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DESIGN OF HYDROGEN STORAGE TANKS FABRICATED FROM COMPOSITE MATERIALS

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ABSTRACT

Use of polymer composites in manufacturing hydrogen storage tanks, allows minimizing the weight, improving the aesthetic and also increasing the pressure vessel mechanical, impact and corrosion behavior. In this paper, cylindrical composite pressure vessels constituting of metallic internal liner and filament wound composite material as the outer shell were investigated. The Finite Element Method is used to predict the mechanical behavior of pressure vessels. The influence of metallic and composite layers thicknesses, number of composite layers and winding angle of filament-wound composite on the designed tank were investigated. A parametric study was performed to find out the optimal tank design.

KEY WORDS

Finite Element, hydrogen storage, tanks, design, composites.

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INTRODUCTION

Filament-wound composite pressure vessels have found widespread use not only for military use but also for civilian applications. Cylindrical composite pressure vessels constitute of a metallic internal liner and a composite outer shell [1] as shown in Fig. 1. The metal liner is necessary to prevent leaking, low permeability of hydrogen, while some of the metal liners also provide strength to share internal pressure load [2, 3].

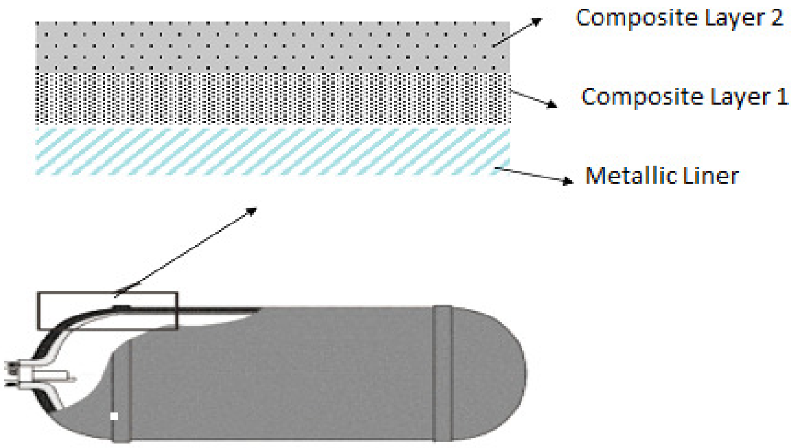


Fig. 1. Hydrogen tank and example of its wall composite polymeric materials layers.

Velosa and Nunes [4] studied the development of new generation of filament composite pressure vessel by using High density polyethylene (HDPE) liner and thermosetting resin as matrix with 70% mass fraction of 2400 Tex type E continuous glass fiber. The ABAQUS Finite Element package was used to predict the mechanical behavior of the cylinder in the range from 6 to 18 bars (0.6 to 1.8 MPa). Finally it was found that failure occur in some cross-ply internal layers having fibers oriented at 20° at lower vessel internal pressure.

Lung [5] studied the detected damage of pressure vessels with little or no maintenance required. To meet the need for a safe, reliable fuel storage system, a low-cost, acoustic-ultrasonic system has been developed to detect damage in high-pressure storage cylinders made of Carbon Fiber Reinforced Polymers (CFRP). This structural health monitoring system could lead to lighter, lower cost cylinders, and improved safety in automotive applications that utilize hydrogen and natural gas. Finally, Tomonori et al. [6] investigated the failure of a pressurized FRP cylinder under transverse impact loading.

The objectives of the present study are to design a gaseous hydrogen storage tank (pressure vessel) consisting of aluminum liner wrapped with a filament winding glass fiber reinforced polymer matrix structure in the outer layer of vessel. Thus a parametric Finite Element study was performed to investigate the optimal composite layer setup, including number of layers, layers thickness, fiber orientation and fiber volume fraction. The optimal design (minimum tank weight and cost) was finally concluded.

