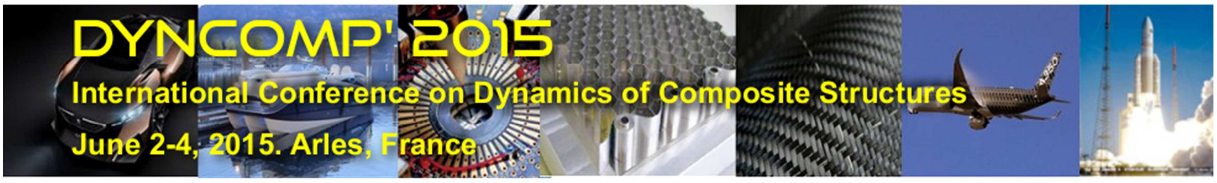

HYPERVELOCITY IMPACTS ON COMPOSITE OVERWRAPPED PRESSURIZED VESSELS

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ABSTRACT

In the framework of its R&T activities, French Space Agency CNES has entrusted the study of the consequences of high velocity impact on a composite overwrapped pressurized vessels to two SMEs THIOT INGENIERIE and IMPETUS AFEA. The general context of this project is to study the vulnerability of a pressurized tank onboard spacecraft impacted by a projectile at high velocity. Tanks selected for this study are commercially available that consist of an aluminum liner and four composite layers made of carbon fibers and silica fibers. The impact tests, performed by THIOT INGENIERIE, were instrumented with suitable metrology in the field of shock to identify the main physical phenomena associated to the hypervelocity impact of a few grams aluminum ball on a pressurized tank. Numerical simulations of these impact configurations were performed with IMPETUS AFEA solver which is based on innovative and advanced numerical methods: High order Finite Elements, meshless method called γSPH. This unique approach has been fully implemented in 3 dimensions and represents the real geometry of the tanks (as opposed to 2D axisymmetric simulations). Performing comparison with experiment, numerical simulation reproduces the main physical phenomena identified in the experiments, as the 3D cracking failure modes. Although some items would need to be improved to better reproduce the physical mechanisms, the reliability of these calculations is sufficient to extrapolate these first results in a range of more representative impact operational applications (impact velocity > 15 km / s). Thus a method for analyzing such impact configurations is set to address the risk of tank loss or explosion and space debris generation. The proposed method to answer this question is to implement in a coordinated way, tests of impact on tanks, load calculations and material behavior characterization in the ranges encountered in these extreme impacts configurations.

1 INTRODUCTION

Vulnerability of spacecraft to debris impacts is a burning issue which has led to many Research & Development actions in CNES, especially since the *Loi relative aux Opérations Spatiales* has entered into force in 2009. Indeed, hypervelocity impacts on satellite structure could lead to exponential increase of space debris which, in the worst scenario, would not allow to use anymore orbits for spacecraft operations. In that frame, CNES has started to study modelling of HVI on pressurized vessels since many years [1]. Even if tests could be done, modelling is not a small matter when dynamic reaches several km/s for impacts, coupled with hydrodynamic effects due to pressurized gas and with an appropriate model for composite behavior. Aim of this study was to work out a methodology to model theses effects and to correlate with dedicated tests. In order to reduce costs and to concentrate on phenomenon rather than on a specific part, tanks selected for this study are commercially available and not tanks dedicated for space applications. They consist of an aluminum liner and four composite layers made of carbon fibers and silica fibers. Approach is to build a general method that could be suitable to reproduce expected and observed effects. This method has to be usable in an industrial context and should be later implemented to extrapolate results for different velocity range and different pressure vessels configuration. The objective is to better assess risks of explosion of a tank submitted to different size of high velocity debris.

