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Vulnerability analysis of a pressurized aluminum composite vessel against hypervelocity impacts

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Abstract. Vulnerability of high pressure vessels subjected to high velocity impact of space debris is analyzed with the response of pressurized vessels to hypervelocity impact of aluminum sphere. Investigated tanks are CFRP (carbon fiber reinforced plastics) overwrapped Al vessels. Explored internal pressure of nitrogen ranges from 1 bar to 300 bar and impact velocity are around 4400 m/s. Data obtained from Xrays radiographies and particle velocity measurements show the evolution of debris cloud and shock wave propagation in pressurized nitrogen. Observation of recovered vessels leads to the damage pattern and to its evolution as a function of the internal pressure. It is shown that the rupture mode is not a bursting mode but rather a catastrophic damage of the external carbon composite part of the vessel.

1. Introduction

The context of this paper is the vulnerability of high pressure vessels subjected to high velocity impact of space debris. The increase number of these debris leads to a new regard on these phenomena. From an operational point of view, it is essential to know the limit between the perforation regime and the bursting regime of the vessel as a function of the internal pressure and of the impact characteristics (velocity, projectile weight, impact angle).

One of the first study on this topic has been performed by NASA in 1963 [1]. The context of this paper is the vulnerability of high pressure vessels subjected to high velocity impact of space debris. The increase number of these debris leads to a new regard on these phenomena. From an operational point of view, it is essential to know the limit between the perforation regime and the bursting regime of the vessel as a function of the internal pressure and of the impact characteristics (velocity, projectile weight, impact angle, . . .).

One of the first study on this topic has been performed by NASA in 1963 [2–5].

Since 1995, EMI and ESA group have presented a lot of experimental, numerical and analytic works on the vulnerability of high pressure vessels [6–10]. Interesting experimental results are the visualization of the debris cloud in high pressure gas and the deceleration of this debris by this gas. Most of these tests have been realized at normal incidence, at a velocity around 7 km/s with aluminum spheres as projectiles. The impact tests were performed on cylindrical pressure vessel which were unshielded or shielded and made of AL5754, Al2219, unalloyed Ti or Ti6Al4V. Most of the cylindrical vessels had a wall thickness of 1 mm, a diameter of 150 mm and a length of 350 mm.

In 2001, a French group (EADS, INSA, CNRS and CNES) has presented some numerical simulations with SPH algorithm on the behavior of high pressure composite tank under an hypervelocity impact. This numerical study has been used to prepare a following experimental campaign on composite tanks [11, 12].

The aim of the work presented in this paper, is to analyze the different damage process of a pressurized composite/metal vessel subjected to an hypervelocity impact. These regimes are the penetration mode, the critical rupture and fragmentation mode, and finally the bursting mode. Driving parameters are impact velocity, debris characteristics and internal pressure level.

As for the previous paper, the effects of internal nitrogen (N2) pressure vessel on the response of the vessel is analyzed for an 8 mm aluminum sphere at an impact velocity of 4400 m/s. The first difference with previous published studies is the tested vessel which is an overwrapped carbon fiber on an aluminum liner. The second difference concerns the internal pressure, which ranges from 1 to 300 bar.

The results presented in this paper are a first part of a more important program supported by CNES and which includes numerical simulations with adapted hydrocodes and also characterization of material behavior and equation of state. In this idea, hypervelocity impact experiments are performed with specific measurements in order to have enough data to discriminate the calculations.

During the test, two types of metrology are used in order to analyze the physical phenomena: flash X rays to observe the postimpact behavior of the projectile through the vessel and PVD interferomer system to monitor particle velocity profile at the back side of the vessel.