THEORETICAL

For cylinders, radius to thickness (R/t) ratios that is typically less than 10, thin-shell design equations are not accurate [7], and thick-shell design equations have to be used. Considering a long thick cylindrical shell of inner radius R_i and outer radius R_o subjected to an internal pressure (P_i), as shown in Figure 2, and denoting the ratio of the outside to inside radii as m; (**m = R_o/R_i**), the radial and hoop stresses can be evaluated as;

$$\sigma_{rad} = \frac{P_i}{(m^2-1)}\left[1-\frac{R_0^2}{r^2}\right] \tag{1}$$

$$\sigma_{hoop} = \frac{P_i}{(m^2-1)}\left[1+\frac{R_0^2}{r^2}\right] \tag{2}$$

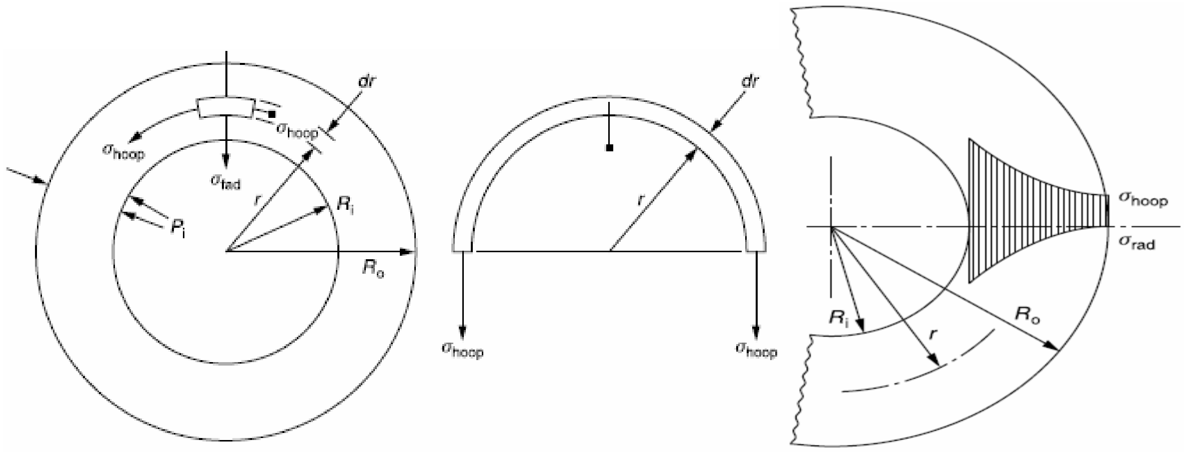


Fig. 2. Radial and hoop stress distribution inside cylinder walls.

Although equation [1-2] are not valid for composite materials, but had been utilized for verification of the simple case of one Aluminum layer . Another validation comparison was considered with Lawrence [8].who modeled a steel cylinder with inner radius (r_1) of 127mm, outer radius (r_2) of 152 mm and internal pressure of 6.9 MPa. That indicated a large thickness and high weight of the tank. The validation showed high agreement in optimal results.

Multi Layer Numerical Model

Due to geometry and load symmetry about cylinder longitudinal axis, quarter of a cylinder was modeled in the three dimensions. The model represents a quarter segment of a long, open-ended cylinder. The longitudinal-axis of the cylinder is the axis of symmetry.

Aluminum (6061-T6Al) was used as liner of a cylindrical vessel with overall thickness of 25 mm (where the cylinder inner radius is of order 150 mm). The outer layers are orthotropic material made of high and/or low toughness GFRP (Table 1) and have different fiber winding angles winding directions. Set of composite layers of reinforcement provided the thickness of 20 mm. The layers winding angles were oriented symmetrically and anti-symmetrically during the parametric study.

Table 1. Material properties of Low and High toughness GFRP [6].

