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Acoustic emission for assessment of impact and lightning damage to woven carbon fibre laminates

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Abstract

Composite materials are being increasingly used in the aerospace industry; however they are highly susceptible to impact and lightning damage. Such damage can be very difficult to detect by external visual inspection, hence it is envisioned to introduce Structural Health Monitoring systems that are capable of detecting such events and the damage that they lead to. In this paper, standard Compression After Impact samples were subject to different impact energy levels whilst being monitored with Acoustic Emission sensors; a separate set of specimens was subject to lightning strike events. After damage, the residual compressive strength of those samples was assessed; Acoustic Emission activity was recorded throughout the tests. A correlation between Acoustic Emission energy, impact damage and post-impact residual strength was found. Moreover, the Acoustic Emission data suggests the capability for an early detection of impact damage (i.e. before failure loads).

1 INTRODUCTION

The aerospace industry is increasingly reliant on composite materials for skin and structural assemblies, but there still are concerns about certain types of damage, such as impact, which are not easy detectable during inspections. This has led to the need for the introduction of Structural Health Monitoring (SHM) techniques that may help detect damage and thus enable on-demand maintenance via safe real-time assessment of potentially detrimental events, such as bird strikes, debris impact and lightning strike [1, 2].

A commercial airliner will be struck by lightning, on average, once per year and, hence, understanding how modern composite material interact with this is important [3]. Lightning strikes are very different to other types of impact, such as bird strikes and debris, as they deliver a large amount of energy in an incredibly short period, often within a fraction of a microsecond. Composites may react differently to this ‘impulse’ compared to other impacts over longer periods.

It is important to note that, although composites can behave in complex and often destructive ways when struck by lightning because of their inherent bulk non-conductive properties, all modern commercial aircraft incorporate lightning protection systems consisting of metallic meshes layered on top of the aircraft skin, or lightning rods in other areas, e.g. nose cones [4].

Here, only the behaviour of composite materials without this protection system is studied and, in terms of lightning, it is not what an actual modern aircraft would experience as the metal would conduct most of the energy away. It is useful to study how a raw material reacts to different types of impact.

Acoustic Emission (AE) is a SHM technique based on passive piezo-electric transducers [5] which has the potential of detecting and localizing impacts and damage development in a structure. It has been shown [6] that AE is capable of detecting impact events; it is also known that AE energy [7] is an indicator of the amount of damage a structure has experienced. The relationship between AE energy, impact energy, delamination area and residual compression after impact strength are investigated in this work, in order to assess the suitability of AE to detect impact events and post-impact or lightning damage in such structures.

2 MATERIALS AND METHODS

Carbon fibre pre-preg laminate samples were prepared from woven carbon fibre pre-impregnated sheets (Cytec Industrial Materials), T700 fibres 2x2 twill, 200gsm area density, MTM28 resin (42% by weight). 16-plies panels were prepared, vacuum bagged and cured in autoclave following the manufacturer's suggested curing cycle. The panels were then cut into 100mm x 150mm samples (based on [8]); a total of 16 samples was prepared for the testing campaign. The panel were examined in a water tank ultrasonic C-scanner in order to confirm the absence of pre-existing manufacturing defects.

Nine of the panels were subject to an impact on a Instron Dynatup 9250HV drop weight testing machine, fitted with a 12.5 mm hemispherical steel indenter (Figure 1). 3 impact energies (15J, 20J and 25J) were selected. The samples were fitted on a pneumatic circular frame.

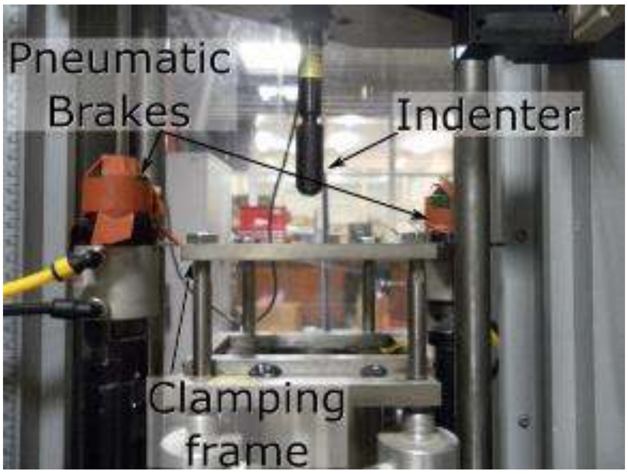


Figure 1: impact machine fixture

Acoustic Emission data was recorded during the impact with a Pancom Pico-Z AE sensor, bonded within the framed area with cyanoacrylate glue. The sensor was connected to a Physical Acoustics µdisp/NB-8 AE acquisition unit through a preamplifier; hit data was recorded throughout the impact test.

