STRUCTURAL INTEGRITY EVALUATION OF CNG COMPOSITE CYLINDERS BY ACOUSTIC EMISSION MONITORING

OLIVIER SKAWINSKI¹, PATRICE HULOT¹, CHRISTOPHE BINÉTRUY¹ and CHRISTIAN RASCHE²

¹ Department of Polymers and Composites Technology & Mechanical Engineering, Ecole des Mines de Douai, 941 rue Charles Bourseul, B.P. 838, 59508 Douai Cedex, France; ² Dynetek Industries Ltd., 4410-46th Avenue SE, Calgary, AB, Canada T2B 3N7

Keywords: AE damage detection, composite materials, CNG cylinders

Abstract

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 fiber-reinforced polymers. 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 has 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 aluminum-liner reinforced with a carbon-fiber 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

In recent years, compressed natural gas (CNG) has become an attractive alternative as a fuel for vehicles, such as public buses. Compared to oil based fuels, the use of CNG reduces carbon dioxide and nitrogen oxides emission. Furthermore, the use of fiber-reinforced polymers in the design of CNG cylinders has led to attractive lightweight solutions. 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 (Bunsell, 2006).

For several years now, acoustic emission (AE) technique has been successfully applied for composite materials. By comparison with classical methods, such as hydraulic proof test or visual inspection, acoustic emission technique allows the detection of damages which are not visible at the surface of the material. 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 (Barré et al., 1994; Hamstad, 1982; Kotsikos et al., 1999). The development of this non-destructive testing method has also led to successful industrial applications for periodic inspection of glass-fiber reinforced plastic storage tanks (ASTM E1067) and of composite bucket trucks, used for inspecting the high-voltage transmission lines (ASTM F914) (Wevers et al., 2000).
Furthermore, recent works have shown the potential of AE technique for inspection of composite pipes and pressure vessels (Dong et al., 1998, Gebski et al., 2001, Webster, 1999, Wood et al., 2000). 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.

After the pressure test with AE monitoring, each cylinder was submitted to a fatigue test to increase their mechanical ageing, in order to estimate the severity of each defect.

**Experimental**

**Specimens:** This study concerning AE analysis of fully wrapped aluminum 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
- 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 (cf. Fig. 2). 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). After drop test, each cylinder presented two impacted areas: the first one, the main impact area, corresponds to the main impact, while the second one, the rebound impact area, occurred on the opposite dome after the rebound of the structure (cf. Fig. 4a).

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. The ballistic tests were performed by the French Defense Research Agency in Paris (DGA) with a gas gun facility, developed to fire a projectile up to 600
Fig. 2. Drop test on cylinders.

m/s. Preliminary tests were carried out in order to adapt the velocity of the projectile in order to generate a non perforating damage.

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 pressurization accurately by means of a programmable automatic device. The equipment used for this test is depicted in Fig. 3; it includes:

- an 11-kW mono-pump producing a maximum pressure of 250 bars,
- an accumulator,
- a multiplying unit used to pressurize 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 4 presents the sensors location for the different pressure tests with AE monitoring.

Before the pressure test with AE monitoring, calibration of the sensors is realized through Hsu-Nielsen test in order to simulate an acoustic event using the fracture of a brittle pencil lead. This generates an intense acoustic signal, quite similar to a natural AE source, such that the sensors detect it as a strong burst. It also allows to check whether the transducers are in good contact with the cylinder.

**Results**

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 ten 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>
<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>Σ Hits = 769, Σ Counts = 3,666</td>
</tr>
<tr>
<td>J3386</td>
<td>Drop test, 500 J</td>
<td>Σ Hits = 9,780, Σ Counts = 61,690</td>
</tr>
<tr>
<td>J3416</td>
<td>Drop test, 1000 J</td>
<td>Σ Hits = 25,688, Σ Counts = 160,053</td>
</tr>
<tr>
<td>J2105</td>
<td>Drop test, 2000 J</td>
<td>Σ Hits = 44,232, Σ Counts = 366,804</td>
</tr>
<tr>
<td>J3462</td>
<td>Ballistic impact, 137 J</td>
<td>Σ Hits = 9,784, Σ Counts = 322,891</td>
</tr>
<tr>
<td>J2041</td>
<td>Ballistic impact, 280 J</td>
<td>Σ Hits = 34,729, Σ Counts = 1,184,880</td>
</tr>
<tr>
<td>J2043</td>
<td>Ballistic impact, 419 J</td>
<td>Σ Hits = 79,719, Σ Counts = 2,736,485</td>
</tr>
<tr>
<td>J2112</td>
<td>Flaws, 1.25 mm deep</td>
<td>Σ Hits = 173,772, Σ Counts = 6,668,306</td>
</tr>
<tr>
<td>J2144</td>
<td>Flaws, 2.5 mm deep</td>
<td>Σ Hits = 141,975, Σ Counts = 6,542,613</td>
</tr>
<tr>
<td>J3419</td>
<td>Flaws, 5 mm deep</td>
<td>Σ Hits = 160,280, Σ Counts = 6,423,255</td>
</tr>
</tbody>
</table>

Table 2. Results of the fatigue test.