Material properties	Low toughness Uni-Direction plate(GFRP)	High toughness Uni-Direction plate(GFRP)
Density (kg/m^3)	1210	2031
E_x (GPa)	3.63	46.3
E_y (GPa)	1.06	11.6
E_z (GPa)	1.06	11.6
G_{xy} (GPa)	0.43	4.28
G_{yz} (GPa)	0.42	4.18
G_{zx} (GPa)	0.43	4.28
υ_{xy}	0.25	0.25
υ_{yz}	0.39	0.39
υ_{yz}	0.06	0.062

The model was created using ANSYS Multi-Layer Solid element (Solid-46), while the material properties and loading conditions were specified to simulate the actual conditions, as long cylinder. Solid-46 is a layered version of the 8-node structural solid element designed to model layered thick-shells or solids [9]. This element allows up to 250 different material layers. The element has three degrees of freedom at each node (translations in the global directions).

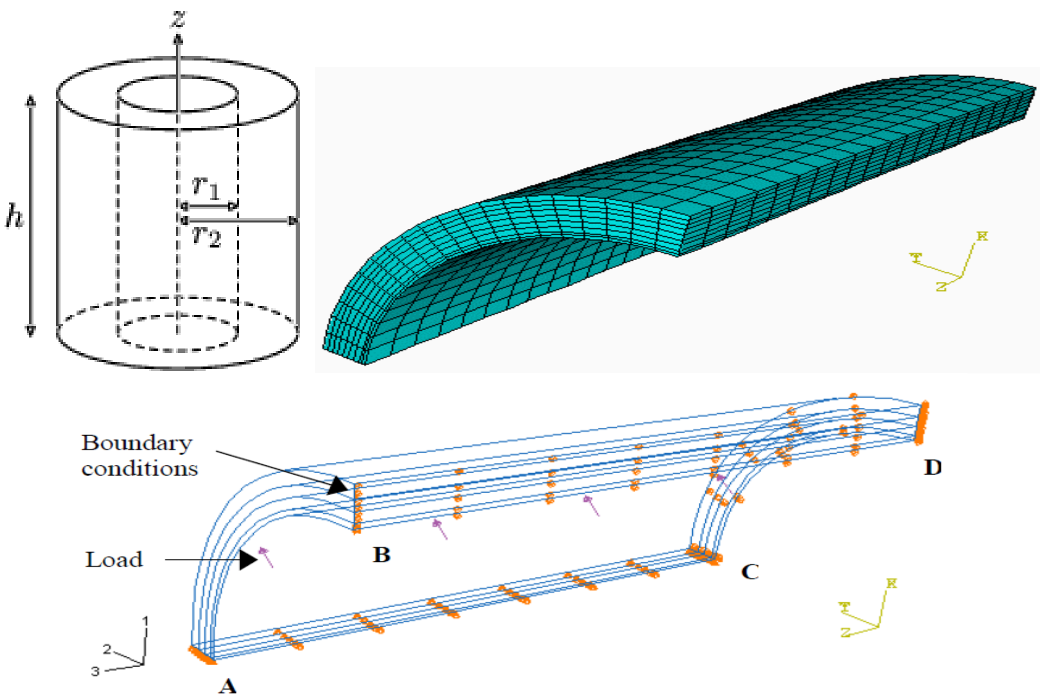


Fig. 3. F.E. proposed model after meshing, and load / symmetric boundary conditions.

Boundary conditions were defined as symmetric B.C. at corresponding planes of symmetry of the quarter model. Each side surface was subjected to pressure loading as shown in Fig. 3. The internal pressure was set to 1000 psi (6.9 MPa), while the outer pressure was set to ambient conditions.

The Tsai-Wu failure theory was used to predict composite failure [10] in an orthotropic lamina if and when the following equality is satisfied:

$$f1\sigma 11 + f2\sigma 22 + f6\tau 12 + f11\sigma^2 11 + f22\sigma^2 22 + f66\tau^2 12 + 2f12\sigma 11\sigma 22 = 1 \qquad (3)$$

RESULTS AND DISCUSSION

Low toughness GFRP, and High toughness GFRP at 60% V_f, materials were investigated. In addition to; using two and four layers of the composite materials (having total thickness 20mm), wounded around the Aluminum liner (of 5mm thickness) as the major part of the parametric study. Fiber winding orientation angles were also studied along wide range from 10° to 88°, with symmetric and anti-symmetric arrangements. Comparing the hoop and radial stresses results of the 64 case studies covering the above mentioned parameters resulted in; Fig. 4 demonstrates comparison between the obtained results of radial stresses among two arrangements of four composite layers (symmetric and anti-symmetric), with winding angle of 20°.where the comparison showed no significant different between using symmetric or anti symmetric composite polymeric layers.

