RESIDUAL PERFORMANCE OF COMPOSITE PRESSURE VESSELS SUBMITTED TO MECHANICAL IMPACTS

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ABSTRACT

Type IV pressure vessels are commonly used for hydrogen on-board, stationary or bulk storages. During their lifetime, they can be submitted to mechanical impacts, creating damage within the composite structure, not necessarily correlated to what is visible from the outside. When an impact is suspected, or when a cylinder is periodically inspected, it is necessary to determine whether it can safely stay in service or not. The FCH JU project Hypactor aims at creating a large database of impacts, characterized by various non destructive testing (NDT) methods, in order to provide reliable pass-fail criteria for damaged cylinders. This paper presents some of the tests results, investigating short term (burst) and long term (cycling) performance of impacted cylinders, and the recommendations that can be made for impact testing and NDT criteria calibration.

1.0 INTRODUCTION

Motivated by the emerging hydrogen mobility usages, especially the need for storing a high amount of energy in a small and lightweight volume, fully-wrapped composite pressure vessels have been rapidly introduced into the market over the last years. Type IV vessels represent the state-of-the-art technology for storing hydrogen at 70 MPa in vehicles, and their use is also spreading for stationary applications such as refuelling station buffers (up to 100 MPa) or transportable applications such as tube trailers [1]. They are made of a non-load bearing liner, generally polymeric, assembled with metal bosses and wrapped into a carbon fibre / epoxy composite shell to ensure the mechanical strength.

Current standards define high safety factors (ratio of minimal burst pressure over service pressure) for each application, ensuring the safety of the vessels through their lifetime despite a lack of knowledge about their behaviour in certain operating conditions [2, 3, 4]. In particular, the creation of damage inside the composite shell in case of mechanical impacts or drops, and the evolution of such damage under service loading are not fully understood. Indeed, the literature about impact on composite structures has been driven mostly by thin laminates for aeronautic applications [5, 6, 7, 8, 9], whereas only few studies recently focused on thick filament-winded structures [10, 11, 12] and investigated the residual performance of impacted pressure vessels [13, 14]. A deeper knowledge of how the different damage mechanisms appearing inside the thick composite overwrap (delamination, matrix cracking, fibre breakage) affect the residual burst pressure and fatigue resistance of the vessel is required; as well as associated non destructive testing (NDT) methods to assess if a cylinder is still fit for service after impact.

Current procedures for the inspection of composite pressure vessels are the same as those used for metallic ones. Typically, a visual inspection is performed to look for damage on both the external surface of the composite and the internal surface of the liner. Then a hydraulic proof test is performed to ensure the vessel can withstand a pressure higher than the maximal pressure seen in service [15]. Still, the existing documents can be hard to use in the field, especially when it comes to quantifying the damage.

The Hypactor project - a three years pre-normative research program funded by the FCH JU – was set up in order to address this knowledge gap [16]. It brings together partners with complementary expertise: a technology centre (CEA), pressure vessel manufacturers (Hexagon Composites) and end-users (Air Liquide), experts of industrial non-destructive testing (Institut de Soudure), and academics with strong knowledge of pressure vessels testing (Wroclaw University of Technology) and modelling (Norwegian University of Science and Technology). Within the Hypactor project, a large impact testing program was carried out in order to investigate the link between impact parameters, the damage created (observable by different NDT methods), and the residual performance of vessels.

This paper presents the first results of the impact tests performed on empty 36 L cylinders, with different levels of impact energy. The visual observation of damage on the surface of the cylinder, and the residual burst pressure and cycling performance after impact are discussed and presented.

2.0 IMPACT TESTS CARRIED OUT

2.1 Cylinders

The results presented in this paper were obtained on vessels of water volume 36 L provided by the partner Hexagon Composites, which can be seen in Fig. 1 (a). They were designed according to on-board storage regulation for use at 70 MPa, with a safety factor of 2.25. The liner is polymeric and the composite shell is carbon / epoxy. For confidentiality reasons, no details about the materials or wall thickness are displayed and all residual burst pressures will be expressed as a fraction of the average burst pressure of 17 healthy vessels (${P_b}^0$). Because of the natural variability of the materials and the winding process, there is a discrepancy on the initial burst pressures of healthy vessels which is taken into account by the manufacturer, meaning that ${P_b}^0 > 2.25 \times 70$ MPa. The external diameter of the cylinder is around 320 mm.

(a) (b)

Figure 1 (a) Hexagon 36 L cylinder; (b) Hemispherical impactor used

2.2 Impact conditions

All of the presented impacts were performed using a hemispherical steel impactor (diameter 56 mm), as seen in Fig. 1 (b). A hemispherical impactor is expected to produce less damage to the composite than a sharp one, because there will be no direct cutting of carbon fibres [7, 14], but such damage is harder to visually detect: a vessel exhibiting a deep cut will surely be removed from service, whereas one with a light external mark could continue its service life. It was therefore more relevant to study the residual performance of vessels impacted with a hemispherical surface.

