Vulnerability of fuel tanks with respect to hydrodynamic ram pressure - Experiments and FE modellings

E. Deletombe, J. Fabis, Jacques Dupas

Vulnerability of fuel tanks with respect to hydrodynamic ram pressure – Experiments and FE modellings

E. Deletombe[1]
J. Fabis[1], J. Dupas[1]

[1] DADS/CRD, ONERA, France,eric.deletombe@onera.fr

Résumé — A qualitative and quantitative analysis is proposed to define relevant equivalent load functions to be used for non linear structural analysis of aircraft fuel tank subject to 7,62 mm hydrodynamic ram effects. For the qualitative point of view, the main conclusion is that any load case that would only be based on peak pressure analysis would underestimate the final damage level in the structure : both the "acoustic" wave and the cavity in the wake of the 7,62 mm bullet potentially generate (at different time scales) more significant energy/momentum loads onto the structure walls.
Mots clefs — HRAM, Vulnerability, fuel tanks, 7,62 mm.

1 Introduction

Reducing vulnerability of aircraft fuel tanks against the hydrodynamic ram pressure effects generated by a high speed/high energy 7,62 mm projectile is a complex fluid/structure mechanical problem. The projectile is meant to perforate the fuel tank wall with enough remaining energy to induce high energy and momentum transfer to the fluid, hence generating a short transient shock wave (1-3 ms), followed by a longer cavity bubble growth and collapse phase (10-30 ms) that would both possibly rupture the structure at different time scales [1]. The accurate non linear simulation of the full HRAM phenomenon would require the use of complex multiphasic fluids and nonlinear rupture material/assembly models : it first leads to very high computing costs, and also raises many numerical questions (code coupling, stability, mesh sensitivity, accuracy, …). Such a multi-physical and multi-scale (time and space) modelling is still in the field of theoretical and numerical Research.

The engineering objective of the presented work is to rapidly and roughly discriminate what has to be modelled to estimate the induced level of HRAM damage in a tank structure, assess its residual strength, and possibly improve its design. The final goal is to use an explicit lagrangian FE code to study the structural response of the fuel tank, using generic equivalent "load" functions (mapping process) instead of modelling the fluid medium and its interaction with the projectile, first, and the structure, second. The first hypothesis that is made is that one would only consider minor changes of the fuel tank design, that would not affect the generic load functions in return (soft coupling of the fluid vs structure responses). There are two possibilities to do so : either we model the full complex problem then extract the load functions that are computed at the interface between the fluid and the structure, which is another ongoing Research work at ONERA/DADS/CRD, or we use experimental results (and perform different tests for each specific HRAM configuration : projectile speed and energy, fuel tank geometry and overall stiffness) to get such generic loads.

The present work concerns the second approach. The case of a 7,62 mm ballistic impact is studied where the HRAM scenario differs from cases when the projectile has a constant shape with no cavity "bubble" but only a wake being created in the liquid [4]. The tests which are documented in the paper have been performed at ONERA/DADS/CRD in the frame of the RTP3.32 EUCLID project, funded by the French MoD (DGA). Note that the general experimental observation are very similar to those described in [2] (to see for more bibliography), where a 12,7 mm bullet was used.

2 General considerations to derive Vulnerability requirements

In the field of dynamic strength of structures, the authors consider that the main point to care about is the energy (rate) transferred to the targeted structure that has to cope with. For instance, the structure "adaptation" might be kinetic (fragments projection), by heat or by irreversible solid deformation, damage and rupture. The studied mechanical system in which energy conservation principle is applied, is made of different "sub-systems" (7,32 mm projectile, cavity bubble, liquid medium, and solid structure). For each sub-system, different physical phenomena are involved, and ranked, according to the energy amount they would dissipate, store and release during the HRAM event. Some of them can be evaluated from the available test data, but others cannot.