2 SIMULATION APPROACH

Finite elements methods widely spreaded in industrial simulation codes are limited to predict large deformations behaviors or phenomena localization. IMPETUS AFEA looked for new modeling solutions to be able to simulate a hypervelocity impact of an aluminum ball of few grams on a pressurized tank made up of aluminum liner and CFRP composite. IMPETUS AFEA solver is based on two innovative and advanced numerical methods:

- **High Order Solid Finite Elements**
- **Meshless method called γSPH (Smooothed Particle Hydrodynamics)**

Originally developed to simulate gas and fluid behaviors, SPH method is used for impact simulation since 1996 [2]. This method is particularly adapted to hypervelocity impact on axisymmetric structure or small nonsymmetrical structure. SPH method drawback is a long calculation time and instability for high tensile stress. A full SPH approach is therefore limited to 2D case study and is not able to evaluate intermediate states between perforation, cracking and total explosion. IMPETUS AFEA focused on a more robust approach to predict large deformation and pressurized tank cracking: a third order solid finite elements formulation (64 integration points). γSPH [3] method remains the relevant method for the tank gas/fluid modeling.

2.1 High order finite elements

IMPETUS AFEA has developed a high order finite element approach for transient dynamics. The main features obtained are the following:

- High precision for large deformation and plasticity.
- Low finite elements sensitivity to a poor aspect ratio
- No zero energy deformation mode (exact integration)
- Simulation of inter elements cracks (node splitting)

Given these characteristics IMPETUS AFEA approach is perfectly adapted to tanks modeling.

2.2 IMPETUS AFEA simulation approach for hypervelocity impacts on pressurized tank.

An innovative approach that couple γSPH and high order finite elements is proposed and illustrated in Figure 1.

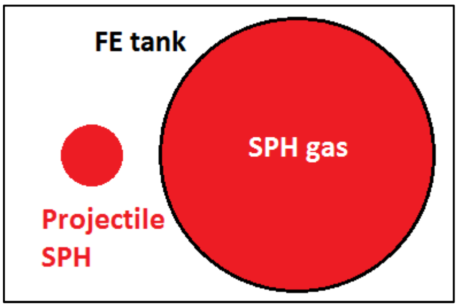

Figure 1. Modeling approach

The projectile is described by the γSPH method to keep its exact mass and simulate a "cloud" generation.
Internal gas or fluid modeling is also based on a γSPH formulation to take properly into account interactions between fragments in the fluid and the propagation of the shock wave generated by the impact.
Tank structure model is based on a high order finite elements approach. This approach enables to simulate advanced mechanisms like aluminum cracks and composite damages and delamination.

2.3 Composite structure modeling

2.3.1 Intra lamina modeling

IMPETUS AFEA solver uses an advanced method to predict damage evolution in the fibre reinforced plastic (CFRP) structure. This method is based on unidirectional lamina damage functions derived from Hashin criteria [4], damage variables growth rates governed by a damage rule suggested by [5], a damage coupling functions described hereafter, a node-splitting formulation to enable crack propagation and a strain-rate dependent functions for the elastic moduli.
Three damage functions are used for fiber failure, one in tension/shear, one in compression, and another one in crush under pressure. They are chosen in terms of quadratic strain forms as follows.

- Tension/Shear:

$$f_1 - r_1^2 = \left(\frac{E_a\langle\varepsilon_a\rangle}{\sigma_{aT}}\right)^2 + \left(\frac{G_{ab}^2\varepsilon_{ab}^2 + G_{ca}^2\varepsilon_{ca}^2}{\sigma_{FS}^2}\right) - r_1^2 = 0 \quad (1)$$

- Compression:

$$f_2 - r_2^2 = \left(\frac{E_a\left\langle\varepsilon_a^{'}\right\rangle}{\sigma_{aC}}\right)^2 - r_2^2 = 0 \quad (2)$$

$$\varepsilon_a^{'} = -\varepsilon_a - \frac{\langle -E_c\varepsilon_c - E_b\varepsilon_b\rangle}{2E_a} \quad (3)$$

- Crush:

$$f_3 - r_3^2 = \left(\frac{E_c\langle -\varepsilon_c\rangle}{\sigma_{FC}}\right)^2 - r_3^2 = 0 \quad (4)$$

