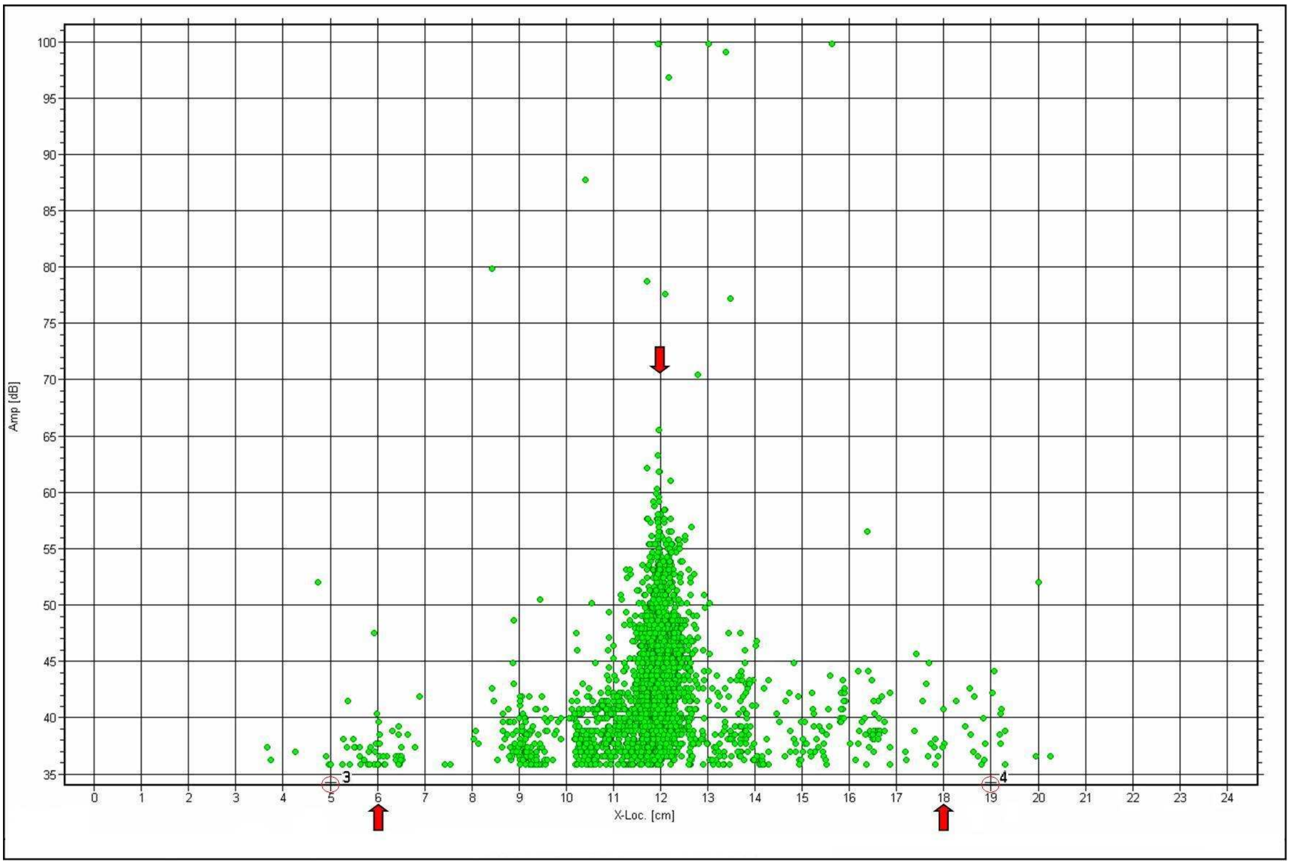

Figure 4 Typical AE X-localisation plots during flexural loading on beam samples.

As suggested above, rear side uplifting of a B-type indented sample is clearly observable from the thermogram, whilst A-type indented laminate shows a clearer penetration-like pattern with no obvious preferential direction of damage can be observed (Figure 5). More specifically, the damage pattern can be summarised as more easily extending beyond the indented region in the case (B-type) in which no plate support is provided (Figure 6).