So this part of the paper focuses on general theoretical considerations. It is not here question of performing any formal thermodynamical analysis of the problem (are we considering an isenthalpic, isentropic, isothermal, adiabatic, etc, process when studying our HRAM problem ?). We only propose to perform a coarse energy evaluation exercise on the open mechanical system with is constituted by : the cavity bubble, the liquid mass, and the solid structure. We will neglect any cavitation at the interface between the structure and the liquid. We assume that our fuel tank is at equilibrium at initial time (before impact), and that the different initial potential energies in each sub-system will not be released into damage increase during the HRAM event. The energy which is added in the system (part of the initial kinetic energy of the bullet) will be distributed between different energy parts :

ΔE_S	System Total Energy Increase
$f(E_B)$	Bullet Energy (Source)
ΔE_{sC}	Sub-system/Cavitation Bubble Energy
ΔE_{sL}	Sub-system/Liquid Energy
ΔE_{sT}	Sub-system/Tank Energy

During the process we suppose that :

$$\Delta E_S = f(E_B), \text{ and } \Delta E_S = f(E_B) = \Delta E_{sC} + \Delta E_{sL} + \Delta E_{sT} \quad (1)$$

We consider in the present work that the way the transferred energy (and momentum) are dealt with by the structure is properly solved by the explicit FE code that will be used in the end (wave propagation, momentum, material behaviours, etc). Then the structural problem may be written in terms of energy as :

$$\Delta E_{sT} = f(E_B) - \Delta E_{sC} - \Delta E_{sL} \qquad (2)$$

Each sub-system energy variation is divided into different components, for instance : the kinetic energy of the sub-system, the potential (internal stored) energy of the sub-system, and the dissipated energy in the sub-system. A number of assumptions is made to deal with unknown quantities, hopefully in a conservative way with respect to the ultimate goal of the study : the damage prediction in the structure.

2.1 Assumptions concerning the 7,62 mm bullet sub-system energy

Different assumptions are made concerning $f(E_B)$:

1) as we cannot measure precisely the bullet velocity and mass just after it has perforated the front wall of the fuel tank, we will assume the initial mass and velocity is unchanged,
2) though we know that the 7,62 mm will tear apart and probably heat when it tumbles across the fluid, we will not consider the associated dissipated energy because we do not know their value,
3) we will neglect other kind of potential energy (such as gravity).

Then we assume that all the (initial) kinetic energy of the bullet sub-system is progressively transferred into the other sub-systems energies, and that this approximation should maximise the energy transferred to the composite fuel tank structure to damage it. The amount of transferred energy that is considered in the present study is shown on fig. 1 : the initial velocity of the 9 g bullet is about 800 m/s before impact, and the tank dimensions about 300 mm in height (bullet trajectory), 550 mm in width and 650 mm in depth. It is fully filled of water. The bullet velocity was recorded/evaluated using high speed digital cameras (two walls of the caisson are PMMA windows).

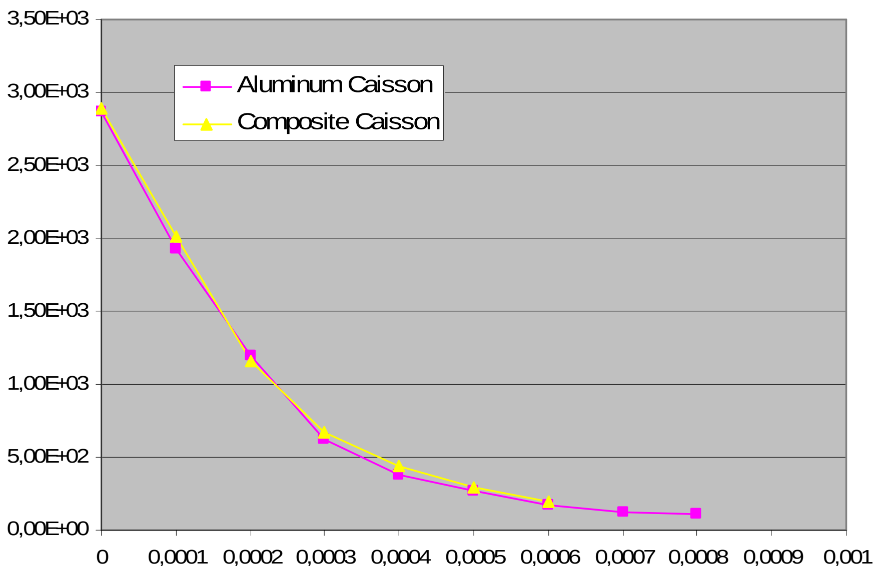

FIG 1 : Evolution of Kinetic Energy (J) vs Time (s) of the 7,62 mm bullet in the tank