All impacts were carried out by CEA, and two different setups were used, depending on the speed and the energy required: a drop tower and a pneumatic cannon, as displayed in Fig. 2. In all cases, the same impactor was used; it was attached to different weights and dropped from different heights. All impacts were located on the cylindrical part of the neck-mounted pressure vessel. During the Hypactor project, vessels were impacted also while pressurised at 70 MPa, but only the results for empty vessels are presented here. For all impacts, the kinetic energy of the impactor before and after the impact was recorded by using high speed cameras. The impact energies ranged from 300 J to 10 kJ, and were performed using weights from 1.2 kg to 102 kg and speeds from 3.5 m/s to 132 m/s. It was previously found in the literature that both impactor mass and speed effects can be combined into a combined effect of impact energy, which can be used to describe the impact as long as all other parameters remain unchanged [17, 18, 19].

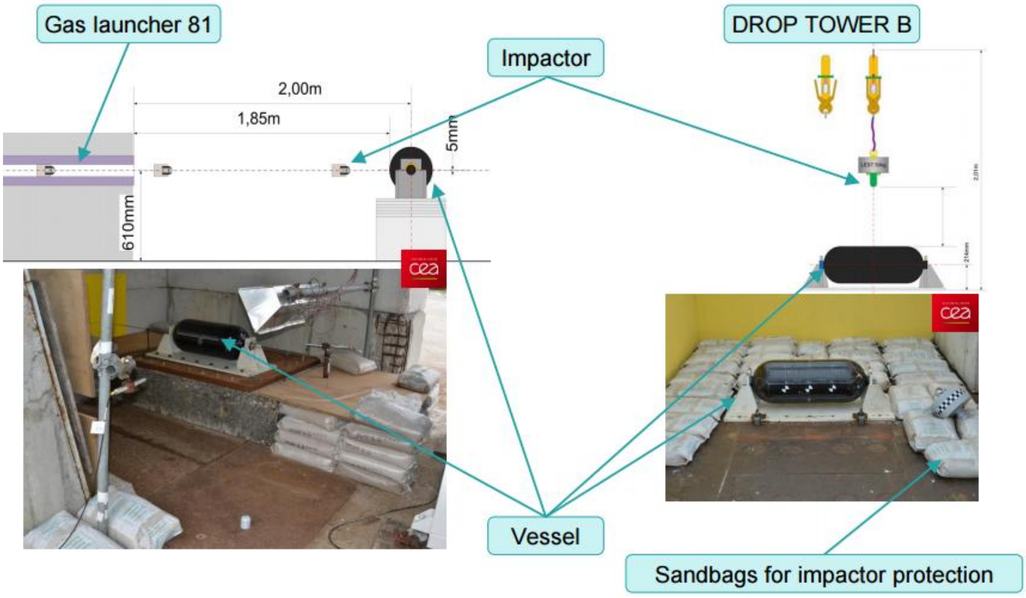


Figure 2 The impact setups : left, pneumatic cannon; right, drop tower. The vessel was always neck-mounted and empty, and the impactor is hemispherical with a diameter of 56 mm in all cases.

3.0 RESULTS OBTAINED

3.1 Decrease of burst pressure

For this section, only one impact was carried out on each empty cylinder, located at the middle of the cylindrical part. The cylinder was then pressurised until burst, and the residual burst pressure was compared to its initial value. The results are plotted in Fig. 3. As explained above, the residual burst pressures are given as a fraction of the average initial value. Three points are plotted for healthy cylinders, representing the maximal, average, and minimal burst pressure obtained from 17 vessels. In addition to this initial variability, the impact tests setup and particularly the drop tower also induce variability (e.g. due to wind or impactor rebound). Damage propagation may also depend on local defects initially present in the composite, such as porosities or cracks, hence more variability in the response of the structure under impact. This has not been quantified, and is not evident from Fig. 3, but must be kept in mind when analysing the burst pressure reduction.

It can be seen that the vessel impacted at 1 kJ shows a burst pressure inside the range of non-impacted ones. This means that its strength was not significantly reduced by the impact. Possibly, it was initially in the upper part of the burst pressure range and its burst pressure was slightly reduced.In either case, this cylinder still has the residual burst pressure higher than the minimal normative requirement (157.5 MPa). Three other vessels were submitted to the same impact condition (1 k, empty) before a fatigue test, and all three successfully passed 15000 hydraulic pressure cycles according to EN 12245. It can then be considered that these cylinders show no significant reduction of performance according to the transportable pressure vessels regulation.

