



Fotouhi, M., Suwarta, P., Jalalvand, M., Czel, G., & Wisnom, M. (2016). Acoustic emission based method to characterise the damage modes in UD thin carbon/glass hybrid laminates. In *ECCM 2016 - Proceeding of the 17th European Conference on Composite Materials* European Conference on Composite Materials. <http://www.eccm17.org/conference-information.html>

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ACOUSTIC EMISSION BASED METHOD TO CHARACTERISE THE DAMAGE MODES IN UD THIN CARBON/GLASS HYBRID LAMINATES

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Keywords: Carbon/glass hybrid, Pseudo ductility, Acoustic emission, Fragmentation

Abstract

The aim of this paper is to investigate the relationship between the features of acoustic emission (AE) signals and the corresponding damage modes in S-Glass/carbon UD hybrid laminates subjected to tensile loading. The investigated laminates were fabricated by sandwiching thin carbon plies between translucent standard thickness glass plies to produce pseudo-ductility. The gradual damage mechanisms identified included fragmentation of the carbon fibre and delamination of the glass/carbon interface, which were observable due to the translucent glass layers. Since the damage modes were observable, it was possible to establish qualitative and quantitative correlations between these observed failure modes and the features of the AE signals. Based on our observations, two significant failure modes occurred during the tests: i) fibre failure, which was associated with the high energy and amplitude range of the AE signals and ii) delamination, which was related to the low energy and amplitude range. These results demonstrate that AE signals provide potentially useful information to characterise damage modes in hybrid laminates, which could be especially useful when the laminate is thick or opaque, or when the damage is too small to be visible. Further, these results could be developed into a method or protocol for assessing damage in hybrid laminates.

1. Introduction

Recently, pseudo-ductile stress-strain response in thin carbon/glass plies was introduced as a successful method to address the lack of ductility in composite laminates [1-4]. It was reported that when the carbon layer is thin enough, catastrophic delamination propagation following the first carbon layer fracture is suppressed and further fractures in the carbon layer occur. This damage mode was called fragmentation of the carbon layer. In those studies, it was observed that the damage modes causing pseudo-ductile behaviour in thin-ply UD carbon/S-Glass laminates are carbon ply fragmentation and delamination of the carbon/glass interface.

Understanding the failure mechanisms which have introduced pseudo-ductility is of importance for the optimal use of a component and can then be applied to optimise the design of more general layups. But the characterization of these damage mechanisms is a challenging issue, especially when the different damage modes are not visible due to the thickness of the laminate or when the laminate is opaque.

This study proposes an efficient method to investigate damage development and to identify the type of damage in thin-ply UD carbon/glass hybrid laminates using acoustic emission (AE). The AE technique is designed for on-line monitoring of acoustic emissions produced within the material during loading and failure [5].

Several researchers tried to correlate AE parameters to the damage caused, and it was concluded that the amplitude, energy and frequency ranges of different damage modes were different from each other [5-8].

The literature review indicates that the AE technique can characterise the damage modes in laminated composites. However, the applicability of the AE technique in complex loading cases and hybrid laminates remains a hypothesis not proven by direct observation. In our previous study acoustic emission events were correlated to direct observations of the corresponding fragmentation and delamination in thin-ply carbon/glass hybrid laminates [9].

The aim of this study is to establish a direct correlation between the observed damage mechanisms and the recorded AE signals in UD carbon/S-glass hybrid laminates under tensile loading. To achieve this goal, thin-ply hybrid materials were investigated in which progressive fragmentation of the carbon/epoxy layer and stable delamination of the carbon/glass interface were the main failure modes.

