STRUCTURAL INTEGRITY EVALUATION OF CNG COMPOSITE CYLINDERS BY ACOUSTIC EMISSION MONITORING

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Abstract

In recent years, compressed natural gas (CNG) has become an attractive alternative as a fuel for vehicles, such as public buses. The use of fibre-reinforced polymers in the design of CNG cylinders has led to attractive lightweight solutions. Nevertheless, the traditional inspection techniques used for steel cylinders are generally not well adapted to the composite materials. In order to ensure the safety of the users, new inspection techniques have been investigated to give an accurate evaluation of the structural integrity of composite cylinders.

The present work investigates the ability of the acoustic emission (AE) technique to detect serious damages in CNG composite cylinders. Internal pressure tests with AE monitoring were performed on CNG Type-3 cylinders (per ISO 11439 and ECE R110), made of an aluminium-liner reinforced with a carbon-fibre composite. The experiments were conducted on cylinders submitted to drop tests from different heights, cylinders submitted to ballistic impact at different energies and cylinders with longitudinal and transverse notches with different depth. Results of the AE as a function of the damage type and severity are discussed.

Introduction

Over the past decades, the increasing use of compressed natural gas (CNG) as an alternative fuel for vehicles has led to the design of attractive lightweight cylinders by the use of fibre-reinforced polymers. For the safety of the users, structural integrity of such composite cylinders must be accurately checked. Nevertheless, the actual inspection techniques, derived from the techniques used for steel cylinders, may not be well adapted to the composite materials.

For several years now, acoustic emission (AE) technique has been successfully applied for composite materials. Various studies performed on composite coupons with a polymer matrix have shown that the AE amplitude distribution can be used to clearly identify the main damage mechanisms [1, 2]. The development of this non-destructive testing method has also led to successful industrial applications for periodic inspection of glass-fibre reinforced plastic storage tanks (ASTM E1067) and of composite bucket trucks, used for inspecting the high-voltage transmission lines (ASTM F914) [3].

Furthermore, recent works have shown the potential of AE technique for inspection of composite pipes and pressure vessels [4-7]. The AE technique presents a great potential for the inspection of CNG composite cylinders, as it should not require the removal of the cylinders from the vehicles. This technique could be used as an on-board inspection method and structural integrity of the composite part could be checked by AE monitoring during the filling of the cylinder to its service pressure, for example.

In the present work, the AE technique has been used during a hydraulic pressure test in order to check CNG composite cylinders with typical critical defects:

- Damages from low velocity impact (drop test),
- Damages from ballistic impact (high velocity),
- Longitudinal and transverse notches inside the composite overwrap.
Experimental

Specimens: This study concerning AE analysis of fully wrapped aluminium liners was performed on Dynecell® composite cylinders, manufactured by Dynetek (cf. Fig. 1).

- ECE approval n°: E1 110R-000039
- Working pressure: 200 bar @ 15°C
- Nominal internal volume: 76 liter
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- Working pressure: 200 bar @ 15°C
- Nominal internal volume: 76 liter
- Nominal dimension: 402 x 864 mm
- Nominal weight: 28 kg

Fig. 1. Characteristics of the tested composites cylinders, Dynecell®.

Ten cylinders (1 reference specimen with no defect + 3 specimens submitted to drop test + 3 specimens submitted to ballistic impact + 3 specimens with notches) were tested. Three cylinders, each completely filled with water, were dropped once at a 45° angle onto a concrete surface, impacting one of the dome end. These three cylinders, referenced J3386, J3416 and J2105, were respectively dropped from a height of 0.472 m, 0.944 m and 1.888 m (corresponding approximately to impact energies of 500 J, 1000 J and 2000 J).

Ballistic tests were performed on the cylindrical part of three cylinders, referenced J3462, J2041 and J2043, which were respectively impacted at an energy level of 137 J (velocity = 158 m/s), 280 J (velocity = 226 m/s) and 419 J (velocity = 276 m/s) with a steel projectile with a conical head and a weight of 11 g.

Two notches, one longitudinal and the other transverse, were made with a Dremel® tool on three cylinders in the central part along two planes forming an angle of approximately 120°. The two notches were made with a 1-mm-thick cutter to a length in the bottom of the notch of 50 mm (equal to approximately five times the composite thickness). The notches for the three cylinders, referenced J2112, J2144 and J3419, are respectively 1.25-mm, 2.5-mm and 5-mm deep.

