LIGHTWEIGHT, ENERGY-DENSE SYSTEMS FOR GASEOUS HYDROGEN STORAGE

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Introduction

Hydrogen can be stored for transportation in three forms: liquid hydrogen, pressurized hydrogen or metal hydrides. Dogan (2006) reported that high-pressure steel containers can sustain up to 200 bars to store 5 kg of hydrogen in 390 liters (1wt.%). Composite containers made of aluminum or plastic liners overwrapped with carbon fibers that sustain internal pressures up to 700 bars. Such Doagn (2006) reported that such vessels would store 5 kg of hydrogen in 250 liters at 350 bars (11.3 wt.%). The use of 700-bar pressure vessel is still limited as its design utilized expensive aerospace grade carbon fibers and high molecular weight polymer to serve as a liner (Ko et al., 2005). As the storage tank size became an issue to be conformable within the space available in the car, there is a great need to store the hydrogen at even higher pressures. Review of pertinent research studies revealed that all current design configurations utilized cylindrical shape for the storage tanks with two end domes. This paper summarizes the findings of a recent study performed by West Virginia University to examine various design configurations and devise lightweight and safe hydrogen storage system for on-board automotive applications.

FE Analysis of Composite Cylindrical Tanks

3D finite element analysis was performed for a composite cylindrical tank made of 6061-aluminum liner overwrapped with carbon fibers subjected to a burst internal pressure of 1610 bars. As the service pressure expected in these tanks is 700 bars, a factor of safety of 2.3 is kept the same for all designs. The tank was sized to be 305 mm in diameter and 560 mm in length to be occupied with 5 kg of gaseous hydrogen. Figure 1 illustrates the stress distribution in the composite tank at the named internal pressure.

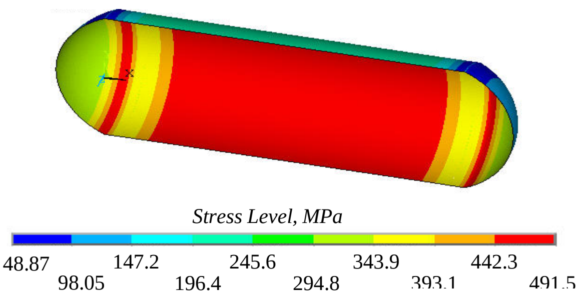


Figure 1 Stress Distribution in Cylindrical Tank

Figure 1 reveals that the stresses develop in the aluminum liner reach a magnitude of 491.5 MPa at the interior surface of the tank, which exceed the tensile strength of the aluminum liner, 310 MPa (Boresi and Schmidt, 2003). This qualitatively agrees with experimental results published by Dubno (2006) who built and tested a tank prototype that failed at internal pressure of 410 bars versus an expected burst pressure of 804 bars.

The aforementioned results clearly indicate that the aluminum core is not suitable for lightweight design of hydrogen tanks, since it does not reduce the stress levels developed on the inner wall surface of the pressure vessel. Additionally, the presence of the aluminum at the inner surface will make the aluminum always subjected to the maximum stress due to an internal pressure. Although the aluminum is able to sustain such stress at pressures in the magnitude of 350 bars, the results in Figure 1 indicate that it will fail under pressures of 700 bars or higher. Therefore, hydrogen tanks ought to be built entirely of composite layers based on carbon fibers or other innovative composite materials. The concept of using a carbon composite liner seems to be promising in overcoming the low strength of the aluminum liner at internal high pressures. This could be further enhanced by using MetPreg filament winding to produce such a liner.

