Research on a methodology for flexible fuel tank development

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Résumé :

Depuis de nombreuses années, l'industrie aérospatiale a fait un grand effort pour réduire la masse des aérostructures dans le but de réduire la consommation de carburant. Cette démarche de réduction de masse a été appliquée, d'abord aux éléments structuraux secondaires et récemment primaires (utilisation massive de composites). Dans cet articlenous présentons la recherche d'une méthodologie pour modéliser des réservoirs à parois souples afin de pouvoir mettre en place une démarche d'optimisation. Différentes problématiques seront étudiées, comme la modélisation de l'interaction fluide-structure ainsi que du matériau utilisé dans les parois.

Abstract :

For many years, the aerospace industry has made a major effort to reduce the structural weight of aircraft in order to reduce fuel consumption. This weight reduction procedure has been applied, firstly to secondary and more recentlyto primary structural elements (massive use of composites). In this paper we present the research of a methodology for modelling soft-walled tanks in order to implement an optimization approach. Different problems will be studied, such as the modelling of the fluid-structure interaction as well as the material used in the walls.

Mots clefs : Composites, Sollicitations dynamiques, Interaction Fluide Structure

1 Introduction

As the price of energy increases more and more, the aerospace sector has been investing to lighten aircraft weight. This lightening has been achieved (in past years) introducing composite materials in secondary and, more recently, primary structures. The fuel tank has also an important contribution in the total aircraft weight, especiallyfor military and small size aircraft, so a mass reduction of this component helps to achieve this mass reduction goal. According to Kim and Kim [1], the survivability of the tank is a major concern the integrity of the whole aircraft. Another feature, also very important, is the self-sealing under ballistic impacts. Some studies of the tank behavior under this kind of impact can be seen in [2-3]. Reducing the weight of tanks walls implies a more accurate design of their walls and self-sealing materials. It means that the use of numerical simulations becomes capital to reduce the design phase and to guide designers to a better solution at less cost.

In the past, a lot of research has been done in fields related to the subject of the current study. Along with the development of the finite element method (FEM), it has become possible to perform impact simulations of increasing complexity. Among others, Timmel et al. [4] addressed the issue of impact forces inside a hyperelastic material, whereas Karagiozova and Mines [5] discussed the modelling and simulation of the impact of a cylindrical rubber specimen. Two topics seem to be determinant to the tank design: Fluid-solid interaction and material modelling. A review of different numerical techniques of FSI simulations can be found in [6]. An accurate modelling of interaction between fluid and structure allows to determine correctly the loading applied to the walls and, in this way, determine the optimal quantity of material. The tank's wall can be seen as a composite material composed of several layers of elastomer matrix composites (called anti-crash fabric) and seal-sealing foam. The modelling of this material behavior becomes a real challenge due to the heterogeneity of materials, which show an hyperplastic, anisotropic behavior. The goal of this study is to develop a methodology to simulate a tank drop test in a reliable, robust and fast way. Several techniques of FSI will be compared with a focus in ALE and SPH approaches. In the same way, some different approaches will be studied to model the wall's material regarding the trade-off between accuracy, complexity and global behavior. All the simulations will be performed using the commercial code RADIOSS from Altair which is widely used in the domain of crash and defense applications [7]. The paper starts with a description of the structure and drop test characteristics. Secondly, we will address the problem of FSI modelling using a simplified tank model. After that, the material model chosen for this application will be showed, thus the material model calibration. Finally, a first simulation of the real fuel tanks will be analyzed.

2 Fuel tank description and drop test requirements

The general dimensions of the certification fuel tank and the test conditions are given by the norm MIL-DTL -27422E and European CS27 or 29. The fuel tank to be modelled and tested is observed in Figure 1. The tanks walls are composed of several layers of an anti-crash elastomer-matrix composite with an internal layer of self-sealing foam. From a structural point of view, we can assimilate this wall to a sandwich structure. Some characteristics like corners radius are variables which can be modified by tank designers. Two stiff inserts are positioned upside to represent the connection between the tank and the environment and in one vertical side.

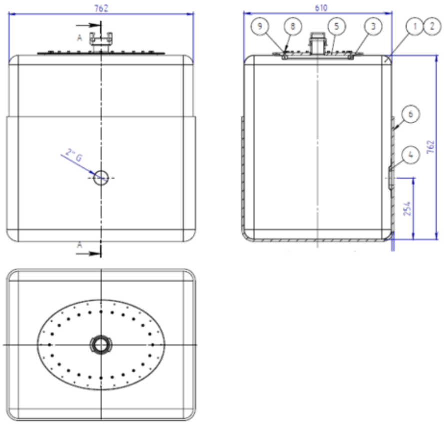

Figure 1. Tank Geometry

The drop test configuration is the following one: the tank is dropped from a height of 15 meters. Two set-ups are allowed: in the first one, a net of straps which retains the tank is also dropped with. In the second configuration, the tank rests on a platform, which is dropped. In the case of this study, the second mechanism has been chosen, because it's easier to control the orientation and state of the tank during the drop. Regarding the tank, it has to be filled of water at 80% of its capacity and the conditions to be successful is to not have any leaks after the crash.

