

Finite Element Analysis of Composite Over-wrapped Pressure Vessels for Hydrogen Storage

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ABSTRACT

This paper presents 3D finite element analysis 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 optimal design configuration of such high pressure storage tanks includes an inner liner used as a gas permeation barrier, geometrically optimized domes, inlet/outlet valves with minimum stress concentrations, and directionally tailored exterior reinforcement for high strength and stiffness. Filament winding of pressure vessels made of fiber composite materials is the most efficient manufacturing method for such high pressure hydrogen storage tanks. The complexity of the filament winding process in the dome region is characterized by continually changing the fiber orientation angle and the local thickness of the wall. The research work presented in this paper reveals that the continuously changing angle orientation and local laminate thickness in the dome regions can be modeled by a unique approach that utilizes suitable transformations of the macromechanical composite properties and the local coordinate system. Accurate representation of the exterior reinforcement allows for detailed analysis of the dome structure as well as the nozzle/valve connection. A metallic insert is utilized to connect the dome structure to the valve system. A comparative study between different insert geometries and locations in the dome has been performed. It shows that an insert extending through the dome geometry increases the resulting stress at the cylinder-dome juncture. The most effective design approach entails an insert to the boss region.

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INTRODUCTION

Hydrogen has been realized as an alternative energy carrier that can enhance long-term energy security while mitigating the effects of air pollution and greenhouse gas emissions [1]. The current state-of-the-art in hydrogen storage reveals that the development of a lightweight, energy dense, cost effective tank for the on-board storage of compressed hydrogen is one of the most technically challenging barriers limiting the commercialization of fuel cell vehicles. Safe and efficient on-board storage of compressed hydrogen is a key enabling technology for the advancement of the hydrogen economy. It is well known that hydrogen has the highest energy content per unit weight of any fuel; however it has very low energy content per unit volume. This poses a challenge for storage, because it requires the storage of hydrogen in compact containers to be stored in a compact container in its gaseous form. This challenge exists for all fuel cell installations that use

hydrogen. It is most acute in light-duty vehicles, as storage systems for vehicles must operate within stringent size and weight constraints, enable a driving range of over 300 miles, which is considered to be the minimum for widespread driver acceptance based on the performance of today's gasoline vehicles.

Hydrogen storage tanks prototyped and manufactured so far by numerous manufactures are cylindrical in shape with two spherical dome ends having a length to diameter ratio of about 3:1. The inner liner of the tank is made of either aluminum or high density polyethylene (HDPE) that serves as a hydrogen gas permeation barrier. Such a liner is overwrapped with Toray T700S carbon fiber-epoxy resin composite shell that acts as the gas pressure load carrier component. Additionally, an outer shell is designed to cover the tank for impact and damage resistance [2, 3, 4, 5, 6, 7, 8]. Such tanks were close to meeting the 2007 targets for weight, energy density, and specific energy of 6% hydrogen by weight. However, they utilized premium aerospace-grade

carbon fiber reinforcement to satisfy the structural requirement of supporting 1,610 bar burst pressure. Therefore, they could not achieve the cost goal since the reported cost was \$10-\$17 per kW-h [3]. Low-cost, commercial grade carbon fibers were employed to fabricate 700-bar storage tanks for compressed hydrogen with the same level of performance as tanks fabricated from high-cost, aerospace grade carbon fibers [2]. Although such tanks could yield a specific energy density of approximately 1.3 kW-hr/kg, further design improvements are necessary, most likely through unconventional means, to exceed this value [4].

Development of lightweight, compact on-board hydrogen storage system must satisfy the high pressure containment, volumetric constraints and safety requirements. Currently, the filament winding process is utilized as a rational means of production of hydrogen storage tanks. However, in order to implement new designs, studies of failure mechanisms must be thoroughly performed prior to any application. Experimental analysis of composite pressure vessels is costly and complex compared to typical experimental procedures. In order to experimentally determine the burst pressure of a high storage capability (30,000 psi) pressure vessel, one must apply the pressure with a high performance compressor and monitor the vessel during the loading process. Catastrophic failure must be contained within the environment where the vessel is being tested. The involved process of experimentally evaluating pressure vessel systems cannot always be readily performed. Therefore, detailed and accurate finite element modeling methods are critical as first evaluations of pressure vessel analysis.

Experimental evaluations of composite wound pressure vessels have shown that liner failure to occur in the dome region as shown in [Figure 1](#). Such failure was attributed to inhomogeneous deformations which gave rise to local necks and local strains at the specific point of failure [9]. The liner was made of 6061-T6 aluminum. The liner had a dome radius of 305 mm and was of spherical geometry. The crack propagation in the liner occurs at 6.75 inches from the center of the tank. For a spherical dome geometry having a radius of 305 mm, the location of the failure crack is in the relative area of the slope transition which occurs at the change in geometry of the pressure vessel from the end dome to the nozzle region.

In this paper, finite element models detailing the dome structure of composite over-wrapped composite pressure vessel used for hydrogen storage applications were created using ANSYS finite element software. The designs in this study highlight the isotenoid geometry, thickness variation and varying winding angle orientation. Liner systems and insert applications using configurations of aluminum, stainless steel and high density polyethylene (HDPE) were also analyzed. The material used for the filament wound exterior reinforcement is T800 carbon fiber and epoxy. The orthotropic material properties are listed in [Table 1](#).

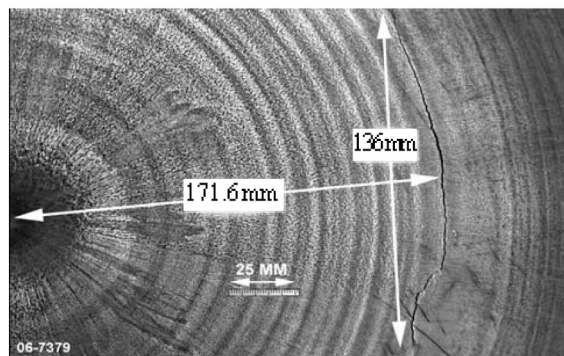


Figure 1. Failure of Composite Over-wrapped Pressure Vessel Aluminum Liner [9].

Table 1. Material Property of T800/Epoxy[10].

Property	Value
E_1	161.3 GPa
E_2, E_3	8.820 GPa
G_{12}, G_{13}	5.331 GPa
G_{23}	2.744 GPa
ν_{12}, ν_{13}	0.33
ν_{23}	0.45
X_t	2300 MPa
X_c	1080 MPa
Y_t	30 MPa
Y_c	70 MPa
Density, ρ	$1.5 \times 10^{-6} \text{ kg/mm}^3$

FINITE ELEMENT ANALYSIS

The FE models were modeled using 2-dimensional axisymmetric approach to represent the geometry, orthotropic material properties, and isotenoid characteristics. The 2D Axisymmetric modeling introduced in this work takes a unique approach to the finite element modeling of filament wound reinforced pressure vessels by utilizing the parameters determined from netting analysis and isotenoid theory and implementing them into the model by segmented area divisions representing the angle change and its respective material transformation in its own local coordinate system. The local coordinate system is defined to align the x-axis with the fiber direction ($+\alpha$). The composite macromechanics material transformations are used to transform the corresponding ($-\alpha$) material properties to the local x-axis. The concept of a local coordinate system is beneficial for an accurate representation of the angle ply fiber orientation and for post processing analysis. The stress resultants and strains can be evaluated at each local coordinate system, therefore giving the resultants in the desired fiber direction. Isotenoid theory states that the stress induced by internal pressure will