ONE YEAR OSIRHYS IV PROJECT SYNTHESIS: MECHANICAL BEHAVIOUR OF 700 BAR TYPE IV HIGH PRESSURE VESSEL CODE QUALIFICATION

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Abstract
In this paper we present results of the OSIRHYS IV French project which aims to develop and validate models and methods for composite high pressure design and optimization with behavior uncertainties knowledge. Models of the five partners of this project are presented and burst simulation results are compared for three test temperatures (-40°C, 15°C and 85°C).

1 Introduction

Hydrogen is an alternative to traditional energy sources like oil and natural gases. It offers great advantages as no greenhouse gas emission. For more than a decade, this way has been the focus of research and development efforts. Hydrogen storage stays a key issue for the high scale deployment of fuel cell applications. Different ways exist to store hydrogen, such as liquid storage tank [1], polymer and composite foam [2], metal hydrides [3], gaseous high pressure storage vessel [4]…

The gaseous hydrogen storage at high pressure with type IV vessels (with a polymeric liner fully-wrapped with a fiber-resin composite) is the best technology nowadays. To be efficient, this storage must be done at high pressure (above 350 bar and up to 700 bar for on-board applications). Recent developments on 700 bar type IV vessels have demonstrated very promising results (high cycling resistance, burst pressure, hydrogen tightness, gravimetric and volumetric storage capacities…).

To reach commercial deployments, this technology needs research and development to cut costs and improve performance, reliability and durability of current high pressure vessels. The composite shell allows withstanding high mechanical stresses due to internal pressure. The massive use of carbon fiber represents 50% to 70% of the final cost of the vessel (figure 1). An optimization of composite structure will allow reaching a significant cost reduction of hydrogen devices. An improvement of numerical simulation is needed because today most of the engineers work with simplified models frequently far from the real problem.

OSIRHYS IV is a project supported by the French Research National Agency (ANR) through "Hydrogène et Piles à Combustible" program (HPAC program). The purpose of this project is to clarify uncertainties and approximations of high pressure vessel composite design and

calculation. The project is dedicated to all conception and simulation chain. It aims at improving material and process (filament winding) characterization and at establishing a strong and shared database between all project partners. The goal of OSIRHYS IV project is to develop and validate models and methods for composite high pressure design and optimization with behavior uncertainties knowledge (figure 2).
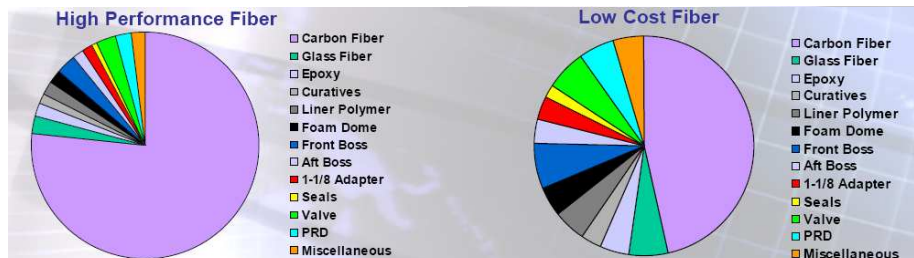