Where a, b, c are the fiber direction, transverse direction and out of plane direction, $\langle\cdot\rangle$ are Macaulay brackets, σ_{aT} and σ_{aC} are the tensile and compressive strengths in the fiber direction, and σ_{FS} and σ_{FC} are the layer strengths associated with the fiber shear and crush failure, respectively.
Matrix mode failures must occur without fiber failure, and hence they will be on planes parallel to fibers. Two matrix damage functions are chosen:

- Transverse compression mode:

$$f_4 - r_4^2 = \left(\frac{E_b\langle -\varepsilon_b\rangle}{\sigma_{bC}}\right)^2 - r_4^2 = 0 \quad (5)$$

- Perpendicular matrix mode:

$$f_5 - r_5^2 = \left(\frac{E_b\langle\varepsilon_b\rangle}{\sigma_{bT}}\right)^2 + \left(\frac{G_{bc}\varepsilon_{bc}}{\sigma_{bc0}+\sigma_{SRB}}\right)^2 + \left(\frac{G_{ab}\varepsilon_{ab}}{\sigma_{ab0}+\sigma_{SRB}}\right)^2 - r_5^2 = 0 \quad (6)$$

where σ_{bT} is the transverse tensile strength, σ_{ab0} and σ_{bc0} are the shear strength values of the corresponding tensile modes $\varepsilon_b > 0$ or $\varepsilon_c > 0$). Under compressive transverse strain ($\varepsilon_b < 0$ or $\varepsilon_c < 0$), the damaged surface is considered to be "closed", and the damage strengths are assumed to depend on the compressive normal strains based on the Mohr-Coulomb theory:

$$\sigma_{SRB} = E_b \tan(\varphi)\langle -\varepsilon_b\rangle \quad (7)$$

Where φ is a material constant as $\tan(\varphi)$ is similar to the coefficient of friction.

The damage thresholds, r_j, j = 1,2,3,4,5 have the initial values equal to 1 before the damage initiated, and are updated due to damage accumulation in the damage modes.

A set of damage variables $\dot{\varpi}_i$ with i = 1, …6, are introduced to relate the onset and growth of damage to stiffness losses in the material. The compliance matrix [S] is related to the damage variables as [5]:

$$[S]=\begin{bmatrix} \frac{1}{(1-\varpi_1)E_a} & \frac{-\nu_{ba}}{E_b} & \frac{-\nu_{ca}}{E_c} & 0 & 0 & 0 \\ \frac{-\nu_{ab}}{E_a} & \frac{1}{(1-\varpi_2)E_b} & \frac{-\nu_{cb}}{E_c} & 0 & 0 & 0 \\ \frac{-\nu_{ac}}{E_a} & \frac{-\nu_{bc}}{E_b} & \frac{1}{(1-\varpi_3)E_c} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{(1-\varpi_4)G_{ab}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{(1-\varpi_5)G_{bc}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{(1-\varpi_6)G_{ca}} \end{bmatrix} \quad (8)$$

The stiffness matrix C is obtained by inverting the compliance matrix.

As suggested in Matzenmiller et al. [5], $\dot{\varpi}_i$ is governed by the damage rule:

$$\dot{\varpi}_i = \max\left\{\dot{\phi}_j q_{ij}\right\} \quad (8)$$

where the scalar functions $\dot{\phi}_j$ control the amount of growth and the vector-valued functions qij (i=1,…6, j=1,…5) provide the coupling between the individual damage variables (i) and the various damage modes (j). Five damage modes are taken into consideration in this model.

$$\phi_j = 1-\exp\left(\frac{1}{m_j}\left(1-r_j^{m_j}\right)\right) \quad (9)$$

Equation (9) gives $\dot{\phi}_j$ evolution law. m_j is a material constant for softening behavior.

The damage coupling functions qij are considered for the unidirectional and fabric models as:

$$q_{ij}^{UD}=\begin{bmatrix} 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 \end{bmatrix} \quad (10)$$

2.3.2 *Inter lamina modeling*

Cohesive links method is used to simulate delamination. Cohesive links are implemented between each composite plies and between the first composite ply and the aluminum liner.

