Composites: Part A 103 (2017) 230–235

Contents lists available at ScienceDirect

Composites: Part A

journal homepage: www.elsevier.com/locate/compositesa

Short communication

Do high frequency acoustic emission events always represent fibre failure in CFRP laminates?

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ARTICLE INFO

Article history:
Received 17 May 2017
Received in revised form 4 October 2017
Accepted 12 October 2017
Available online 13 October 2017

Keywords:
Polymer-matrix composites (PMCs)
Acoustic emission
Transverse cracking
Delamination

ABSTRACT

When damage in carbon fibre reinforced composites (CFRP) is monitored by acoustic emission (AE), it is a common belief that high frequency AE events originate from fibre failure. This shows that this statement may not correspond to the reality, and matrix cracks can emit high frequency AE signals. Quasi-static tension of $[-45_2/0_2/+45_2/90_2]_s$ laminates was monitored by AE, Digital Image Correlation (DIC) on the surface of the sample and in-situ optical microscopy on the sample's polished edge. Unsupervised k-means clustering algorithm was applied to the AE results. By comparison with the direct DIC and microscopic observations, the AE cluster with high frequency and low amplitude was found to correspond to directly observed matrix cracks.

1. Introduction

Acoustic Emission (AE) registration allows monitoring damage during mechanical loading of composite materials. Cluster analysis of the multi-parametrical AE signals is a commonly used method for their classification and identification of the damage mode which caused an AE event [1–4]; the spatial position of the signal source can be identified when two AE sensors are used. Peak frequency and the signal amplitude are assumed to be the most important AE parameters for damage classification. There is a common conclusion in literature that AE signals with high peak frequency correspond to fibre failure [2–10]. This conclusion is relied on different reasons, such as; optical observations after final failure [3,7,9], fibre failure predictions with numerical or analytical methods [4,10], models of AE propagation [3] and results from single constituents' tests [5,8,10–12]. The identification of the high frequency events is often non-critically used as an established fact [4,13,14]. However, a strong, actual, "in-situ" evidence to prove this interpretation has not been presented yet. Moreover, there exist observations which point to the contrary. Baker et. al. [15], and Maillet et. al. [16] have shown that matrix cracking in cross-ply laminates can also generate high frequency AE events due to transverse matrix cracks in 90° plies and that an identification of the damage mode requires more detailed analysis of the acoustic wave propagation and attenuation in the laminate.

In the present paper we report results of simultaneous monitoring of damage in quasi-isotropic (QI) $[-45_2/0_2/+45_2/90_2]_s$ laminates under quasi-static tension with AE, Digital Image Correlation (DIC) on the sample surface and microscopic crack observation on the sample's edge, which shows by direct optical observations that matrix cracking in the 90° and ±45° layers generate AE events with weighted frequency over 260 kHz and amplitude below 66 dB, which a number of studies [2,3,5–12] classify as fibre failure. We want to draw the reader's attention to the title question "Do high frequency acoustic emission events always represent fibre failure in CFRP laminates?", to which our results, based on the direct observation of the damage in correlation with AE registration, give a negative answer.

2. Material and experimental methodology

Material used in this study is Hexcel's AS4/8552. Its fibre volume fraction and nominal thickness are 57.4% and 0.184 mm respectively. QI plates were manufactured according to the Manufacturer's Recommended Cure Cycle (MRCC) in an autoclave at Bog aziçi University's Composites Laboratory. Specimens were cut with a diamond saw and prepared according to ASTM D3039 Standard [17]. $[-45_2/0_2/+45_2/90_2]_s$ specimens with 3 mm thickness, 15 mm width and 175 mm length are tested in this study. QI GFRP composites with 1.5 mm thickness and 50 mm length are used

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https://doi.org/10.1016/j.compositesa.2017.10.013
1359-835X/

for end tabs. Their gage section ends are tapered to 20°-30° to minimize stress concentrations and prevent failure from grip sections.

Multi-instrument in-situ monitoring techniques are applied in this study. The tests are performed with electro-mechanical Instron 4505 universal testing machine with a rate of 1 mm/min. Real time AE monitoring with Vallen AMSY-5 system is applied with two broadband Digital Wave B-1025 AE sensors (frequency range 25–1600 kHz). Distance between the sensors is 50 mm. The AE events location was determined by standard AMSY algorithms based on the difference in the signals arrival times. Using only AE registration technique during tension tests is not sufficient to identify damage modes and correlate them with corresponding AE events. So, in addition to AE; DIC is used to observe damage on the sample surface and macro damage in the laminate. One surface of the specimens are speckled for the DIC calculations. Crack observation from a 5 mm region on the sample's edge with a high magnification, high-speed Charge-Coupled Device (CCD) camera shows direct detection of micro damages at inner layers. One edge of the specimen is polished for a clear observation.

Unsupervised k-means++ clustering algorithm, developed by Li et al. [4] is used to classify the AE events. Details of this algorithm are not given here for the sake of brevity, readers should refer to the cited reference.

