Characterisation of Damage in Composite Structures using Acoustic Emission

M Eaton1, M May2, C Featherston1, K Holford1, S Hallet3 and R Pullin1

1Cardiff School of Engineering, Cardiff University, Queens Buildings, Newport Road, Cardiff, CF24 3AA
2Fraunhofer Institut für Kurzzeitdynamik, Ernst-Mach-Institut, Eckerstr. 4, 79104 Freiburg
3Department of Aerospace Engineering, University of Bristol, Queens Building, University Walk, Bristol, BS8 1TR
eatonm@cf.ac.uk, michael.may@emi.fraunhofer.de, featherstoncaf@cardiff.ac.uk, holford@cardiff.ac.uk, stephen.hallett@bristol.ac.uk, pullinr@cf.ac.uk

Abstract. Detection and characterisation of damage in composite structures during in-service loading is highly desirable. Acoustic emission (AE) monitoring of composite components offers a highly sensitive method for detecting matrix cracking and delamination damage mechanisms in composites. AE relies on the detection of stress waves that are released during damage propagation and using an array of sensors, damage location may be determined. A methodology for damage characterisation based on measuring the amplitude ratio (MAR) of the two primary lamb wave modes; symmetric (in-plane) and asymmetric (out-of-plane) that propagate in plate like structures has been developed. This paper presents the findings of a series of tensile tests in composite coupons with large central ply blocks. The specimens were monitored using AE sensors throughout loading and once significant AE signals were observed the loading process was stopped. The specimens were removed and subjected to x-ray inspection to assess for any damage. The onset of damage was successfully detected using AE and was identified as being matrix cracking using the MAR methodology. The results were validated with x-ray inspection and a strong correlation was observed between the number of significant AE signals recorded and the number of identified matrix cracks.

1. Introduction
In recent years the increasing use of composite materials has seen their application spread to larger and more safety critical components and structures, with long service lives. A clear example of this is the increasing amount of composite materials used in the modern aircraft, such as the A380 for which composite materials contribute to approximately 25% of the airframe mass. It is also one of the first aircraft to have a composite centre wing-box, a crucial primary structure which connects the wings to the fuselage. This is set to be an increasing trend with many of the large aircraft manufacturers claiming they will no longer make aluminium aircraft and pledging to produce a new generation of all composite aircraft. Other large-scale structures also utilizing composite materials include pressure vessels, pipelines, wind turbines and ground transport. Driven by the increasing usage of composite
materials, research demands have begun to focus on the development of effective and reliable structural health monitoring (SHM) systems, techniques and methodologies for use on composite materials and structures.

An SHM system for large-scale structures needs to effectively fulfill three key tasks. Firstly it must be able to detect the occurrence of a damage event or the degradation in integrity of a structure. Secondly it must be able to provide an accurate location of any damage within a structure. And thirdly it must be able to estimate the severity of the damage, in particular the damage type and size. Only with a combination of these three pieces of information can a meaningful assessment of the integrity of a structure be made.

Acoustic Emission (AE) is a highly sensitive Non-Destructive Testing (NDT) technique. It relies on the detection of transient elastic waves that are released within a material under stress, in areas of plastic deformation or damage growth. The transient waves propagate through the material to and along its surface, where they are detected by piezoelectric transducers. The passive nature of the AE approach lends itself well to large-scale SHM systems, allowing continuous and global monitoring of structures.

The AE technique has been applied to monitoring composite materials for many years, examples of this include full composite airframe testing [1], Formula One racing car components [2] and there are even standard test procedures such as those for composite pressure vessels [3]. These activities have shown that AE is very effective at detecting the occurrence of damage in composite materials, fulfilling the first of the three required functions of an SHM system. However, the complex properties of composite materials that vary with material direction make accurate location and damage characterization much more problematic. The work in this paper focuses on the characterization of damage types in composite materials.

Utilising a methodology based on the modal analysis of recorded AE signals to identify in-plane matrix damage in carbon fibre composite tensile tests. The developed methodology for damage characterisation uses the ratio of the amplitudes of the two primary lamb wave modes that propagate in plate like structures.

A series of carbon fiber composite tensile specimens with thick central ply blocks was studied for two different configurations: [0_2,90_4]s and [0_2,60_4]s. For the first configuration, matrix cracks initiate under pure tensile opening mode I; for the latter configuration matrix cracks initiate under a mixed-mode combination of tensile opening and shear. The specimens were monitored with AE throughout loading to detect the damage onset. The recorded AE signal waveforms were analysed post test to identify damage types and the results were validated using microfocus X-ray imaging. The results of one [0_2,90_4]s specimen and one [0_2,60_4]s specimen are presented here in.