2. EXPERIMENTS

2.1. MATERIALS

The materials considered in this study are thin carbon/epoxy prepreg and standard thickness glass/epoxy prepreg. Characteristics of the prepregs are listed in table 1. The high strain material of the hybrid laminates is UD S-glass/913 epoxy prepreg supplied by Hexcel. The low strain material is thin carbon prepregs from SK Chemicals (South Korea) under the trade name of SkyFlex USN020A. The carbon fibres in the thin USN020A prepreg are Pyrofil TR 30 made by Mitsubishi Rayon with the modulus and fibre failure strain given in Table 1. The corresponding matrix is SK Chemical's type K50 epoxy resin.

Table 1. Characteristics of the prepregs and fibres used.

Prepreg type	S-glass/epoxy	TR30/epoxy
Fibre modulus E (GPa)	88	234
Fibre failure strain (%)	5.5	1.9
Cured nominal thickness (mm)	0.155	0.029
Fibre mass per unit area (g/m ²)	190	21.2
Fibre volume fraction (%)	50	41

2.2. Specimen design and manufacturing

The hybrid plate was laid up in the sequence of $[G_1/C_2/G_1]$ where G stands for S-glass plies and C for TR30 carbon plies. The benefit of using glass prepreg was that it is translucent, allowing crack and delamination detection visually.

Since characterization of different damage types was the aim of this paper, the lay-up was chosen to have a combination of damage modes, i.e. both fragmentation in the carbon layer and delamination. Different possible failure modes for different relative and absolute carbon layer thicknesses are illustrated by the damage mode map [3] for S-glass/TR30 hybrids in Figure 1. The damage mode map in Figure 1 shows that $n=2$ for TR30 carbon configurations results in the combined fragmentation and dispersed delamination failure mode.

The laminate was cured in an autoclave at the recommended cure temperature and pressure cycle for the Hexcel 913 resin (60 min@125 °C, 0.7 MPa). Fabrication of the specimens was done using a diamond cutting wheel.

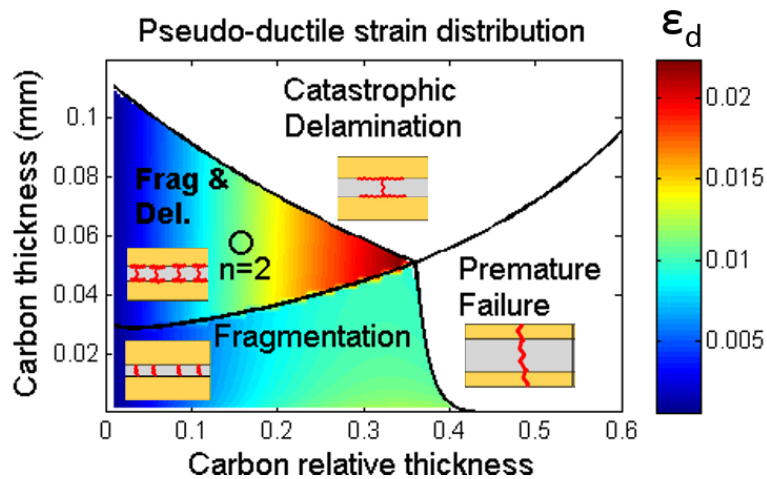


Figure 1. Distribution of pseudo-ductile strain for [G1/C2/G1] laminates made with TR30 carbon.

2.3. Test procedure

Tensile testing of the hybrid laminates was executed under uniaxial loading and displacement control using a crosshead speed of 2 mm/min on a computer controlled Instron 8801 type 100 kN rated universal hydraulic test machine with wedge type hydraulic grips (see figure 2). A 25 kN load cell was attached for better resolution in the expected load range. The nominal specimen dimensions for the tests were 240/160/20/h mm overall length/free length/width/variable thickness respectively. 8 specimens were tested. To measure the strains with a nominal gauge length of 130 mm, an Imetrum video gauge system was used, tracking the points applied on the specimen face using points over a particular gauge length. An AE data acquisition system (PAC) PCI-2 with a maximum sampling rate of 40 MHz was used to record the AE signals. Two PAC R15 resonant-type, broadband, single-crystal piezoelectric transducers were used as AE sensors to monitor the damage events. The frequency range of the sensors was 20–900 kHz, and the gain selector of the preamplifier and the threshold value were set to 40 dB. The test sampling rate was 5 MHz.