Pressure test: The pressure required to perform the hydraulic test is supplied by a servo-hydraulic intensifier system. This system is able to control the rate of pressurisation accurately by means of a programmable automatic device. The equipment used for this test is depicted in Fig. 2; it includes:

- an 11-kW mono-pump producing a maximum pressure of 250 bars,
- an accumulator,
- a multiplying unit used to pressurise the specimen by quadruplicating the pressure of the pump. This transfer booster enables to transfer the pressure from oil to water, the pipes being pressurized with water,
- a servo-valve allowing the control of the applied pressure.

The loading procedure for pressure test on the composite cylinders at ambient temperature is composed of a pressure cycle described as followed:

- Pressure ramp at a pressurization rate of 1 bar/s up to $P_{\text{Test}} = 300$ bar,
- Hold period of 4 min at 300 bar,
- Unload at a depressurization rate of 1 bar/s down to atmospheric pressure.

After the pressure test with AE monitoring, the cylinders were subjected to a hydraulic fatigue test (5000 cycles between 30 and 300 bar at 5 cycles/minute and room temperature) in order to investigate the evolution of each defect and to estimate its severity.
AE equipment: The Euro Physical Acoustics (EPA) DISP® system was used to monitor the AE signals during the tests, based on two PCI-4 boards, with the following characteristics:

- 8 AE channels,
- Frequency bandwidth: 10 kHz-2 MHz,
- Minimum threshold: 18 dB,
- 8 parametric input channels.

During the pressure tests, four R15 AE sensors, supplied by EPA, (150 kHz resonant frequency, operating frequency range: 50-200 kHz) were used with 2/4/6 preamplifiers. The gain of preamplifiers was 40 dB while fixed 40-dB threshold level was applied for the tests. Silicone grease 500 was used as a couplant at the structure-to-sensor interface. Figure 3 presents the sensors location for the different pressure tests with AE monitoring.

Results and Discussion

In this work, the considered approach aims to relate basic AE parameters (the cumulative number of hits and counts) to the damage type and severity in order to investigate the structural integrity of the composite cylinders. Table 1 presents the AE activity recorded during the pressure test on the 10 cylinders. By comparison to the damaged cylinders, the cylinder without defect shows a low AE activity and could be then clearly identified by this technique.
Table 1. Results of the AE monitoring.

<table>
<thead>
<tr>
<th>Cylinder reference</th>
<th>Defect</th>
<th>AE test results</th>
</tr>
</thead>
<tbody>
<tr>
<td>J2045</td>
<td>None</td>
<td>$\Sigma$ Hits = 769, $\Sigma$ Counts = 3,666</td>
</tr>
<tr>
<td>J3386</td>
<td>Drop test, 500 J</td>
<td>$\Sigma$ Hits = 9,780, $\Sigma$ Counts = 61,690</td>
</tr>
<tr>
<td>J3416</td>
<td>Drop test, 1000 J</td>
<td>$\Sigma$ Hits = 25,688, $\Sigma$ Counts = 160,053</td>
</tr>
<tr>
<td>J2105</td>
<td>Drop test, 2000 J</td>
<td>$\Sigma$ Hits = 44,232, $\Sigma$ Counts = 366,804</td>
</tr>
<tr>
<td>J3462</td>
<td>Ballistic impact, 137 J</td>
<td>$\Sigma$ Hits = 9,784, $\Sigma$ Counts = 322,891</td>
</tr>
<tr>
<td>J2041</td>
<td>Ballistic impact, 280 J</td>
<td>$\Sigma$ Hits = 34,729, $\Sigma$ Counts = 1,184,880</td>
</tr>
<tr>
<td>J2043</td>
<td>Ballistic impact, 419 J</td>
<td>$\Sigma$ Hits = 79,719, $\Sigma$ Counts = 2,736,485</td>
</tr>
<tr>
<td>J2112</td>
<td>Flaws, 1.25 mm deep</td>
<td>$\Sigma$ Hits = 173,772, $\Sigma$ Counts = 6,668,306</td>
</tr>
<tr>
<td>J2144</td>
<td>Flaws, 2.5 mm deep</td>
<td>$\Sigma$ Hits = 141,975, $\Sigma$ Counts = 6,542,613</td>
</tr>
<tr>
<td>J3419</td>
<td>Flaws, 5 mm deep</td>
<td>$\Sigma$ Hits = 160,280, $\Sigma$ Counts = 6,423,255</td>
</tr>
</tbody>
</table>

AE activity recorded during the pressurisation of the cylinders with drop impact damages is plotted in Fig. 4. AE activity increased almost linearly with the impact energy. AE activity recorded during the hydraulic pressure tests on cylinders with ballistic impact damages is plotted in Fig. 5. As in the previous case, AE activity increased almost linearly with the impact energy.

