USE OF ACOUSTIC EMISSION FOR INSPECTION OF COMPOSITE PRESSURE VESSELS SUBJECTED TO MECHANICAL IMPACT

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Abstract:

Motivated by the emerging hydrogen mobility uses, especially the need for storing a high amount of energy in a small and lightweight volume, type IV composite pressure vessels have become a state-of-the-art technology for high pressure hydrogen. They comprise a non load-bearing liner, generally made of plastic and assembled with metallic bosses, around which a carbon fibre-epoxy composite is wound. Though such vessels can already be operated safely, there is a lack of knowledge concerning their residual performance after a mechanical impact. There is a need for associated nondestructive examination (NDE) methods, able to assess whether a cylinder is still fit for service after impact. The FCH-JU funded pre-normative research project HYPACTOR was set up to investigate the damage created in type IV pressure vessels by mechanical impacts, and then the use of Acoustic Emission to build rejection criteria during inspection. The methodology was to combine several AE tests on healthy and impacted vessels and correlate the results with residual performances. The developed criteria were applied to a wide database of Type IV composite vessels with different sizes, design specifications and working pressures. The validation was carried out on 114 hydraulic tests on healthy and impacted vessels. Results have demonstrated a capacity to differentiate damaged cylinders from healthy ones, with some small influence of the number of pressure cycles between impact and inspection.
1. Introduction

Composite overwrapped pressure vessels (COPVs) are widely used for many applications. The combination of their light weight and high mechanical strength is a major benefit for transportation of large quantities of gas. Type IV composite pressure vessels have become a state-of-the-art technology for high pressure hydrogen (>350 bar), in transportable and on-board application. They comprise a non load-bearing liner, generally made of plastic and assembled with metallic bosses, around which a carbon fibre-epoxy composite is wound.

Though such vessels can already be operated safely, there is a lack of knowledge concerning their residual performance after a mechanical impact. There is a need for associated nondestructive examination (NDE) methods, able to assess whether a cylinder is still fit for service after impact.

Periodic inspection of transportable composite vessels is based on visual examination combined to hydraulic proof test [1]. This procedure, inherited from metallic vessels (type I) is not well adapted for composite structures assessment and leads to industrial drawbacks such as dismounting and handling steps, process disruption, need of drying process after hydraulic test... In this way, Acoustic Emission Testing, already used for some metallic vessels, may be a good candidate to perform a periodic inspection of COPVs.

The FCH-JU funded pre-normative research project HYPACTOR was set up to investigate the damage created in type IV pressure vessels by mechanical impacts, to assess the residual performances after impact in terms of burst (short-term performance) and cycling (long-term performance), and then the use of Acoustic Emission to build AE criteria. It has to be noted that an important work item of Hypactor was the construction of the relationship between impact, created damage and vessels residual performance to define rejection criteria for inspection purpose.

2. Description of work

The experimental trials were performed mainly on a certified 36L 70MPA type IV cylinders provided by Hexagon Composites. They are designed according to the on-board storage regulation EC79/EU406 [2] with a safety factor of 2.25. The liner is a polymeric and the composite shell is a carbon fibre reinforced polymer (CFRP) filament wound. Other larger cylinders 255L and 513L were also tested. One impact per vessel was chosen to assess residual performance at short term and long term (after further pressure loads in service). Different levels of impact energy were carried out in order to determine the burst pressure reduction curve. All impacts were performed using a hemispherical steel impactor in order to produce less damage to the composite than a sharper one and therefore make damage detection difficult or barely visible using visual inspection (less favorable situation for identification of damaged vessels by visual inspection and therefore assess acoustic emission ability). All impacts were carried out in the cylindrical part, using two different setups depending on the speed and energy required: a drop tower and a pneumatic canon, displayed in Figure 1.
AE monitoring was performed using an advanced AMSY5/6 systems supplied by VALLEN, and eight resonant R15α sensors. Six spring-loaded sensors were placed on the cylindrical part of the COPV by means of three belts, and acoustically coupled with vacuum grease. Two sensors were placed on bottoms. The eight sensors are distributed so that the COPV is fully covered. An example of sensors implementation is shown in Figure 2. The AE signals were amplified by a 34 dB fixed gain, using an AEP3N preamplifier. A relatively large pass-band [25-850] kHz hardware filter was used to detect a wideband of frequencies. A trigger threshold of 40 dB was selected, which was above the background noise level.