Three samples were subject to a lightning strike test at the Morgan-Botti Lightning Laboratory (Cardiff University), to allow a comparison of damage caused by impact against that caused by a lightning strike. The tests were conducted at three different nominal peak currents; 50kA, 100kA and 150kA. The panels were secured between two 550 x 550mm pure aluminium plates, with a circle of radius 80 mm cut in the centre of both plates such that the lightning would directly strike the carbon-composite panel. The aluminium plates were then securely bolted to the earthed lightning rig. A thin initiation wire was connected between the electrode and the centre of the carbon fibre panel, which was used to direct the path of the lightning arc onto the panel and not the surrounding aluminium plate in accordance with EUROCAE ED105 [9]. Photographs of the set-up can be seen in Figure 2. No AE data was recorded during the lightning strike events due to the unsuitability of AE sensors to the exposure to the harsh electromagnetic environment during the strike.

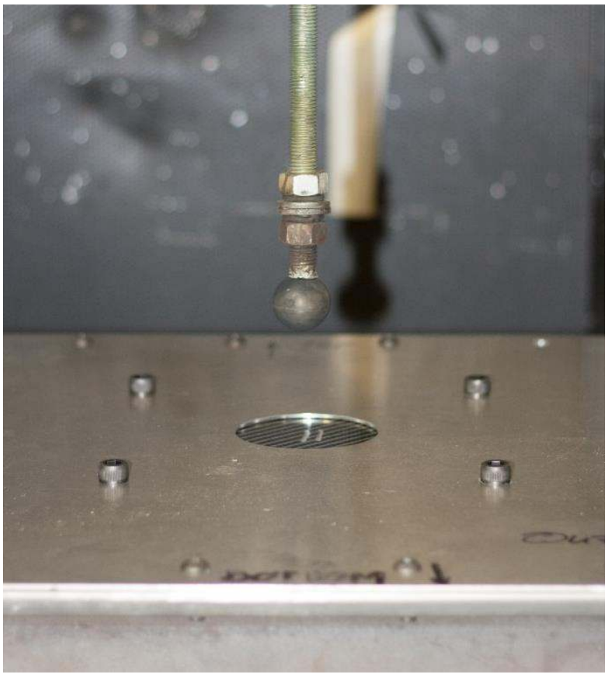


Figure 2: lightning strike laboratory cathode and specimen fitted within the aluminium frame. The initiation wire is not shown.

Lightning arcs at 50 and 100 kA of duration 100 µs were conforming to the D waveform, and the 150kA lightning arc of duration 200 µs conforming to the A waveform respectively, as specified in [9].

A separate set of three samples were kept undamaged to act as a control during the compression tests. Table 1 summarizes the samples used in the test campaign.

Table 1: summary of specimens

Panel ID	Type of damage
2, 3, 4	20J impact
5, 6, 7	25J impact
8, 9, 10	15J impact
11, 12, 13	Lightning strike
14, 15, 16	None

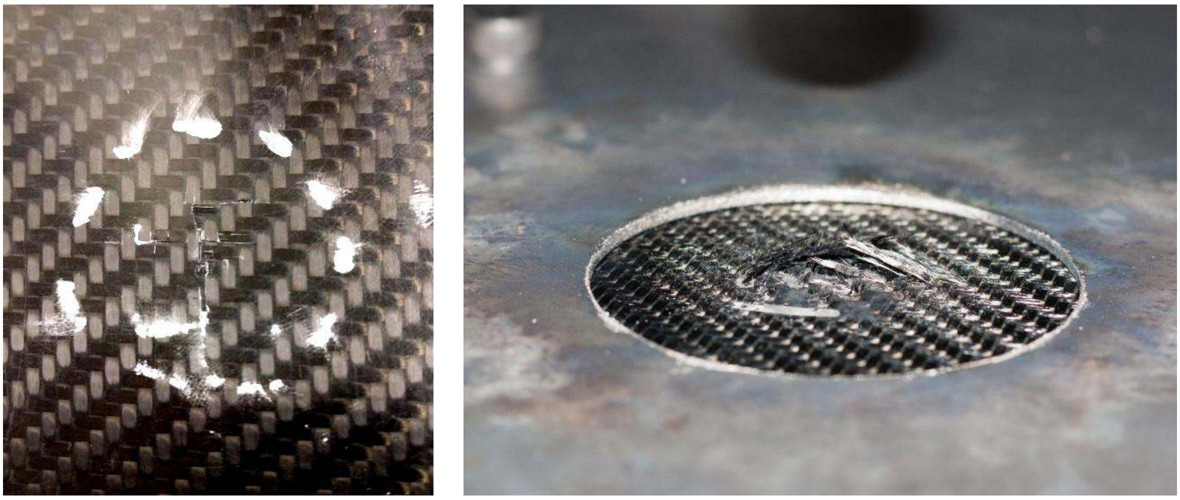
After generating the damage on the samples, each sample was C-scanned again and the delamination area was measured. To maintain consistency in the ultrasonic measurements, all specimens were scanned in the same batch.