3 TEST FACILITY AND INSTRUMENTATION PLAN

3.1 Existing facilities and previous works

Based on IADC works, hypervelocity phenomenon is defined for a velocity higher than typically 1km/s. With this velocity, projectile and the target are severely damaged in impacted areas. Some works have been previously achieved performing HVI on tanks, among them NASA laboratories (USA) and EMI (G) have performed HVI tests (Vp~6.5 km/s) on metallic tanks (aluminum and Titanium) pressurized up to 25 bars, with high-velocity camera. HVI up to 8 km/s could be reached by double-stages laboratory launcher using gas, without damaging the projectile. Other technologies like 3-stages launchers or explosive launchers could reach velocities higher than 8 km/s but most of the case without keeping integrity of projectiles.

For this tests campaign, the double stage launcher HERMES in THIOT INGENIERIE has been used.

3.2 Phenomena to be characterized

HVI effects on tanks could be depicted in 3 phases:

- Hydrodynamic: energy transmitted by the target and contained by the projectile will diffuse, creating a shock wave which will allow transfer kinetic energy from projectile to target. Hemispheric crater arises and ejection of material starts.

- Shock damage: the spherical shock will propagate, with attenuation, which leads to damage the target: plastification or fragmentation, depending on ductility or fragility of the material.
- Damage by reflected shock wave: propagation and reflection of shock waves could even lead to plastification of thin targets under high velocity conditions, near free surface.

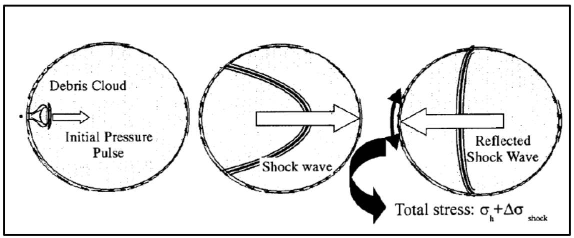

Figure 2. Illustration of impact phenomena

3.3 Instrumentation plan

In order to bring out the different steps and associated parameters, following metrology has been implemented:

- Velocity laser barrier to record impact velocity
- Deformation gauge to characterize CFRP tank deformation.
- Interferometer (PDV or VH system) to measure local material velocity
- Flash X-Ray 150 keV to characterize post impact cloud of fragments.

Instrumentation has been changed between the first two trials and the five remaining in order to improve information recorded relative to fragments cloud and to guarantee a sufficient number of measurement points.

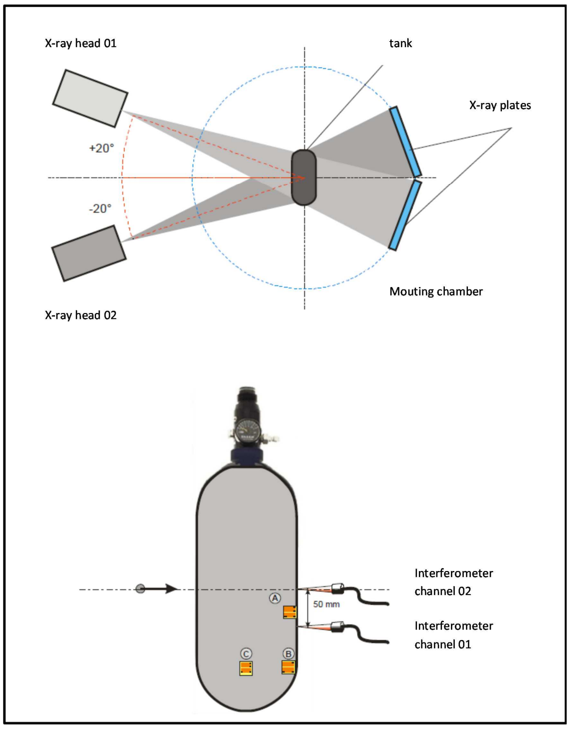

Figure 3. Instrumentation used for end of test campaign

3.4 Test plan

Test campaign has been based on 7 impact trials and one quasi-static trial without HVI. Hereafter are descripted the parameters associated to each trial.