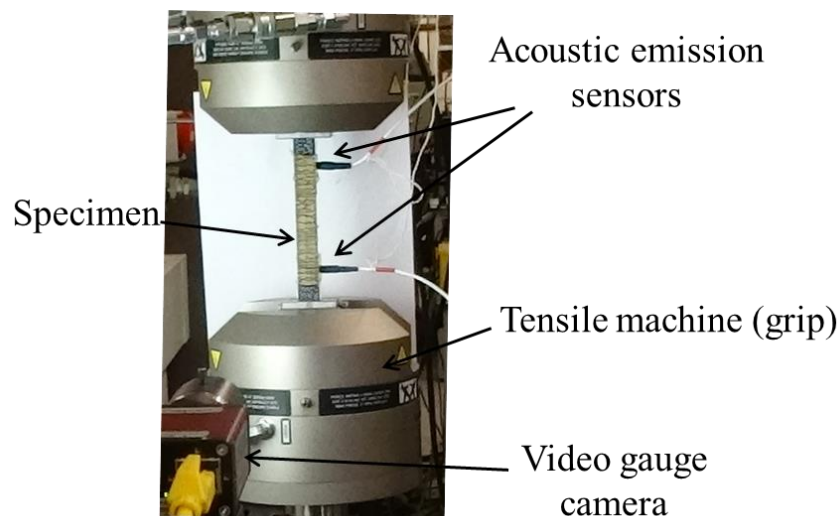


Figure 2. Schematic of the experimental setup.

3. Results and discussion

A typical stress-strain plot and its relationship with AE energy are shown in Fig. 3a, for a typical TR30/S-glass hybrid specimen. AE events with different energy levels can be observed for different damage evolution stages in Figure 3a.

In order to identify and separate AE signals originating from the failure modes, AE characteristics of a mode II stable delamination were obtained by producing pure carbon/glass interface delamination. This was done by inserting a pre-cut in the carbon layer [9]. The amplitude of the AE signals was between 60 and 85 dB while the event energy was between 30 and 800 aJ for delamination.

By knowing the characteristics of the AE events corresponding to pure delamination, the obtained AE signals were then classified into two categories with low and high energy and amplitude of the AE signal. Based on our observation, two significant failure modes occurred during the tests. Ply fragmentation was related to the high energy and amplitude range of the AE signals and delamination was associated with the intermediate energy and amplitude range. The ranges of the AE energy and amplitude for the failure modes are indicated in Figure 3b. In addition, there were some weak AE signals from the start of the test with amplitude < 65 dB and energy < 30 aJ which were not related to the delamination and considered as noise.