A Compression After Impact (CAI) test according to [8] was then performed on each sample. A bespoke frame was fitted to an electro-mechanic compression testing machine (Figure 3). Knife edges held the specimen in place in order to promote the failure location in the damaged area, and avoid edge failure. Load was increased up to 10kN, released to 2kN and then increased again until failure. The test was performed in displacement control at a rate of 1mm/min. During all the compression tests, AE data was recorded as well with the same setup used during impacts.

Figure 3: CAI specimen fitted in the compression rig

3 RESULTS

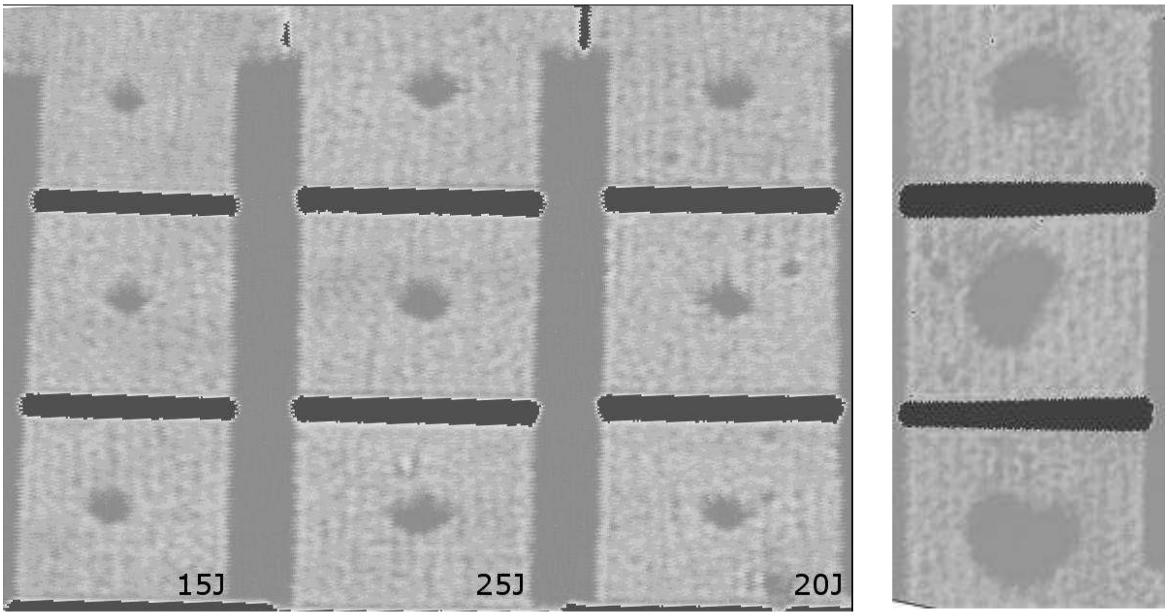
Impact damage produced Barely Visible Impact Damage (BVID) on the indenter side, while, consistently with what expected, produced visible splitting (Figure 4a) on the other side. All lightning-struck specimens showed outward projection of fibres in a more chaotic fashion (Figure 4b), together with evidence of charring and apparent lack of resin around the fibres that were projected outwards.



(a) (b)

Figure 4: impact damage on the bottom face of a sample (a) and post-lightning strike damage (b)

C-scans on impacted specimens showed evidence of delamination on all specimens (Figure 5a). Lightning-struck specimens showed generally larger delamination areas (Figure 5b).