Test ID	Projectile velocity (m/s)	Nitrogen pressure (bar)
#HE0183	4334±60	1
#HE0184	4425±60	200
#HE0187	4322±60	250
#HE0188	4310±60	300
#HE0208	4638±120	1 bar Water
#HE0212	No HVI : quasi-static explosion	687
#HE0213	4341±40	400
#HE0214	4410±40	500

Table 1. Trial parameters

Used projectile is a 8mm diameter aluminum ball, projected with velocities around 4350 m/s and a normal incidence. Internal pressure is varying from one trial to the other, in order to determine if there is a threshold beyond which the impact leads not to perforation but to an explosion of the CFRP tank.

3.5 Test results

3.5.1 Quasi-static burst pressure test (#HE0212)

This reference test, performed to rescale the tank model, has led to a burst pressure determination of 687 bar. Nonlinear behaviour of the tank has been highlighted with a non-homogeneous deformation of the tank when pressure exceeds 300 bar. To explain this phenomenon, following assumptions have been made:

- Local strain of supports on which were glued the gauge (external coating and CFRP plies)
- Non homogenous strain of CFRP plies
- Pre-stresses of CFRP lies with non-uniform thicknesses on metallic liner which could also have variable thickness.

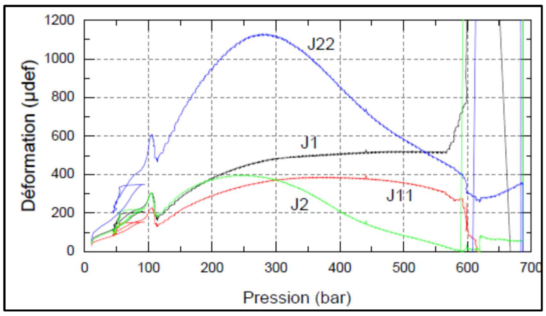

Figure 4. Strain vs. Pressure

3.5.2 Impact tests

First test has been performed without pressure in the tank to start with a reference configuration. Pressure has been progressively increased for the following trials, until 500 bars. Only one trial has been performed with the CFRP tank filled with 1bar water, in order to increase shock pressure effects in fluid with respect to structural deformation. This trial has led to a simple perforation of the tank with a hole diameter higher than with gaseous configurations. However shockwave could not be characterized under this condition, due to water density not compatible with instrumentation.


Figure 5. Perforation of tank with large mushrooming for trial with water #HE0208

After impact tests on Nitrogen pressure tanks, they are splitted in 3 or 4 main pieces, with numerous fragments of fiber composite. Whereas the tanks have been deeply damaged, they have not exploded. Shock wave in pressurized gas has been highlighted.

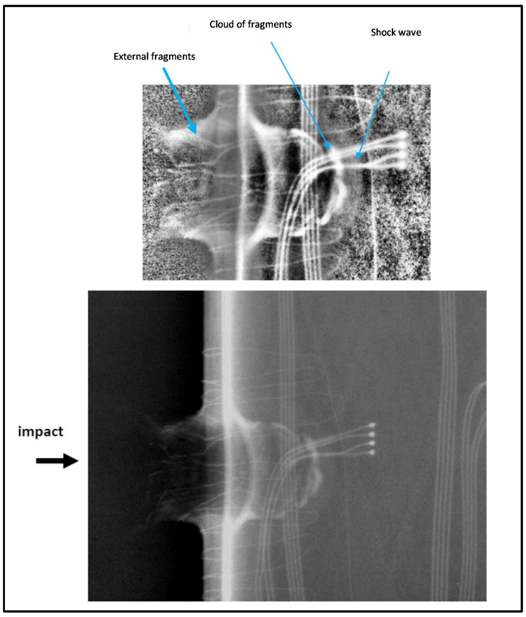

Figure 6. X-Ray diagnosis for trial #HE0184 at 200 bars

This wave foreruns the cloud of fragments and attenuates progressively along its propagation. Moreover, it has been shown that cloud of fragments generated by HVI is slow down by pressurized gas. No fragment has reached opposite surface to impact point except for trial #HE0184 at 200 bars. In velocity diagram for test #HE0184, origin of diagram is taken as impact of the ball on the tank, thus compression wave is observed at 84µs.