2.2 Assumptions concerning the wake and cavity behind the bullet

The cavity bubble (see fig. 2) develops long after the initial pressure pulse (shock wave) has vanished. We will consider that :

1) the kinetic and potential (gravity) energy of the water vapour in the cavity are unimportant compared to its latent energy (energy stored in physico-chemical change),
2) any calorific energy created during the HRAM process will never reverse back into a mechanical energy that could notably load the fuel tank structure (and we do not know how much energy it could be), so we will consider that temperature is constant (ambient) in the cavity during the HRAM process,
3) no viscous energy is dissipated in the liquid vapour.

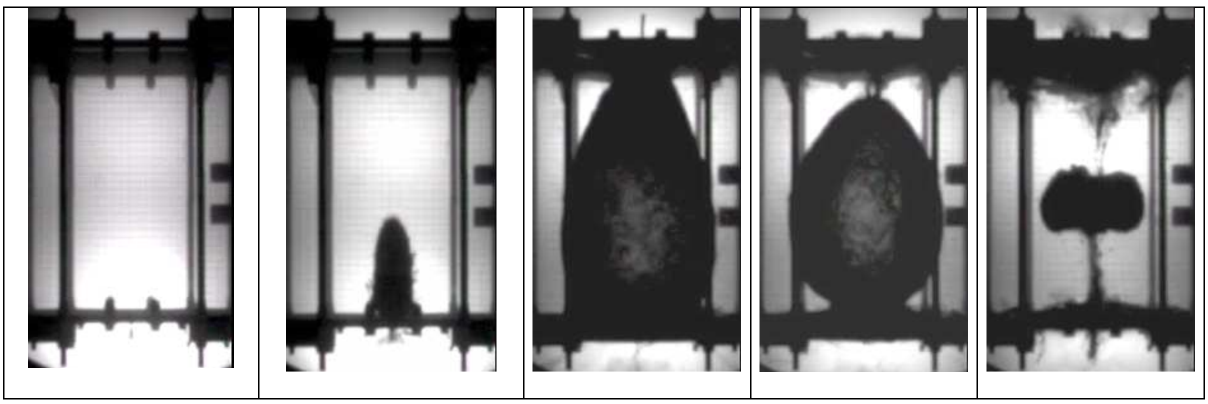

FIG 2 : Pictures (0/0,2/2,5/4,5 and 6,5 ms) in caisson, with high speed camera (10+3 im/s)

The main energy to be considered for the cavity bubble then corresponds to the latent heat. An important question is : what is its amount (in fact, some air is entrapped in the wake of the bullet, and the gaz is an air/water vapour mixture) ? If we consider that the cavity is only full of water vapour (pure cavitation phenomenon), then the latent heat is the amount of energy stored (and released later) by water during its change of state without changing of temperature, meaning a phase transition :

$$Q = \rho_C V_C L_v \qquad (3)$$

where Q is the amount of energy stored (and released) during the change of phase of the water, V_C the volume of the cavitation bubble, ρ_C the vapour density, and L_v the specific latent heat of vapourization. To calculate the latent heat, we need the volume of the cavity bubble V_C. This volume is experimentaly estimated from high speed camera pictures. The point then is to choose values for L_v and ρ_C. Those values would depend on the thermodynamical state of the vapour in the cavitation bubble : temperature and pressure, that we do not know and which possibly vary during the test. Different possible values are given hereafter for the thermodynamical coefficients :

