DAMAGE DETECTION AND MONITORING IN COMPOSITES USING PIEZOELECTRIC SENSORS

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Keywords: acoustic emission, clustering, composite materials, damage detection, damage monitoring, guided waves, pattern recognition, piezoelectric sensors

Abstract
The use of piezoelectric transducers for structural health monitoring (SHM) of composites is increasing due to their relatively low cost, small size, durability, and low power consumption. There is a wealth of research supporting their use for passive and active SHM, yet few studies combine the two.

In this work, a composite cylinder is subjected to multiple cycles of mechanical loading/unloading in a three point bending configuration. The specimen is instrumented with eight piezoelectric wafer active sensors (PWAS), used as passive receivers of acoustic emission (AE) signals during loading. Active monitoring of the specimen is performed using the same piezoelectric sensors, successively, as transmitters and receivers of guided waves, in a pitch-catch configuration. The axisymmetric L(0,2) mode at 250 kHz is shown to be attractive for long distance propagation between axially aligned sensors.

1. Introduction

Composite materials have become more and more attractive for use in structural applications over recent years, but assessment of damage remains a challenge due to their structural complexity. Periodic non-destructive inspections (NDI) of components can give an insight into their performance but the complexity of these techniques often results in significant down-time and increased labour costs. The cost of inspection in aerospace composites, for example, can represent up to a third of the lifecycle costs [1]. Since composite materials allow for the integration of sensors, with negligible effect on their mechanical properties, permanent structural health monitoring (SHM) systems have sparked a great deal of interest. Active SHM techniques use small sensors to interact directly with the structure, while passive techniques use sensors for monitoring over long periods of time [2].

In this work, a network of piezoelectric wafer active sensors (PWAS) is bonded to the surface of a composite pipe. The pipe is subjected to a 5 J impact followed by multiple cycles of mechanical loading and unloading in a three point bending configuration. Acoustic emissions are monitored from eight PWAS during each loading cycles to detect the initiation of damage and monitor its progress as the maximum load is increased. Between each loading of the specimen, rings of PWAS are used as transmitters and receivers of ultrasonic guided waves.

1.1. Acoustic emission

Acoustic emission (AE) is a passive SHM technique which uses piezoelectric sensors as receivers of waves propagating through the host structure to which they are bonded or integrated. The formation and growth of defects in a material causes the release of energy from the defect tip in the form of elastic waves, which can be recorded by the sensors. A network of sensors can be used to estimate the severity and location of the crack. The use of AE for early damage monitoring is well established [3] and four main damage mechanisms have been identified [4,5]: (i) matrix cracking, (ii) interfacial debonding, (iii) fibre pull-out, and (iv) fibre breakage. Researchers have often used amplitude and frequency distribution analysis [5–12] to identify different damage modes. A summary of analysis by many researchers is given in the authors' previous work [13,14]. Much of the research reported is based on 2D and 3D composite laminates rather than cylindrical structures. A small number of investigations are reported for AE monitoring of glass fibre tubular composites [15–17] and composite pressure vessels [18].

Data mining methods are generally used for analysis of acoustic emission data due to the sheer volume of data points. They can be supervised, unsupervised, or partially supervised, depending on the amount of prior information available for classification of data points. Unsupervised clustering algorithms do not require the input of prior knowledge, making them adaptable for use with acoustic emission data, which can be affected by many factors relating to the specimen, loading condition, sensors and electromechanical noise in the environment. Traditional clustering algorithms tend to be reliant on a single set of parameters, or features, to separate AE data sets into clusters [19–22]. Criteria optimised in standard algorithms, such as K-means, Fuzzy C-means, Gaussian mixture models, self-organising maps, and Gustafson-Kessel, do not take into account the time or space element associated with data points which originate from acoustic emission.

1.2. Guided waves

Guided waves can propagate over long distances without significant loss of energy, which makes them well suited for the inspection of large structures such as bridges, aircraft, ships, missiles, pressure vessels, pipelines, etc. It is necessary to understand the characteristics and modes of wave propagation through the material and the interaction of these waves with defects and damage in the structure. In solid hollow cylinders, three primary wave modes can propagate: (i) longitudinal modes which propagate along the axial direction by compressional motion, (ii) torsional modes which propagate along the axial direction by shear motion parallel to the circumferential direction, and (iii) flexural modes which propagates along the axis by flexural motion in the radial direction. The longitudinal and torsional modes in a cylinder are axisymmetric and can be considered as equivalent to Lamb waves and SH waves in plate structures, respectively [23–25]. The flexural mode is non-axisymmetric and is considered the true specific mode for cylindrical structures [2].