Figure 1. Costs repartition of hydrogen high pressure type IV vessels depending of carbon fiber types T1000/T700 (Quantum, USA)
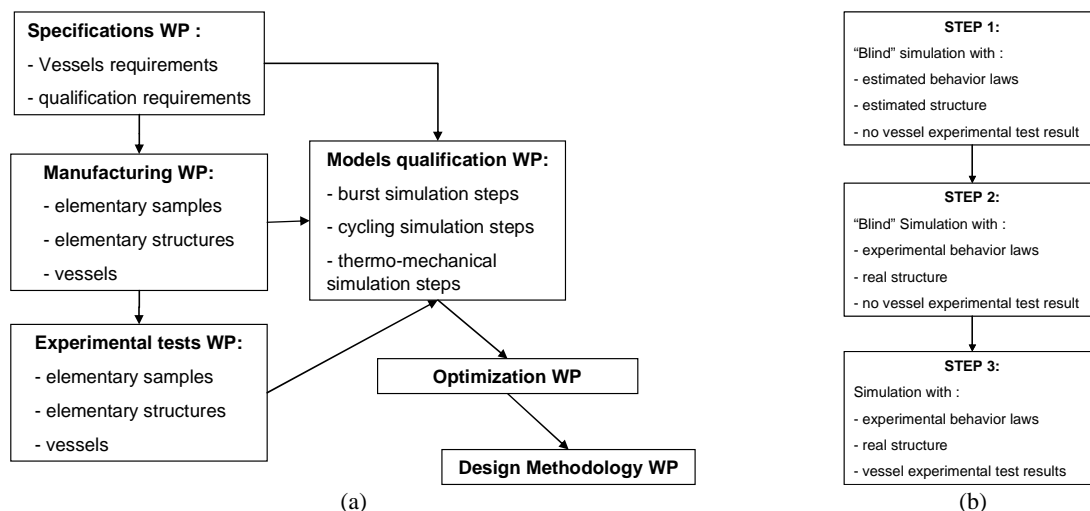

(a)   (b)

Figure 2. (a) Presentation of OSIRHYS IV Work Packages and (b) calculation qualification steps

2 Design and calculation limitations

Facing the enormous range of possibilities in the design of such pressure vessels (materials, topology, process techniques, laminate lay-up, winding angles…), it was decided to limit this study to a particular topology, material and winding process. In any case, pressure vessels should be optimized to hold a maximum of fluid with a limited volume at the best manufacturing costs, load bearing capability and lifespan. However the aim of this approach is to gain in knowledge, have a better comprehension of the behavior of these pressure vessels in order to figure out design rules and effective optimization techniques in relation with manufacturing processes. This previous step is vital before enlarging design parameters and finally answering industrial and economic stakes.

Current simulation limitations are related to different models and behavior uncertainties. We can quote for instance the following aspects:

- The lay-up design about the winding evolution strategies on end-closure revolution areas (thickness evolutions [5], [6], [7], angle evolutions with geodesic winding trajectories based on the Clairaut equation or with non-geodesic winding techniques [8], layer superposition, slippage parameters)

- The choice of the element types in the FE models. Shell elements are mainly suitable for analyzing thin to moderately-thick shell structures whereas solid elements are more appropriate for calculation precision in spite of their more laborious use for winding mesh

procedures, which could appear to be too time consuming in the optimization procedure. Another limitation concerns the accuracy of axisymmetric models to faithfully simulate the composite cyclic periodic behavior.

- The damage models. An optimization procedure will have to take into account all the damage mechanisms (fatigue, failures…) occurring in the structure. The fatigue behavior of composite materials depends on the nature of the constituents, the process parameters and mainly on the application. Numerous damage models for composite structures are available. For example, the more sophisticated are based on micro-scale [9] but are limited by their complexity and costs. Moreover, macro-models [10] seem to be more appropriate for complex and large structures but still remain to be tested on pressure vessels.

- The optimization procedures. An automated optimization technique taking into account all the laminate parameters (different winding angles and thicknesses, slippage tendencies, lay-up and ply numbers) with fatigue and damage models does not exist nowadays for this kind of structure. The more ambitious studies are restricted to the optimization of a part of a pressure vessel or to the optimization of one winding angle without referring to fatigue behavior [11]. Different optimization procedures will be investigated [12].

3 Burst simulation results

The composite tanks that are considered in the OSIRHYS IV project consist in the three following components (Figure 3a):

- The inner plastic vessel (or liner) ensuring the pressure tightness of the tank, it hardly plays a role in the structural strength of the tank;
- The metallic bases ensuring the connection of the tank with the other components of the system in which it is embedded;
- The outer composite shell ensuring the structural strength of the tank.

The main dimensions are: 2 liters in volume, 130 mm in external diameter, 300 mm in total length, 11 mm in composite thickness.