TAB 1. : Vapour physical parameters for different thermomechanical conditions

P	T	ρ_c	L_v	C_v
Pa	°C	kg/m3	J/kg	J/kg
2,00E+03	290,67	0.015	2,46E+06	1,86E+03
1,00E+05	372,79	0.590	2,26E+06	2,03E+03
3,00E+06	507	15.009	1,79E+06	3,41E+03

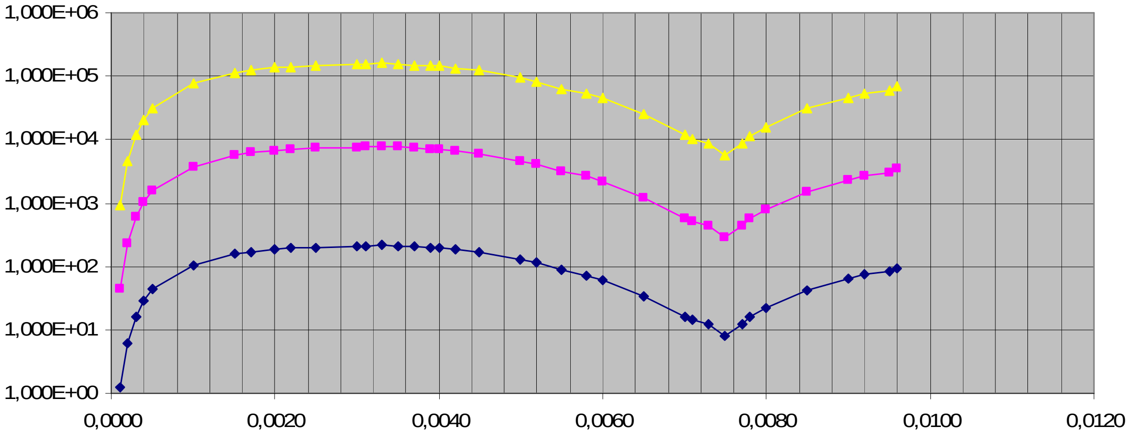

FIG 3 : Order of magnitude of cavitation bubble latent energy (J) vs Time (s) for different level of external pressure (blue 0,02 Patm, pink 1 Patm, and yellow 30 Patm), wrt the observed volume of the cavity bubble

In the end, latent heat evolution can be calculated according to thermodynamical state assumptions. If we consider an isothermic cavitation process in the liquid under 1 Patm, 293 K conditions, then :

$$P_{sat} = P_0 e^{\frac{ML_v}{R}\left(\frac{1}{T_0}-\frac{1}{T}\right)} = 0.0204 \text{ Patm} \qquad (4)$$

with T_0 =373 K, M = 0,018 kg/mol, L_v = 2,455×10+6 J/kg, R = 8,31447 J/K/mol, P_0 = 10+5 Pa. Then the maximum latent energy reaches about 200 J (0,02 Patm), which is the estimation that we will take (no experimental information concerning the air/vapour mixture, the temperature and pressure level in the cavitation bubble during the test). This latent energy will be stored (no dissipation assumed) then released during a 8 ms long process (observed time of collapse of the cavity bubble).

2.3 Assumptions concerning the liquid medium (water)

Concerning the liquid medium :

1) we assume that its temperature is constant, and that it behaves as a non viscous fluid. No energy is then supposed to be dissipated in this sub-system,
2) the potential (gravity) energy rise (part of the water is moved upward) is small compared to

other components,
3) its mass and volume are supposed to be constant (incompressible fluid, vapour mass very small – x1000 times less - compared to liquid mass in the fuel tank),

which means that the main energy components will consist in kinetic and acoustic contributions. The next paragraph is specifically dedicated to the evaluation of the energy transfer function by the liquid medium onto the structure.

3 Evaluation of kinetic energy and momentum in the liquid medium

A number of simplifications or assumptions are made (sometimes because of unknown quantities) to evaluate, in the one hand, the purely acoustic energy (compressible liquid) and, on the second hand, the kinetic energy (cavity expansion, uncompressible hypothesis) in the liquid medium (water). Two kinds of experimental data are available, that concern first the (assumed spherical [3]) pressure shock wave (to derive acoustic energy), and the cavity bubble expansion velocity (to derive liquid velocity fields, then momentum and kinetic energy under uncompressible hypothesis).