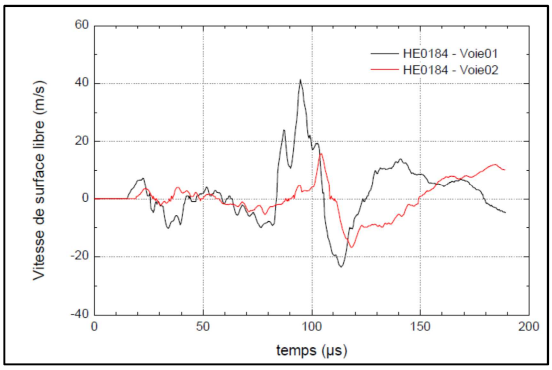

Figure 7. Velocity diagram of rear face for trial #HE0184

3.5.3 TEST CAMPAIGN SYNTHESIS

When comparison is performed between relevant trials on rear face velocity reached perpendicular to impact point, same events are observed at the same time.

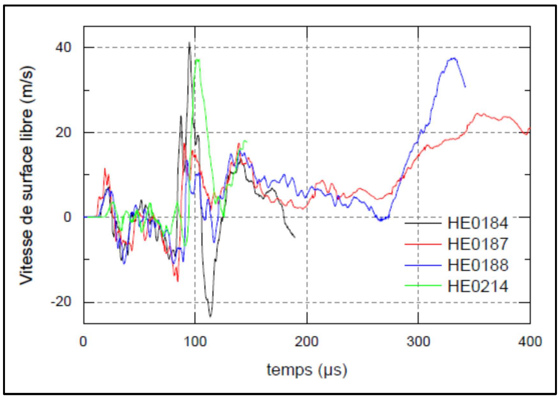

Figure 8. Free surface velocity vs. time

First two oscillations correspond to structural deformation due to compression/relaxation waves. Then around 85µs, higher oscillations are highlighted which could be linked to creation of shock wave transmitted in pressurized gas.

It is worth to notice that damage state of tank after impact is deeply correlated to pressure level. Preload of metallic liner by composite winding under pressure drives mainly the failure mode of the tank.

		Nb of pieces	Central fragment width
HE0184 200 bar		1	40 mm
HE0187 250 bar		1	35 à 70 mm
HE0188 300 bar		2	55 mm
HE0213 400 bar		2	80 mm
HE0214 500 bar		2	105 mm

Figure 9. Overview of highly pressurized tanks after HVI

The ball perforates CFRP layers (also metallic liner) and near the impact, preload of the liner decreases due to damage of the CFRP which was sustaining the pressure loads. Finally it leads to inject high stress directly on the liner which causes its breakdown.

4 MODEL SET UP AND SIMULATION RESULTS

4.1 Model set up

To model hypervelocity impact on a pressurized tank, a strong gas/tank coupling has to be taken into account. Several issues that lead the model set up can are described below.

4.1.1 Impact behavior with a 1 bar pressurized tank.

A first 3D model has been developed to validate the qualitative behavior of a hypervelocity impact on an empty tank (3 order high order finite elements model). The main simulation difficulties of this model are:

- The very large deformations
- Free edges creation (fragmentations or cracking)
- Simulation stability

The model predicts well the tank fragmentation, its energetic balance is relevant. Figure 10 shows simulation and experimental results.

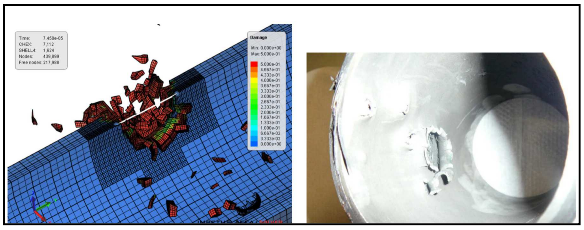

Figure 10. Simulation and experimental results.