The first simulations that have been carried out for this project deal with the burst test of the tank. This normalized test consists in a steady increase of the internal pressure of the tank up to burst. The tank is clamped on one side and remains totally free on the other side. The principle of this test is shown in Figure 3a

Two burst modes may occur (figure 3b): a safe mode (inner expulsion of the metallic bases when the vessel bursts) and an unsafe one (outer expulsion of the metallic bases when the vessel bursts). For this type of test, the OSIRHYS IV project aims, on the one hand, at developing a better numerical prediction of the burst pressure of a given composite tank and, on the other hand, at better understanding the phenomena leading to one burst mode or to the other.
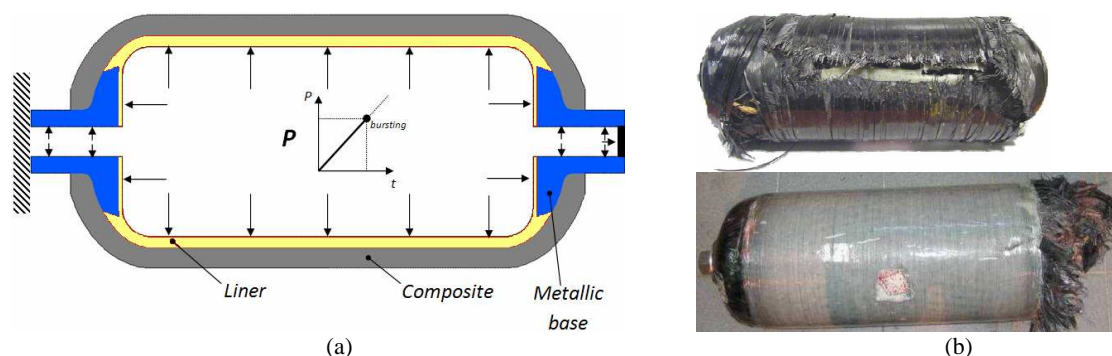

(a)   (b)

Figure 3. (a) Burst test principle and (b) burst modes (safe and unsafe)

The present computation results refer to the first modeling step (Figure2b). This first step considers an initial rough knowledge of the geometrical dimensions, of the composite shell characteristics and of the material properties of the tank. The main objective of this first step is to assess afterwards the impact of the aforementioned uncertainties on the final results.

In this project each partner focuses on a specific topic (development of specific damage laws, modeling of the composite winding in the dome, etc). Each partner thus proposes a particular finite elements model, with the use of a particular damage law for the composite, reliable techniques to model the composite winding in the domes. This paper presents the results obtained by each partner in terms of burst simulation. The simulation results are compared to the results of a test for which the burst mode of the composite tank was safe.

3.1 FE models comparison

Starting from common initial data, each partner has developed its own FE model of the test. This section presents briefly the different FE models that have been developed. Table 1 summarizes the FE modeling hypotheses and the FE software that has been chosen by each partner.

The tank is manufactured using a filament wound process. The composite characteristics (layer orientation and thickness) in the domes cannot be very accurately measured and therefore must be modeled using appropriate methods. Each partner has chosen a specific method: the ABAQUS wound composite plug-in has been used as well as homemade geodesic models or data extraction by inspection of the tank radiography. Table 1 summarizes the techniques used by each partner to model the dome composite winding.

The diversity of the models does not lead to huge differences in the mass of the different parts of the structure as shown in Figure 4a. More specifically, all FE models predict the same mass for the composite in the cylindrical part of the tank. This value corresponds to the exact theoretical value that can be easily computed starting from the details of the composite layer and the geometrical dimensions of the tank. Nevertheless, a little discrepancy of the composite mass in the dome area can be observed. This difference is mainly related to the method used to model the composite winding in the dome areas. Moreover, Figure 4b shows that the mass of the liner is slightly higher in the FE models than in the real tank. The part of the latter in the structural strength of the tank being very limited, this difference has a very small influence on the results of the computations. Finally, the metallic bases masses are very close in all the FE models. The very little differences can be explained by the complexity of the geometry in the area of junction with the liner and the composite domes.

