MECHANICAL BEHAVIOUR OF 700 BAR TYPE IV HIGH PRESSURE VESSEL: COMPARISON BETWEEN SIMULATIONS AND EXPERIMENTS THROUGH OSIRHYS IV PROJECT

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Abstract

This paper deals with the French OSIRHYS IV project. Its project, leading by CEA, aims to develop and validate models and methods for composite high pressure design and optimization with behaviour uncertainties knowledge. It implicates five partners and is divided in several work packages like manufacturing, experimental tests, code qualification (burst, fatigue and thermomechanical behaviour), optimization. This papers presents progress of CEA, particularly, for vessel manufacturing control, burst simulation at different temperatures with fibre failure and matrix cracking, and composite shell optimization.

1 Introduction

New energies are 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. In particular, Hydrogen storage remains a key issue for the high scale deployment of fuel cell applications. Different ways exist to store hydrogen, such as liquid storage tank [1-3], polymer and composite foam [4,5], metal hydrides [6], gaseous high pressure storage vessel [7,8]…

Today, compressed gas vessels represent the most mature technology for hydrogen storage. There are four types of high pressure vessels [9]:

- Type I: metallic vessel,
- Type II: thick metallic liner hoop wrapped with a fibre-resin composite,
- Type III: metallic liner fully-wrapped with a fibre-resin composite,
- Type IV: polymeric liner fully-wrapped with a fibre-resin composite.

Nowadays, gaseous hydrogen storage at high pressure, 70 MPa nominal working pressure, with type IV vessels is the best technology. Indeed, 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…).

1.1 High pressure storage problems

But research and development is still needed to cut cost and improve volumetric performance, reliability and durability of the hydrogen storage systems. The high mechanical stresses generated by internal pressure leads to a massive use of carbon fibre and it is well known that carbon fibre represents the highest part of vessel cost (50% to 70% of the final cost of the vessel as shown in figure 1). So an optimization of vessel composite shell is needed to reduce significantly vessel costs and this optimization involves an improvement of numerical simulations which are, nowadays, far from the real problem due to the using of simplified composite modelling.

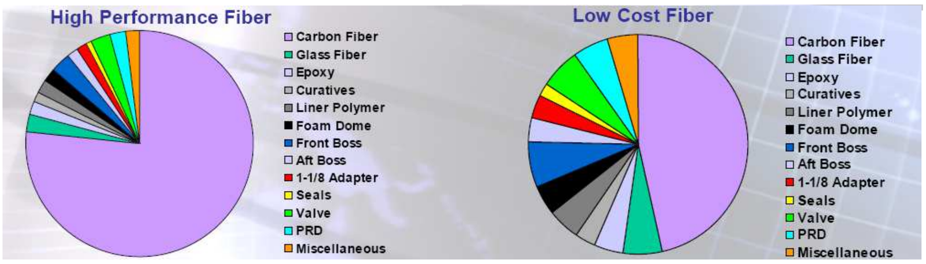
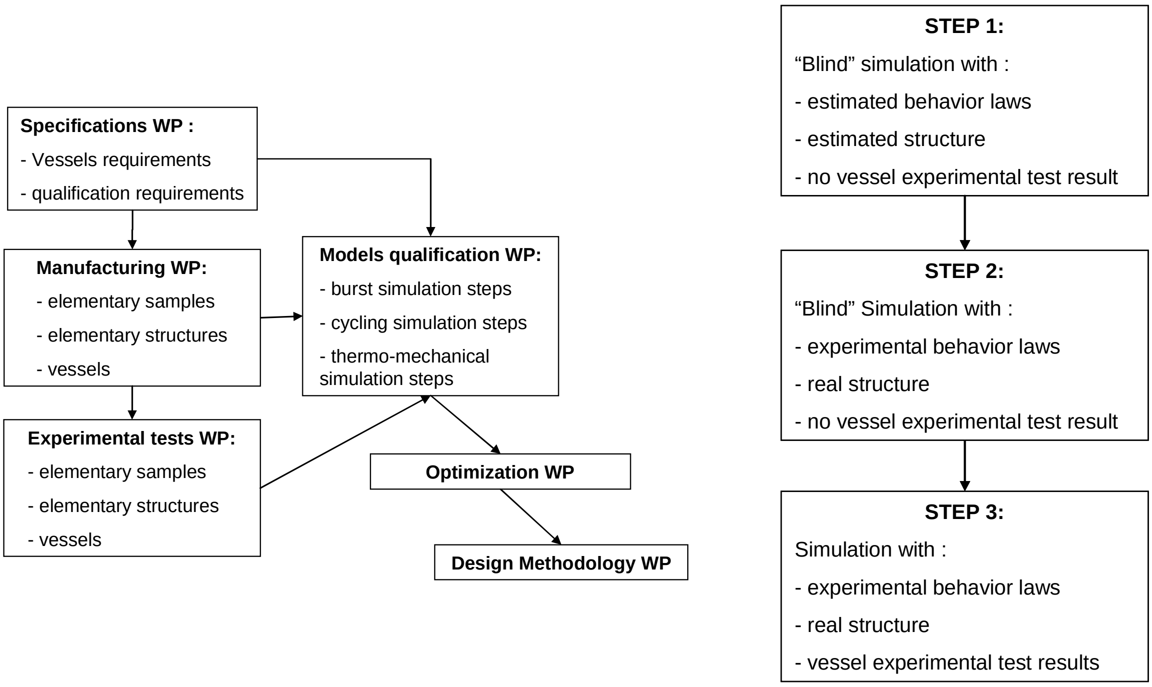