(a) (b)

Figure 5: C-scan results for impacted specimens (a) and lightning struck specimens (b)

As expected, a correlation between impact energy and area of damage, calculated from the C-scan images, was visible (Figure 7). Moreover, Figure 6 shows that the residual strength reduction is proportional to the increase in delamination area.

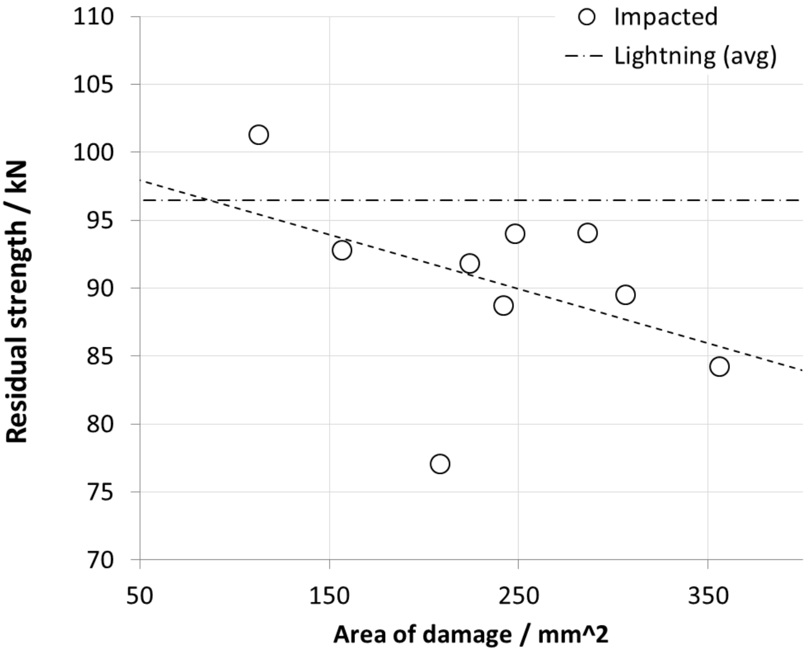


Figure 6: area of damage versus residual strength

From every individual impact, the AE Absolute Energy for the events occurred during the impact was extracted. This parameter correlates well with delamination area as well (Figure 8).