3 FSI modelling study

A reader can find three main approaches to model the fluid-solid interaction. The first one is the Coupled Eulerian Lagrangian approach [7]. The fluid is modelled completely using an Eulerian framework while the structural parts are modelled using a Lagrangian one. The interaction between both domains is managed using a contact interface.The problem of this approach is the diffusivity between the two domains leading to a flow between the fluid domain and the lagrangian one. The second method is the Arbitrary Lagrangian Eulerian approach [8]. In this one, matter can move with respect to the mesh but, unlike the Eulerian framework, the mesh also moves during the computation. This method has proved very efficient to simulate large strains phenomena which often leads to high mesh deformations and numerical instabilities. In our case, fluid is modelled by using solid elements and a multi-material law which allows to compute two/three different fluids in the same mesh (RADIOSS/LAW51). Again, we can manage the interaction between fluid and solid domains by an interface, or with coincident nodes. Finally, we find the Solid Particle Hydrodynamics where the fluid is modelled by using particles. We can find a lot of examples of SPH for FSI applications in the literature [9]. In this case, the framework is totally Lagrangian.

We have chosen to model a simplified version of the fuel tank, in order to limit the complexity of the model and to focus on the comparison between ALE and SPHmodelling techniques. The mesh used for ALE model is generated using a script in order to increase the quality of the mesh as much as possible (figure mesh ALE). Fluid and lagrangian mesh are merged, several problems of instability (first ruptures) have been observed when a contact interface is used between. The presence of this interface avoids the fluid to hook on the wall leading to non-realistic behavior close to the boundary layer. The ALE model shows a good computation time but some strange phenomena appear during the simulations. Firstly, the shock wave created during the flat impact creates a loss of density in the water section. This lack of density doesn't seem to be realistic. We could explain such a phenomenon as an apparition of cavitation due to pressure. By the way, the material law used in this study is not able to simulate correctly this state transition. The second blocking point is the simulation robustness. The final goal of this study is to develop a model that can be used in an optimization loop, so the robustness becomes a necessary asset. The issue in this kind of model is the compliance of the wall structure and the high level of deformation during the wall expansion. This expansion causes a high element deformation near the corners leading to a simulation divergence in many cases. Moreover, the loss of robustness becomes critical if material rupture is included in the model.

The SPH technique has been introduced by [10] and used for long years to model high strains phenomena coupled with rupture [11] and fluid-solid interactions like sloshing and ditching [12]. In our application, both fluids are modelled with two different SPH parts, one for air and the other for water. A special treatment has been introduced in to avoid instabilities in tension as it has been described in [13]. In this methodology, the first objective is to determine the minimum quantity of particles to get a correct behavior of the wall and, at the same time, be as fast as possible. The quantity of particles is determined by the pitch parameter (mean distance between particles) and the method used to pack particles. Twodifferent pitch values are chosen using a cubic centered particle packing (Figure 2 and Figure 3).

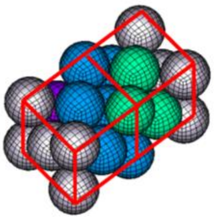

Figure 2. Cubic centered particles

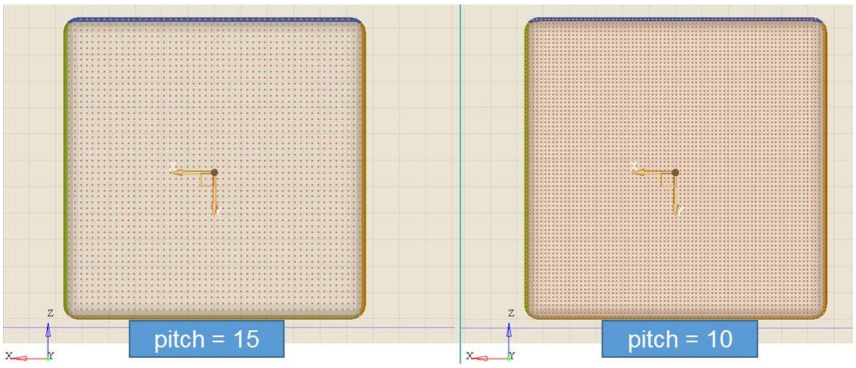

Figure 3. Pitch comparison

The particle mass is calculated following the equation:

$$m_p \approx \frac{h_0^3}{\sqrt{2}}\rho \qquad \text{Eq. 1}$$

where h_0 is the pitch value. A problem that has been observed with SPH models is the adhesion between the fluid and the wall. A normal modelling of this interaction consists in a contact interface between particles and the wall. However, this contact interface captures well the interaction under compression but not under tension. In fact, if the tank expands during the drop test, we can observe how a separation between the fluid and the wall appears, which is not quite physical. The wall SPH method has been used to avoid this spurious phenomenon. This method consists in using particles merged to lagrangian nodes. This particles will affect those present in the fluid part and act as an adhesion force between both entities.