4.1.2 Tank pressure initialization

Next step is to validate the quasi-static state before tank impact. Tank pressure initialization is fulfilled through a 3D model coupling High order(tank) and γSPH(gas) methods. A relaxing dynamic method (damping) is used to obtain a steady state. The pressurized tank steady state is validated comparing the coupled model obtained with a simple finite element model (linear static without gas).

4.1.3 Full fluid/structure coupling for impact simulation.

A full coupled 3D model SPH/EF based on the first 3D model presented in *4.1.1* is done to validate the SPH/EF methods coupling. Simulation shows a hypervelocity impact behavior as well as the tank fragmentation and the gas shock wave qualitatively representative of the physical phenomena.

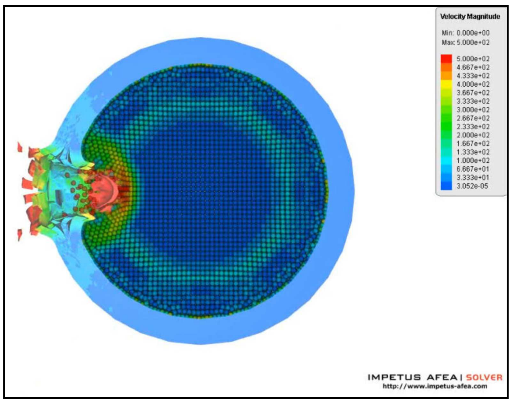

Figure 11. Cut view of a simplified coupled model SPH/EF.

4.1.4 Prestressed quasi-static state

Aluminum liner is prestressed during the composite layering. This prestressed state is taken into account adding a thermal load on aluminum liner that induces 80% of aluminum yield strength at 300 bars. To define this initial state a full 3D coupled model is developed. This model is used later for 3D impact simulations.

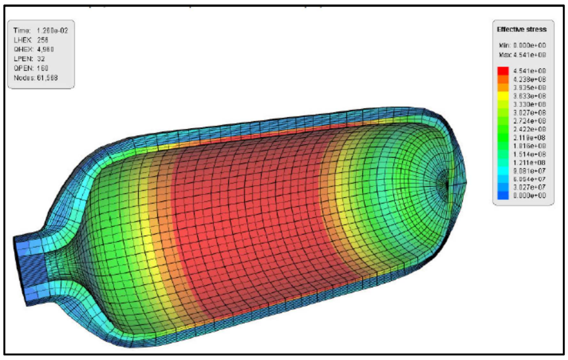

Figure 12. Tank prestress initialization.

4.1.5 2D simulations

2D plane models are developed:

- To set experimental parameters (projectile size, velocity and mass) to obtain the desired failure mode (tank explosion)
- To identify a relevant mesh size for the 3D model (particularly for SPH elements) to simulate properly gas/structure coupling and to value precisely the

coupled method representativeness from a qualitative point of view.

Figure 13. illustrates 2D model results.

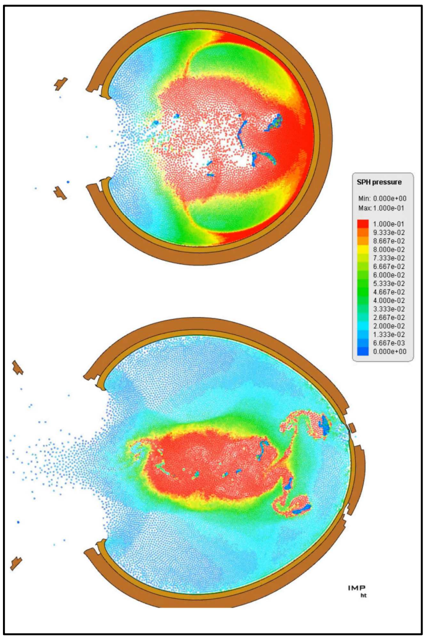

Figure 13. 2D model simulation of the tank explosion.

Such 2D models enable to simulate several cases in a reasonable time scale.

4.1.6 Damage parameters calibration

Damage models parameters have been identified thanks to literature data.