<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>
</tbody>
</table>

AE activity recorded during the pressurization of the cylinders with drop impact damages is plotted in Fig. 5. The total number of hits and counts increases almost linearly with the impact
energy. Most hits were recorded by the sensor N°4, placed close to the main impact area (for the three different impact energies, about 80 % of the total hits were recorded by sensor N°4).

Fig. 5. Evolutions of AE hits and counts as a function of the drop impact energy.

AE activity recorded during the hydraulic pressure tests on cylinders with ballistic impact damages is plotted in Fig. 6a and b. As in the previous case, AE activity increased almost linearly with the impact energy. Most hits (around 70 % of total hits number for the different impact energies) were recorded by sensor N°2, placed at 50 mm far from the impact point; see Fig. 6a.

Figure 7 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 sensor N°1, close to the longitudinal notch, recorded around 60 % of all the hits.

The cylinders were finally submitted to a fatigue test (5000 cycles between 30 and 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 withstood 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 also by leakage during the fatigue test and the number of cycles to failure decreases when the impact energy increases.

Fig. 6. Evolutions of a) AE counts and b) hits as a function of the ballistic impact energy.

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 (cf. Fig. 8).

Discussion

In this work, the severity of the investigated defects can be related to the impact energy for the drop and ballistic tests and to the depth for the notched cylinders. The experimental results show that, for the adopted AE sensor location, the acoustic activity increases almost linearly with the damage severity for the cylinders submitted to drop test and ballistic impact, unlike the cylinders with notches. In the case of impact defects, the severity of the damages may be estimated by the AE method. For the cylinders with notches, considering the results in terms of AE activity
Fig. 7. Evolutions of AE hits and counts as a function of the notch depth.

Fig. 8. Delamination of the cylinders with notches after fatigue.
(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. The loading of the structures during the pressure test does not cause the propagation of the matched notch but mostly delamination that is induced by the longitudinal notch but not influenced by its depth.

The influence of each type of defect on the structural integrity of the cylinders seems difficult to estimate regarding the results of the AE activity in terms of total number of hits and counts. 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. The difficulty to estimate the gravity of the defects by considering the total number of hits or counts may also be related to the failure mode, that was observed during the fatigue tests. For the cylinders which did not pass the 5000 cycles at 300 bar, the failure occurred by leakage, this kind of failure is induced by liner cracking and may occur even if the composite shell keeps good load bearing properties, which could ensure a sufficient burst pressure if the structure was tight. For this reason, it seems that AE monitoring may give a good assessment of the composite shell damage level, but may not give sufficient information for predicting the leakage risk.

Table 3. Results of high amplitude AE (80-100 dB).

<table>
<thead>
<tr>
<th>Cylinder reference</th>
<th>Defect</th>
<th>AE between 80 and 100 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>J2045</td>
<td>None</td>
<td>Σ Hits = 0, Σ Counts = 0</td>
</tr>
<tr>
<td>J3386</td>
<td>Drop test, 500 J</td>
<td>Σ Hits = 0, Σ Counts = 0</td>
</tr>
<tr>
<td>J3416</td>
<td>Drop test, 1000 J</td>
<td>Σ Hits = 2, Σ Counts = 977</td>
</tr>
<tr>
<td>J2105</td>
<td>Drop test, 2000 J</td>
<td>Σ Hits = 13, Σ Counts = 14,423</td>
</tr>
<tr>
<td>J3462</td>
<td>Ballistic impact, 137 J</td>
<td>Σ Hits = 58, Σ Counts = 110,987</td>
</tr>
<tr>
<td>J2041</td>
<td>Ballistic impact, 280 J</td>
<td>Σ Hits = 238, Σ Counts = 481,985</td>
</tr>
<tr>
<td>J2043</td>
<td>Ballistic impact, 419 J</td>
<td>Σ Hits = 495, Σ Counts = 1,192,418</td>
</tr>
<tr>
<td>J2112</td>
<td>Flaws, 1.25 mm deep</td>
<td>Σ Hits = 2014, Σ Counts = 2,265,270</td>
</tr>
<tr>
<td>J2144</td>
<td>Flaws, 2.5 mm deep</td>
<td>Σ Hits = 1990, Σ Counts = 3,003,495</td>
</tr>
<tr>
<td>J3419</td>
<td>Flaws, 5 mm deep</td>
<td>Σ Hits = 1803, Σ Counts = 2,643,058</td>
</tr>
</tbody>
</table>

