Matrix Cracking Detection by Acoustic Emission in Polymer Composites and Counts/Duration ratio

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Abstract
This work re-analyses the results of two previous papers on carbon fibre composites by the Author, the first one based on tensile loading transverse to the fibres in a carbon/epoxy composite [1], while the second one focused on single fibre fragmentation tests monitored in both cases by acoustic emission (AE). In both cases, it is expected that fibre breakage and therefore events related to fibres are limited as for number and extent. In particular, in [1], with load applied at 90° with respect to the fibres, damage is expected to arise in form of matrix cracking and occasionally other types of damage. In [2], the presence of only one fibre in the specimens does forcibly limit the number of fibre-related events.

The main results, which were not highlighted in the original papers, lie in the general confirmation of approximately 100 kHz as main frequency associated with matrix cracking, and in the considerable attenuation of signals not strictly related to fibre breakage events, whenever AE resonant sensors are used, whose maximum sensitivity range is in the 100-300 kHz interval.

Keywords: Acoustic emission, matrix cracking, polymer composites, frequency, counts, duration, amplitude

1. Introduction

One of the main problems which are being studied over the years using acoustic emission on polymer composites reinforced with glass, carbon or Kevlar fibres, is the possible classification of the signals according to the damage mode that generates it, namely matrix cracking, debonding, delamination and fibre breakage. A separation of the different modes, which is somehow effective in a number of cases, is the one based on signal amplitude, has been proposed first in [3] on carbon fibre composites and confirmed a number of times, such as in [4], dealing with monotonic and cyclic loading of glass fibre composites and in [5], dealing with loading of self-reinforced polyethylene. In the latter case, when a tensile loading at a 90° angle with fibre direction is performed, only low amplitude events are detected.

The above partition according to signal amplitudes shows its drawbacks nevertheless especially as regards the so called sub-classification of events, in other words amplitudes are for their nature sensitive also to signal strength. This is particularly true, considering that matrix cracking continues to occur during loading to failure of the laminate. In this way, it appears e.g., that a high amplitude AE event may refer also to an event not necessarily related to fibre breakage, but for example to a particularly broad or otherwise strong matrix cracking event or delamination. This has been shown with particular evidence in [6]. The recognition that real damage events, such as for example impact, in composites involves complex modes of damage, leads to the consideration that a localised event involves a wide range of frequencies, from around 100 to over 400 kHz, as indicated very clearly in [7].

Concentrating on matrix cracking detection, this appears to be the most difficult mode to be isolated, in that most phenomena occurring during composite damage initiation and development are matrix cracks and present the most different features depending on the location and the load of occurrence. A possibility to isolate AE characteristics of matrix cracking systems would be disposing a mechanical test in which only matrix cracking phenomena occur. This could be done by testing the polymer matrix alone, as in [8]. However, indications from the same study suggested that the presence of the fibres may...
influence the mode of failure of the matrix and namely the frequency range of AE events related to matrix cracking. The average frequency of a signal can be obtained from parametric acoustic emission studies, without necessarily involving a formal FFT, whenever data from the counts vs. duration plot are elicited: a thorough study has been done for example in [9], dealing with glass fibre reinforced composites.

Another possibility for isolating matrix cracking is the monitoring of acoustic emission during single fibre fragmentation tests (SFFT), in which only one fibre is present. AE monitoring is carried out with the concealed assumption that the only high amplitude events are dealing with fibre breakage, the rest of events related with matrix cracking or fibre pull-out. This test has been performed in a number of instances and monitored using acoustic emission, leading to possible measurements of the critical length of the fibres i.e., sufficient to produce an effective shear stress transfer between the fibre and the matrix [10]. The accuracy of the test is limited by the approximation in calculation of arrival time at the different sensors [11-12].

Other observations limited further the validity of the results obtained, in the sense that acoustic emission allowed establishing that the real conditions are rather different from what prescribed from the theory and the relevant standard. For example, Netravali et al. remarked that along the fibre break most often a small transverse crack formed with the results that stress is not completely uniform as assumed [13]. As concerns acoustic emission during SFFT, Ni and Jinen observed that the detection of matrix cracking is strongly dependent on its dimension [14].

Even with all these difficulties, a common assumption is that matrix cracking is most frequently detected with events having frequency substantially centred on a 100 kHz value, while for interface events (delamination/debonding) and fibre breakage events a 200 kHz and a 300 kHz can be respectively assumed, as a rough approximation [15]. This paper examines some old AE data from [1] and [2] and tries to make new sense of them, considering the value and limits of the above assumption.

2. Experimental

2.1 Materials and testing

Case 1:
Tensile tests have been carried out using a thermomechanical ZWICK 1488 universal testing machine was used, equipped with hydraulic grips exerting a 10 MPa pressure. Ten eight-layer unidirectional carbon/epoxy laminates, fabricated by RTM using a standard bisphenol A epoxy of dimensions 220x28x1.1 mm, were loaded at an angle of 90° with respect to the direction of the fibres, in displacement control using a cross-head speed of 1.3 mm/min.

Case 2:
A single Torayca T300 high strength carbon fibre filament (7 µm. diameter) was embedded in three different polymeric matrices (polycarbonate, polyurethane and epoxy). A total number of fifteen dog-bone specimens, five per matrix, were prepared, each with total length 45 mm. Tests were performed using the same machine as in Case 1, in displacement control mode with a crosshead speed equal to 0.13 mm/min.