2. Experimental study

2.1. Test setup

The hypervelocity impact tests were performed with the HERMES two-stage light gas gun at Thiot Ingenierie Laboratory [13]. This gun differs from others standard

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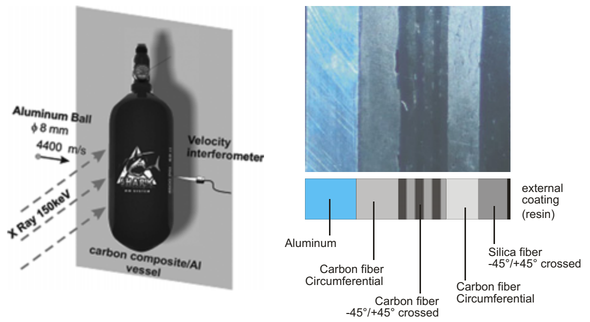

Figure 1. Cut view with description of the Aluminum-Composite vessel (left) and comparison of cut-view with model (right).

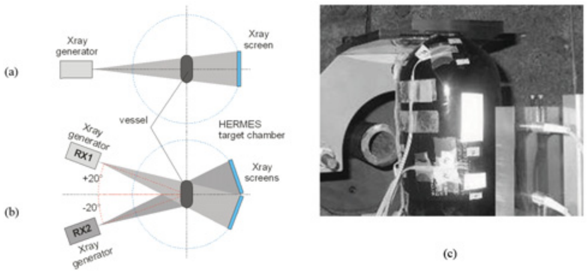

Figure 2. Schematic view of Xray configuration: (a) single beam (b) double beam (c) Composite-Aluminum pressure vessel inside the target chamber.

two-stage light gas guns by its "whole gas version" which avoids the use of powder and therefore the problems due to pyrotechnic safety.

A schematic view of the test apparatus as positioned in the target chamber is illustrated in Fig. 1 – left. It consists in the impact of a 8 mm diameter Al ball, on a CFRP/aluminium vessel at a velocity around 4400 m/s. Maximum allowed internal pressure in the vessel is 300 bar. Pressure was monitored before the test by using a calibrated pressure gauge.

Target vessel is manufactured as "paintball tank". The outer diameter of the vessels is 100 mm and its length 310 mm. The thickness of the vessel is higher near the top and the bottom of this cylindrical shape and lower in the central part. In this central part, the aluminium liner thickness is around 2.3 mm and composite thickness around 4.8 mm (Fig. 1-right). The composite layer is composed of four layers of wrapped composite fibers. From external to internal, the first and third layer are 45 °Cross wrapping while the second one and the fourth one are circumferential wrappings. The thickness of these different layers is about 1.2 mm (Fig. 1-right).

Triggering of the metrology was done by optical barriers and by self-shorting contacts. Impact velocity of the aluminum ball was performed by calculation of the chronometry between all these time information.

Xray 150 keV system (EUROPULSE EP8005 [14]) was used to visualize the state of the vessel and the projectile after the impact. It is triggered at the time of impact and its time duration is 30 ns. Two configurations have been used:

- one Xray channel perpendicular to the shot axis for the first shots (Fig. 2a),

Table 1. Parameters of the hypervelocity impact tests campaign.

Test n°	Projectile velocity (m/s)	Vessel pressure (bar)	Impact Angle (°)
#HE0183	4334 ± 60	1	90
#HE0184	4325 ± 60	200	90
#HE0187	4322 ± 60	250	90
#HE0188	4310 ± 60	300	90

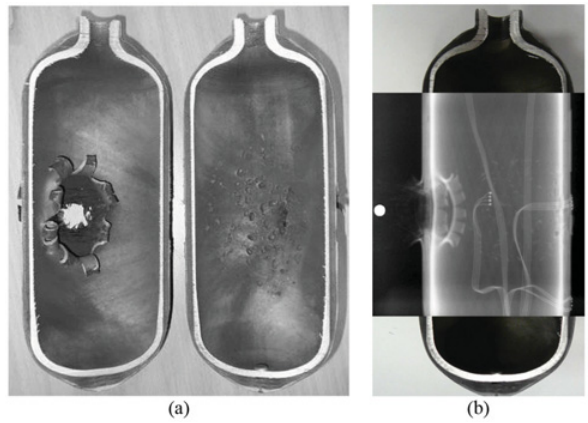

Figure 3. Test #HE0183: (a) Recovered vessel cut in two parts – Left: impact side – Right: rear side (b) Xray radiography at 41 μs after impact.