The vessel impacted at 3 kJ is slightly below the range of healthy ones. It can be estimated that a decrease of burst pressure happens when impact energy is above a threshold located between 1 kJ and 3 kJ for the 36 L cylinder studied. This result is coherent with the behaviour already observed with different pressure vessels [20, 14], where burst pressures become reduced if certain impact energy values are exceeded.

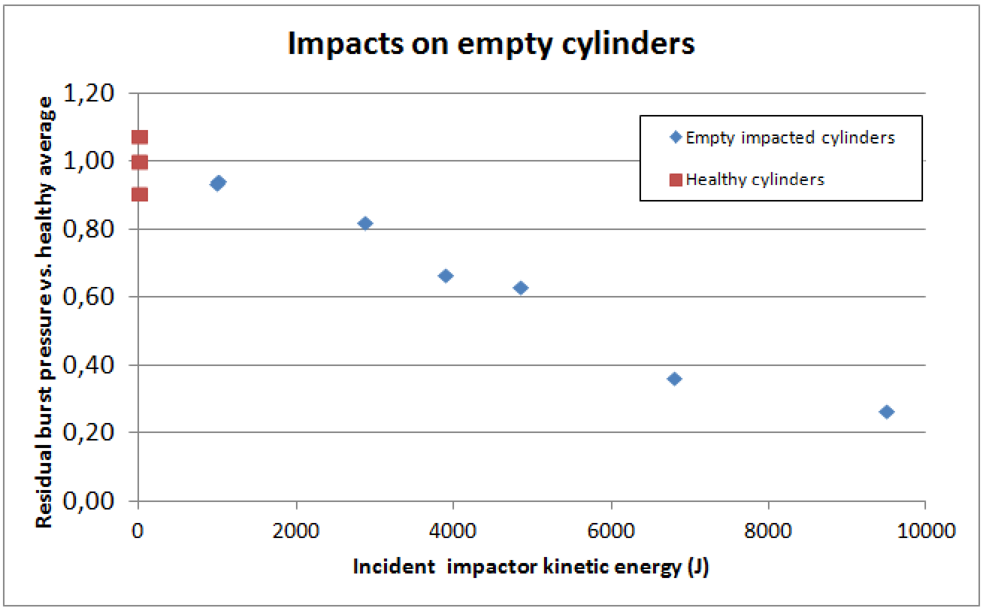


Figure 3 Burst pressure reduction of empty 36 L cylinders impacted at different energy levels

In order to further compare the impact conditions, the impactor rebound energy (kinetic energy after impact) was extracted from the high speed videos. It is assumed that the rotational energy of the impactor is negligible after the impact. The rebound energy is subtracted from the incident energy in order to define the energy absorbed by the vessel E_{abs}, which is expected to create permanent deformation or damage. Fig. 4 displays the fraction of absorbed energy E_{abs}/E_i for each level of incident energy E_i. The average value is 65%, which is in the lower part of the confidence interval reported in [20] for empty plastic liner vessels; which makes sense as the 36 L cylinders considered have a quite thick composite wall (for 70 MPa service pressure) and a small radius, hence a high rigidity.

Moreover, applying the same calculation as in [20] for the estimation of the burst pressure reduction threshold leads to the following estimate, where R_i is the internal radius, ${P_b}^0$ is the average burst pressure of non-impacted vessels and with 65% of absorbed energy:

$$\frac{(E_{abs})^{lim}}{{P_b}^0 \cdot R_i} = 30\ mm^2 \Longrightarrow (E_i)^{lim} = 1080$$

In other words, the criterion of 30 mm^2 established in [20] leads to the estimate that reduction of burst pressure for Hexagon 36 L cylinders (which were not used to establish the criterion) would occur only if incident impactor energy is above 1080 J, which seems coherent with the experimental results from Hypactor.