	FE modeling hypothesis	FE code	Dome modeling method	Number of degrees of freedom
ARMINES	Volume	ZEBULON	Radiography inspection	5.48×10^5
CEA	Axisymmetric	ABAQUS	ABAQUS Wound Composite	2.11×10^4
CEA-SAMTECH	Axisymmetric	SAMCEF	Geodesic model developed by SYMME	6.08×10^4
INSTITUT P'	Axisymmetric	ABAQUS	ABAQUS Wound Composite	1.04×10^5
SYMME	Volume	ANSYS	Homemade geodesic model	3.12×10^4

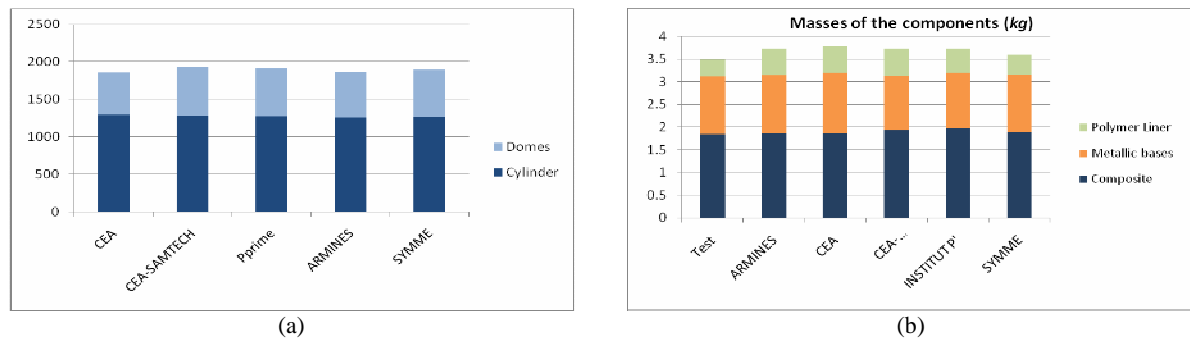**Table 1:** Chosen FE modeling hypotheses

Figure 4. (a) Composite mass of the FE models and (b) Comparison of the components mass

3.2 Burst results comparison at 25°C

All the partners computed a non linear static analysis at ambient temperature (25°C).

Three physical quantities are compared: two local displacements and the burst pressure. The displacement gauges are located at the tip of the free base and at the center of the cylindrical part, on the external composite layer. The same displacements sensors have also been placed on the real tank for the burst test.

Figures 5a and 5b show respectively the results obtained for the axial and radial displacements by the five partners and the comparison of their simulation with the test results. It appears first that none of these simulations represents correctly the axial behavior of the tank during the test. Two non linear phenomena explain these differences. First, it seems that a short but strong non-linear phenomenon occurs at the beginning of the test. It is assumed to be related to gaps in the assembly. The second non linear phenomenon is slighter and more continuous and seems to be less related to imperfections of the test assembly than the previous one. The study of this phenomenon is in progress; the carbon composite properties have been characterized by ARMINES and the results show that the material stiffness is overestimated in the bibliography. Moreover, the composite quantity in the domes has a huge influence on the vessel axial stiffness. More precise models are being built from radiographies performed by the partner ARMINES. Finally, the huge stresses in the metallic bases require the introduction of plasticity in these parts.

The results of the different partners are very similar. As a consequence, it seems that axisymmetric as well as three-dimensional FE models could be used for this type of analysis. Only computation cost, practical modeling considerations or future conclusions related to more complex simulations (e.g. non axisymmetric damage propagation) could lead to recommend one of these two FE hypotheses.

An important fact resulting from this comparison is that the composite must be well modeled in the dome area and that the current models overestimate the composite quantity in these areas. Model improvements are in progress, using precise radiographies.

The radial displacement of the test appears to be much more linear than the axial one. The cylinder modeling does not present huge difficulties, and therefore all the partners present similar results very close from the test results.

The "safe" burst phenomenon experimentally observed for this type of tank is strongly related to the circumferential loads acting in the middle of the cylindrical area of the tank. Therefore it will be mainly driven by the strength of the fibers in the circumferential layers. The comparison of the FE simulations with the test results seems to validate this hypothesis. Indeed, the test results exhibit some local failures (see fluctuations in Figure 5b) in the composite shell occuring close to the theoretical burst pressure predicted by the FE analyses. However, these local failures do not lead to the structure burst.