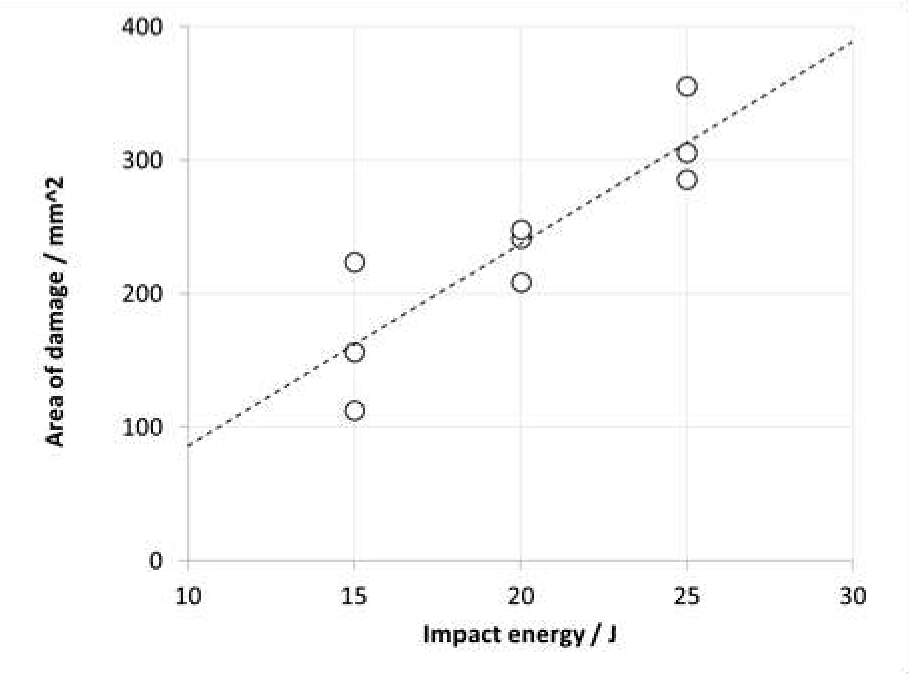


Figure 7: impact energy versus area of damage

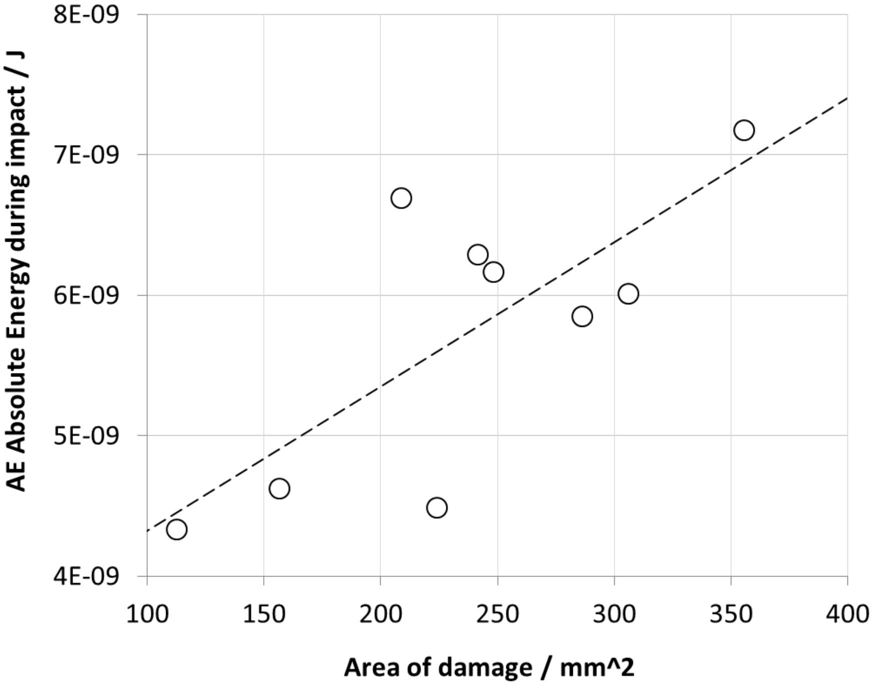


Figure 8: area of damage versus AE Absolute Energy

During the CAI tests, AE activity was evident during the first loading cycle (Figure 9); after unloading, no significant emission was detected until the load exceeded the hold load (i.e. the specimen exibits a strong Kaiser effect). The AE energy increased abruptly shortly after the maximum load was reached; the specimens then tended to fail in the middle section (Figure 10).

