COMPRESSED HYDROGEN FORM-FITTED TANK

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Abstract

This paper deals with hydrogen as an alternative vector of energy, automotive industry needs some form-fitted tanks. This study proposes to use composite rods to reinforce flat surfaces on a liner, and so make a step to achieve this type of tank. An assembly method was analyzed by finite elements and experimental tests. Finally, a prototype of tank is presented and tested under internal pressure loading and shows the capabilities of the method.

1 Introduction

Nowadays, several car makers try to replace the energy source of their vehicles. The main objectives are to give an alternative for oil as the world reserves are decreasing, and to produce low CO_2 emission vehicles. So, Hydrogen could be considered as the best energy vector to achieve these objectives.

1.1 Hydrogen storage

Actually, classical gas engines or fuel cells can use hydrogen to produce energy, the main problem is still the storage. The technologies for storage are gas compressed, metal hydride and liquid hydrogen tanks.

The liquid hydrogen technology means to use an extremely low temperature (20K) for the storage. Therefore, the energetic cost to reach this temperature has to be taken into account [1] as the cost of tank's insulation [2]. As a consequence, the liquid technology seems to be too expensive due to insulation management.

The solid storage state uses the absorption / desorption cycle of metal hydride [3]. Depending on the hydride, it is a low pressure storage which requires a careful management of heat exchange. Metal hydride's density gives an access to low volume tanks at the cost of high weight and complex heat management.

The compressed gas storage actually uses well known structures:

- Type I, a load bearing metal bottle, mainly a tube closed by hemispherical parts
- Type II, type I reinforced by a resin impregnated continuous filament on a cylindrical part,
- Type III, a non-load bearing metal liner fully wrapped and reinforced by a composite
- Type IV, a non-load bearing polymer liner fully wrapped and reinforced by a composite

Type III and type IV tanks are lighter than metal hydride ones, they store more hydrogen per weight unit around 5 % (some authors provide up to 13% [4]) in mass versus 2%The main backwards are pressure and volume, the tank works at high pressure (between 35 MPa and 80 MPa), at 70 MPa the internal volume of the tank is 125 L to store about 5kg of hydrogen.

1.2 Major constraints for automotive industry

This study is a part of the French program HYPE. This project investigates the improvement of compressed gas hydrogen storage, and is intended for automotive industry. In order to decrease the development cost, the tank has to use the remaining space in a car, moreover to be as light as possible to decrease the energy consumption.

This study presents a way to change the overall shape of types III and IV, in order to adapt the tank to the free space on a vehicle, the theoretical and experimental basis for the application, and then the manufacturing and testing of a form-fitted tank.

2 From type III or IV gas tank to a form fitted one

Actually, types III and IV represent a known structure with associated international standards for natural gas [5] or hydrogen [6] storage. The shape used is presented on figure 1, it consists in a cylinder closed by a spherical or ellipsoidal dome. This geometry has a revolution axis therefore it’s easy to reinforce the liner by filament winding and achieve all the design requirements.

Figure 1. Typical liner cross-section of type III and IV

On a second thought, this shape complicates the integration on a vehicle, in most cases the tank reduces the available space for the trunk. To save space, the shape has to be more complex in order to use another site on a vehicle. For instance in figure 2, this geometry could use the space under the floor of the vehicle.

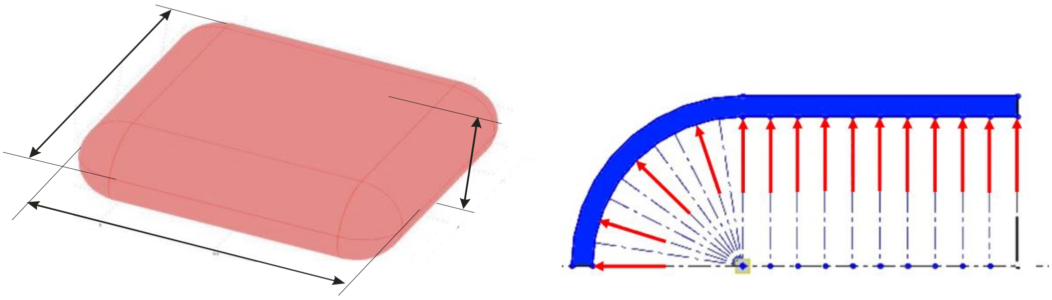

Figure 2. Example of a form fitted improvement – Pressure field on a cross section

A finite elements analysis shows that this structure could not bear the pressure. Indeed at the same burst pressure with a similar thickness of composite, the displacement on the center is about 172 mm, with a maximum strain along fibers of about 16% (which is way above the limit of classical fibers).

In fact, the loss of the revolution axis creates a need of reinforcements parallel to the pressure fields. Therefore, in order to use this design, we have to introduce reinforcement through the thickness of the geometry presented in figure 2.

3 Shape reinforcement

3.1 Type of reinforcement

To reinforce this type of flat surface on a tank without making liner too complex, we decide to insert some rods through the thickness. This choice leads to the following problems: the fixation of the reinforcement and the hydrogen tightness.