2. Experimental set-up

2.1. Materials

The composite pipe used in this work was supplied by Easy Composites Ltd. It comprises a hybrid of unidirectional pre-preg carbon fibres (Toray T700) oriented in the axial direction (0°) and unidirectional pre-preg E-glass fibres oriented in the circumferential direction (90°). The lay-up order of fibres is [0, 90, 0, 90, 0]. The geometry and mechanical properties from the manufacturer are given in Table 1.

Table 1. Geometry and mechanical properties of composite cylinder.

Internal diameter (ID, mm)	Wall thickness (mm)	Density, ρ (kg/m3)	Young's modulus, E (GPa)	Shear modulus, G (GPa)	Poisson's ratio, ν
60.3	1.6	1600	E_1 = 90, E_2 = 19, E_3 = 19	G_{12} = 4.6, G_{23} = 4.6, G_{13} = 4.6	ν_{12} = 0.14, ν_{23} = 0.2, ν_{13} = 0.2

2.2. Low velocity impact

The experimental set-up for impacting the tube is inspired by ASTM Standard G14-04 [26].The tube is held to a V-shaped support measuring 400 mm in length by elasticated straps to prevent vibration when impacted. The tube was impacted with an un-instrumented hemispherical striker with a mass of 510.61 g. The starting height of the projectile was set to 1 metre to achieve a 5 J impact energy.

2.3. Three point bending

Quasi-static three point bending was carried out on the tube using an adaptation of ASTM standard D790 on an Instron testing machine fitted with a 50 kN load cell (Figure 1). The sample was loaded at 1 mm/min crosshead speed. The maximum displacement of the crosshead was increased incrementally in successive cycles in order to encourage the progression of damage through multiple loadings. The distance between the supports measures 750 mm from mid-point to mid-point. The maximum load applied to the sample during each loading cycle was increased incrementally as in Table 2.

Table 2. Load/extension data for each loading cycle.

Cycle	Maximum applied load (N)	Extension at maximum load (mm)
1	2000	4.96
2	4000	7.65
3	6000	10.27
4	8000	13.18
5 (Failure)	9115	15.74

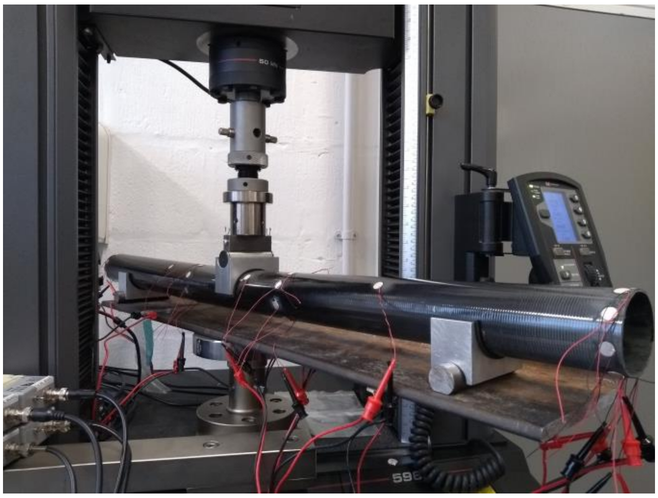

Figure 1. Mechanical three point bending set-up.

2.4. Damage monitoring

Piezoelectric wafer active sensors (PWAS) – PIC255 with 10 mm diameter and 0.5 mm thickness – were used for AE and guided waves [27]. AE data was recorded with a 10 MHz sampling rate and 20 dB of pre-amplification per sensor. An adaptation of the clustering algorithm used in the author's previous work [28] was applied to the concatenated data set. The number of clusters was optimised through assessment of the kinetics and evolution of the clusters over time.