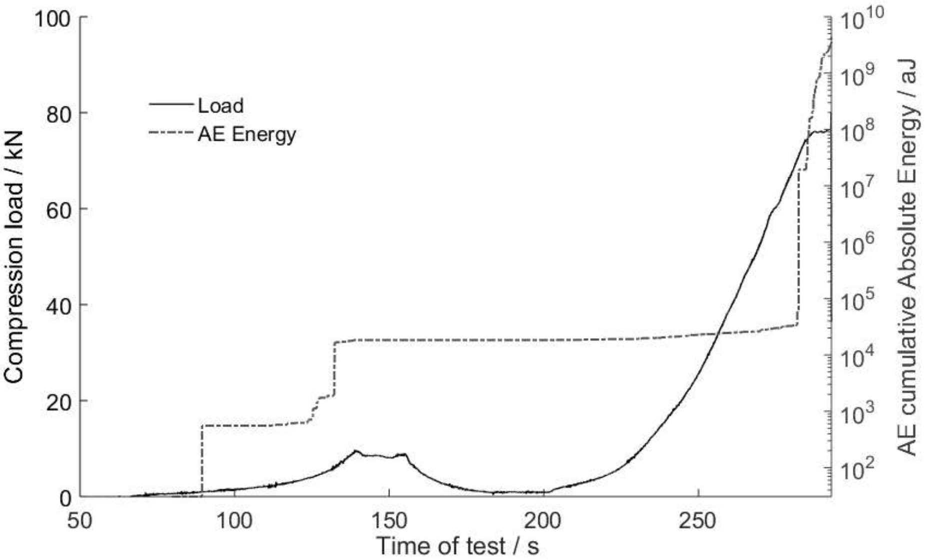


Figure 9: load / AE Energy release during a compression test

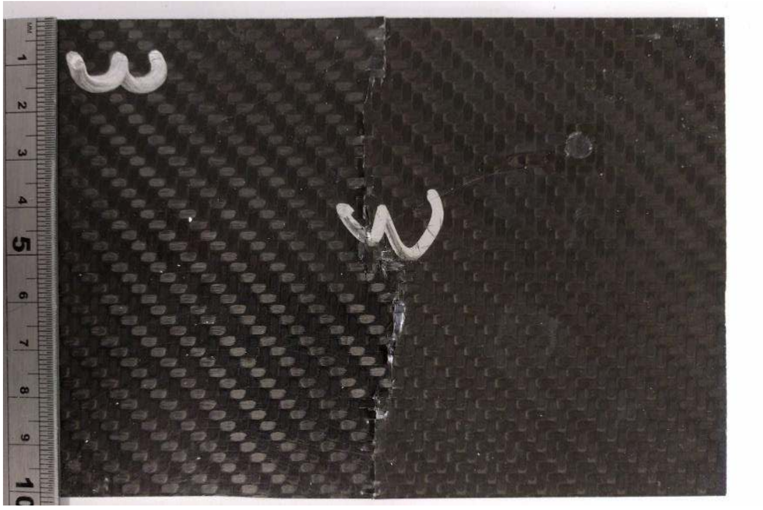


Figure 10: failed specimen after CAI test

The AE energy values during various phases of the test were compared. Figure 11 shows the cumulative energy release for all specimens at the moment when the specimen reached the peak compression load. A power law trend (linear in double-log scale) is visible although the lightning-struck samples tend to show a form of saturation.

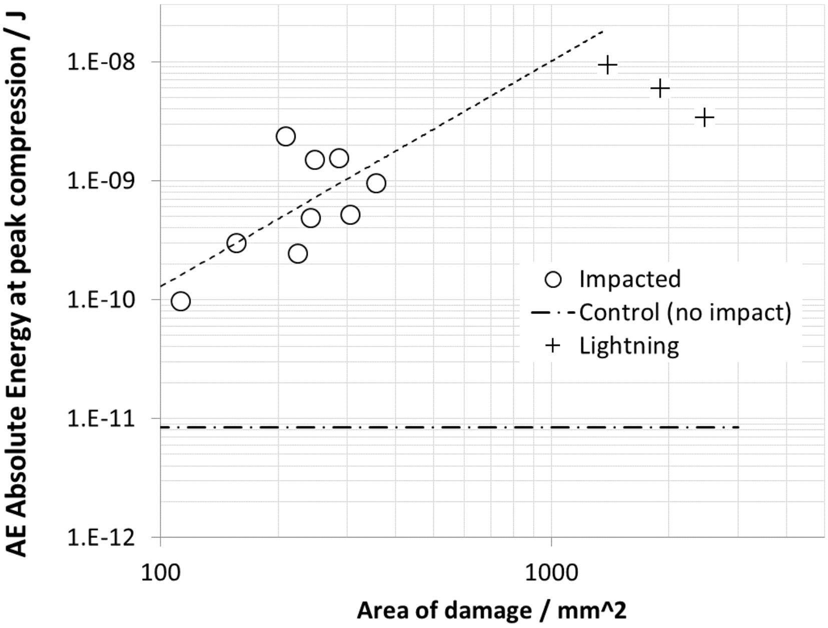


Figure 11: Area of damage versus AE absolute energy released at peak compression

Comparing the AE cumulative energy released during the first phase of the test, until the loading hold, shows no significant correlation (Figure 12).