3.1 Acoustic energy

The pressure gauge is located somewhat in the centre of the tank, at about 0.2 m away from the bullet impact point.on the entry wall of the structure :

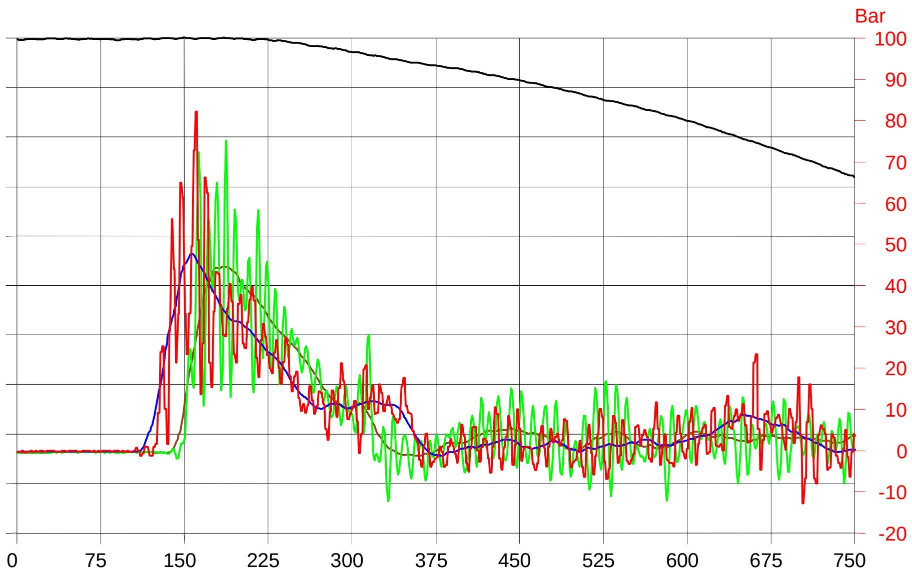

FIG 4 : Relative pressure pulse function P-Patm
(bar) vs time (μs)

For a compressible fluid, a pressure wave induces a density change in the liquid medium (hence and optical indices change) which also means that the fluid particles concentrate thus move when the transient pressure pulse comes through. In an adiabatic process, the acoustic energy corresponds to the internal energy stored in a volume element V when the initial pressure P_0 increases to pa = $P_0 + p$. For a perfect fluid, the internal energy (small perturbations hypothesis) that is transported by pressure waves is known to be made of two components : a kinetic and a purely acoustic one :

$$I = \iiint_V \rho u^2 + \frac{p_a^2}{2\rho c^2} dV \text{ , with : } p_a = c^2(\rho - \rho_0) \qquad (5)$$

with p_a the acoustic pressure, u the fluid velocity, c the sound celerity, and ρ the fluid density (initial and actual values). So we consider a spherical pressure wave radiating from the impact point of the bullet on the tank wall, and inducing an approximated triangular p(t) pulse shape (see fig. 4), that can be correlated in space p(r), knowing the sound celerity and the 0,2 m position of the pressure gage from the impact point. The purely acoustic energy can then be coarsely evaluated from this 5 MPa peak / 0.150 ms long pressure pulse, and reaches a maximum of about 100 J. If we now consider the kinetic component : the increase of density for an average 2,5 MPa pressure peak is only 0,1% of the initial density, but about a 0,3 m^3 volume (then 300 kg) of water is concerned by the pressure pulse, which means that a 3 m/s average fluid velocity increase (in the half-spherical water ring that comes trough the pressure gauge) would be enough to "store" the remaining energy of the bullet initial kinetic energy (once the latent heat and purely acoustic energy is taken out). Unfortunately, it was not possible to measure the fluid velocity field with the experimental techniques that were available at ONERA/DADS/CRD (the particle image velocimetry technique could help, that is used by ONERA/DAAP Department). Nevertheless, this point is of first importance, since this kinetic energy would act on the structural wall thanks to momentum principle.