AE monitoring was performed for both healthy and impacted vessels at short and long term tests. For long term performance, vessels were monitored by AE after three cycling period in order to define pass-fail criteria enabling the identification of damaged vessel whatever the periodicity of control and in particular regardless the time between the occurrences of impact/damage to AE control. Vessels were then cycled between 0 and 875 bar which is the maximum pressure reached during hydrogen filling for a service pressure of 700 bar. Different cycling periods were carried out combined to AE monitoring: 50 cycles at 875 bar + AE at 1050 bar + 5000 cycles at 875 bar + AE at 1050 bar + 10000 cycles at 875 bar + AE at 1050 bar + burst.

For short term performance, AE test was carried out just after impact and then vessels were burst. The loading during AE test, should be gradually increased up to the maximum pressure $P_{max}$, at least 110% of its nominal filling pressure (963 bar) and maximum equal to the test pressure 150% of its service pressure (1050 bar). In this study the test pressure was reached during AE test in order to collect more data related to damage propagation at high pressure. However, AE criteria were defined for a maximum pressure of 110% of the nominal filling pressure. The pressure sequence contains various bearings which allow to identify the
damage state and its evolution at each pressure level but also to avoid a sudden burst. To avoid too sudden stress relaxation, strain rate during depressurization was similar to that during pressurization (<5%Pmax) and regular as possible. An example of pressure sequence is given in Figure 3.

![Figure 3: Pressure sequence for 36L vessels.](image)

3. Results and discussions

In order to establish AE pass/fail criteria to be able to identify damaged vessel, the ideal approach is to record the AE signature of each vessel before and after impact. However, in practice, this proposal generates a complex pattern of vessel travel as well as a complex trials plan (since the impact trials and AE trials on short and long term performance were performed in different countries). To reduce and simplify trials, the solution proposed was to study the long term performance of 3 healthy vessels from different batches. These vessels were considered as a reference providing that AE dispersion is very low. These data were considered as a baseline of healthy vessels. In the case where scatterings would have been very high i.e the AE behaviour of vessels is different, AE tests would have to be performed for each vessel before and after impact.

As it can be seen in Figure 4, dispersion was evaluated at three conditions (after 100 cycles, after 5100 cycles and after 15100 cycles) by comparing the AE activity of the three vessels. The sum of events (first hit channel with Amplitude ≥ 50 dBae) detected by all channels per vessel was calculated for each holds. Results indicate a very low dispersion between vessels whatever the cycling period. These AE data can be considered as a baseline signature for all 36L COPV.
The approach followed to define AE criteria is based on the appendix 7 of the French best practices guideline for Acoustic Emission, approved in 2014 by the French authority [3]. AE criteria are divided into two types, real-time shutdown criteria and post analysis criteria. The first one aims to detect and reject dangerous vessels in real time during the AE test, in case of vessels with high loss of performance to avoid a sudden burst. The second one aims to identify and remove from service vessels with a low loss of performance. Three categories are possible: for category 1 and 2: vessels are accepted while for category 3, vessels are rejected.

Parameters to take into account for real-time shutdown criteria and post analysis criteria are as follows:

- **Setting:** The evaluation threshold is set at 50 dBAe and the reference threshold at 75 dBAe.

- **Activity and intensity evolution during the test.** Activity (number of events and intensity energy) are assessed throughout the duration of the test.

- The number of counts Na, determined by the number of counts generated by the break of fourteen 0.5mm 2H pencil leads at a distance from the sensor corresponding to an amplitude of 60 +/- 1 dBAe, depending on the fibres direction (main or visible on the surface) and at 45° to this direction. The Na value is equal to the mean of the number of counts obtained for each direction multiplied by 10 (value measured from the acquisition threshold).