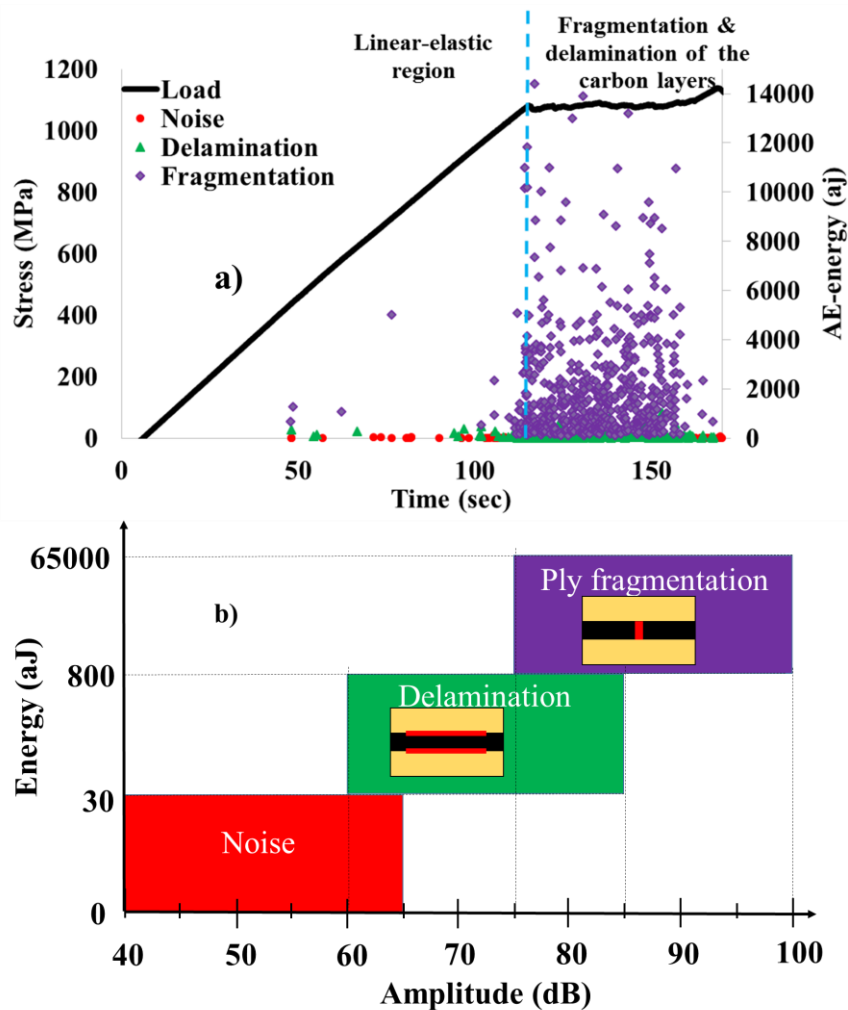


Figure 3. a) Stress-time and AE event energy distribution for a typical TR30/S-glass specimen and b) Event amplitude and energy ranges assigned to different damage mechanisms of ply fragmentation and delamination.

The cumulative AE energy and number of the AE events in each class of signals are illustrated in Figure 4, for a typical TR30/S-glass specimen. Fragmentation associated signals have much higher cumulative energy compared with the delamination associated ones. It can be seen from Figure 3a and Figure 4 that the signals related to fragmentation appear near the plateau in the stress-time diagram and they are well separated from those related to delamination.

In addition, it is possible to count the number of failures in each class based on the number of AE events that hit the sensor. An AE event is the phenomenon which releases elastic energy in the laminate, which then propagates as an elastic wave. In this case, the mechanisms were either fragmentation or delamination and each AE signal can be regarded as a separate damage event. The number of fragmentation events prior to final failure is 628 and the average energy content for fragmentation is 2050 aJ. The number of AE events associated with delamination is also illustrated in the figures.