The main conclusion of this study is that the different FE models tend to underestimate the burst pressure level and to overestimate the axial stiffness of the tank. Some studies are in

progress in order to use accurate composite material properties, fibers trajectory and layer thickness in the domes. The updated models should fit the test results and then predict accurately the burst pressure.
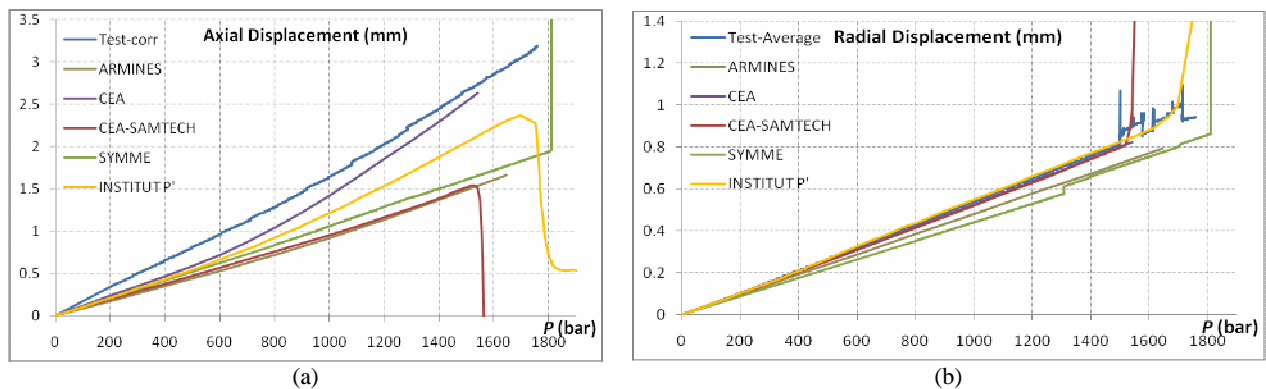

| (a) | (b) |

Figure 5. (a) Axial displacement and (b) Radial displacement

3.3 Influence of temperature on burst pressure

While the previous part dealt with the behaviour of tanks at room temperature, this section presents the main features and the first results of burst simulation at different temperatures, namely -40°C and + 85°C (in addition to 25°C). Since the characterization of the material at these temperatures is in progress, this synthesis explains how the effects of temperature are taken into account. Results of "blind" simulations (*i.e.*, without exact knowledge of the actual behaviour) are here commented.

As far as tensile tests on unidirectional composites samples are concerned, works in the literature [13] show, on the one hand, that an increase in temperature has almost no effect on fracture stress and stiffness in the fibre direction. On the other hand, both characteristics decrease in the direction normal to the fibres. The consequences of a temperature decrease are a fracture stress increase (in the directions parallel and perpendicular to the fibres) and a slight strengthening of the Young modulus in the direction perpendicular to the fibres. The same kind of conclusions can be drawn from tensile tests performed on ±45° samples (fracture stress and stiffness increase for a lower temperature). From these experimental data, mean reduction or amplification (with respect to values at room temperature) coefficients have been chosen (see Table 2).

Whatever the temperature is, unidirectional samples exhibit brittle fracture. The next simulations assume an elastic behaviour and fracture occurs when axial displacement rapidly increases. Under these assumptions, the burst pressure obtained by each partner is presented in Table 3.

Tested sample	Temperature	Fracture stress	Stiffness
Unidirectional	-40°C	+25%	negligible variation
Parallel to fibres	+85°C	negligible variation	negligible variation
Unidirectional	-40°C	+18%	+8%
Perpendicular to fibres	+85°C	-25%	-18%
±45°	-40°C	+8%	+17%
	+85°C	-23%	-28%

Table 2: reduction / amplification coefficients (with respect to room temperature)

The burst mode is safe for each temperature. The simulations of the axial and radial displacements exhibit a very similar behaviour. The difference between the burst pressure at -40°C on the one hand and 25°C and 85°C on the other hand comes from the variation of the fracture stress in the fibre direction: the storage is more resistant at a lower temperature.