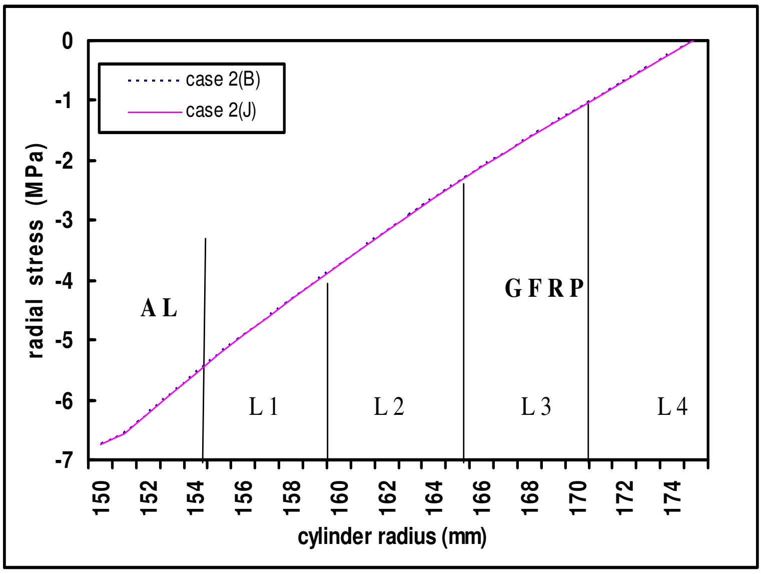
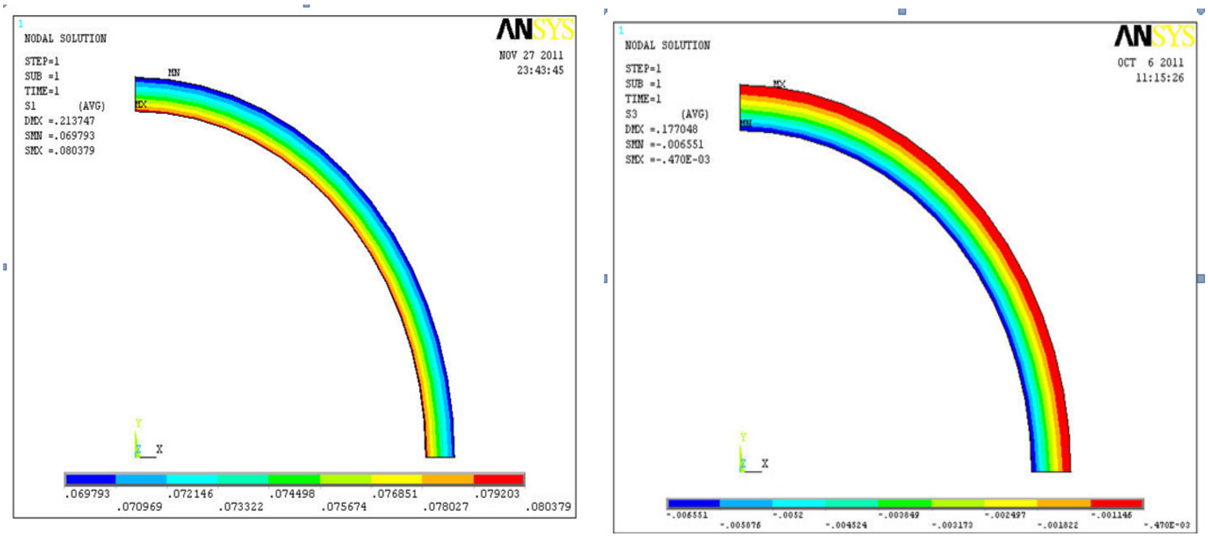


Fig. 4. Comparison between radial stress of symmetrical [+20/-20/-20/+20] and anti-symmetrical [+20/-20/+20/-20] wind angles, where Li is the composite polymeric Layer number.