- **N2s:** Events with Amplitude ≥ 75 dBAe, calculated for the entire duration of the test

- **N3s:** Activity with Amplitude ≥ 50 dBAe during holds

- **Dm:** Number of hits with duration higher than 5 ms

- **FR:** Felicity Ratio calculated during the unload/load ramp
More details about parameters thresholds are available on the appendix 7 [3]. The first step was the compliance assessment of criteria defined in this appendix to our vessels. It has been found that both criteria were conservative; most of healthy vessels (thus with no loss of performance) were systematically rejected. An example of zonal and planar analysis for a healthy vessel after 100 cycles at 875 bar is given in Table 1 and Figure 5. We can note that all parameters are classified in category 3 except the Felicity Ratio. For zonal analysis in particular when considering activity during holds, we talk about category 3 when the number of events exceeds 50 in the case of intermediate holds and 80 for final hold. This threshold is largely exceeded in our case. For planar localization, one red cluster appearance is sufficient to reject the vessel. A red cluster represents more than 50 located events in a very small area. This high activity could be related to the high thickness and high working pressure of on-board/transportable vessels. Indeed, the safety factor and design are different compared to stationary vessels. Although the appendix does not cover on-board and transportable vessels (the case of our study), the control protocol and the analysis methodology are still consistent and remain applicable via some modification.

Table 1: Zonal analysis of a healthy vessel after 100 cycles at 875 bar.

<table>
<thead>
<tr>
<th>Act</th>
<th>Int.</th>
<th>Na</th>
<th>N2S</th>
<th>N3s/Zone (Blue color: 10min hold, analysed from [2 min; 10 min]; Red color: 20min holds analysed from [2 min; 20 min])</th>
<th>D&gt;Dm</th>
<th>Final Classe</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Figure 5: Cluster localization of a healthy vessel after 100 cycles at 875 bar.

For confidentiality reasons, values of criteria thresholds are not communicated in this paper. However, the global approach followed to build and calibrate the AE pass-fail criteria is detailed hereafter.

Methodology is based on the construction of a burst pressure reduction curve, which gives the measured burst pressure for several vessels with respect to impact energy (Figure 6).

Figure 6: Burst pressure reduction curve, with respect to impact energy.

It was demonstrated that the energy at which residual burst pressure starts to decrease is a relevant threshold to define a critical defect limit (from green to red area) where detection needs to be efficient [4, 5, 6].

As a recommendation, Hypactor project proposes to calibrate NDT method using this burst pressure reduction curve, giving the limit where NDT needs to detect a defect with a high reliability. It means that calibration of AE criteria should be performed for each vessel design, and connected to the burst pressure reduction curve, as well as visual inspection calibration.
AE test should be performed on “healthy vessels” (without and with impact but no loss of performance) located in the plateau of the curve of Figure 6 and also on impacted vessel at different energy levels with a loss of performance (red area).

In order to limit the number of destructive tests, a formula to estimate the threshold of critical energy (inflexion point of Figure 6) was given in [4, 5, 6] depending on vessels features.

\[ \frac{E_{\text{abs}}}{(P_{\text{burst}} \cdot R_i)} = 30.10^{-6} \text{ (units = S.I.)} \]

With:
- \( E_{\text{abs}} \) = absorbed energy
- \( E_{\text{incident}} \) = incident energy (impactor total energy)
- \( P_{\text{burst}} \) = burst pressure of healthy vessel
- \( R_i \) = inner vessel radius

By using \( E_{\text{abs}} = 0.65 \ E_{\text{incident}} \) (proposal from [5]), the formula becomes:

\[ E_{\text{incident}} = (P_{\text{burst}} \cdot R_i) \cdot 30.10^{-6} / 0.65 \text{ (units = S.I.)} \]

In terms of damage induced by impacts, testing on empty vessels was found to be more conservative than on pressurized vessels. However, from the point of view of detection by AE, impacts on pressurized vessels is recommended because the propagation of damage will need an overpressure and criticality assessment is more difficult to predict by AE compared to empty condition. The calibration of thresholds of AE criteria is illustrated in the Figure. The methodology is to define the low limit and high limit for each AE parameter based on the burst pressure reduction curve (Figure). Thresholds will depend on vessels features (type, design, mechanical behavior, impact conditions…) and also on the safety factor to be adopted for the category 2. The extent of this category will depend on the safety factor adopted by the stakeholders which could be linked to vessel features and results scatterings.

**Figure 7: Burst pressure reduction curve and calibration of AE criteria protocol.**
AE Criteria were first built in the framework of H2E project (Horizon Hydrogène Energie) [7] on transportable 143L vessels from Stelia Composites. Mechanical impacts have been carried out using a dedicated bench. The configuration of impact was in the dome area at 45°. The developed AE criteria have been used in Hypactor even if the design, impact configuration and operating pressure were different. The aim was to evaluate their application on 36L Hypactor vessels.