Figure 1. Costs repartition of hydrogen high pressure type IV vessels depending of carbon fiber types T1000/T700 (Quantum, USA)

1.2 OSIRHYS IV project

OSIRHYS IV project is a three-year project supported by the French Research National Agency (ANR) through “Hydrogène et Piles à Combustible” program (HPAC program). The goal of this project is to develop and validate models and methods for composite high pressure design and optimization by clarifying uncertainties and approximations of high pressure vessel composite calculation. The project is dedicated to all conception and simulation chain that is represented in several project work packages as presented in figure 2a. Moreover code qualification will be performed in three steps (figure 2b) beginning by totally blind simulations with “state of the art” properties up to a fully knowing of vessel properties and experimental behaviour. Five partners participate to this project: CEA (project leader), Armines, CEA-SAMTECH, Institut P’ and Polytech’ Annecy-Chambéry. Code qualification will be provided by a comparison of partner simulations and experimental test results [10].



(a) (b)

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

This paper deals with the CEA results. First, sample and vessel manufacturing are presented. Then, the experimental test and simulation results are detailed. Finally, vessel optimisation is discussed.

2 Sample and vessel manufacturing

The high pressure vessel studied in OSIRHYS IV project is made of three main components (figure 3):

- a plastic liner which ensure the hydrogen tightness,
- two metallic bosses ensuring connection with other devices,
- a composite shell (CFRP) which is manufactured by filament winding process and which provides the structural strength of the tank.

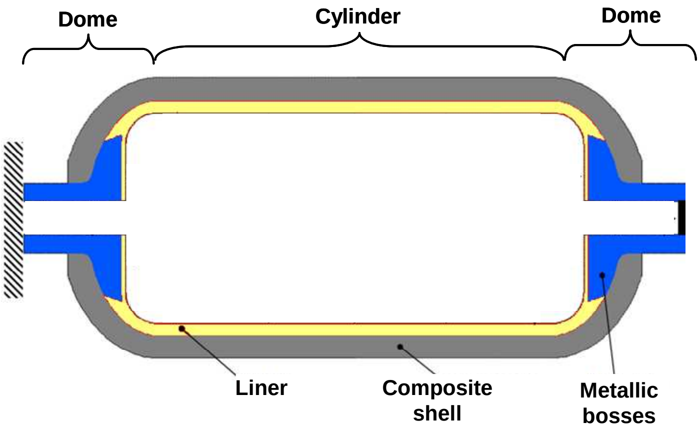


Figure 3. Vessel components

Composite material is being characterized by testing elementary samples with different composite stacking sequences. Tests are performing on composite samples manufactured by CEA. These samples come from plates of which each ply has been manufactured by filament winding process in order to use the same process than for the vessel manufacturing.

One of the project tasks is to perform experimental tests on vessel. So, a composite stacking sequence has been determined at the beginning of the project and all the vessel have been manufactured with this composite stacking sequence. A particular attention has been paid to have a batch of vessel with the higher reproducibility in order to avoid experiment dispersion due to manufacturing process. The composite manufacturing process has been automated. This automation has permit to stabilize composite shell mass as shown in figure 4.