2.2 Acoustic emission

In both cases, AE system used was PAC MISTRAS with two PZT miniaturised sensors (diameter 5 mm), resonant at 300 kHz. In case 1, they were disposed at a mutual centre-to-centre distance of 150 mm on both sides of the middle line and on the same face of the
laminate, whilst in case 2, they were placed at a mutual centre-to-centre distance of 30 mm, again on both sides of the middle line and on the same face of the laminate. The use of guards was not deemed necessary, in that only AE events localised between the two sensors was recorded for analysis. The signal was amplified by 60 dB, 40 dB provided by the pre-amplifier and 20 dB by the system. Signal definition times were 100 µs peak definition time (PDT), 300 µs hit definition time (HDT) and 300 µs hit lockout time (HLT).

3. Results and discussion

Acoustic emission analysis was performed only on most significant samples, which yielded a sufficient number of events. These were three in Case 1, and six in Case 2.

Case 1

The results obtained from the tensile tests are reported in Table 1. Here, it can be noticed as the presence of the fibres leaves virtually unchanged the stiffness of the matrix. This suggests that, as expected, the effect of reinforcement on the transverse modulus can be neglected, results on the other side result in a hindrance to the deformation of the matrix, so that the strain at failure of the composite is way lower than what measured at matrix yield.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Transverse tensile strength (MPa)</th>
<th>Transverse tensile modulus (GPa)</th>
<th>Max. strain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon/epoxy</td>
<td>60 ± 2.5</td>
<td>3.2 ± 0.15</td>
<td>0.019 ± 0.001</td>
</tr>
<tr>
<td>Neat resin*</td>
<td>78</td>
<td>3.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Carbon fibres</td>
<td>120 [16]</td>
<td>8 [16]</td>
<td>0.015*</td>
</tr>
</tbody>
</table>

* As declared by the manufacturer
** Yield strain

Table 1 Mechanical properties of composites

In Figure 1 the global amplitude distribution over testing on the three laminates considered is depicted. The distribution includes in this case both localised and non localised hits, the latter being either detected with peak amplitude exceeding the threshold by just one channel or having difference in arrival time between the channels out of the acceptable range. It is observable that, as expected, most hits have amplitude lower than 60 dB, although a substantial number of them are also present at very high amplitudes. It needs also to be noticed that the percent of localised events is very low, in the region of 10% for all samples, which indicates that the signals are very attenuated, as can be expected again for acoustic emission deriving from matrix cracking. In Figures 2, 3 and 4 the analysis of acoustic emission data is presented for each of the three samples separately. Here, a significant, though never very pronounced, acoustic emission activity starts only at the very end of loading process, approximately when exceeding 80% of ultimate tensile stress, as can be observed in time histories reported in the above figures. Another information is the point where the failure occurs, where distribution of hits (localised and not localised) shows a clear peak, which is likely to correspond to a matrix tearing process to failure. In Figure 5, lines at 100 kHz (red) and 200 kHz (green) are highlighted on the magnified counts vs. duration distribution for the three laminates. This confirms that, according to the frequency classification, no fibre fracture appears to be detected, but most localised events are to be related with delamination and debonding. In contrast, matrix cracking appears mainly to be not localised, possibly since most of the relevant signals are not sufficiently strong to be detected by both channels.
Case 2

The study reported in [2] was aimed at the determination of the critical length of fibres and therefore only localised events were taken into consideration. In Figure 6 the counts and duration distribution of events with respect to their location on the samples is reported. It can be noticed, as from the analysis reported in Figure 7, that the mean frequency of these events, as described by the counts/duration ratio, is centred around 100 kHz, the minimum and maximum measured over the whole batch being around 35 kHz and 140 kHz respectively. This appears to indicate that what is really mainly detected during these tests using acoustic emission is the process of matrix cracking leading to fibre pull-out and breakage, more than fibre fracture itself, as suggested from the considerations made e.g., in [8], on the frequency classification of AE signals. Figure 8, where the amplitudes of the localised events are reported, suggests also that, in spite of non indicating fibre fracture, some of these events can have a medium to high amplitude, even exceeding 60-65 dB, which further indicates that amplitude may be affected by the extension of the interface fracture (be it matrix cracking, delamination or debonding), as highlighted in [6].

4. Conclusions

This work indicates to confirm that the adoption of resonant sensors for the acquisition of acoustic emission on composites is able to lead to a clear classification of signals pertaining to the different failure modes (matrix cracking, delamination/debonding, fibre fracture), based on counts/duration ratio and amplitude This is improved whenever the background noise of the instrument is lower, allowing easier events localisation, which is particularly beneficial for the detection of matrix cracking related signals.

REFERENCES


Figure 1 Case 1: Amplitude events distribution during tensile testing

Figure 2 Case 1: AE analysis (sample n.1) (the red line represents 100 kHz frequency)
Figure 3 Case 1: AE analysis (sample n.2)

Figure 4 Case 1: AE analysis (sample n.3)

Figure 5 Case 1: Duration vs. Counts plots enlarged (samples 1, 2 and 3)
Figure 6 Case 2: AE Analysis (counts and duration vs. location) (samples 1 to 6)
Figure 7 Case 2: Frequency distribution of localised events

Figure 7 Case 2: AE analysis (amplitude vs. location) (samples 1 to 6)