Refined criteria have shown satisfying results despite the high number of parameters (Table 1 & Figure 5). However, real time analysis requires a solid experience of the operator. The alternative proposed by the Institut de Soudure for real time criteria, is based only on two criteria, one zonal (N2s) and one using localization analysis (Clusters during holds). These criteria are very fast to analyze and simple to automate.

For healthy vessels, impacted vessels at 1kJ on empty condition and impacted vessels at 3kJ on 700 bar condition (all those vessels were without any loss of performance), only three vessels were stopped in real time during the AE test:

- 2 impacted vessels at 1kJ empty condition
- 1 impacted vessel at 3kJ 700 bar condition

After verification using visual inspection, it has been found that an external damage was located in the critical area identified by AE. Damage was induced by the rebound of the impactor after impact. A severe fiber cut was then identified.

*Figure 7 : Vessel impacted at 3kJ@700 bar. Rejection of vessel is due to a harsh surface damage induced by the projectile rebound. A) Localization of AE sources. B) Damage induced by the rebound.*
All vessels impacted at high energy and presenting a loss of performance were also rejected by real time and post analysis criteria. An example of classification is given in the following tables (Table 2, Table 3).

**Table 2 : Result of classification obtained by AE on impacted vessels at high energy at empty condition.**

<table>
<thead>
<tr>
<th>Number of vessels</th>
<th>Impact conditions</th>
<th>AE test condition</th>
<th>Burst pressure</th>
<th>AE Real time criteria</th>
<th>AE Post analysis Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3 kJ@empty</td>
<td>After impact, after 50 cycles</td>
<td>decrease</td>
<td>Rejected</td>
<td>Rejected</td>
</tr>
<tr>
<td>1</td>
<td>4 kJ@empty</td>
<td>After impact, after 50 cycles</td>
<td>decrease</td>
<td>Rejected</td>
<td>Rejected</td>
</tr>
<tr>
<td>1</td>
<td>5 kJ@empty</td>
<td>After impact, after 50 cycles</td>
<td>decrease</td>
<td>Rejected</td>
<td>Rejected</td>
</tr>
<tr>
<td>1</td>
<td>7 kJ@empty</td>
<td>After impact</td>
<td>decrease</td>
<td>Rejected</td>
<td>Rejected</td>
</tr>
</tbody>
</table>

**Table 3 : Result of classification obtained by AE on impacted vessels at high energy at 700 bar condition.**

<table>
<thead>
<tr>
<th>Number of vessels</th>
<th>Impact conditions</th>
<th>AE test condition</th>
<th>Burst pressure</th>
<th>AE Real time criteria</th>
<th>AE Post analysis Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4 kJ@700b</td>
<td>After impact, after 50 cycles</td>
<td>decrease</td>
<td>Rejected</td>
<td>Rejected</td>
</tr>
<tr>
<td>1</td>
<td>5 kJ@700b</td>
<td>After impact, after 50 cycles</td>
<td>decrease</td>
<td>Rejected</td>
<td>Rejected</td>
</tr>
<tr>
<td>1</td>
<td>6 kJ@700b</td>
<td>After impact, after 50 cycles</td>
<td>decrease</td>
<td>Rejected</td>
<td>Rejected</td>
</tr>
</tbody>
</table>

The validation has been carried out on a large data base of 114 vessels from different type, dimensions, working pressure and manufacturer.
4. Conclusion

Currently there is no AE standards applicable for transportable COPVs. In FCH-JU Hypactor project, many AE test have been performed on type IV composite vessels in order to define AE rejection criteria for periodic inspection.

The methodology was to combine several AE tests on non-impacted and impacted vessels and correlate the results with vessels residual performances. The approach followed by ISA was to refine criteria thresholds from the appendix 7 of French Guide to good practice for acoustic emission testing [3] and adapt them for type IV vessels using zonal and cluster localization analysis. The use of both localization methods offers the possibility to obtain consistent result. This approach allows a calibration of AE criteria to accept or reject a vessel during pressurization. The developed criteria were applied to a wide database of Type IV composite vessels with different sizes, design specifications and working pressures.

Acoustic emission tests (AE) using developed ISA criteria have provided a good assessment of damage.

More details in www.hypactor.eu

Acknowledgment

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