Figure 5 shows typical results of hoop and radial stresses distributions across the cylinder thickness (Aluminum liner, and composite layers). The comparison between the different cases didn't show significant difference to comment.



a) Hoop stress b) Radial stress

Fig. 5. Stress distribution across the vessel walls.

- The best angles of fiber orientations in symmetric and anti-symmetric arrangements fall between 60° and 75° (see Figure 6). As a result of the analysis, the best angle for the composite pressure vessel loaded by internal pressure was found to be of order 65°.

- Low toughness GFRP material properties with high toughness GFRP materials for the composite pressure vessel analysis with the internal pressure loading cases did not change the previous results by showing the same range of fiber winding angles. Therefore, the optimal winding angle of fiber in symmetric and anti-symmetric composite layers arrangement is of order of 65°.

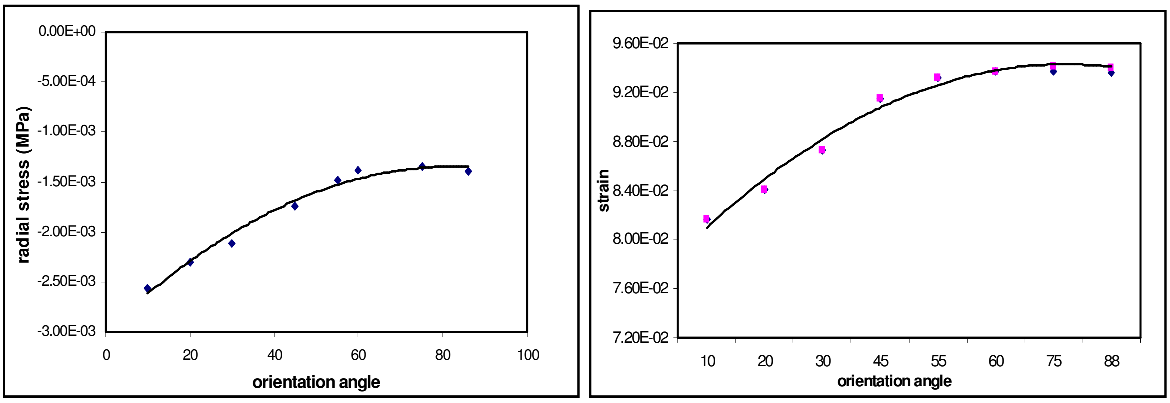


Fig. 6. Variations of radial stress, and strain with increasing winding angle at symmetrical and anti-symmetrical wind angular at radius 160mm.

- Using one, up to four composite layers (vary in thickness), and use different arrangements, showed insignificant change in the slope of radial stress results across the thickness. That according to governing equations the stresses generated on tank walls depends on tank geometry only (independent on tank material).

- Finally, comparison between three design cases (Aluminum liner, with four, three, and one composite layer), lead to an optimal design having minimum weight and cost out of all 64 cases having different arrangements as shown in table 2. Optimal design was found to be 8mm thickness of Aluminum liner, and one composite layer of high toughness GFRP material with thickness of 6mm.

Optimal Design			
case	**Weight(Kg)**	**Cost (L.E)**	**cost/Weight(L.E/kg)**
(Al, High toughness polymeric layer)	20	1000	50

CONCLUSIONS

The Finite Element Method was used to investigate the mechanical behavior of pressure vessels. The influence of metallic and composite polymeric layers thicknesses, number of composite layers and winding angle of filament-wound composite on the designed storage tank were studied. A parametric study including 64 cases, shooting minimum tank weight and cost was performed. Using different thickness of composite polymeric layers is significant the same over all composite layers thickness Optimal design was found to be 8mm thickness of Aluminum liner and one composite layer of high toughness GFRP material with thickness of 6mm at angle 65°.

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