Full 3D model is readjusted through 2 impact tests (Case 1: 8mm ball, 4500m/s speed and 1 bar pressure, see trial #HE0183. Case 2: 8mm ball, 4500m/s speed and300 bar pressure, see trial #HE0188). This approach limits the model predictability. A complete identification phase should be performed for industrial use.

4.2 3D Simulation results

Main failure mechanisms are well predicted by IMPETUS AFEA 3D model (cloud propagation and shock wave). Figure 14 show a predicted wave front delay. This delay is not observed at t=13µs (left part of Figure 14) but at 28µs (right part of Figure 14). Two factors could explain this delay: a too rough SPH elements meshing or/and a state equation not precise enough.

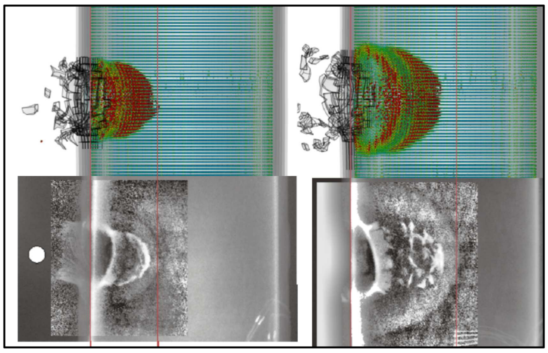

Figure 14. Simulation vs. test wave front comparison.

Failure modes of experimental cases that led to a simple tank perforation without a total explosion are well predicted in simulations.

Figure 15 and 16 show that coupling between aluminum ductile behavior and composite fragile behavior that leads for the highest energy cases to a longitudinal cracks until bifurcation points and a total tank explosion is well simulated as well.

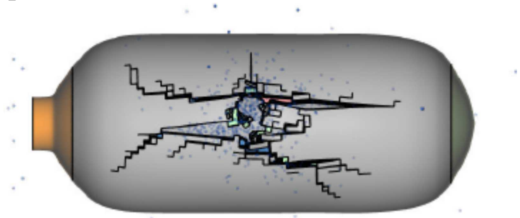

Figure 15. 300bars, 20000m/s, t=100 µs.

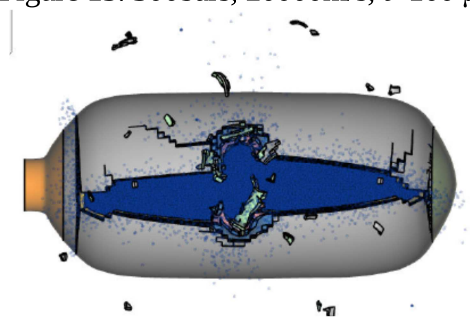

Figure 16. 300bars, 4500m/s, t=200 µs.

Mean computational time is 12 hours (1CPU+1GPU). The development of an axisymmetric SPH approach on a GPU (Graphics Processing Unit) should reduce computational time to 1h.

Simulations show total energy conservation.

5 CONCLUSION

Simulations performed by IMPETUS AFEA software have shown that using innovative methodologies (Lagrangian and γSPH) is appropriate to model properly the physical phenomena identified during experiments performed by THIOT INGENIERIE:

- Perforation of front face of the tank and mushrooming correlated to pressure level.
- Generation of a cloud of fragments which will be progressively slow down by the gas, depending on pressure level
- Generation of a shock wave in pressurized gas, which foreruns the cloud of fragments
- Generation of a structural deformation wave in the tank
- Damage and fragmentation of the tank correlated to the pressure level.

Total energy conservation has been respected. Time calculations while important (~ 12h) are realistic from an industrial point of view and can be significantly reduced using a SPH axisymmetric method.

IMPETUS AFEA simulation method has the potential to well assess risks of tank explosions submitted to different kind of high velocity debris, efforts have to be done on its predictability. A complete damage and material parameters identification has to be fulfilled for any industrial use.

Next step would be to consider a typical spacecraft tank which characteristics are slightly different from the tank considered here, particularly in term of structure (thinner liner, thicker composite).

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