2. Modal Analysis

Due to the laminate nature of composite materials, they are commonly manufactured as thin walled and plate like structures. This plate like geometric characteristic has a unique effect on the propagation of transient elastic waves through the material. The bounding surfaces of the plate act as a wave guide for bulk transient elastic waves, which causes the surface displacements to couple and produce plate waves or Lamb waves. These propagate as two principle wave modes, demonstrated in Figure 1a for the symmetric mode (s_0) with the predominant particle motion in the plane of the plate and Figure 1b for the asymmetric mode (a_0) with the predominant particle motion out of the plane of the plate. The propagation behaviour of plate wave modes is described by dispersion curves relating velocity to frequency and thickness. It is also possible for higher order modes to be supported but this is more common in thick plates and there amplitude is normally considerably less than the principle modes. Modal Analysis of AE signals is the consideration of the plate wave modes in digitised and stored representations of the transient elastic waves. This can enable the user to gain greater information about the source of a signal, including its location and the damage mechanism that produced it.
Plate waves have been observed in AE testing for well over twenty years [4]. Studies have utilised artificial AE sources, in both aluminium and composite plates, to show how the amplitude of the s0 mode reduces and the amplitude of the a0 mode increases as the source orientation changes from 0° to 30°, 60° and 90°, with respect to the plane of the plate [5,6]. Further studies have investigated in-plane matrix cracking sources in tensile coupon tests showing a corresponding large s0 mode amplitude for real in-plane damage sources [7,8]. Other authors have utilized the ratio of the wave mode amplitudes to provide a measure of the source orientation in both composite materials and steel structures [9,10,11] and in particular Carter [12] who proposed the calculation of the measured amplitude ratio (MAR) using Equation 1.

\[
MAR = \left( \frac{Amplitude\ S_0}{Amplitude\ A_0} \right) \times 100
\]  

In the context of composite materials it is expected that in-plane sources such as matrix cracking, fiber matrix debonding and fiber breakage will result in signals with larger s0 mode amplitudes and out-of-plane sources such as delamination will result in signals with larger a0 mode amplitudes (Figure 2). It is generally considered that signals with an MAR value less than 100 result from out-of-plane sources and those with MAR values above 100 result from in-plane sources. However, it is likely that a grey area or band exists above and below which the source orientation can be confidently predicted, but within which source orientation is less certain. The definition of such a band would require extensive testing to ensure accurate specification of its limits, however, this effect should still be considered when interpreting results.

Figure 1 Principle Lamb wave modes a) symmetric and b) asymmetric

Figure 2 Example of MAR for in-plane and out-of-plane sources
3. Experimental Set Up

A series of carbon fibre composite tensile specimens were cut from two plates manufactured from Hexcel IM7/8552 unidirectional prepreg tape using a water cooled diamond tipped cutting wheel. Three specimens were cut from the first plate which consisted of 2 plies oriented at 0° on the outsides and a thick block of 8 plies oriented at 90° in the centre ((0₂,90₄₈)). A further three specimens were cut from the second plate in which the thick 90° block was replaced with 8 plies of unidirectional prepreg tape oriented at 60° ((0₂,60₄₈)). The plates were cured in an autoclave using the manufacturer’s recommended curing cycle. After the cure both panels had an average thickness of 1.52 mm corresponding to an average ply thickness of 0.127 mm. Glass/epoxy end tabs were bonded onto the specimens using Hexcel Redux® 810 epoxy adhesive. The specimen edges were then ground and polished to a 2500 Grit finish ensuring damage does not initiate from imperfections on the edges caused by the cutting process of the specimen. The final specimen dimensions are shown in Figure 3.

The specimen end tabs were held in self tightening wedge style grips and quasi-statically loaded under tension in a 600kN Avery-Denison universal test machine at a rate of 0.01 mm.s⁻¹.

The specimens were instrumented with a single Physical Acoustics Corp. WD AE sensor, mounted at the centre of the specimen using electrical tape and brown grease as an acoustic couplant. The correct mounting of the sensors was assessed using a Hsu-Neilson artificial source [13,14]. The specimens were continuously monitored, throughout loading, using a PAC PCI-2 acquisition system and all waveforms were sampled at 2 MHz for 600 μs and stored for consideration post test. Following testing the sampled waveforms for each specimen were manually assessed, to find the peak amplitude of the two principle plate wave modes and therefore the MAR. Testing was stopped when the first few significant AE signals (~100 dB) were recorded, indicating matrix failure in the central ply block.

To validate the AE findings micro-focus X-ray images of the specimens were taken at BAE Systems’ Advanced Technology Centre (ATC) Sowerby laboratories. The specimens were soaked in X-ray dye-penetrant for at least 24 hours at room temperature to enhance the contrast on the X-ray images. The X-ray dye-penetrant is a mixture of Zinc Iodide (250 g), distilled water (80 ml), Isopropyl alcohol (80 ml) and Kodak Photoflo™ (1 ml).