- two Xrays channels (named RX1 and RX2) tilted at $+20°$ and $-20°$ from the horizontal for the last shots (Fig. 2b).

The second metrology is a velocity interferometer system characterized by a response time of 1 ns and a error of 1% on the measured velocity. This system is referred as PDV (Photonic Doppler Velocity) or VH (Velocimeter Heterodyne). It leads to the profile of the free surface velocity at the rear face of the vessel.

A photograph of the Composite-Aluminum pressure vessel in the target chamber is displayed in Fig. 2c. Strain gauges measurements, not included in this paper, have also been used during this experimental campaign.

2.2. Experimental results

Experimental parameters of the four experiments performed in this study are presented in Table 1. For all experiments, impact have been performed at normal incidence.

2.2.1. HE0183

The first test #HE0183 was performed at an impact velocity of 4334 m/s and an internal pressure of 1 bar in the vessel. The measurement location of VH optical head is not in the axis of the impact but has been moved downward by 20 mm. The recovered vessel was cut in two parts in order to observe the impact zone and the back side of the internal aluminum liner (Fig. 3a).

The corresponding photograph shows the petaling shape of the impact area and the highly damaged

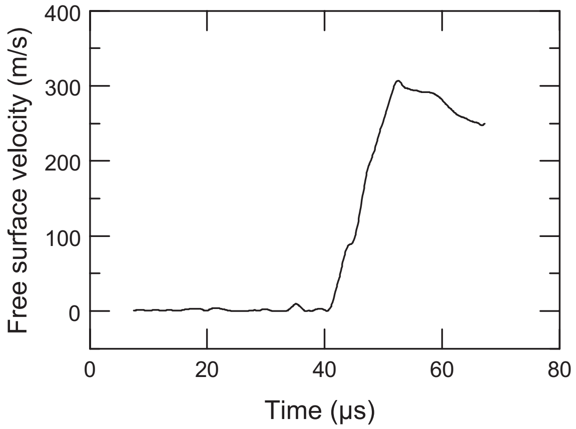

Figure 4. #HE0183: free-surface particle velocity diagram obtained at the rear face of the vessel.

composite around the impact hole. The back side is characterized by many craters done by the debris cloud.

The radiography obtained at 41 μs after the impact, is depicted in Fig. 3b with superposition of a half portion of the initial vessel. This picture shows the shapes of the retrojet, of the impact crater and of the debris cloud. The white line corresponds to others measurements (strains gauges) not included in this paper. The shape of the projectile has been added on this picture (white circle on the left of the radiography).

The particle velocity profile obtained with VH metrology at the rear face of the vessel (Fig. 4) shows an increase at a velocity of 300 m/s at time 41 μs after the impact of the projectile on the rear face of the vessel. This value of velocity corresponds to the impact of at least one large fragment on the rear face of the debris cloud generated after the impact. The fragment velocity is estimated at 2300 m/s with this chronometry.

2.2.2. HE0184

The second test #HE0184 was performed at an impact velocity of 4425 m/s and an internal N2 pressure of 200 bar in the vessel. The recovered vessel (Fig. 5) is not fully failed but a large portion has been removed. The dimension of this portion corresponds to the impact hole: its width is the same as the diameter of the impact hole and its length is a half diameter of the vessel. The composite is fully damaged in this portion. Observations of the internal liner of this recovered vessel show no impact or crater specifically at the rear side.

The radiography obtained at 15 μs after the impact (Fig. 6) shows the shapes of the retrojet, of the impact crater and of the debris cloud. The front wave which is visible forward to the debris cloud, is interpreted as the shock wave transmitted in the pressurized gas.

The particle velocity profile obtained with VH metrology at the rear face of the vessel (Fig. 7) has an oscillating shape. The maximum value corresponds to a velocity of 40 m/s at time 95 μs after the impact. This value of velocity is about eight times lower than the equivalent value obtained during the previous test. This leads to the conclusion that the debris are slowed down by the pressurized gas.