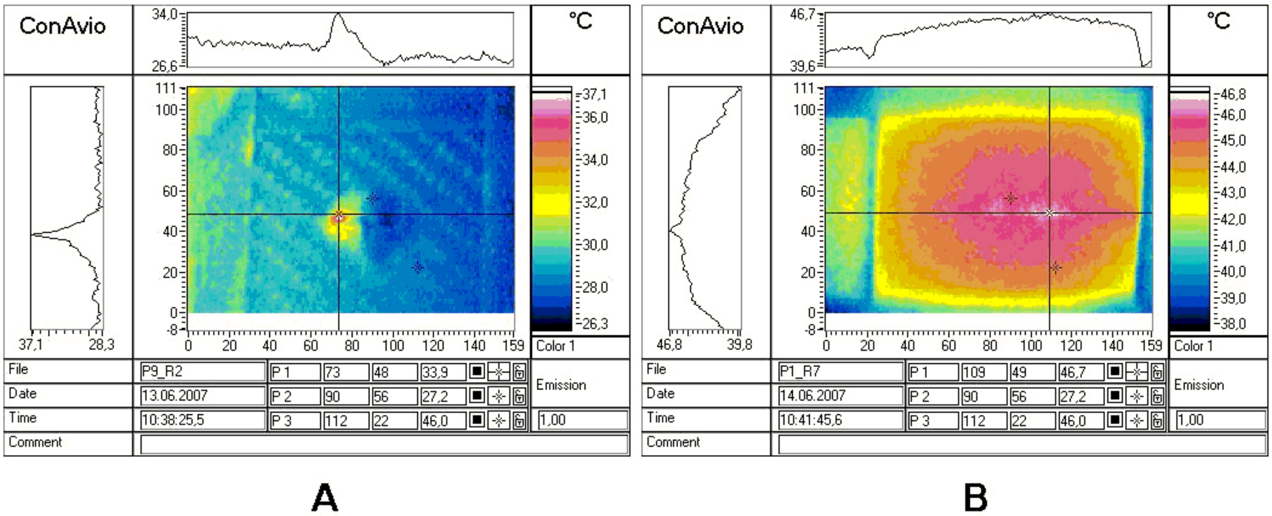

Figure 5 IR thermograms of the rear side of indented carbon/epoxy laminates
(A-type indentation, left; B-type indentation, right)

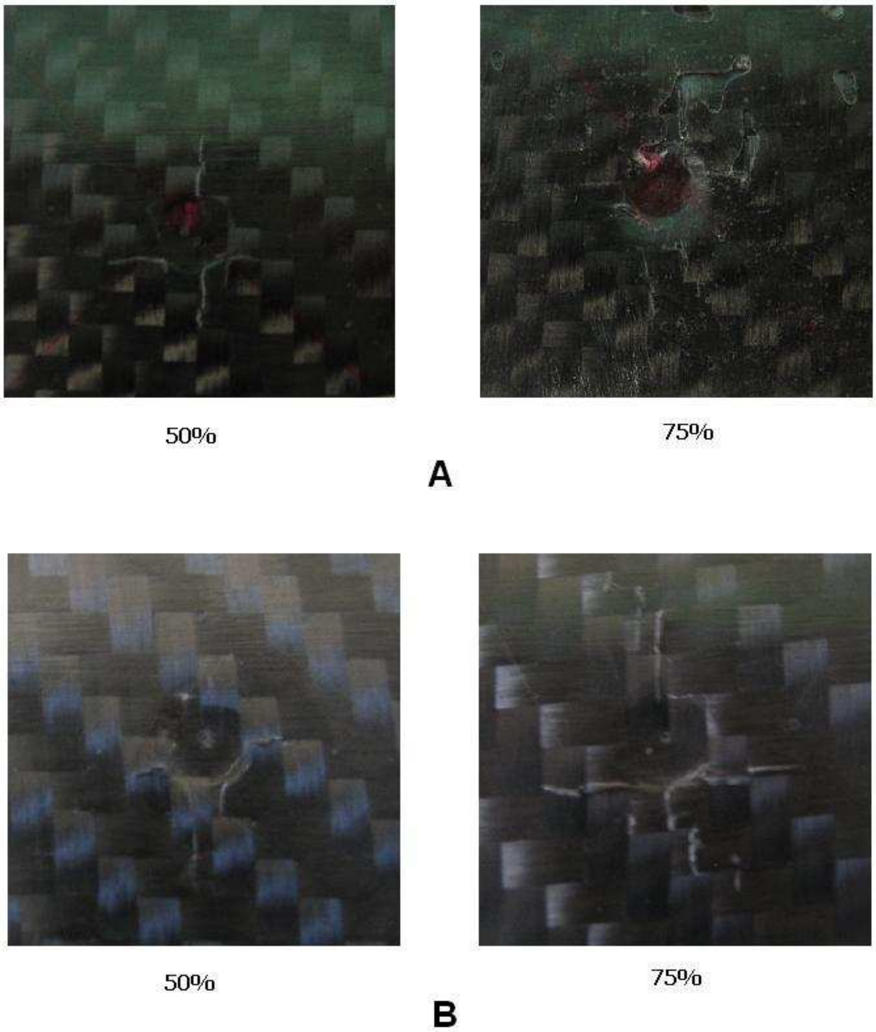

Figure 6 Damage patterns on laminates indented with the two different procedures at displacements corresponding to 50 and 75% of the maximum flexural displacement

The results appear to indicate that both types of indentation tests can be representative of low-velocity impact procedures, unlike what previous studies suggested. A-type indentation (with plate) appears to be closer to the typical impact loading procedure, as standardised e.g., in BS EN 2782 part 3. In contrast, B-type indentation would rather account for the occurrence of flexural impact, with samples tested in a bending rig, and could be compared with static flexural testing results.
Acoustic emission and IR thermography helped substantially in establishing the differences in the two indentation loading patterns.

4. Conclusions

The possible combined application of the two indentation procedures, together with flexural testing, can offer indications on a possible range of values of linear stiffness, first load drop, and total absorbed energy. This can be particularly significant on materials, such as plant fibre composites and glass/plant hybrid laminates, where the mode of failure is usually brittle and sometimes led by tear forces (see e.g., in [9-10]). Indentation testing can in this case possibly offer repetitive indications about the partition of elastic, plastic and damping energy. This could be comparable with those yielded by low velocity impact, a test which is often difficult to perform on not very resistant materials for the low height/high mass procedure required.

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