Figure 2 shows the sensor arrangement for guided waves; data was collected in pitch-catch between rings of sensors. The generated signal was a three cycle tone burst (sinusoidal with a Hanning window); this was transmitted with a 12 Vpp amplitude amplified x10. A series of response signals were obtained by varying the frequency of the excitation signal from 200 kHz to 300 kHz in steps of 10 kHz. For each signal, the time of flight of the first peak was used to calculate the group velocity of the first wave packet. The tuning curves obtained between rings 2 and 3 is shown in Figure 3. The lay-up order of fibres clearly has an influence on the velocity and attenuation of the L(0,2) mode as it travels from one end of the tube to the other. Based on the tuning curves obtained, the remainder of experiments focused on a narrower range of excitation frequency: 230-270 kHz.

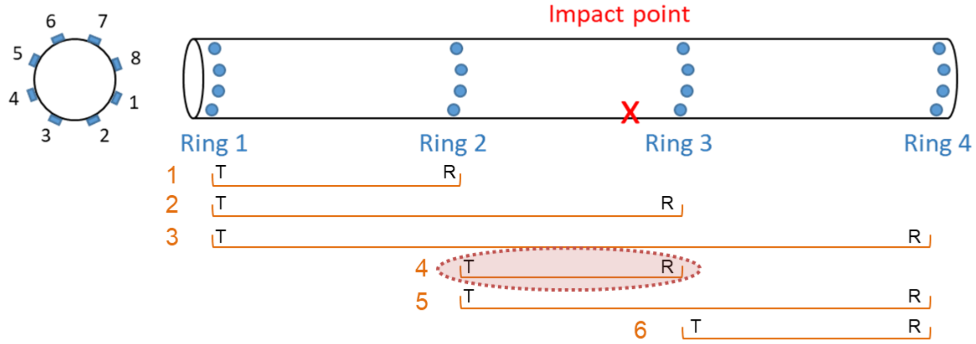

Figure 2. Position of piezoelectric sensors used to transmit and receive ultrasonic guided waves. PWAS are divided into four rings of eight sensors, numbered as above.

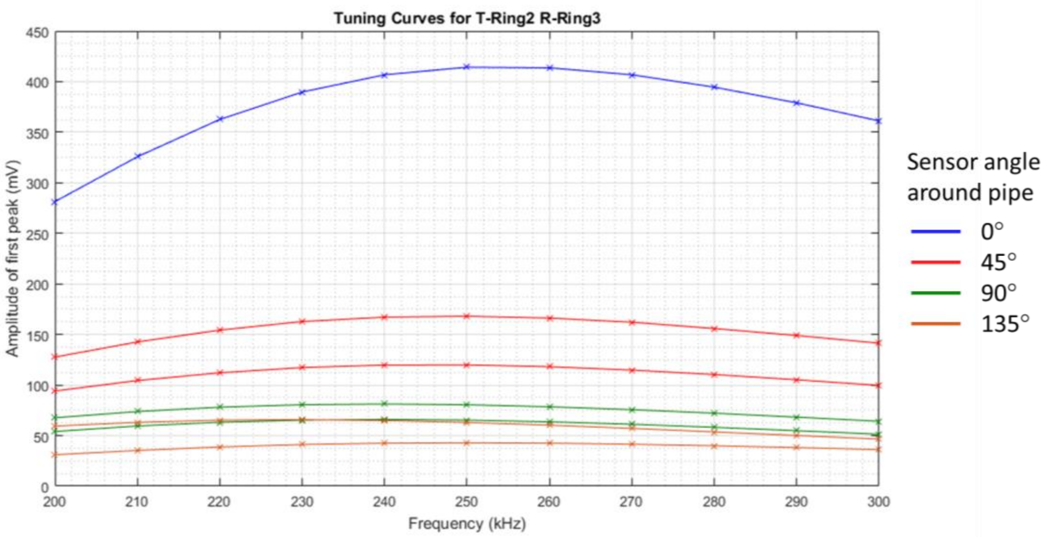

Figure 3. Tuning curves between sensor rings 2 and 3 (configuration 4).

3. Results and discussion

3.1. Acoustic emission monitoring

The maximum amplitude of each acoustic emission signal, is commonly used to identify the damage mechanisms in a composite material. Figure 4 shows the maximum amplitude of recorded hits above the threshold of 55 dB, detected during each loading cycle. It is noted here that in general, further AE hits are not recorded until the previous maximum load (denoted here by time due to the constant test speed) is exceeded. This is a feature observed in composites known as the Felicity effect [29], which can be used to distinguish between the formation of new damage and growth of existing defects in a structure. A plot of the maximum amplitude vs. duration of each signal reveals that many of the high amplitude, long duration signals are received during the final loading cycle. These signals are believed to correspond to delaminations.