Figure 5. Test #HE0184 (N_2 pressure of 200 bar): recovered vessel.

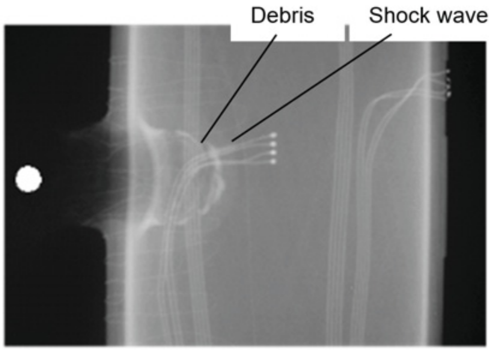

Figure 6. Test #HE0184 (N_2 pressure of 200 bar): Xray radiography at 15 μs after impact.

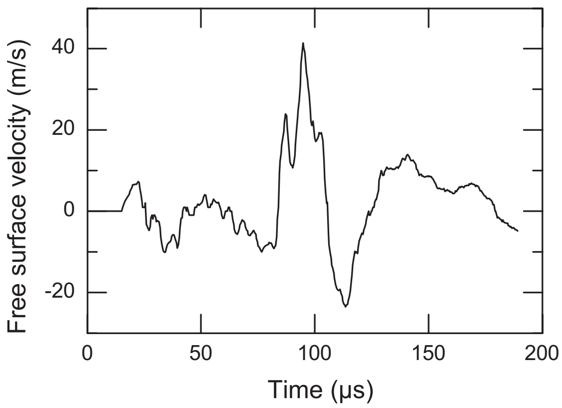

Figure 7. Test #HE0184 (N_2 pressure of 200 bar): Free surface velocity diagram obtained at the rear face of the pressurized vessel.

2.2.3. HE0187 and HE0188

For the two last tests #HE0187 and #HE0188, the experimental set-up has been improved by using two Xray channels. Test #HE0187 was performed at an impact velocity of 4322 m/s and an internal pressure of 250 bar in the vessel and test #HE0188 at 4310 m/s and 300 bar.

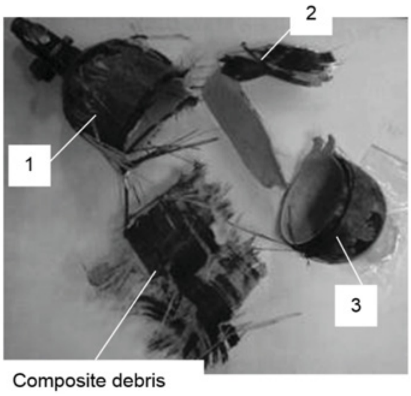

Figure 8. Test #HE0187 (N_2 pressure of 250 bar): recovered vessel.

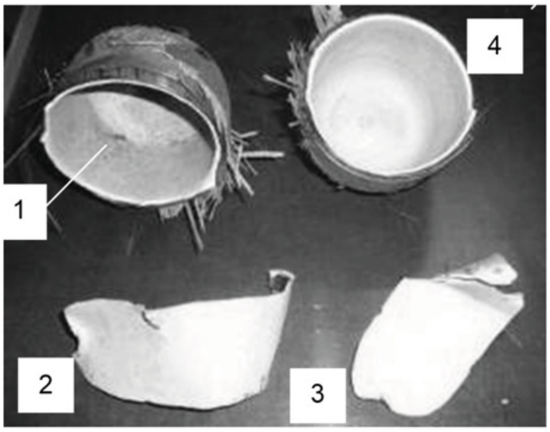

Figure 9. Test #HE0188 (N_2 pressure of 300 bar): recovered vessel.

The tested vessels (Fig. 8 and Fig. 9) are recovered in three and four parts:

- a bottom part,
- a top part,
- a central part (one piece for #HE0187, two pieces for #HE0188).