3. Results and discussion

Results of five tests are reported here. Specimens are loaded up to 70–80% and 90% of the ultimate strength (540 MPa). In order to show the consistency and repeatability of the tests, stress vs. strain graphs are plotted with two most important AE parameters in Fig. 1; note that the end of the stress–strain diagrams corresponds to the test stop and not to the specimen failure. Tests #3 and #5 are performed with all damage monitoring instruments listed before; AE registration to emit stress waves of damage modes, DIC for surface cracks and edge microscopy for micro damage modes at inner plies. These samples are loaded up to 90% of its ultimate strength. Only AE and DIC are used during quasi-static tension for the rest of the specimens. Fig. 1.a shows that test results are highly repeatable. Peak frequency distributions are plotted in Fig. 1.b. The pattern of the event frequency is remarkable: it shows high peak frequency values (250...800 kHz) during mid-strain levels and their disappearance afterwards. According to the peak frequency trends cited in literature [2–10] these high peak frequency signals should be due to fibre breakages. However, they are recorded between strain levels of 0.0048–0.0072 (which corresponds to stress levels of 240–320 MPa). So, do fibre breaks start really so early for this laminate, if the failure strain for the AS4 fibres is, according to the data sheet, 0.0182? This question was asked previously by Li et. al [4]. They tried to show a correlation between high frequency AE events with fibre breaks by using a fibre bundle model based on Weibull estimation. Number of high frequency AE events throughout the tests are compared with estimated number of fibre breaks. It showed earlier start of individual fibre breaks than AE cluster for woven fabric yarns. Two reasons were proposed for such discrepancy. Firstly, it was believed that isolated fibre breaks could not create a noticeable AE event and high frequency signals were not recorded during early strain levels. Secondly, Weibull estimates higher number of breaks than reality. DIC and edge observations in this study provide an answer to abovementioned question and that is "NO". These high peak frequency events are due to matrix cracks at the inner 90° and 45° plies.

Micro damage and DIC strain maps recorded during test #3 are presented in Fig. 2. Test #5 gave the similar results. Coloured regions in Fig. 2 are area of interest for DIC calculations. This area is divided into subsets and individual strains are calculated. They consist overall strain maps and shown with colour scales as shown in Fig. 2. Average strain values of this area of interest are used for Fig. 2. Test direction, $+\varepsilon_1$, and contraction in transverse direction, $\pm\varepsilon_2$, are mentioned on Fig. 2.

Following Fig. 2, the damage sequence is as follows. First damage initiates in 90° plies. It propagates through the adjacent 45° plies. Transverse cracks in the middle 90° and the adjacent 45° plies become visible from the edge at 0.0058 strain level; the same damage pattern is seen at 0.0067 strain. Micro delaminations between 90/45 intersections are also seen, coinciding with transverse cracks. After the strain level of 0.0067, the ε_2 strain map shows separation of the map in two zones. The zone with the "normal" transverse strain values (upper part of the map), corresponding to the low values expected from the low Poisson contraction of the laminate, containing 90° plies, and high negative values (lower part of the map), which evidence much more pronounced Poisson effect. This phenomenon can be attributed to macro delamination, initiated from the unpolished (lower) edge of the specimen. The delaminated plies are not connected to the 90° plies and are free to contract transversely. Appearance of the macro delamination at the end of the test is shown at the bottom of Fig. 2. From 0.0067 strain level until the end of the test, macro delaminations on the unpolished edge and the existing micro delaminations between the 90/45 intersections continue to propagate with appearance of new micro delaminations on the polished edge.

This understanding of the sequence of damage is corroborated by different means of optical monitoring used during the test. In-situ edge observations detect micro damage in the 90° and 45° plies, micro delaminations between the 45/90 and the 0/45 plies whereas 2D DIC emphasizes the onset and propagation of the

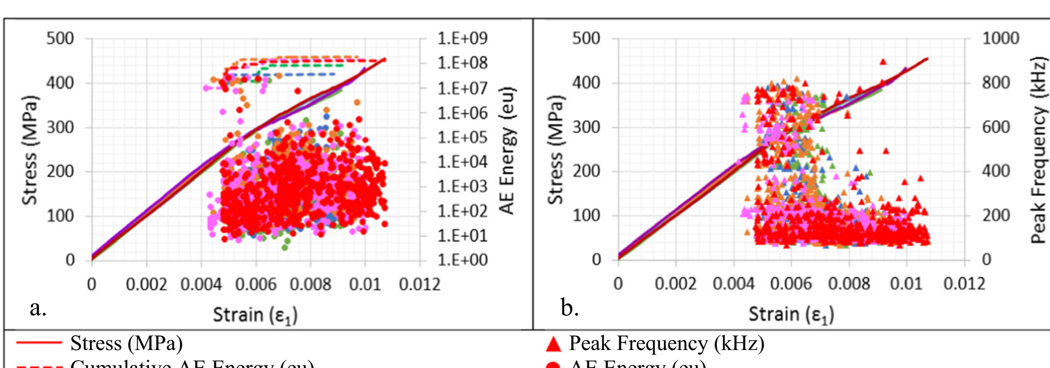

Fig. 1. A summary of the stress–strain curves and AE registration for $[-45_2/0_2/+45_2/90_2]_s$ CFRP laminates, data for five specimens are shown with different colours of lines and dots: (a) Stress- and AE energy vs. strain (b) Stress- and peak frequency vs. strain.