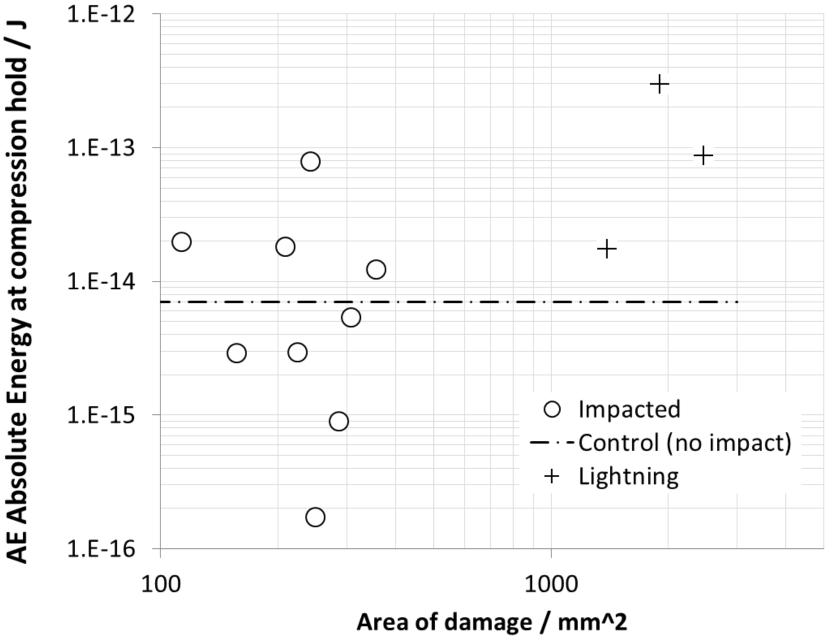


Figure 12: Area of damage versus AE absolute energy during the first load ramp

Comparing the total AE energy release at 95% of the peak (failure) load results in a relationship similar to the one seen at peak load (Figure 13).

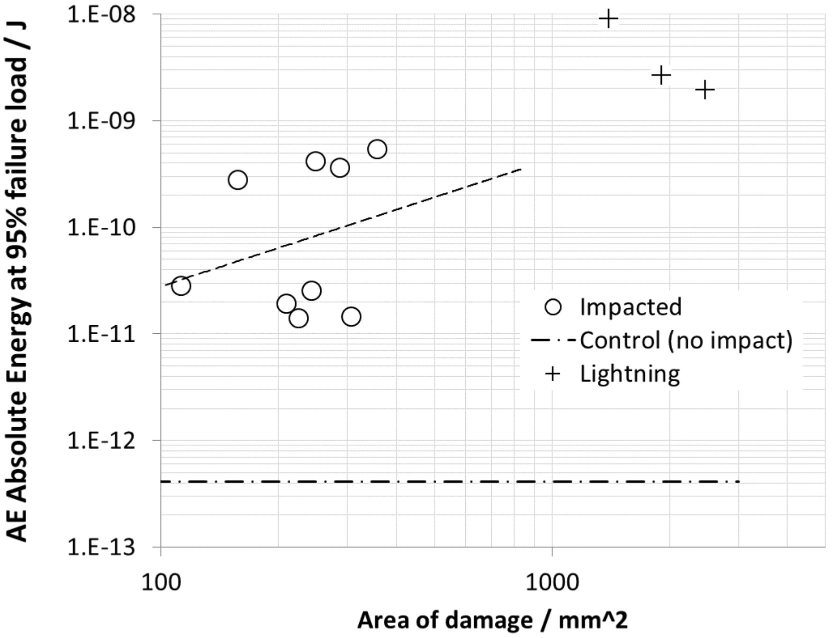


Figure 13: Area of damage versus AE absolute energy at 95% failure load

4 DISCUSSION

From the compression after impact tests, it was found that the residual strength of the impacted panels was, as expected, inversely proportional to area of damage. The lightning struck panels exhibited a similar behaviour regardless of the lightning energy. The delamination area measured by the C-scan was an order of magnitude larger than the impacted specimens; however, those samples showed a relatively high residual strength, comparable to the impacted specimens. This is believed to be due to the substantial difference in the post-impact damage nature. Impacted samples suffer from thorough delamination and cracking phenomena, which tends to affect all the layers, hence reduce the overall compressive strength. Examination of the lightning struck panels however showed a larger but more superficial damage, with large effects on the surface layers but potentially lower through-the-thickness effects, as the damage is believed to be mainly due to thermal expansion of gases trapped in the composite layers.

AE data during impacts showed a good correlation of AE energy and the area of the post-impact damage. Moreover, AE energy correlates well with the area of damage during failure load and 95% peak load, making the technique suitable for inferring damage severity during and after impact. This correlation was also found in lightning struck panels.

5 CONCLUSIONS

The relationship between AE energy, impact energy, lightning strike energy, delamination area and residual compression after impact strength were investigated. AE was found to be a suitable method for establishing the severity of an impact; it was also found that post-impact and post-lightning strike damage are linked to pre-failure and up-to-failure AE energy release.

If used in conjunction with state-of-the-art parameter correction techniques that take into account the sensor-impact distance, AE can be used to assess and quantify impact or lightning damage on carbon fibre structures, thus driving an operator's decision about maintenance, flight continuation and/or flight interruption.

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