The chosen reinforcements are T700 carbon fiber / epoxy resin rods made by Soficar, table 1 gives the mechanical characteristics. The manufacturing process of the rod is pultrusion, this process could made large quantities at a moderate cost.

Young modulus [MPa]	160000
Ultimate tensile strength [MPa]	3000
Ultimate Strain	2%
Shear modulus [MPa]	3200
Shear strength [MPa]	88
Density	1,59

Table 1. Mechanical characteristic of composite rods

These rods are used for several applications, civil engineering, offshore exploration… The main way to make an assembly is to use adhesive joints, so an intermediate part has to be designed, the rods would be sticked to this part. This one could be weld or stick to the liner. Figure 3 presents the rods, the attaching parts and an assembly ready to be tested in tension.

Figure 3. Carbon/epoxy rods, attaching parts, and testing systems

To design exactly the fixation, we need to know the characteristics of the adhesive joints, length and thickness.

3.2 Fixation parts : numerical study

The shear stress inside the adhesive joint is determined by equation 1.

$$\tau = \frac{F}{\pi \cdot d \cdot l} \tag{1}$$

where τ is the shear stress,
F the tensile strength,
d the diameter of rod,
l the length of adhesive joint.

If we consider that the adhesive joint mustn't fail before the rod, F is determined by equation 2.

$$F = \sigma_{max} \cdot \pi \cdot d^2 \tag{2}$$

where σ_{max} is the ultimate strength of the rod
The equations 1 and 2 define a design rule as equation 3

$$\frac{d}{l} = \frac{\tau_{max}}{\sigma_{max}} \tag{3}$$

where τ_{max} is the ultimate shear strength of the adhesive joint
For the rest of the study, the diameter of rods is 6 mm and the design of the fixation part is presented on figure 4

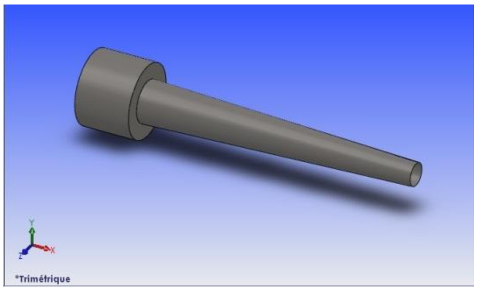

Figure 4. General design of a fixation part

The fixation parts consist in a cylinder for welding or sticking on the liner, and a cone to increase the length of the adhesive joint. To determine the cone angle, we made some finite elements analysis. Figure 5 presents the evolution of the shear stress along the adhesive joint, there is one curve by calculation step. Table 2 gives the maximum shear stress for a given angle.

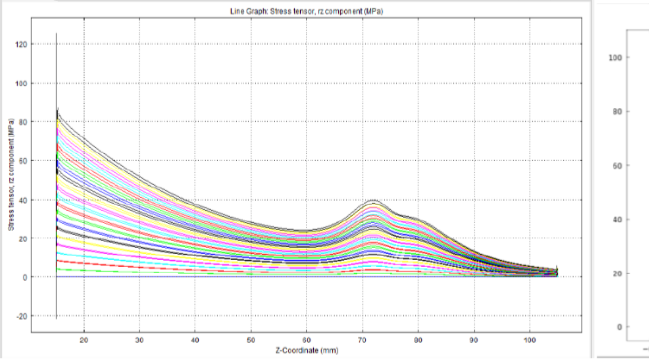

Figure 5. Numerical study of the shear stress in the adhesive joint – Cone angle 5°

Cone Angle	Maximum shear stress [MPa]
2°	40
5°	80
15°	225
30°	350

Table 2. Maximum shear stress for different cone angles

As the figure 5 and Table 2 show, the shear stress is maximum at the beginning of the adhesive joint and increase with the cone angle. As a consequence, the chosen cone angle is 2°. The optimum thickness of the joint would be determined experimentally for a given adhesive length of 90 mm

3.3 Fixation parts : experimental study

In order to realize a complete mock-up of form fitted tank, we have tested different adhesives, protocols and different thicknesses. For every case, at least 10 tests were realized. Table 3 presents the three different adhesives used and their properties

Adhesive°	Shear Stress [MPa]	Curing Cycle
A	23	1h at room temperature (RT)
B	25	6 min at RT
C	13,6	1h at RT

Table 3. List of used adhesives

Two protocols for bind fixation parts and rods were used :

- Protocol 1: The contact surface on the fixation part and the rod was coated with an adhesive and then the rod is inserted in the fixation part
- Protocol 2: Only the rod is coated with glue and then inserted in the fixation part

The protocol 1 hasn't be used for adhesive B because the pot life was too short for applying it. When all the samples were prepared, the tensile tests have been realized, strength and displacement were recorded and measured, the loading rate was 100 N/s for all tests. Figure 6 presents the typical observed behavior.