3.2 Liquid medium kinetic energy due to wake/cavity growth

Another water kinetic energy component is due to the 0.125 m radius / 10 ms cavitation bubble growth and collapse, that can coarsely be calculated. Looking at the high speed camera pictures, we assume as a first order approximation that the volume of water is a sphere of radius $R_2(t)$ with a gaz bubble of radius $R_1(t)$ inside, both in radial expansion (u=$\dot{r}$), and that ρ is constant (uncompressible hypothesis).

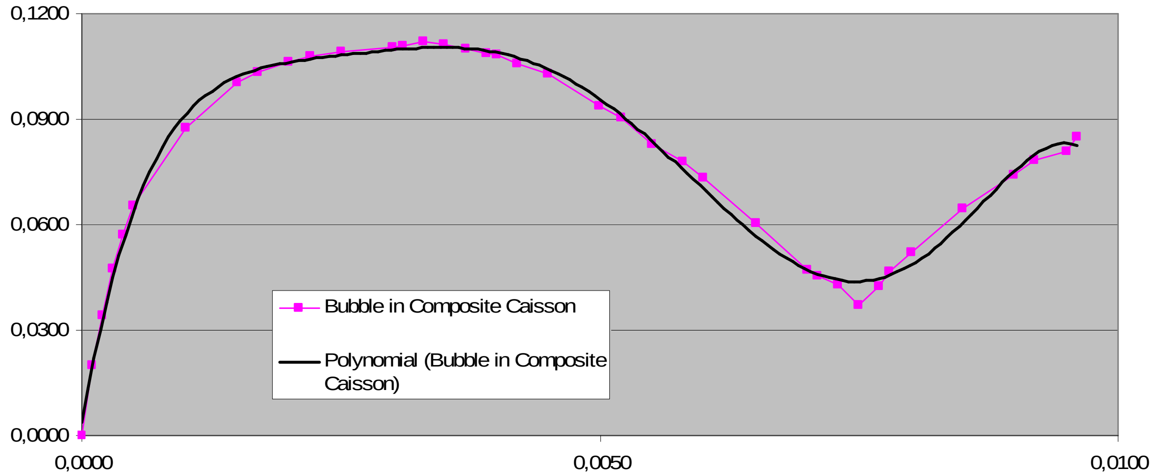

FIG 5 : Cavitation Bubble Radius R_1 (m) vs Time (s) in composite caisson.

Then, the associated variation of kinetic energy in the liquid can be expressed as :

$$\Delta E_{sL}^{k}(t) = \frac{1}{2}\rho\int_0^{\pi}\sin\phi d\phi\int_0^{2\pi}d\theta\int_{R_1(t)}^{R_2(t)}\dot{r}^2 r^2 dr \qquad (6)$$

The conservation of mass of the liquid (i.e. dm/dt=0) gives :

$$R_2^2(t)\frac{dR_2(t)}{dt} = R_1^2(t)\frac{dR_1(t)}{dt} \qquad (7)$$

And more generally : $$\dot{r} = \frac{K}{r^2} \qquad (8)$$

Then : $$\Delta E_{sL}^{k}(t) = \frac{1}{2}\rho\int_0^{\pi}\sin\phi d\phi\int_0^{2\pi}d\theta\int_{R_1(t)}^{R_2(t)}\frac{K^2}{r^2}dr \qquad (9)$$

$$\Delta E_{sL}^{k}(t) = 2\pi\rho K^2(t)\left(\frac{1}{R_1(t)} - \frac{1}{R_2(t)}\right), \text{ with : } K(t) = \dot{r}r^2 = \dot{R}_1 R_1^2 \qquad (10)$$

The conservation of volume (incompressible fluid assumption) is now written to discard R_2 from the above equation :

$$\frac{4}{3}\pi R_2^3(t) = V_0 + \frac{4}{3}\pi R_1^3(t) \qquad (11)$$

The kinetic energy due to the cavity bubble growth (and collapse) can then be calculated from the experiment : a polynomial interpolation of R_1 (from test data) is found and derivated to get $\dot{R}_1(t)$, which makes it possible to get K(t) and compute $\Delta E_{sL}^k(t)$.