Partner	Burst pressure (bar)		
	-40°C	+25°C	+85°C
CEA	1948	1541	1483
LMS Samtech	1890	1520	1473
ARMINES	2193	1715	1642
SYMME	2245	1759	1799
PPRIME	2158	1700	1604

Table 3: Burst pressure at -40°C, +25°C and +85°C

Simulations including the influence of the difference between the thermal expansion coefficients have been performed by Samtech. Figure 6a shows the stress induced by a uniform temperature loading (increment of 65°C): these stress levels are non negligible in the internal layers of the dome and could lead to non safe burst modes (note that the expansion coefficients have not been experimentally determined, although they are representative of the composite material at stake in this project).

This pivotal influence of the thermal properties has been confirmed by Pprime: Figure 6b represents the simulated stress in the fibre direction after curing and cooling of the tank. The circumferential layers undergo a non negligible compressive stress.
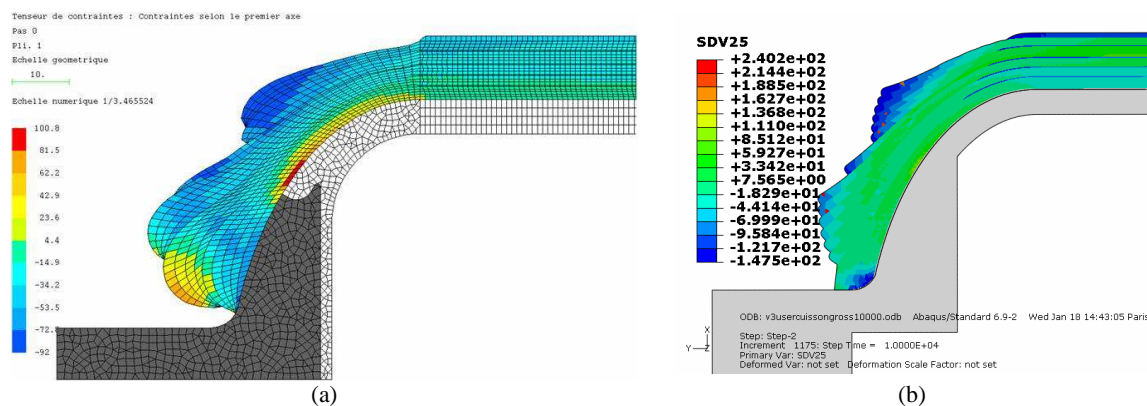

Figure 6. (a) Stress (MPa) due to a uniform temperature loading and (b) stress (MPa) in the fire direction after curing and cooling of the tank

4 Prospective work

Future works aim at refining estimations of radial and axial displacements, mass and fracture mode by investigating four possible ways of improvement:

- Improvement of material knowledge: a precise estimation of the burst pressure requires to understand the different damage mechanisms (fiber failure, fiber/matrix debonding, delamination) leading to final failure. With this end in view, tests on elementary samples are in progress.

- Improvement of full composite architecture knowledge: first results (especially the discrepancy observed between measured and simulated axial displacement) show the necessity of a better knowledge of the vessel geometry especially in the vessel domes (fiber orientations and layer thicknesses). Detailed analyses of vessel geometry on a real structure are in progress.

- Improvement of behaviour modelling: behaviour modelling has to be improved by taking into account more physical phenomena as, for example, viscosity, fibre interlacing… Concomitantly to these modelling improvements, tests on structures (flat samples with fibre interlacing due to filament wound process) are planed in order to build up a set of experimental data which will be useful to validate the modelling hypotheses.

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- Improvement of FE model: a precise geometrical representation of the tank domes, as well as their complex stacking, remains a pivotal issue to simulate satisfactorily the axial displacement and the mass of the composite. Furthermore, the perfect contact between metallic bases, liner and composite seem to be too simplistic, as these zones undergo a high shear level. Plastic behaviour of the metallic bases should also be taken into account.

In the long term, durability under more complex loadings will be tested and simulated: as these hydrogen tanks are required to be filled up and emptied many times, the residual burst pressure has to be assessed after cyclic loading.

Acknowledgements

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