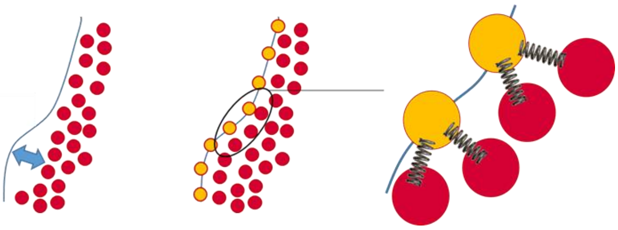

Figure 4. Wall SPH

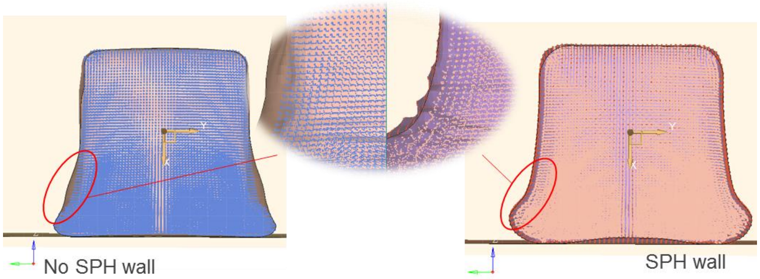

Figure 5. Effect of wall SPHtechnique in fluid behavior

We can observe in figure 4 and 5 how this technic allows us to better reproduce the water behavior during the wall expansion. Thanks to this technique we get the same kind of wall behavior observed in the ALE model, where fluid is better modelled than using SPH.

Concerning the material model, we used a hydrodynamic material law where the deviatory tensor is calculated as follow:

$$S_{ij} = 2\rho\nu\dot{e}_{ij} \qquad \text{Eq. 2}$$

And pressure is calculated using following equation of state.

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu)E_n \qquad \text{Eq. 3}$$

Where $\mu = \frac{\rho}{\rho_0} - 1$ and E is the internal energy per unit of volume. C parameters take different values depending on the fluid which is modeled, for example, for a perfect gas:

$$C_0 = C_1 = C_2 = C_3 = 0; \quad C_4 = C_5 = \gamma - 1$$

With γ being the perfect gas constant.

5 Bladder Material modelling

The Bladder material can be assimilated to a composite structure with several layers of:

- Elastomer matrix composite
- Self-sealing foam
- Elastomer

In this study, we have focused on the elastomer matrix modelling. Two approaches have been considered: the first one related to an accurate model (dedicated to validation purposes) where each layer is modelled separately and the second, simpler and easier to set up, but implying several strong hypothesis about the behavior of some components. This last model will be used for optimization / design exploration purposes because of a lower number of elements.

5.1 Accurate model

We used two different material models available in Radioss to reproduce each bladder layer, that is, the fabric and the elastomer. Fabric is modelled using a dedicated anisotropic material law where fibers are modelled explicitly (inside the element). An example of this approach for fabric modelling can be found in [14]. This material model can take into account the initial state of yarns before traction and the influence of mono or bi axial loading (Figure 6).

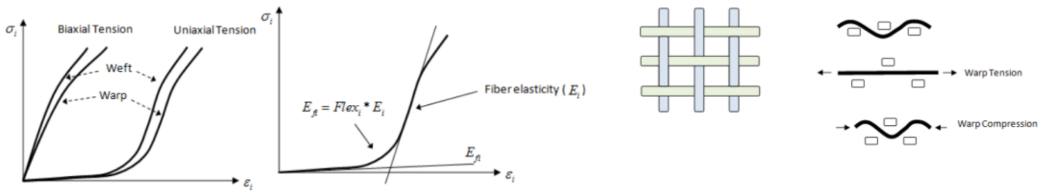

Figure 6

The elastomer matrix is modelled using a hyperelastic material Ogden-type law [17]. The bladder is composed of layers of elastomer and one fabric layer. Two elements are used (one for fabric) and one for the elastomer material. Both elements haveidentical nodes (which are merged during the set-up of the model) as it is showed in the following figure

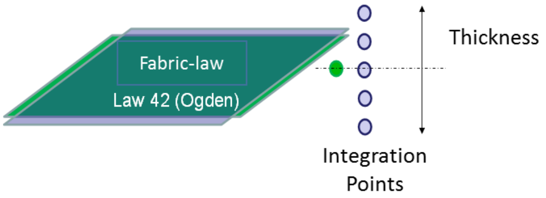

Figure 7. Bladder detailed modelling

The identification of all material parameters becomes a hard task due to the big number of parameters. We resume in the table the parameters needed to define correctly both material laws.