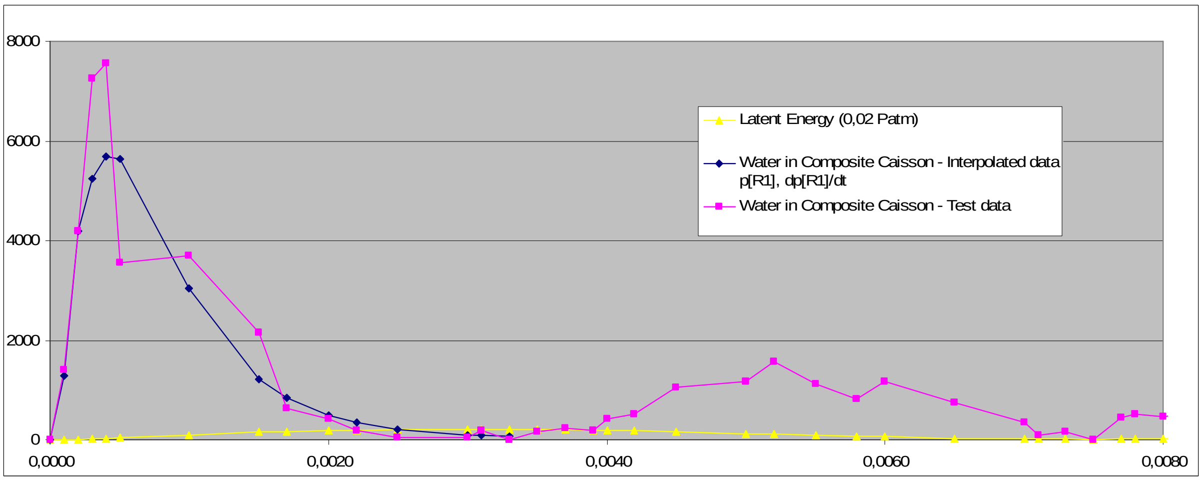

FIG 6 : Evaluation of water kinetic energy (test and interpolation) and latent heat

The kinetic energy largely overpasses the initial kinetic energy of the bullet at the beginning of the penetration phase, which can be easily attributed to experimental “errors” on the cavity “bubble” (which is more a wake than a bubble) radius measurements (see fig. 2). Once the cavity bubble dimension turns to be more measurable (around 0,001 s) the energy amount gets back around the initial kinetic energy of the bullet (which is at that time almost integrally transferred to the system, see fig. 1). Note on fig. 7 that a maximum 3 m/s value would then be obtained as an order of magnitude at the composite wall distance.

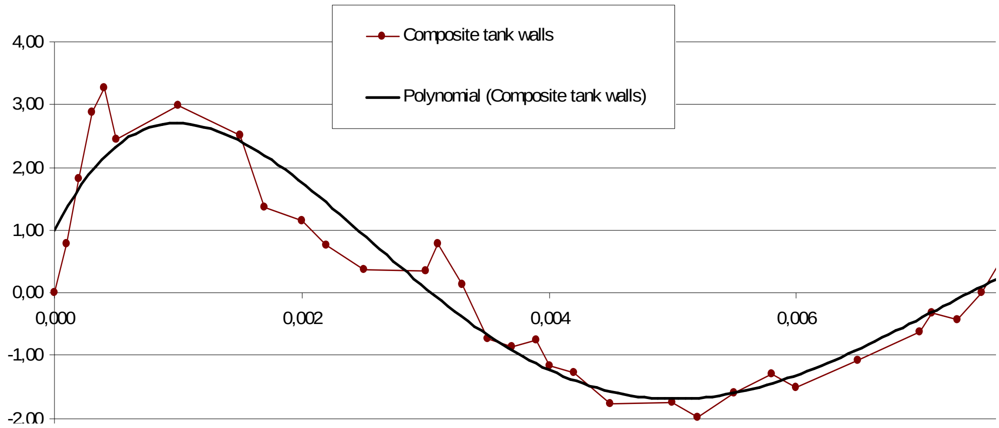

FIG 7. : Evaluation of the liquid velocity at the tank wall location, based on the measurement (and interpolation) of the cavity bubble dimension (uncompressible assumption).