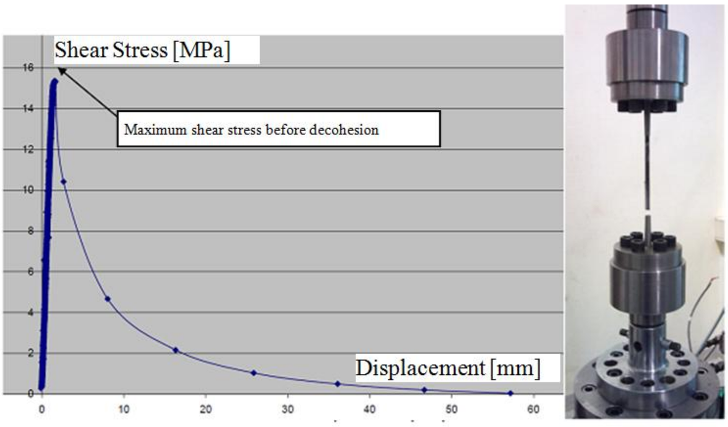

Figure 6. Shear stress versus displacement

The behavior presents a linear increase of shear stress until debonding and then sliding of the rod out of the fixation part. Figure 7 presents for each adhesive, each thickness and each protocol the average of maximum measured shear stress.

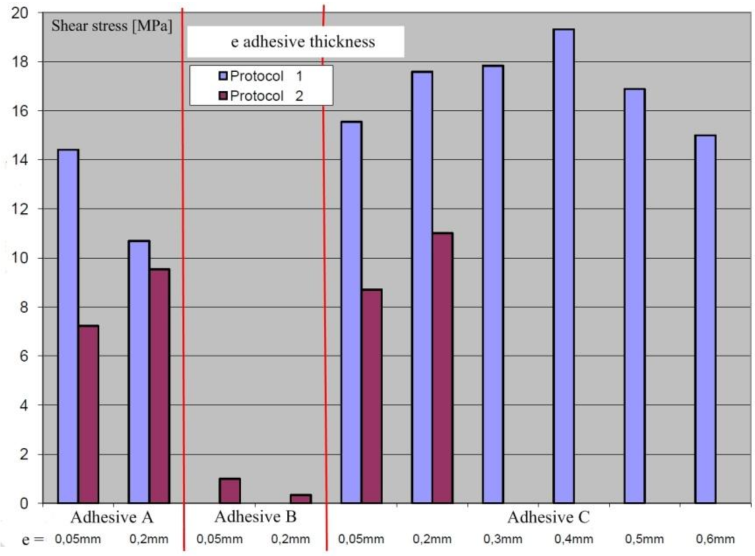

Figure 7. Maximum shear stress in the glue joint

According to figure 7, the adhesive C has the best performances, the shear stress increases with thickness until 0.4 mm and then decreases with it. This result was also confirmed by Arenas et al. [7]. So, adhesive C with a thickness of 0.4 mm was used to realize a prototype of a form-fitted tank.

4 First mock-up

4.1 Materials and process

Figure 8 shows a tank with two flat surfaces which were realized in order to test the reinforcement, the inner volume is about 6L, 18 rods reinforce the liner. In order to wrap the resulting liner by filament winding, aluminium alloys parts were made to soften sharp edges. Total outside dimensions are 300 mm x 205 mm x190 mm.

Figure 8. Form fitted liner made of stainless steel – aluminium shape adapter

Finally, we use filament winding to wrap the liner with T700 carbon fibres / epoxy resin composite as showed on figure 9. After winding, the tank was cured 16 hours at 85°C.

Figure 9. Filament winding of the form-fitted tank

To create a reference, a second prototype was made with the same shape but without the rod.

4.2 Internal pressure testing

We made two types of tests on the prototypes, air tightness they were loaded at 10 bar of air pressure during 24 hours and a burst test under hydraulic pressure. Table 3 presents the results of the test tank 1 is the reinforced one

Tank n°	Air tightness	Pressure [MPa]	Type of Failure
1	OK	51,1	leakage
2	OK	38,5	leakage

Table 3. Maximum pressure test

Figure 10 shows the crack responsible of the leak, it is located on a welded joint.

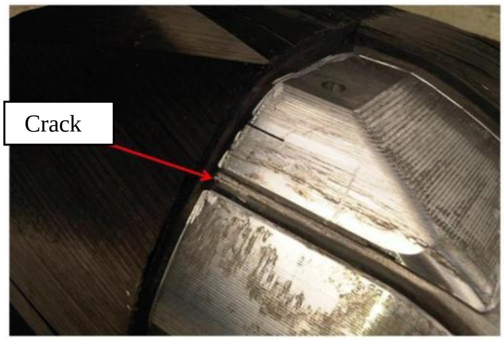

Figure 10. Crack on the welded joint - source of the leakage

The burst limit of the prototype was not observed, but the leakage appears at a 24% higher pressure on the reinforced one.

5 Conclusion and acknowledgement

This paper introduces a way to reinforce form fitted tanks by using composite rods and the developments of some theoretical and experimental points to achieve the reinforcement and design. Finally, two prototypes were tested and even the first results are encouraging. Further developments have to be done for completing this study

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