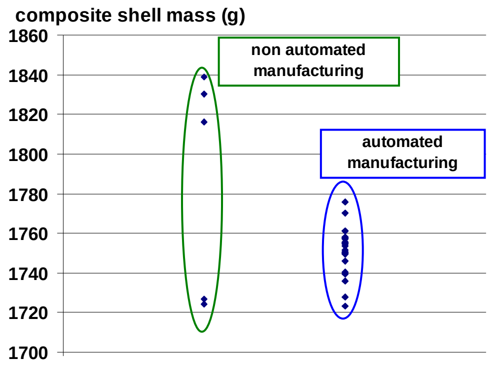


Figure 4. Composite shell masses of vessel manufactured for OSIRHYS IV project

3 Experimental tests

In the project, different tests (burst tests and fatigue tests) at different temperatures (-40°C, +25°C and +85°C) are planed. The first step of the experimental study is the burst test at +25°C. Several burst tests have been performed, sometimes monitored by displacement sensors. It permits to have a first database of the vessel behaviour which could be compared to simulation results as shown in figure 6. The next step will be to perform all the tests planned in the project with several monitoring as optical fibres, acoustic emission, strain and displacement measurements, pressure sensors or fast digital camera. The aim is to record accurate data which can permit the qualification of codes.

4 Vessel behaviour simulations

An axisymmetric geometry has been built in Abaqus/CAE®. The plug-in "Wound composite" has been used to generate the vessel composite shell geometry (layer thicknesses, fibre orientations…). One boss extremity is blocked. 20095 quadratic elements are used. Model geometry is presented in figure 5.

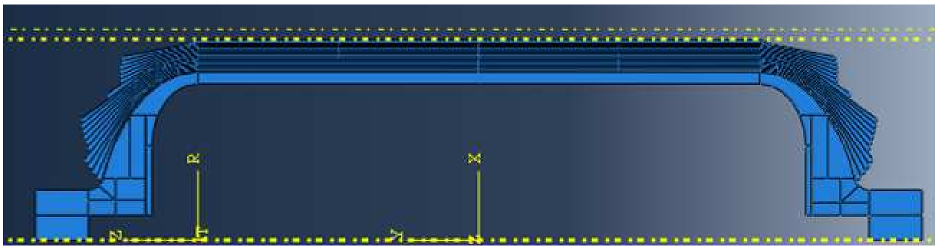


Figure 5. Model geometry view

4.1 Burst simulation

Burst simulations at +25°C have been performed within the framework of step 1 and step 2 of burst code qualification (figure 2b). Step 1 modelling have been performed with "state of the art" composite properties and step 2 modelling with experimental composite properties measured on samples presented in part 2 (table 1). A uniform pressure up to 2000 bar is applied on the vessel inner surface.

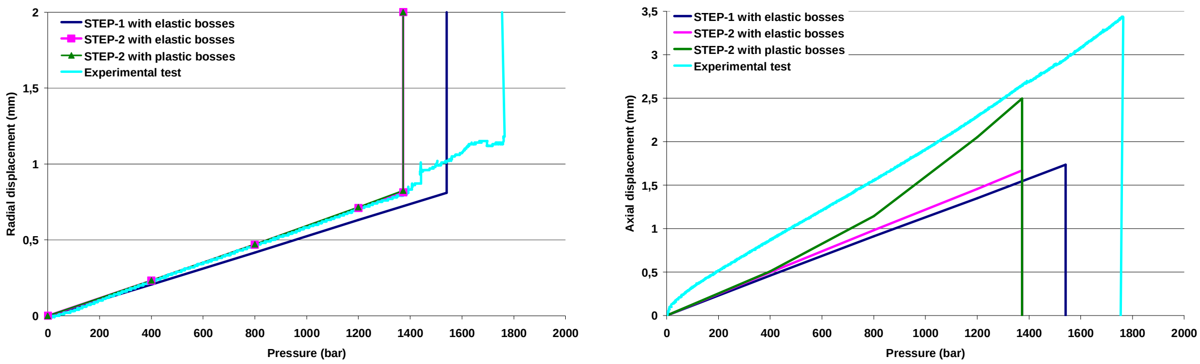
	E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	G_{23} (MPa)	ν_{12}	ν_{23}	σ^r_{11} (MPa)	σ^r_{22} (MPa)
Step 1	155480	7780	4130	2820	0.36	0.38	2450	/
Step 2	134220	8175	4697	2962	0.36	0.38	2104	48

Table 1. Composite properties at +25°C used for step 1 and step 2

At first, linear static computations have been performed with step 1 and step 2 composite properties. For these first simulations, an elastic behaviour of liner and bosses has been chosen. The burst pressure has been computed considering a very simple fibre failure criterion in the composite layers. This criterion is systematically reached at the middle of the tank in the axial direction for the most inner circumferential layer.