The defect effect on the structural integrity could also be evaluated by the high amplitude AE events. Several works, performed on fiber-reinforced polymer (composite) coupons, have shown that AE amplitude distribution can be used to identify the main damage mechanisms (matrix cracking, interface fracture, fiber pull-out, fiber fracture) in composite materials (Barré et al., 1994; Kotsikos et al., 1999). High amplitude signals, over 80 dB, are generally associated to fiber fractures, which can be considered as the most critical damage mechanism regarding the structural integrity of the cylinders. Nevertheless, this correlation between the AE amplitude distribution and the damage mechanisms is generally difficult to apply to large composite structures due to significant attenuation of acoustic waves in the heterogeneous materials. Table 3 presents the high amplitude AE activity (amplitude between 80 and 100 dB), recorded by the four AE sensors during the pressure tests. For the cylinders after drop test and ballistic impact, the
number of high amplitude hits increases with the impact energy. Only a few hits between 80 and 100 dB were recorded for the cylinders after drop test. The highest numbers of high amplitude hits were obtained for the cylinders with notches and the high amplitude activity does not seem to be influenced by the notch depth. Considering the results of the high amplitude activity, the notches should be considered as the most critical defect for the structural integrity of the cylinders.

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) is significantly higher than for the other sensors (60 to 80 % of the total number of hits was recorded by the sensor close to the damage). Furthermore, from the Hsu-Nielsen tests performed on the reference cylinder, the attenuation coefficient, $\beta$, and the wave speed, $v$, was determined for different directions (cf. Fig. 9). These results show an anisotropic behavior and a significant attenuation of the acoustic signals. 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 position will have an influence on the recorded AE events.

$$\beta = 58 \text{ dB/m} \quad v = 4800 \text{ m/s}$$

$$\beta = 36 \text{ dB/m} \quad v = 6500 \text{ m/s}$$

$$\beta = 36 \text{ dB/m} \quad v = 4500 \text{ m/s}$$

Fig. 9. Attenuation coefficient, $\beta$, and acoustic wave speed, $v$.

![Attenuation coefficient and acoustic wave speed](image)

Fig. 10. Evolution of AE hits as a function of the ballistic impact energy without results from the AE sensor close to the damage.
Furthermore, the influence of the sensor in the vicinity of the damaged area may be estimated by considering the previous results without taking into account the hits recorded by this sensor. Figure 10 shows the number of hits, recorded by all the AE sensors except the one close to the impact point, versus the impact energy for the cylinders after ballistic impact. The total number of hits increases almost linearly with the impact energy and the defect severity may still be estimated without taking into account the sensor close to the defect. On the contrary, for the cylinders after drop test (cf. Fig. 11), no linear relationship between hits and energy can be established when the hits, which were recorded by the sensor close to the main impact area, are not taken into account. For the ballistic impact, the damaged area is mainly restricted to a limited zone around the impact point. After a drop test, two damaged areas may be identified (cf. Fig. 4a): the main impact area under the impact point, and the rebound impact area on the opposite dome. Without the hits from the sensor close to the main impact area, the evaluation by AE monitoring mainly concerns the second damaged area, as shown by the significant number of hits, recorded by the sensor N°3, close to the rebound impact area, for impact energies of 1000 and 2000 J.

![Figure 11. Evolution of AE hits as a function of the drop impact energy without results from the AE sensor close to the damage.](image)

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.

For the different investigated damages, considering the total number of hits and counts, and particularly considering the high amplitude acoustic signals, appears insufficient to estimate the structural integrity: the highest AE activity was obtained for cylinders with notches, and these structures did not fail during the fatigue test. But, this difficulty to determine a basic AE criterion in order to evaluate the cylinder integrity may also be related to the failure mode. Failure by
leakage is not acceptable for the integrity of a pressure vessel, but this kind of failure, related to
the liner tightness, can happen even if the composite shell keeps good mechanical properties. For
this reason, even if the proposed AE analysis may give a good evaluation of the damage level for
the composite material, it seems insufficient for the leakage risk prediction.

This work also confirmed the significant attenuation of acoustic signals in composite materi-
als. This result underlines that the number and the position of AE sensors may be a critical point
for large composite structures.

References

S. Barré, M. Benzeggagh (1994), "On the use of acoustic emission to investigate damage mecha-
nisms in glass-fibre-reinforced polypropylene", Composite Science and Technology, 52, 369-
376.

A. R. Bunsell (2006), "Composite pressure vessels supply an answer to transport problems", Re-
inforced Plastics, 50 (2), 38-41.

Structures, 40 (2), 149-158.


M. Hamstad (1982), "Testing fiber composites with acoustic emission monitoring", Journal of
Acoustic Emission, 1, 151-164.

corrosion fatigue damage accumulation in glass fibre reinforced polyester laminates”, Polymer
Composites, 20 (5), 689-696.

Composite Materials Book, vol. 5, eds. A. Kelly, C. Zweben, R. Talreja, J.E. Manson, Pergamon,
pp. 345-357.

C. Webster (1999), "Assessment of the use of acoustic emission as an inspection method for FRP
wrapped cylinders", Transport Canada Publication N° TP 13505E, Powertech Labs Inc.

B. Wood, R. Harris (2000), "Structural integrity and remnant life evaluation of pressure equip-
ment from acoustic emission monitoring", International Journal of Pressure Vessels and Piping,
77, 125-132.