![Figure 3 Tensile specimen a) dimensions b) during testing](image-url)
4. Results and Discussion

Results are presented for two out of the six specimens tested, specimen 1 with a \([0_2, 90_4]\), layup and specimen 2 with a \([0_2, 60_4]\). Because the specimen loading was stopped at the onset of damage, it is assumed that signals received in the earlier stages of the tests are noise from the grips bedding in, which will apply increasing pressure as the tensile load increases. Due to their self-tightening nature AE sources from the grips are likely to be perpendicular to the plane of the plate (out-of-plane). Only towards the end of the test will in-plane matrix damage begin to appear, although it should be noted that grip noise may still be present throughout the test.

Figure 4 presents the AE signal amplitudes versus time (black diamonds) overlaid with the tensile load applied to the specimen (grey line) for specimen 1. It can be seen that as the applied load increases the amplitude of the recorded AE signals increases until a large 100dB signal was recorded accompanied by a small drop in load. This was deemed to be the beginning of failure in the central ply block and loading was stopped. Figure 5 shows the micro-focus X-ray images of specimen 1, where a single full width matrix crack is identified which corresponds excellently to the single AE signal recorded with a 100dB amplitude. This demonstrates that the onset of damage in the specimens with a \([0_2, 90_4]\), layup was effectively detected using acoustic emission.

![Figure 4](image1.png)

**Figure 4** AE signal amplitude (black diamonds) and tensile load (grey line) versus time for specimen 1

![Figure 5](image2.png)

**Figure 5** Micro-focus X-ray image of specimen 1
During the loading of specimen 1 13 AE hits and their corresponding waveforms were recorded, out of these signals 9 of the waveforms had recognisable plate wave modes. There are two main reasons that the wave modes may not be recognisable in the recorded waveforms. Firstly, the small dimensions of the specimen, means that signal reflections from the specimen boundaries will occur and can therefore cause interfere with the signal on a direct path to the sensor resulting in a complex waveform where the two modes cannot be clearly identified. Secondly, a small amount of signal propagation distance is required before the plate wave propagation modes develop; hence any signals originating from underneath or close to the sensor may not have identifiable plate wave modes. Figure 6 presents the MAR values for the 9 signals with recognizable wave modes versus applied load. It can be seen that there is a general trend for signals with higher MAR values to appear at the end of the test. There are five signals recorded at various loads throughout the test that all have MAR values well below 100, suggesting they are from out-of-plane sources, concurrent with the increasing compression of the end tabs within the grips. As the load approaches failure (~10.5kN) three signals with MAR values approximately between 150 and 300 are observed indicating the presence of in-plane matrix damage. At ~6.5kN a single signal with an MAR value of ~175 is present this is not considered to be from matrix damage because the load is far below that at which it is anticipated damage onset will begin. It is assumed that the signal was produced by grip noise and it maybe the case that this signal sits within the band of uncertainty discussed above, where a definitive source orientation cannot confidently be assigned.

It is clear from Figures 4 and 5 that there is only one large full width matrix crack and one corresponding large AE signal, however there are several signals with higher MAR values. Although only one crack is visible in the micro-focus X-ray there is likely to be smaller micro-damage present that cannot be detected using his approach or indeed the micro-damage may have been the initiation point for the full width matrix crack observed.

![Figure 6 Measured amplitude ratio versus load for specimen 1](image)

Figure 7 shows the AE signal amplitudes versus time (black diamonds) overlaid with the tensile load applied to the specimen (grey line) for specimen 2. It can be seen that at approximately 550 seconds there is a drop in load which corresponds to the specimen slipping within the grips. There is a corresponding increase in recorded AE signals at this time, one of which has an amplitude of 100dB. This was discounted as the onset of damage because the specimen was observed to slip within the grips and the load was below that expected at the onset of damage. The signal amplitudes stayed
below ~75dB until a 100dB signal was observed accompanied by a small drop in load at approximately 15kN. This was deemed to be the beginning of failure in the central ply block and loading was stopped. Figure 8 shows the micro-focus X-ray images of specimen 2, where a single full width matrix crack is identified and indicated by the arrow, the features observed on the far right of the image are from fine metallic wire used to aid the focusing process. This again corresponds excellently to the single AE signal recorded with a 100dB amplitude observed at ~15kN. This demonstrates that the onset of damage in the specimens with a \([0_2, 60_4]\_s\) layup was effectively detected using acoustic emission.