The external composite layers are highly damaged especially in the central area where they are fully broken. Inspection of the internal face of the aluminium liner reveals no craters and no trace of impact specifically on the rear side.

Radiographies obtained at 13 μs and 28 μs after the impact (Fig. 10 and Fig. 11) shows (from the left to the right) the retrojet near the impact zone, the shape of the impact crater, the debris cloud and the shock wave in the pressurized nitrogen. Due to the tilted configuration of the Xray stations, the shape of these different points seems more asymmetric than in the two previous shots.

The particle velocity profiles obtained with VH metrology at the rear face of the vessel (Fig. 12) have an oscillating shape similar to the previous test. The maximum value corresponds to a velocity of 18 m/s at time 95 μs for test #HE0187 and 16 m/s at time 94 μs for test #HE0188.

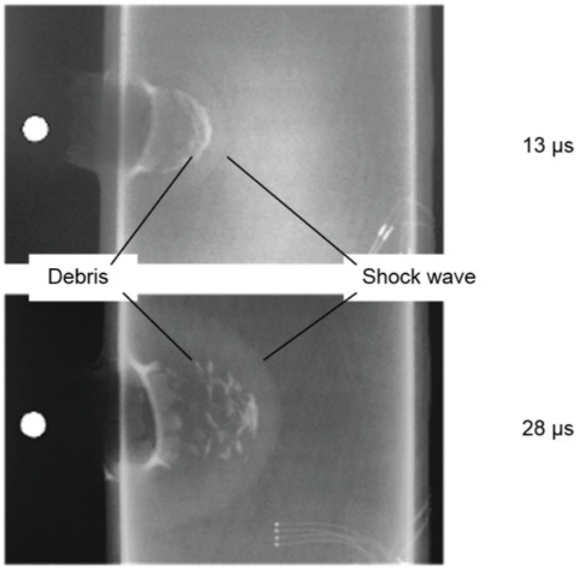

Figure 10. Test #HE0187 (N_2 pressure of 250 bar): Xrays radiographies at 13 μs and 28 μs after impact.

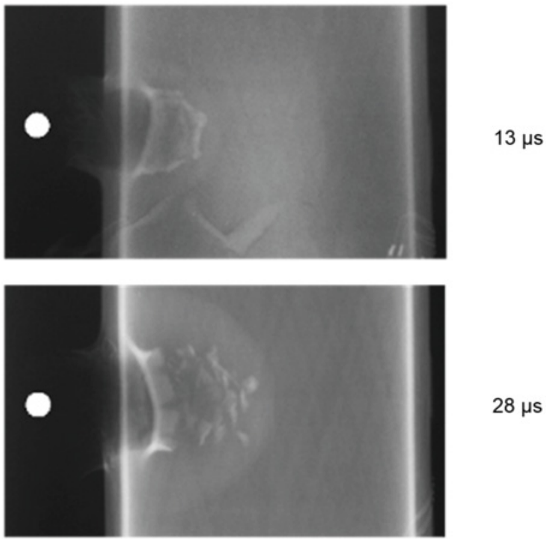

Figure 11. Test #HE0188 (N_2 pressure of 300 bar): Xrays radiographies at 13 μs and 28 μs after impact.

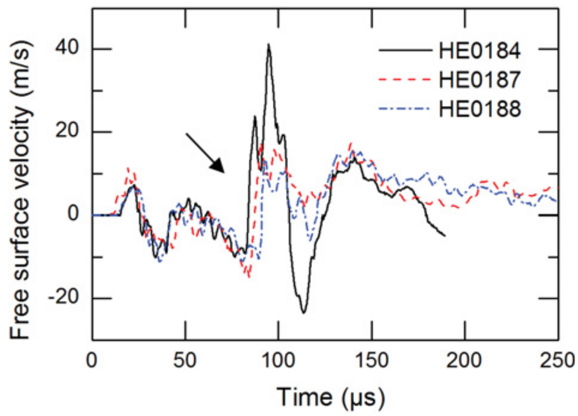

Figure 12. Free surface velocity diagrams obtained at the rear face of the pressurized tank for the three tests with pressurized vessels.