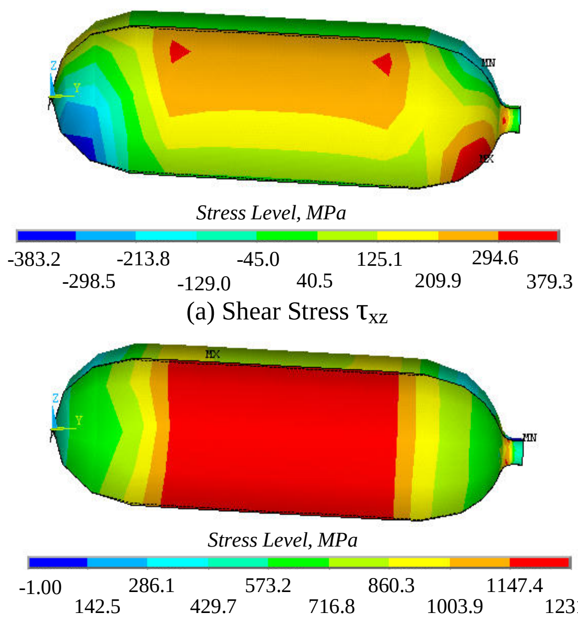
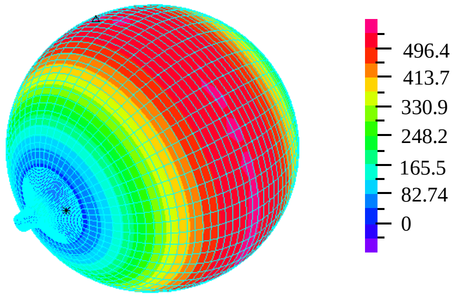


Figure 2 Stress Distribution in All-composite Cylindrical Tank

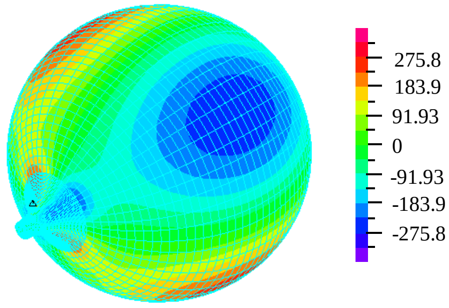
To further illustrate this point, a 3D finite element model was developed for a cylindrical tank with a 305 mm diameter and the length of the cylindrical part is 560 mm. The inlet has a length of 38 mm and its diameter is 50 mm. The tank wall is assumed to be built of 100 layers of carbon fibers. The thickness of each layer is 0.23 mm, thus a total wall thickness is 23 mm. The fiber orientation is 30°/60°/±45° with orientation percentages of 45%/45%/10%. The stress components were calculated under the effect of an internal burst pressure of 1610 bars. Figure 2 illustrates by fringes the shear stress components developed in the tank wall under burst pressure. Noticeable is the formation of stress concentration zones in the vicinity of the neck, which makes this region more susceptible for initiating failure in the tank. This is also confirmed by examining the maximum principal stress and maximum shear stress.

FE Analysis of Composite Spherical Tanks

Acknowledging the basic engineering principles that internal stresses are half in magnitude for a spherical tank as opposed to cylindrical tank designs the focus of tank configuration moved to spherical concepts. A shape optimization was performed to analyze various spherical and cylindrical tank configurations.



(a) Hoop stresses



(b) Shear stresses

Figure 3 Stresses in Spherical Tank.

Spherical tanks of internal diameters of 478 mm (15-gallon tank) and was modeled. Different thicknesses were assumed for each model and the stresses were calculated under the effect of an internal burst pressure of 1610 bars. Figure 3 illustrates by fringes the stress distribution in the tank wall. Noticeable are the stress concentration zones that developed around the neck vicinity, which constitute the main zone for potential tank failure.

Conclusions

The state-of-the-art in the area of compressed hydrogen storage reveals that the current configuration of the hydrogen storage tank is a seamless cylindrical part with two end domes. The tank is composed of an aluminum liner overwrapped with carbon fibers. Such a configuration was proved to sustain internal pressures up to 350 bars (5,000 psi). Based on the finite element analysis conducted herein, the following conclusions could be made:

– A stress reduction could be achieved by a geometry change only, which could increase the amount of pressure sustained inside the vessel and ultimately increase the amount of hydrogen stored per volume.
– Stress reductions will decrease the thickness dimension required to achieve a particular factor of safety in a direct comparison to a cylindrical design. Minimal thickness will reduce the cost per storage system by limiting the usage of high performance materials i.e. carbon fiber.
– Options to vary the spherical dimensions will utilize free space on-board a standard vehicle. Various sizes of spherical tanks can be dimensioned to allowable free space inside a vehicle frame, chassis, cargo areas, etc.
– The aluminum liner is not suitable for lightweight design of hydrogen tanks, since it can not withstand the high tensile stress developed on the inner wall surface of the pressure vessel. Therefore, a carbon composite liner will need to be fully developed and tested for this purpose.

References

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