Law 58 (Fabric)	***Law 42 (matrix)***
E1, E2, B1, B2, Flex *G, GT, αt*	*μ1, μ2, α1, α2* *τ1, τ2, τ3* *G1,G2,G3*

Tableau 1. Parameters to determine

Law 58 (Fabric)		**Law 42 Ogden**	
E1	Young modulus in warp direction	μ1	First ground shear hyperelastic modulus
E2	Young modulus in weft direction	μ2	2nd ground shear hyperelastic modulus
B1	Warp softening coefficient	α1	First material exponent
B2	Weft softening coefficient	α2	Second material exponent
Flex	Fiber bending modulus reduction factor	τ1	Relaxation time of viscous prony series
G	Initial shear modulus	τ2	Relaxation time of viscous prony series
GT	Tangent shear modulus	τ3	Relaxation time of viscous prony series
αt	Shear Lock angle	G1	ith multiplier of the Prony viscous term
		G2	ith multiplier of the Prony viscous term
		G3	ith multiplier of the Prony viscous term

An optimization loop is used to set all these parameters. We consider a constant thickness for each component: For a total thickness T, fabric is considered as a layer of T/2 thickness and the other T/2 is divided in two elastomer layers placed at the bottom and the top of the bladder laminate. The process developed to identify all parameters is the following:

- We use an inverse method based on optimization for a given strain rate corresponding to the 500mm/min test. A Global response surface method is used as optimization algorithm.
- Once all parameter are fixed for this strain rate, we use other tests at different rates to identify the Prony coefficients which allow to introduce the strain rate effect on the material behavior [15].

The scheme of this method is showed in the figure below.

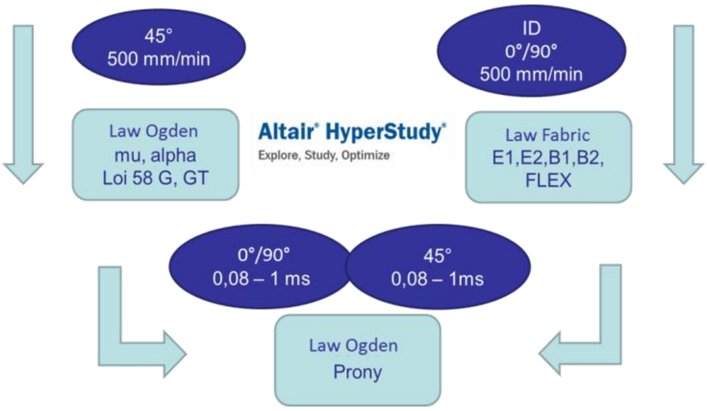

Figure 8. Identification methodology

Final results obtained with this method are the following ones:

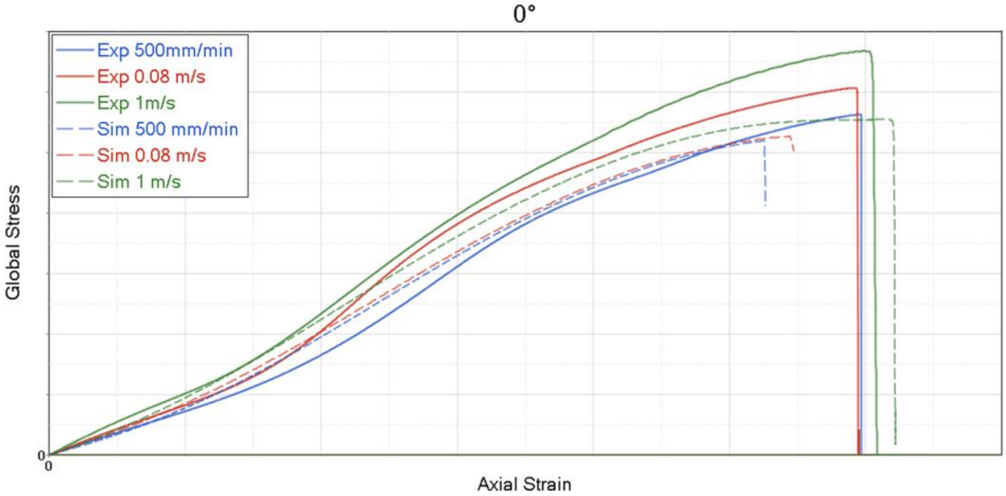

Figure 9. 0/90° Test correlation

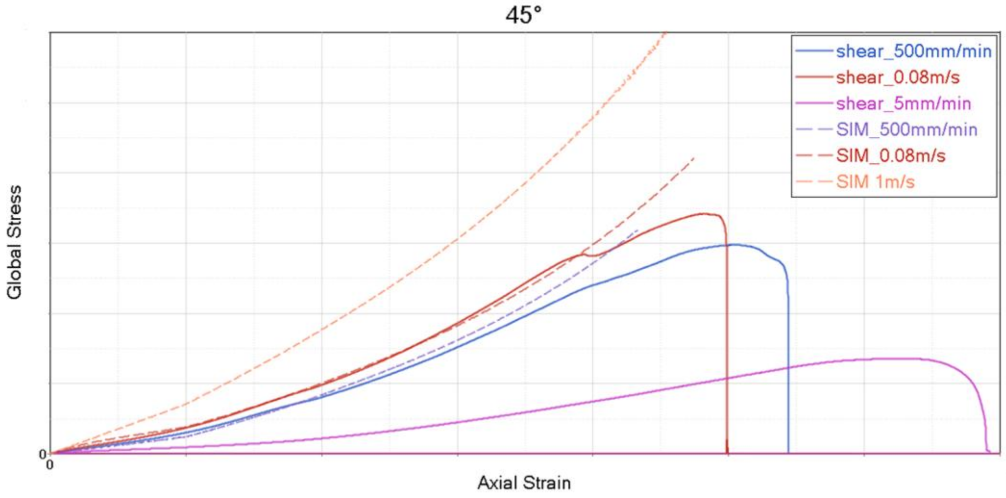

Figure 10. 45° test correlation

We can see how the strain rate influences lightly the behavior in the orthotropic system (fiber direction) and much more in shear, where the matrix contribution to the global behavior is preponderant. However, Radioss doesn't offer a dedicated failure model to this kind of material. This is one of the reasons to keep this modelling away from the optimization modelling described in the next section. Anyway, some fuel tanks drop test have been simulated in order to quantify the effect of taking into account (or not) the strain rate in the bladder material.

5.2 Design/optimization model

The goal is to propose a simplified way to model the fuel tank wall composite. We use a Radioss element used often to model any kind of composite material (Shell Sandwich) and a combination of linearized material laws for bladder and self-sealing foam. Bladders are modelled using the law 25, which is a specific behavior law for composite materials with an organic matrix, in particular epoxy matrix composites. It is able to simulate the orthotropic behavior of this type of material. A Tsai Wu plasticity is introduced in each direction allowing different nonlinear behaviors as a function of the direction of stress [16]. Viscoelasticity effect is introduced with a Prony (eq 4) series acting only in shear stress.

$$s_{ij} = \int_0^t G(t-s)\frac{\partial dev\left[\varepsilon_{ij}\right]}{\partial s}ds \qquad G(t) = \sum_{i=1}^{M} G_i e^{-\beta_i t} \quad \text{Eq. 4}$$

With G_i being the shear relaxation for i^{th} term and β_i the shear decay.

To identify this law, we linearizedthe material behavior to get the Young modulus for each direction. This is a strong hypothesis, mostly for shear behavior (which is highly non-linear). The Prony series are identified as follows: we chose a stress measure corresponding to a fixed strain quantity. The expression of shear stress as function of the strain rate is given by:

$$s_{12} = \sum_{m=1}^{5} \frac{G_m.\,\dot{\varepsilon}_{12}.\left(1-e^{-\beta_m t}\right)}{\beta_m} \quad \text{Eq. 5}$$

We build a curve with the experimental data and the equation 5. An optimization is carried on again to identify all G and β. The difference between test and simulated points is minimized (Eq 6).

$$\min \sum \left(\frac{f_i - \tilde{f}_i}{\tilde{f}_i}\right)^2 \qquad \text{Eq. 6}$$

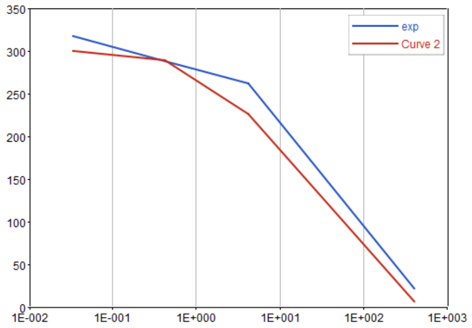

Figure 11. Test and initial guest

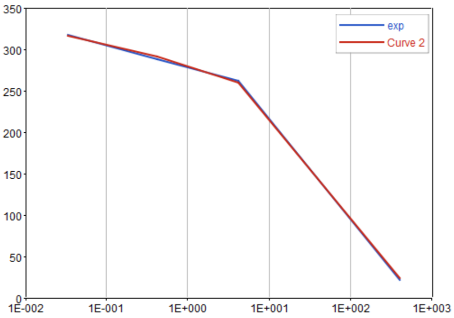

Figure 12. Result after identification

This modellingallows us to use a wide range of failure models. We have chosen to keep it simple and a strain based failure model is used. An example of the obtained behavior for a given strain rate is showed in the following figure:

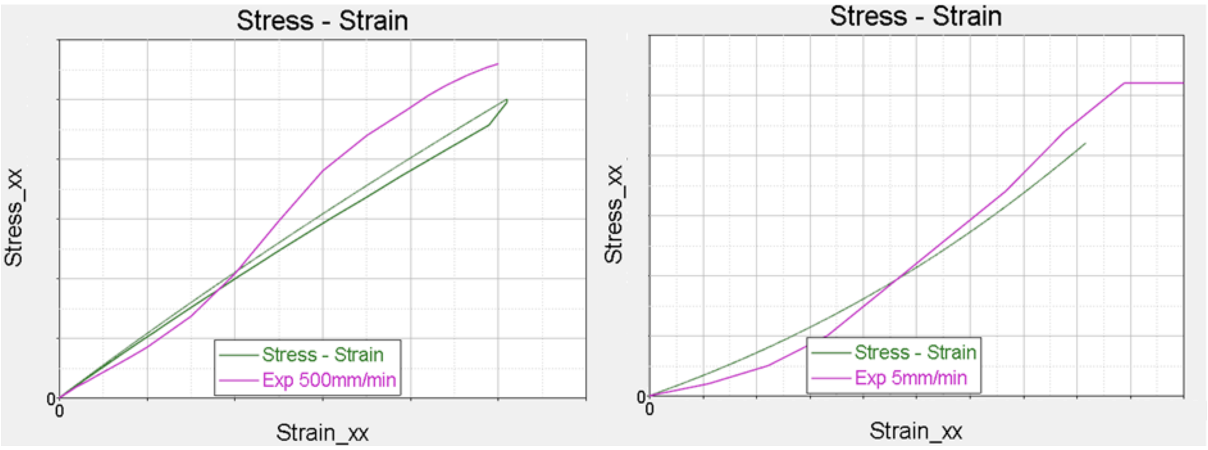

Figure 13. Correlation using simplified model.

5.3 Comparison

Both models are used to simulate another test which represents better the biaxial stress state of the fuel tank wall during the drop test. In this test, carried out by ONERA, a circular specimen of tissue is impacted by a spherical punch. Results obtained for 1 m/s test are shown in the figures below:

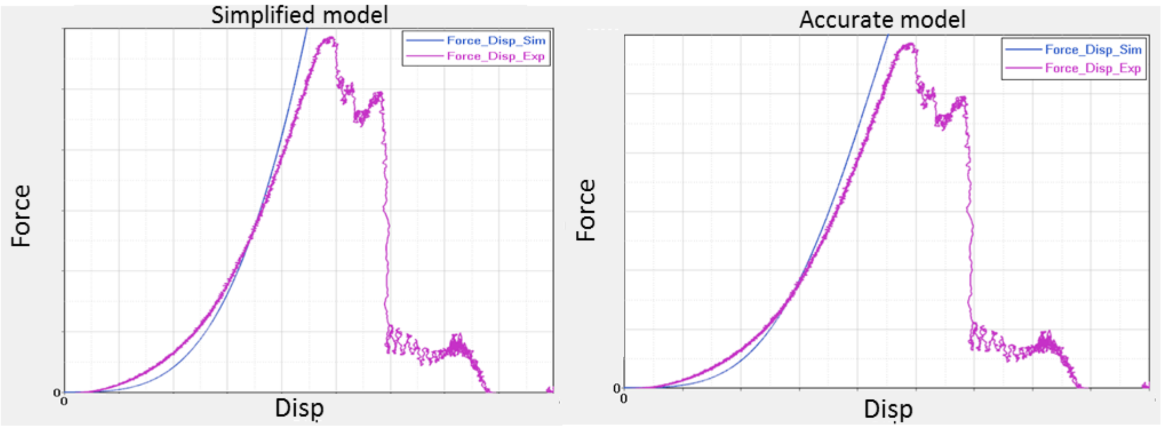

Figure 14. Comparison between detailed and simplified model in punch tests correlation

We can observe how the results are really similar using both material laws. The accurate model gives a slightly better correlation in the beginning of the test, probably due to the better modelling of elastomer matrix behavior. Anyway, the complexity of the accurate model doesn't justify the small improvement of quality results. Moreover, the methodology we look for is oriented to the design phase, so it must be fast and robust. This is the reason why the simplified model is chosen to model the fuel tank. The accurate modelling won't be used in the drop test simulation which will be presented in this paper. However, recent improvements in Radioss will make it possible to mix elastomer and fabric dedicated material laws in one single finite element simplifying the building of the fuel tank model.

6 Real tank drop test simulation

In this section we will show some results of the drop test. The lagrangian part, that is, the tank walls are modelled with shell finite elements. This part contains about 214000 elements. This model presents two metallic insert, also modelled with shell elements and linked to tank wall using a glued contact interface (/INTER 2). Both models show similar results before the onset of rupture, after that moment, the ALE approach diverges after several cycles. SPH approach is able to continue and simulate the propagation of rupture. Another important point is the behavior of models energy during the simulation. ALE model shows a strange loss of energy (Figure 15) even if the behavior of the wall seems to be correct and equivalent to the sph model.