Results are presented in figure 6. It shows that burst pressure is underestimated and moreover, results are worse with step 2 composite properties. It can be explained by a lower σ^r_{11} than for step 1 composite properties. Nevertheless, step 2 radial displacement is perfectly fitted with test radial displacement showing an improvement of the global vessel radial behaviour due to characterization of composite properties with samples. But, figure 6b also shows that linear static computations are not sufficient because the test axial displacement is non linear.

Indeed, there are a high non linearity at the beginning of the test (at low pressure) and then a lower non linearity in the second part of the test. First non linearity can be due to gaps between composite and liner. For the second non linearity, a plastic behaviour of bosses could explain that. So the model has been improved by adding a “state of the art” plastic behaviour for boss parts. Results show that this plastic behaviour law has no influence on the radial displacement and on the computed burst pressure. To explain that, we can remember that failure criterion is reached on the middle of the tank, so far from bosses. Nevertheless, figure 6b show that a boss plastic behaviour permits to enhance axial displacement by adding non linearity. Boss plastic behaviour will be characterized.



(a) (b)

Figure 6. Comparison between experimental burst test at 25°C and without-damage simulation results: Pressure vs. (a) radial displacement and (b) axial displacement

To improve the model, damage has been added in composite properties. Two types of damage have been taken into account: matrix cracking and fibre failure. It consists in reducing some composite properties in accordance with the damage type. Simple maximal stress failure criterions have been applied, one for fibre failure and an other for matrix cracking. The property reductions for each damage type are the following:

- Fibre failure:

$$E_1 = E_2 = E_2^0 \; ; G_{12} = G_{12}^0 \quad (1)$$

- Matrix cracking:

$$E_1 = E_1^0 \; ; E_2 = E_2^0 * (1\text{-}0.75) \; ; G_{12} = G_{12}^0 * (1\text{-}0.75) \quad (2)$$

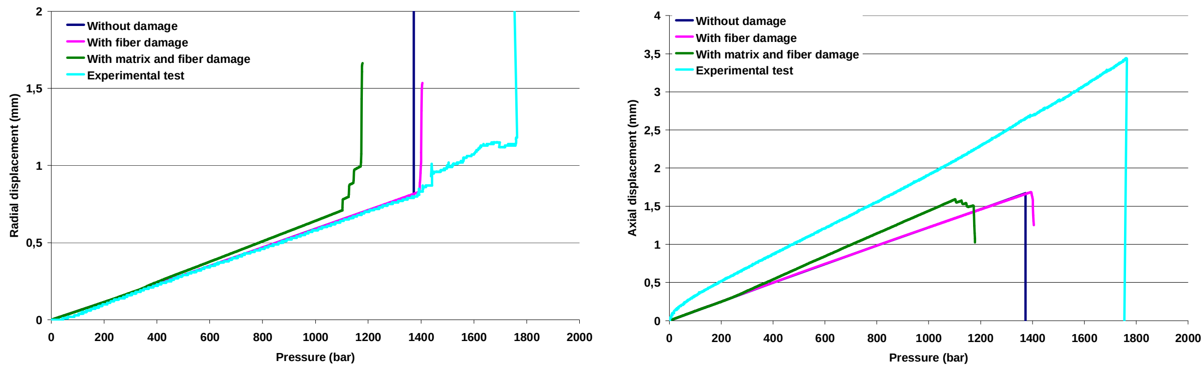
- Fibre failure and matrix cracking:

$$E_1 = E_2 = E_2^0 * (1\text{-}0.75) \; ; G_{12} = G_{12}^0 * (1\text{-}0.75) \quad (3)$$

Where, for equations (1), (2) and (3):

$$E_3 = E_2 \; ; G_{13} = G_{12} \; ; G_{23} = E_2 / (2 * (1 + \nu_{23})) \quad (4)$$

New computations have been performed with fibre failure and with both matrix cracking and fibre failure. A comparison has been made with the experimental test and with the step 2 with elastic bosses computation. Results are presented in figure 7. Figure 7a show that damage has a weak influence on the radial stiffness. Nevertheless, it can be noticed that matrix cracking reduces burst pressure. Matrix cracking induces a load transfer to carbon fibres so fibre failures occur earlier leading to an early vessel burst. Figure 7b shows an axial stiffness loss due to matrix cracking. Indeed, during pressure increase, matrix cracking propagates preferentially in the vessel dome. Moreover, damageable computations permit to simulate burst mode with an inner expulsion of the metallic bosses and a burst on the vessel cylinder.