4 Conclusions

HRAM is a very difficult phenomenon to observe and quantify. Most of the time, the structural response of containers is measured (strain gauges, accelerometers, post-mortem analysis) which gives an indirect access to the loading they have to cope with. To study the liquid behaviour, traditional pressure transducers are often immersed in the tanks, but recent works propose to use high speed digital image cameras to observe and measure the dynamic evolution of the geometry of the wake behind, and the cavity around, these projectiles. The originality of the Research compared with the few papers found in the open literature, is that most of them consider constant projectile in shape and then drag coefficients, and only the very first stage of the penetration process (less than 1 ms). The present paper studies two firing tests performed in “confined” water containers, using a deformable NATO 7.62 mm bullet which tumbles and is torn apart during the water penetration process.

A qualitative and quantitative analysis is then proposed to define which kind of simplified equivalent load functions should be applied for FE non linear structural analysis of aircraft fuel tank subject to 7,62 mm hydrodynamic ram effects (subsonic projectiles, large fuel tanks). For the qualitative point of view, the main conclusion seems to be that any load case that would only be based on peak pressure analysis would underestimate the damage level in the structure (except at the entry point where the local pressure might be higher than the material strength [3], particularly for supersonic projectiles [5]). Then, both the acoustic pressure and the cavity growth that forms in the wake of the projectile could potentially transport a most significant kinetic energy trough the fluid, then momentum onto the structure. The share of kinetic energy due to acoustic and cavity mechanisms was not possible to get from the present work. Both of these kinetic energies will act (impulse, momentum) onto the structure walls, but at different time scales : the pressure wave crosses the tank within 0,2 ms and the cavity bubble expansion lasts around 10 ms (with a complex growth/collapse/rebounce scenario), and would both possibly constitute serious threats for the fuel tank integrity.

As it is not possible to share the energy between these two mechanisms, the final proposal would then be to model two “limit” cases with all the energy transported either by the acoustic wave (compressible fluid), on the one hand, or by the “cavity growth”, on the other hand. Both cases can be used to derive impulse or momentum fields (pressure or velocity) that could then be applied onto the tank walls without modelling the bullet/fluid systems : this possibility will be studied at ONERA/DADS in the frame of the EDA BaTolUS project.

The authors would like to thank the French MoD and DGA, for their financial support in the frame of the EUCLID RTP3.32 and EDA BaTolUS projects. The caisson specimens were designed and manufactured by EADS-IWF in the frame of the EUCLID RTP3.32 project.

Références

[1] D.B. Ankeney, *Physical Vulnerability of Aircraft due to Fluid Dynamic Effects*, AGARD Advisory Report n°106, July 1977.

[2] Varas D, Lopez-Puente J, Zaera R., *Experimental analysis of fluid filled aluminium tubes subjected to high velocity impact*, International Journal of Impact Engineering 2008.

[3] Lecysyn Nicolas & al., *Experimental study of hydraulic ram effects on a liquid storage tank : Analysis of overpressure and cavitation induced by a high-speed projectile*, Journal of hazardous materials, ISSN 0304-3894, vol. 178, no1-3, pp. 635-643

[4] Masahiro Nishida, Koichi Tanaka, *Experimental study of perforation and cracking of water-filled alumi-num tubes impacted by steel spheres*, International Journal of Impact Engineering, Volume 32, Issue 12, December 2006, Pages 2000-2016.

[5] Townsend D. , N. Park, P.M. Devall, *Failure of fluid filled structures due to high velocity fragment impact*, International Journal of Impact Engineering 29 (2003) 723–733.