Damage detection and monitoring in composite pipes using piezoelectric sensors

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Abstract

Composite materials have become more and more attractive for use in structural applications over recent years, but assessment of damage remains a challenge since this is barely visible, especially when subjected to relatively low energy impact events. The use of piezoelectric transducers for structural health monitoring (SHM) of composites is increasing due to their ability to be embedded without disturbing the structure, 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 multi-layered carbon fibre/epoxy composite pipe 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 signals during loading. It is possible to track the location of damage as the test progresses, by triangulation of AE signals. Active monitoring of the specimen is performed using piezoelectric sensors successively as transmitters and receivers of guided waves, in a pitch-catch configuration. Signals are recorded between successive loadings of the specimen to assess the state of damage at each stage, and compare against the ‘pristine’ condition. Cross-comparison of tuning curves obtained from the pristine condition and test data show attenuation in amplitude of the L(0,2) mode. A damage index is proposed based on this amplitude reduction.

1. Introduction

Fibre reinforced composite materials have become the preferred material choice in a variety of structural applications. They are stronger, corrosion resistant and lightweight compared to traditional metals and metallic alloys and have become competitive in cost in recent years. However, widespread composite implementation still remains a challenge, since there is limited test data available to support their long term durability, particularly with respect to damage tolerance and failure predictions. 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]. Where non-destructive evaluation (NDE) and SHM techniques are used together, it becomes possible to carry out “focused” non-destructive inspections, saving both time and money.

1.1 Ultrasonic guided waves

Ultrasonic guided wave based SHM is one of the most prominent options for inspection and monitoring of composite materials. 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 [3–5]. The flexural mode is non-axisymmetric and is considered the true specific mode for cylindrical structures [2]. 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 important to study the propagation of waves for the purpose of acoustic emission in tubular composites to be able to understand the difficulties when analysing waves for quantification of structural damage and defects.

1.2 Acoustic emission in composites

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 [6] and four main damage mechanisms have been identified [7,8]: (i) matrix cracking, (ii) interfacial debonding, (iii) fibre pull-out, and (iv) fibre breakage. Researchers have often used amplitude and frequency distribution analysis [8–15] to identify different damage modes. Analysis of the signal geometry is also not uncommon: A-type signals (slow increase times around 10-20 µs) are associated with matrix cracking, B-type (sharp rising, lasting for around 10 µs and abruptly decreasing) associated with fibre/matrix debonding, C-type signals associated with fibre breakage, and D-type (long rising times, high amplitudes, and long duration) are associated with delamination [8]. A summary of analysis by many researchers is given in the authors’ previous work [16,17]. 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 [18–20] and composite pressure vessels [21], however the specific AE waveform data has not always been made available.
2. Experimental work

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 I.

Table I. Geometry and mechanical properties of the composite cylinder.

<table>
<thead>
<tr>
<th>Internal diameter (ID, mm)</th>
<th>Wall thickness (mm)</th>
<th>Density, ρ (kg/m³)</th>
<th>Young’s modulus, E (GPa)</th>
<th>Shear modulus, G (GPa)</th>
<th>Poisson’s ratio, ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>60.3</td>
<td>1.6</td>
<td>1600</td>
<td>E₁ = 90</td>
<td>G₁₂ = 4.6</td>
<td>ν₁₂ = 0.14</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E₂ = 19</td>
<td>G₂₃ = 4.6</td>
<td>ν₂₃ = 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>E₃ = 19</td>
<td>G₁₃ = 4.6</td>
<td>ν₁₃ = 0.2</td>
</tr>
</tbody>
</table>

2.2 Low velocity impact

The experimental set-up for impacting the tube is inspired by ASTM Standard G14-04 [22]. 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 uninstrumented 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: ‘Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials’, on an Instron 5969 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, as shown in Figure 2. The maximum load applied to the sample during each loading cycle was increased incrementally; the maximum load and maximum extension are recorded in Table II.

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

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Maximum applied load (N)</th>
<th>Extension at maximum load (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2000</td>
<td>4.96</td>
</tr>
<tr>
<td>2</td>
<td>4000</td>
<td>7.65</td>
</tr>
<tr>
<td>3</td>
<td>6000</td>
<td>10.27</td>
</tr>
<tr>
<td>4</td>
<td>8000</td>
<td>13.18</td>
</tr>
<tr>
<td>5 (Failure)</td>
<td>9115</td>
<td>15.74</td>
</tr>
</tbody>
</table>
2.4 Damage monitoring during loading

For AE monitoring, piezoelectric wafer active sensors (PWAS) – PIC255 with 10 mm diameter and 0.5 mm thickness – are used [23]. AE data was recorded by the software ‘AEWin’ from Mistras with a sampling rate of 10 MHz and 20 dB of pre-amplification per sensor. Guided wave experiments were completed using the piezoelectric sensors arranged as shown in Figure 3. All data was collected in a pitch-catch configuration, between rings of sensors as in Table III. A National Instruments PXI platform equipped with a function generator and oscilloscope was used to generate a three cycle tone burst signal of 60 V (6 V amplified x10) to excite a single transmitter. The received signal was recorded with a sampling rate of 10 MHz and as an average of 500 successive scans to increase the signal to noise ratio. 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.
Figure 3. Position of piezoelectric sensors used to transmit and receive ultrasonic guided waves. PWAS are divided into four rings of eight sensors, numbered as above.

Table III. Configurations of PWAS as transmitters and receivers of guided waves.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Ring of transmitter-PWAS</th>
<th>Ring of receiver-PWAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

The tuning curves obtained for configuration 4 (in the pristine condition) are shown in Figure 4. 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 4. Tuning curves for configuration 4 in the pristine condition.
3. Results and discussion

3.1 Ultrasonic guided waves

For each transmitter-receiver pair, dispersion curves and tuning curves were obtained to determine which modes were present at each excitation frequency. Figure 10 shows the position of three Transmitter-Receiver pairs used. Figure 11 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 show clearly that the presence of impact damage causes a higher attenuation of signals for whom the impact location is on the direct path.

![Figure 5. Position of sensors referred to in the discussion.](image)

Figure 6. 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.

3.2 Acoustic emission monitoring

The maximum amplitude of each acoustic emission signal, is commonly used to identify the damage mechanisms in a composite material. Figure 7 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 [24], which can be used to distinguish between the formation of new damage and growth of existing defects in a structure.
Figure 7. Maximum amplitude of AE hits received by all sensors during each cycle.

Figure 8 shows the accumulated AE hits received and the maximum amplitude of each of these signals during loading cycle 5, which led to failure of the specimen. Apart from a few signals received halfway through the test, there is a clear correlation between the increase in AE hit rate and the amplitude of those signals in the later stages of the test. A plot of the maximum amplitude vs. duration of each signal, shown in Figure 9, 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.

Figure 8. Accumulated AE hits and maximum amplitude of hits vs. time for cycle 5.
Figure 9. Maximum amplitude vs. duration of AE hits received by all sensors during each loading cycle.

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 ability to distinguish between different types of damage arising in composites, while 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.

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