The final clustering result obtained when the data from the 5 cycles of loading is concatenated in time is shown in Figure 5. As indicated in the figure, we have attempted to speculate on the types of signals which may be included in each cluster of this final result. It is probable that the first and second clusters are not directly damage related, since we do not expect to find damage at low loadings of the specimen. Similarly, it is probable that the fifth cluster is related to the final failure of the specimen; this is futher supported by the fact that signals in this cluster exhibit long durations (factor of 10 magnitude compared with the other clusters). This leaves the third and fourth clusters, which we believe correspond to the initiation and growth of damage during loading. It is not possible to say with certainty whether the signals indicate any specific damage modes; it is more likely that they comprise signals from a combination of modes, as the damage progressed through-the-thickness of the tube.

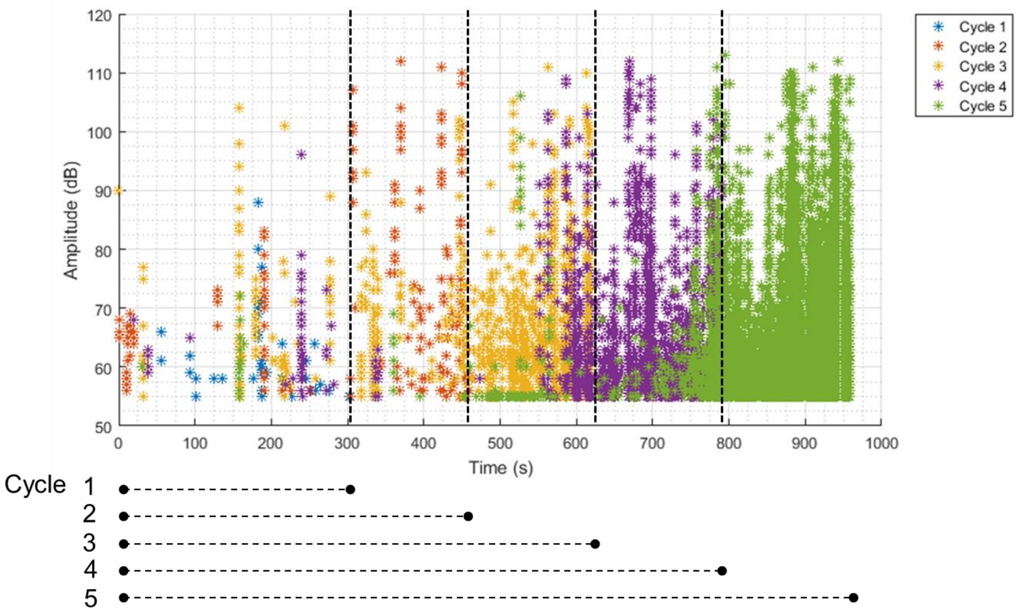

Figure 4. Maximum amplitude of AE hits received by all sensors during each loading cycle.

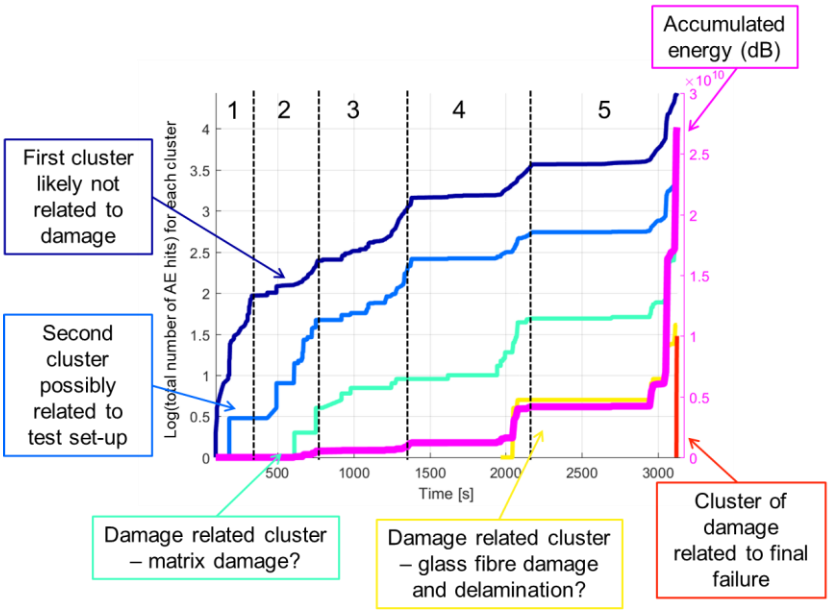

Figure 5. Cumulated AE hits divided into 5 clusters, over the 5 cycles of loading.