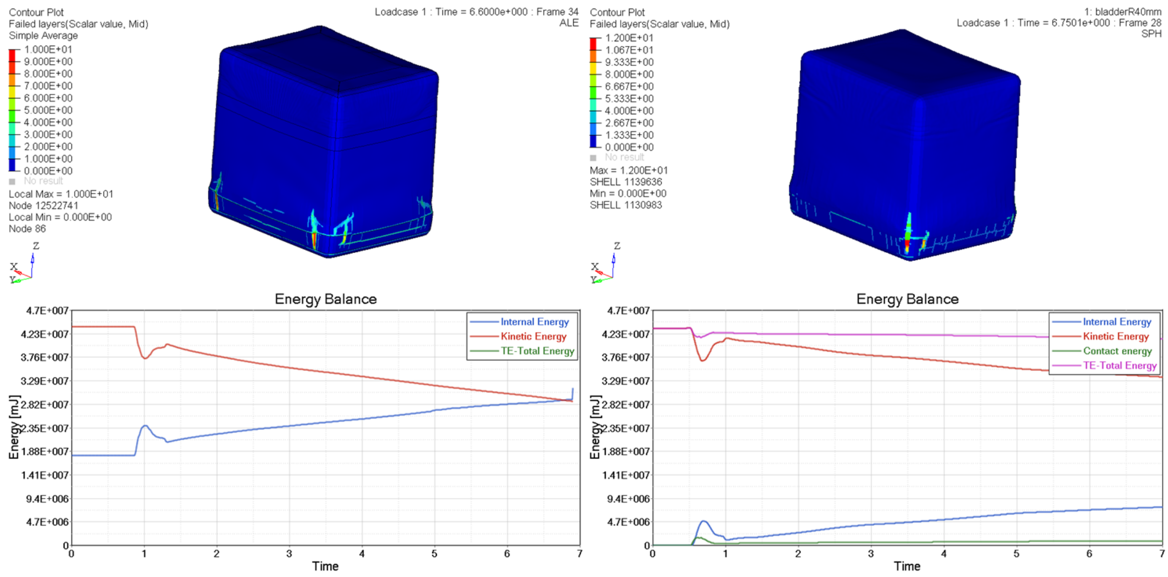

Figure 15. ALE and SPH tank models

This is the reason why we'll privilege the SPH approach. All results presented from here are obtained using this approach.One can observe as the energy balance of the SPH model is correct, the first pic in internal energy is due to contact interaction. After that, the evolution of both internal and kinetic energy is quite linear until the rupture.

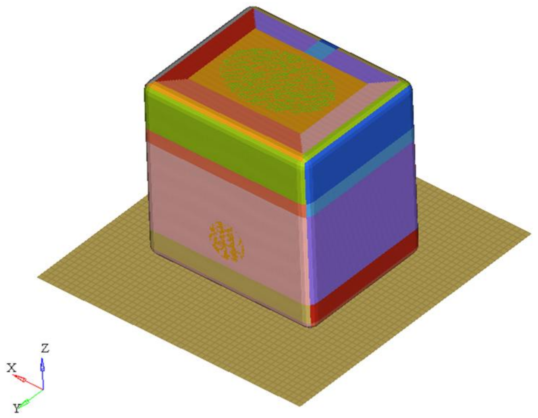

Figure 16. Tank Model

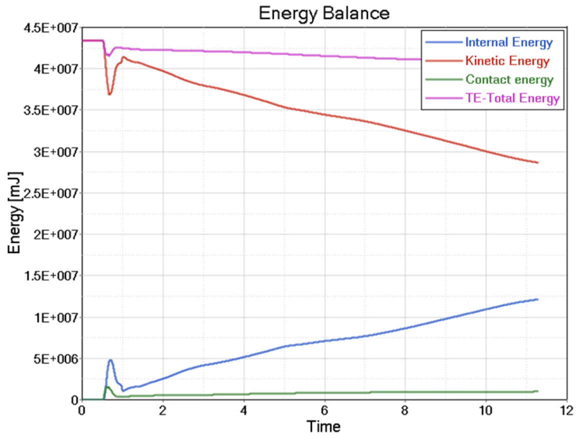

Figure 17. Energy balance.

The fluid behavior seems to be quite physical and the presence of particles merged to the lagrangian wall works correctly and the fluid follows the wall during the expansion (Figure 19). An image of the pressure wave is showed in Figure 18.