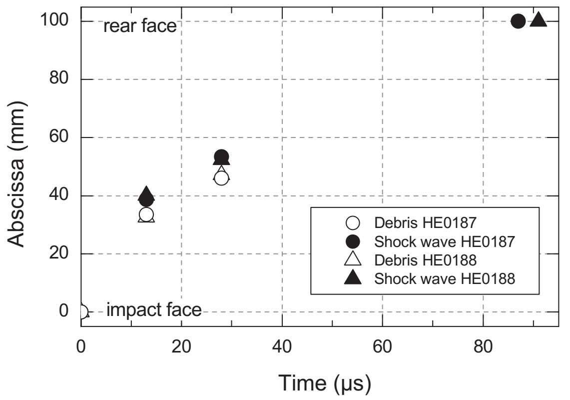

Figure 13. Evolution of the shock wave velocity and the debris in the N2 pressurized vessels.

2.3. Analysis

Analysis of the data and the results obtained during the four hypervelocity impacts on composite-Aluminum vessel confirms the results already presented on similar studies: the velocity of the debris cloud generated by the impact is reduced by the effect of the gas. Two observations confirm this analysis:

- the internal face of the aluminium liner shows no trace of impact when pressure vessel is higher than 200 bar,
- the velocity of the debris decreases between two radiographies.

Measured points for test #HE0187 and test #HE0188 are plotted in a XT diagram in Fig. 13. Abscissa corresponds to the distance in the vessel from the impact face up to the rear face. Open points correspond to debris and black points to the shock wave in pressurized nitrogen. Three points have been selected: first radiography, second radiography and free surface velocity profile. For this last point, the time of arrival has been identified with the third wave at a time between 90 μs and 100 μs (arrow in Fig. 12). This last point is an hypothesis which has to be confirmed by complementary measurements. Nevertheless, this diagram shows the consistency of the measured points.

A mean value of 900 ± 50 m/s is calculated for the debris velocity and for the shock wave velocity between RX1 and RX2 and a mean value of 780 ± 20 m/s for the shock velocity between RX2 and rear face.

Failure of the pressurized vessel increases with the inflated pressure, but for all the pressure investigated (200–300 bar) failure mode is the same: it leads to 2, 3 or 4 main debris of the aluminium layer of the vessel and a highly damaged state for the composite layers.

Failure mode is directly dependent of the composite stacking sequence. The penetration of the aluminum sphere leads to the rupture of the composite fibers. The confining stress induced by these overwrapped fibers is then released in this circumferential portion which results in the rupture of the aluminum liner at this same location.

3. Conclusion

The response of gas-filled pressure composite-aluminum vessels subjected to hypervelocity impacts has been analyzed from experimental results.

Investigated tanks are manufactured CFRP (carbon fiber reinforced plastics) overwrapped Al vessels. Explored internal pressure of nitrogen ranges from 1 bar to 300 bar and impact velocity are around 4400 m/s at normal incidence. Projectiles consists in a 8 mm diameter Al sphere. Data obtained from Xrays radiographies and particle velocity measurements show the evolution of debris cloud and shock wave propagation in pressurized nitrogen. Observation of recovered vessels leads to the damage pattern and to its evolution as a function of the internal pressure.

Analysis of the data and the results obtained during the hypervelocity impacts confirms the results already presented on similar studies: the velocity of the debris cloud generated by the impact is reduced by the effect of the gas. At an internal pressure level of 250 bar, debris cloud is fully stopped by the gas and no debris reaches the rear face of the vessel. It has been found that failure of the pressurized vessel increases with the inflated pressure and that failure mode is directly dependent of the composite stacking sequence. It is shown that the rupture mode is not a bursting mode but rather a catastrophic damage of the external carbon composite part of the vessel.

This first analysis has to be confirmed by future calculations and complementary experiments.

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