![Figure 7](image1.png)

**Figure 7** AE signal amplitude (black diamonds) and tensile load (grey line) versus time for specimen 2

![Figure 8](image2.png)

**Figure 8** Micro-focus X-ray image of specimen 2

During the loading of specimen 2 270 AE hits and there corresponding waveforms were recorded, out of these signals 190 of the waveforms had recognisable plate wave modes. Figure 9 presents the MAR values for the 190 signals with recognizable wave modes versus applied load. In the earlier stages of the test, up to ~10kN, the MAR of signals is generally observed to be low with values below ~150 with only two signals having slightly higher values up to ~200. This again corresponds well to the increasing pressure on the end tabs from the self-tightening grips generating out-of-plane AE sources. Between 10 and 12 kN is where the grips were observed to slip, resulting in a large amount of recorded signals, the majority of which have low MAR values, mostly less than 100 with a small number up to ~175. Within this load range there are also some signals with higher MAR values (~225-450). Due to the load being below that expected for damage onset and the observation of grip movement it is concluded that these signals resulted from in-plane sources generated during the grip
movement. Above 13kN as the load approaches the onset of damage at ~15kN the majority of signals have higher MAR values, generally above 200, and without the presence of grip movement these signals can be attributed to development of in-plane matrix damage within the specimen. As with specimen 1 there are more signals with higher MAR values than identified cracks, however, it is likely that these are from undetected micro-damage or from micro-damage that initiated the full width matrix crack identified.

![Figure 9 Measured amplitude ratio versus load for specimen 2](image)

It has been shown that AE can be successfully used to detect damage onset in composite materials and analysis methodologies such as the measured amplitude ratio can be used to characterise source orientation and damage mechanisms. If such functionality can be combined in a SHM system with advanced source location techniques then accurate location and characterization of damage within composite structures would be possible. Such a system could provide reliable in service assessment of the structural integrity of safety critical structures.

5. Conclusions
A series of tensile tests were conducted in which AE was successfully used to detect the onset of matrix damage. Micro-focus X-ray imaging was used to validate the results and a strong correlation between the number of high amplitude AE signals and the number of identified full width matrix cracks was observed.

The MAR of recorded signals was investigated and a trend for signals with higher values of MAR, indicating in-plane matrix damage, to be present at higher loads towards the onset of damage was observed. Signals with MAR values below ~150-200 were considered to be from out-of-plane sources and signals with MAR values greater than ~200 were considered to be from in-plane matrix sources.

The results successfully demonstrated the potential of AE to detect the onset of damage and to characterise damage mechanisms in laminated composite materials. This functionality is a highly desirable feature in SHM systems for large-scale composite structures and components.
References

[1] Lindahl D and Knuuttila M 1999 Acoustic Emission Monitoring of the JAS39 Gripen Combat Aircraft Conference of USAF Aircraft Structural Integrity Program, 30 Nov – 2nd Dec

[2] Rowlands C, Butler L and Preston M 2004 Acoustic Emission testing Technique to Assist the Formula One Designer in Structural Design 26th European Conference on Acoustic Emission Testing, Berlin, 15-17th September 411-426

[3] ASTM-E2191-02, E2191-02 2002 Standard Test Method for Examination of Gas-Filled Fillament-Wound Composite Pressure Vessels Using Acoustic Emission American Society for Testing Materials

[4] Pollock A A 1986 Classical Plate Theory Practical AE Testing Progress in Acoustic Emission III, Proceedings of the Eighth International Acoustic Emission Symposium, The Japanese Society for Nondestructive Testing 708-721.

[5] Prosser W H 1991 The propagation Characteristics of the Plate Modes of Acoustic Emission Waves in Thin Aluminium Plates and Thin Graphite/Epoxy Composite Plates and Tube John Hopkins University

[6] Gorman M R and Prosser W H 1991 AE source orientation by plate wave analysis Journal of Acoustic Emission 9 283-288.

[7] Gorman M R and Ziola S M 1990 Plate waves produced by transverse matrix cracking Ultrasonics 29 245-251.

[8] Prosser W H 1996 Advanced AE Techniques in Composite Materials Research Journal of Acoustic Emission 14 1-11.

[9] Surgeon M and Wevers M 1999 Modal analysis of acoustic emission signals from CFRP laminates NDT & E International 32 311-322.

[10] Pullin R, Holford KM and Baxter M G 2005 Modal acoustic emission signals from artifical and fatigue crack sources in aerospace grade steel Key Engineering Materials 293 217-224.

[11] Eaton M J 2007 Acoustic Emission Monitoring of Buckling and failure in carbon fibre composite structures Cardiff University

[12] Carter D 2000 Acoustic emission techniques for structural integrity monitoring of steel bridges Cardiff University

[13] Hsu N N and Breckenbridge F R 1979 Characterisation and Calibration of Acoustic Emission Sensors Material Evaluation 39 60-68

[14] ASTM 1994 Standard Guide for Determining the Reproducibility of Acoustic Emission Sensor Response American Society of Testing and Materials E976