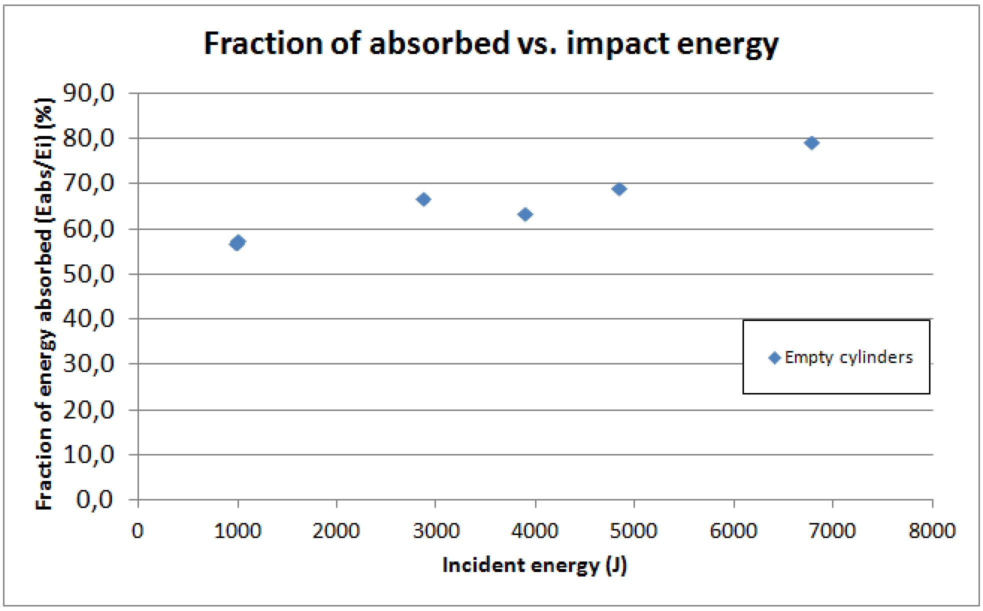


Figure 4 Fraction of energy absorbed by the cylinder

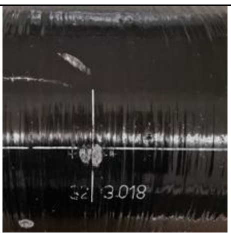
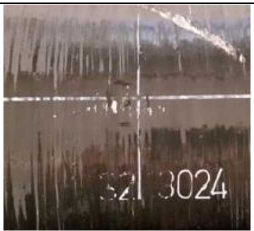
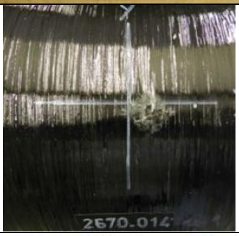
It seems also that the fraction of energy absorbed by the cylinder increases with impact energy. Unfortunately the measurement could not be performed for the impact at 10 kJ. Results from the other impact tests performed in the projects will be analysed in order to confirm this trend.

3.2 Visual inspection

One of the objectives of the Hypactor project is to provide recommendations and pass/fail criteria for visual inspection of composite cylinders. It is expected to determine whether a visual inspection is able to reliably recognise cylinders which have a decreased residual performance, in order to remove them from service before filling them. In another part of the project, multiple impacts were performed on vessels in order to create a database of visual defects. These cylinders were neither burst nor cycled afterwards, because the multiplicity of impacts makes it hard to interpret results.

Table 1 gathers pictures taken from 36 L cylinders impacted while empty with similar energy levels. Energies given should be taken as +/- 150 J. The lack of precision of visual inspection would make it irrelevant to be more precise. For each level of energy, the first picture is from the vessel which was then burst and led to the result in Fig. 3.

Table 1 Picture database for visual inspection of Hexagon 36 L cylinders

Impact energy	Pictures			
1 kJ				
3 kJ				
4 kJ				
5 kJ				
7 kJ				
9 kJ				

4.0 DISCUSSION AND CONCLUSIONS

When comparing the results of Fig. 3 and Table 1, it can be observed that in the present impact condition (hemispherical impactor, empty cylinder) it seems possible to use visual inspection as a first examination method: as a high level of energy is required to trigger a significant decrease of performance, the marks left on the cylinder surface are visible. Moreover, it seems possible to separate the visuals from high energy impact (5 kJ and above) from low energy impacts (1 & 3 kJ).

In the following parts of the project, these results will be compared with those obtained on pressurised vessels. In this case, it is expected that for a same energy level, the reduction of burst pressure should be lower; but in the mean time the external visual will likely be reduced also. When a vessel is inspected and an impact is detected, most likely the impact conditions will be unknown; hence the need for a unique pass-fail criterion covering both cases.

The case of a sharp impactor can be discarded, as it will lead to a specific visual imprint with cut fibres. For hemispherical impactors, the burst pressure reduction curves obtained with empty and pressurised cylinders can be used to draw the line between “acceptable” cylinders, which can be safely kept in service because the burst and cycling performance is not significantly decreased, and “rejected” cylinders which should be removed from service before further filling. Modelling activities are also carried out [21], and could enrich the experimental results by predicting the performance under other impact conditions or for other geometries of vessels. Thanks to the large database of pictures created, the levels of energy leading to performance reduction can then be correlated to the visual aspect left in surface.

It can be seen from Table 1 that some pictures for intermediate levels of energy (3, 4, 5 kJ) look quite similar. To avoid rejecting too many cylinders, such cylinders could be submitted to more advanced inspection methods, such as ultrasonic or acoustic emission testing, or x-ray tomography. Such NDT are also investigated in Hypactor [22], with the same approach of using residual burst pressure and cycling performance in order to define reliable pass-fail criteria for impacted cylinders.

5.0 ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) for the Fuel Cells and Hydrogen Joint Technology Initiative under grant agreement n° 621194. http://www.hypactor.eu/

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