Figure 6 shows the evolution of AE hits and counts recorded during the pressure test as a function of notch depth. As confirmed by these 2 graphs, the severity of the damage (in our case the notch depth) seems to have no influence on the AE activity. Among all the tested cylinders, the total number of hits and counts is the highest for the specimens with notches. The highest number of recorded AE hits or counts was obtained for the cylinder with 1.25-mm deep flaws.
The cylinders were finally submitted to a fatigue test (5000 cycles at 300 bar) in order to have an estimation of the defect influence on the structure integrity. Results of these tests are presented in Table 2. Most of the cylinders withstand the fatigue test without failure. The cylinder, impacted at low velocity and with an energy of 2000 J, failed approximately after 3000 cycles with a leak before break, a safety issue as required by the standards. All the ballistic impacted cylinders failed during the fatigue test and the number of cycles to failure decreases when the impact energy increases.

<table>
<thead>
<tr>
<th>Cylinder reference</th>
<th>Defect</th>
<th>Fatigue test results</th>
</tr>
</thead>
<tbody>
<tr>
<td>J2045</td>
<td>None</td>
<td>No failure after 5000 cycles</td>
</tr>
<tr>
<td>J3386</td>
<td>Drop test, 500 J</td>
<td>No failure after 5000 cycles</td>
</tr>
<tr>
<td>J3416</td>
<td>Drop test, 1000 J</td>
<td>No failure after 5000 cycles</td>
</tr>
<tr>
<td>J2105</td>
<td>Drop test, 2000 J</td>
<td>Failure after 2924 cycles</td>
</tr>
<tr>
<td>J3462</td>
<td>Ballistic impact, 137 J</td>
<td>Failure after 4376 cycles</td>
</tr>
<tr>
<td>J2041</td>
<td>Ballistic impact, 280 J</td>
<td>Failure after 3216 cycles</td>
</tr>
<tr>
<td>J2043</td>
<td>Ballistic impact, 419 J</td>
<td>Failure after 892 cycles</td>
</tr>
<tr>
<td>J2112</td>
<td>Flaws, 1.25 mm deep</td>
<td>No failure after 5000 cycles</td>
</tr>
<tr>
<td>J2144</td>
<td>Flaws, 2.5 mm deep</td>
<td>No failure after 5000 cycles</td>
</tr>
<tr>
<td>J3419</td>
<td>Flaws, 5 mm deep</td>
<td>No failure after 5000 cycles</td>
</tr>
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</table>

After the cycling test, significant delamination of a circumferential composite strip was observed on both side of the longitudinal notch for each cylinder with notch defect. Considering these results in terms of AE activity (no significant difference regarding the notch depth) and damages, observed after cycling, it seems that the delamination was the main source of AE during the pressure test with AE monitoring. The fact that delamination propagation occurred in a similar way for the three different notch depths could explain why no significant difference in AE activity was recorded and why the number of AE hits or counts could not be representative of the defect severity for the range of notch depth considered in this study. In comparison with the cylinders with notches, the AE activity due to ballistic impact damages is lower. Nevertheless, regarding the failure of these cylinders during the fatigue test, the impact ballistic defects are found to be more critical.

In this study, the results also show that the number of AE events recorded by the sensor placed close to the defects (i.e., the main source of AE signals) can be significantly higher than for the other sensors (cf. Fig. 4-6), because the signal amplitude decreases as the wave travels through the structure. Considering this significant attenuation effect for the composite materials and the fact that a critical damage might not be clearly localized before placing the sensors on the structure (which was not the case in this study for the created defects), measurements show that the number of sensors and their positions will have an influence on the recorded AE events.
Conclusions

This work shows the influence of critical defects (flaws, ballistic impact, drop test) on the AE activity of composite cylinders.

For the ballistic and drop test impact, AE activity increases almost linearly with the impact energy, and in this case, the damage severity may therefore be estimated by the number of AE hits and/or counts monitored during the AE test. For notches, the damage severity has no influence on the AE activity. It seems that delamination, induced whatever the notch depth is, is the main source of acoustic emission.

References