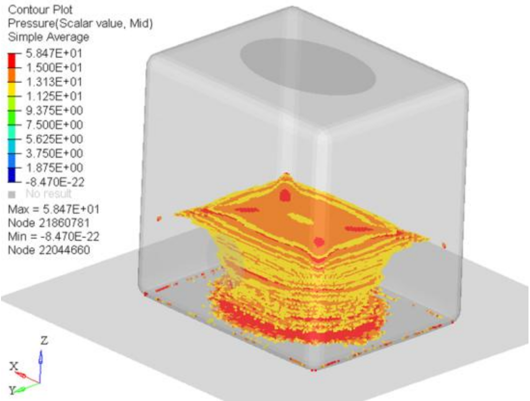

Figure 18. Pressure wave

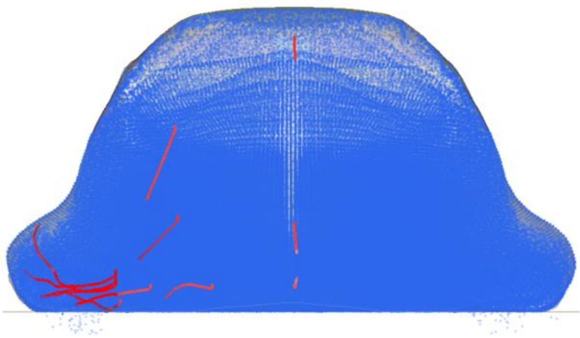

Figure 19. Fluid particles trajectories.

The goal of this model is to capture the rupture of tank bladders and be able to optimize them in the future. Figure 20 shows the evolution of failed layers during the drop test simulation. The maximal value plotted in this picture corresponds to 6 failed layers, and, when this point is reached, a global crack appears and grows until it causes the total failure. The explanation is simple: the anti-crash fabric layers are responsible of the larger of mechanical strength. When this layer breaks, the stress is suddenly redistributed on the others (weaker than anti-crash fabrics) leading to a total failure of the laminate.

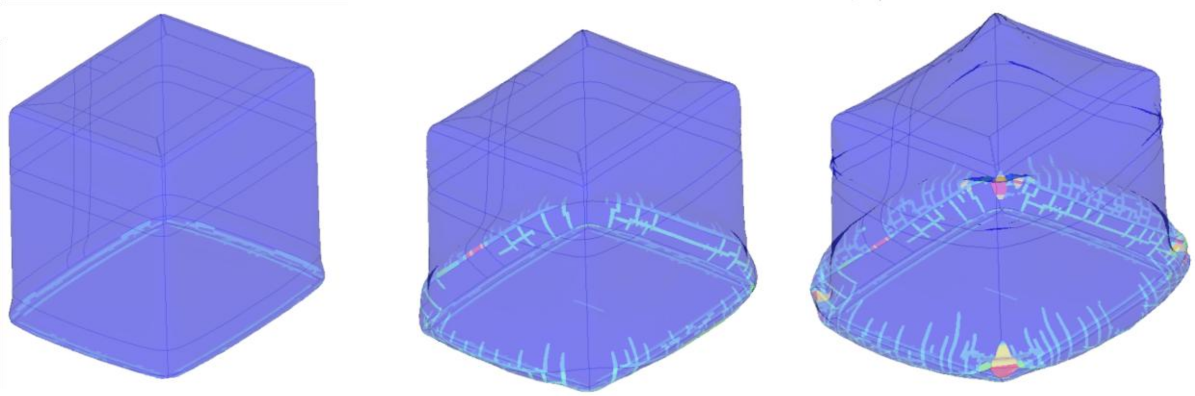

Figure 20. Failed layers

An interesting point to observe is the failure pattern. It is clear that the tank expansion during the first milliseconds corresponds to the maximum of the loads supported by the wall. Critical damage appears on the four corners of the tanks, which indicates that this zone have to be designed carefully in order to reduce/avoid the failure risk. Some tests with more anti-crash layers showed that rupture always happens and that the main cause of the rupture is the tank circumferential expansion.

7Conclusion

A research of a robust and simple methodology to model flexible wall tanks has been presented. Two main topics have been addressed, the fluid-solid interaction and the material modelling. Two approaches, ALE and SPH have been used and compared. ALE approach seems to simulate better the fluid behavior but it presents an important lack of robustness when tank is highly deformed. SPH approach has showed itself slower, but much more robust. This robustness will allow its usage in further optimization loops, which is one of the major objectives of the researched methodology and model. In the material side, we have tried to develop an accurate model of the bladder – foam composite and proposed a linearized model. After a comparison of both models using identification samples and circular samples, we realized that the simplified model gives very correct results allowing us to use a lot of different failure criteria. Finally, the two fuel tanks models (ALE and SPH) are used. Some results about rupture patterns and tank walls kinematics are analyzed. Both modes have already been used to carry on some shape optimizations, specifically the radius of tank corners. The conclusions of this study are the same using both models and have helped designers to choose the best design in order to reduce the failure risk.

Acknowledgements

This work has been done during the FUI project BALLOO which was supported by BPI France, Hauts-de-France region and DGA.

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