3.2. Guided waves

Figure 6 shows the position of three Transmitter-Receiver pairs used. Figure 7 shows a comparison of the tuning curves obtained when the structure was in a pristine condition (baseline signal) with signals taken after the 5 J impact to the pipe. Based on the amplitude reduction of the signals, a damage index is proposed:

$$\text{Damage Index, } DI = \frac{A_0 - A_1}{A_0}$$

Where A_0 and A_1 are the amplitude of the first peak in the pristine condition and test condition, respectively. The damage indices shows clearly that the presence of impact damage causes a higher attenuation of signals for whom the impact location is on the direct path.

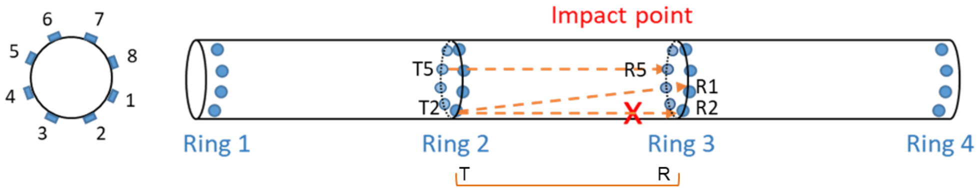

Figure 6. Position of sensors referred to in the discussion.

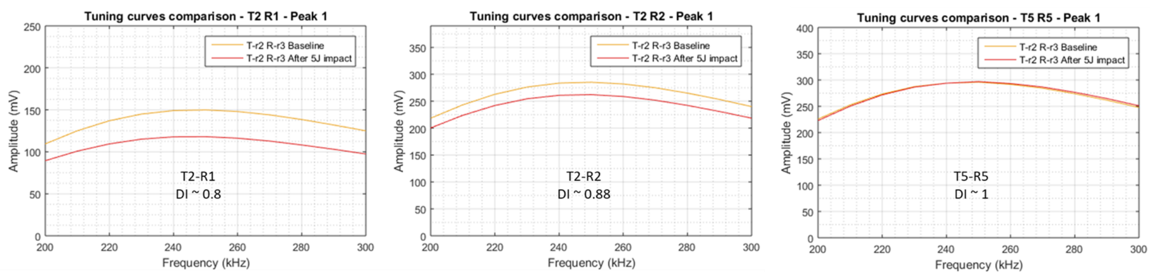

Figure 7. Tuning curves before and after 5J impact and calculated damage indices for sensor paths T2-R1, T2-R2, and T5-R5 in configuration 4: T-Ring2 R-Ring3.

4. Concluding remarks

The use of piezoelectric sensors for damage monitoring in composite materials can be particularly beneficial if the same sensor network can be utilised in multiple ways. The use of acoustic emission monitoring during loading has demonstrated the potential to distinguish between different damage modes. In particular, we can separate signals arising from damage events. Further work will involve exploration of criteria that can be used to influence the results of the clustering algorithm, such as through cross-correlation with AE-based location data, or correlation with the results of guided wave experiments.

On-demand assessment by the transmission of ultrasonic guided waves between sensors can be used to provide information about damage events such as by impact. Further work will entail assessment of ultrasonic guided wave signals from the remainder of the configurations mentioned, both for impact damage and between loading cycles. Wavelets based analysis in the time-frequency domain will also allow the analysis of AE data recorded during the impact event and during three point bending, in order to determine whether specific wave modes can be directly related to the damage mechanisms observed.

Acknowledgments

The authors acknowledge the funding and technical support from BP through the BP International Centre for Advanced Materials (BP-ICAM) and financial support from EPSRC (EP/L01680X) through the Materials for Demanding Environments Centre for Doctoral Training which made this research possible. The authors also acknowledge Laboratoire d'Excellence ACTION (contract ANR-11-LABX-0001-01) and FEMTO-ST Institute for both funding and technical input to support the collaboration.

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