(a) (b)

Figure 7. Comparison between experimental burst test at 25°C and with-damage simulation results: Pressure vs. (a) radial displacement and (b) axial displacement.

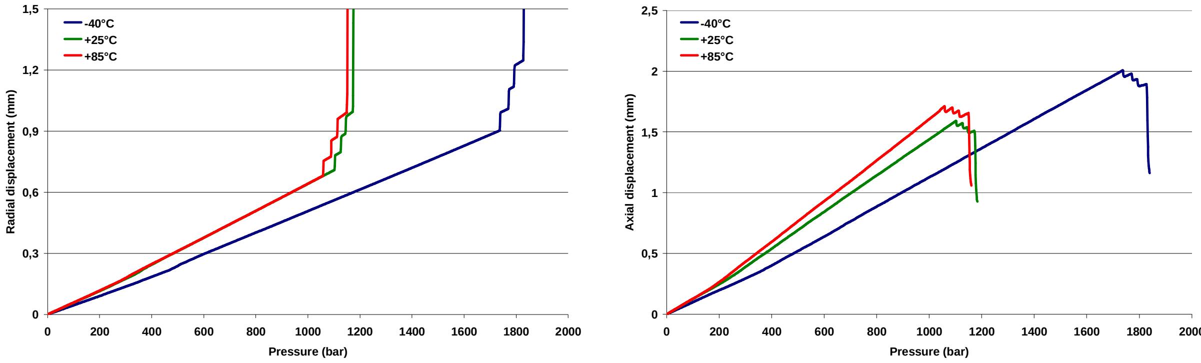
4.2 Thermomechanical behaviour simulation

An other task of OSIRHYS IV project is the vessel thermomechanical behaviour simulation. It concerns burst test and fatigue test at different temperatures (-40°C, +25°C and +85°C). This paper presents the first burst simulation. Composite properties at each temperature have not been yet determined by experimental tests so we use reduction or amplification coefficients in relation with +25°C step 2 composite properties. These coefficients are from literature [11]. Composite properties at each temperature are presented in table 2. Liner and boss properties are the same for each temperature.

Temperature	E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	G_{23} (MPa)	ν_{12}	ν_{23}	σ^r_{11} (MPa)	σ^r_{22} (MPa)
-40°C	134220	8829	5495	3199	0.36	0.38	2630	57
+25°C	134220	8175	4697	2962	0.36	0.38	2104	48
+85°C	134220	6703	3382	2429	0.36	0.38	2104	36

Table 2. Composite properties at different temperatures

New computations have been performed with these new composite properties. These computations take into account matrix cracking and fibre failure. Results are presented in figure 8. It shows that computed burst pressure is similar at +25°C and +85°C but it is higher at -40°C. It can be explained by the higher σ^r_{11} (+25%) at -40°C. Moreover, global radial stiffness is similar at +25°C and +85°C while global axial stiffness is higher at +25°C than at +85°C. It shows that cylinder behaviour is lead by circumferential layer (so by fibres) and dome behaviour is more sensitive to matrix behaviour. The computed burst mode is safe (no ejection of the metallic bosses) for each temperature.



(a) (b)

Figure 8. Comparison between with matrix and fibre damage simulation at different temperature: Pressure vs. (a) radial displacement and (b) axial displacement

5 Optimization

A first step of vessel optimization has been performed at the beginning of the project. It permits to reduce from 24% composite mass in comparison with the final vessel of a previous project (from 2300g to 1750g). Moreover, this optimization permits to increase burst pressure from 1725 bar to about 1800 bar. The CEA optimization methodology consists in iterations between numerical design and experimental burst tests. The manufacturing process is also improved to lead to the best quality for composite shell.

6 Conclusions

A CEA progress report of OSIRHYS IV project has been presented in this paper. Project aims have been detailed. Vessel automated manufacturing permitted to improve composite shell quality. Different burst computations have been performed and compared to an experimental test. Different steps of simulation have been performed from simple linear static computations to non linear computations with fibre failure and matrix cracking. Results show that the FE model has to be improved to better fit with experimental data. So different experimental test batches are planed. Then, code qualification will permit to optimize composite shell to cut vessel cost.

7 Acknowledgements

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