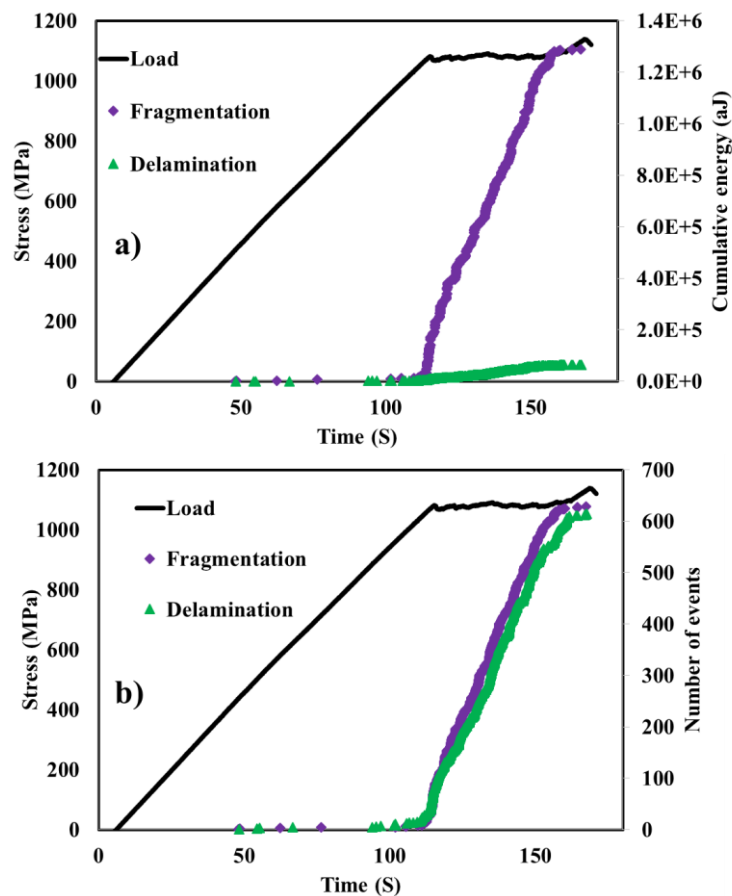


Figure 4. The cumulative of a) AE event energy and b) number of the AE events in each class of the AE signals for a typical 2TR30/S-glass specimen with two carbon plies [9].

These results are in good overall agreement with our visual inspection of the specimens and the videos captured during the tests. A low magnification microscope image obtained from the surface of the specimen is shown in Figure 5. The delaminated back surface of the glass layer blocked the visibility of the carbon. Therefore, the well bonded areas appear black, and within the locally delaminated light areas, the cracks in the carbon layer are visible as sharp bright lines. From our observation during the tests and as illustrated in Figure 4, fragmentation and delamination occur concurrently and are the origin of most of the AE signals.

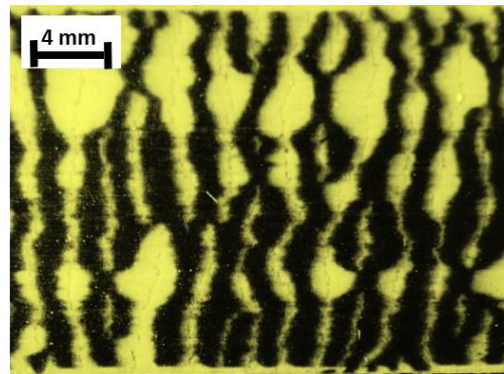


Figure 5. Microscopic images from the surface of a typical 2TR30-S-glass (Localised delaminations around multiple carbon-ply cracks)

4. Conclusions

In this paper, the link between AE events and the corresponding damage modes in thin-ply UD carbon/glass hybrid laminates under tensile loading was investigated. The results showed two groups of the AE events, the high and low values of energy and amplitude, which were associated with fragmentation of carbon plies and delamination of the glass/carbon interface, respectively. Since the laminates were translucent it was possible to establish quantitative correlations between the observed failures and the AE events during the tests. It is concluded that the AE technique is capable of identifying the type of damage. The proposed method is very useful, especially where the laminates are opaque and/or thick so it is not possible to monitor the damage evolution optically. Therefore, this method can be used as an effective way to accurately detect fibre fragmentation, as well as to subsequently track its evolution and accumulation in more complex layups and loading cases.

Acknowledgments

This work was funded under the UK Engineering and Physical Sciences Research Council Programme Grant EP/I02946X/1 on High Performance Ductile Composite Technology in collaboration with Imperial College, London. Gergely Czél acknowledges the Hungarian Academy of Sciences for funding through the Post-Doctoral Researcher Programme fellowship scheme, the János Bolyai scholarship and the Hungarian National Research, Development and Innovation Office - NKFIH, for funding through grant OTKA K 116070. The authors acknowledge Hexcel Corporation for supplying materials for this research. Supporting data can be requested from the corresponding author, but may be subject to confidentiality obligations.

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