Modeling and Simulation of Hydrogen Storage Tanks
Fabricated From Composite Materials

By

Eng. Bahaa Mostafa Kamil Mehany

A Thesis Submitted to the
Faculty of Engineering at Cairo University
in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE
IN
Mechanical Design and Production

FACULTY OF ENGINEERING, CAIRO UNIVERSITY
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Shortage oil in the world lead to develop the fuel cell technology. This technology is depending on the hydrogen element. With ongoing improvements in hydrogen production through thermal, electrochemical and biological processes [1], other relevant issues have to be addressed as well. These are high storage capacity, good thermodynamics, fast kinetics, effective heat transfer, high gravimetric and volumetric densities, and long lifetime cycles in adsorption and desorption, high mechanical strength and durability, safety under normal use and acceptable risk under extreme conditions [2]. The storage of hydrogen among these can be considered as the crucial step for fuel cell applications.

Hydrogen is the lightest element in the world with a density of 0.08988 kg/m\(^3\) at room conditions, where it is assumed gaseous phase. The liquefaction and solidification temperatures are 20° K and 14° K respectively at atmospheric pressure. The maximum boiling point can not exceed 33° K under a pressure of 1.3 MPa. Higher pressures stay ineffective in increasing this temperature [3]. It is the most abundant element in the nature but present only in compounds mostly in water (H\(_2\)O). As the smallest element, hydrogen has the highest energy density which is 120 MJ/kg [3] since it has the highest ratio of electrons to overall particles. This energy density is approximately three times the energy density of gasoline (44.5 MJ/kg) and diesel (42.5 MJ/kg) [3]. Also compared to other forms of energy as mechanical energy, chemical energy (gasoline), electric or magnetic fields and nuclear fuels [4], hydrogen has the advantage being most environmental friendly, having unlimited resources that makes it possible, the fuel cell technology to achieve high efficiencies. In addition, hydrogen remains nontoxic if it reacts with oxygen, but not with the air. The reaction with air results in toxic nitrogen oxides.
1.1 Composite Pressure Vessels:

Pressure vessels have been manufactured by filament winding for a long time (details about composite materials and its manufacturing techniques are demonstrated in Appendices A. Although they appear to be simple structures, pressure vessels are among the most difficult to design. Filament-wound composite pressure vessels have found widespread use not only for military use but also for civilian applications. This technology originally developed for the military’s internal use was adapted to civilian purpose and later extended to the commercial market. Applications include breathing device, such as self-contained breathing apparatuses used by fire-fighters and other emergency personnel, scuba tanks for divers, oxygen cylinders for medical and aviation cylinders for emergency slide inflation, opening doors or lowering of landing gear, mountaineering expedition equipment, paintball gas cylinders, etc. A potential widespread application for composite pressure vessels is the automotive industry. Emphasis on reducing emissions promotes the conversion to Compressed Natural Gas (CNG) fuelled vehicles worldwide. Engineers are seeking to replace fuel oils with natural gas or hydrogen as the energy supply in automobiles for air quality improvements and reduce global warning. Fuel cells in concert with hydrogen gas storage technologies are key requirements for the successful application of these fuels in vehicles. Many limitations like lack of vehicle range between refueling stops, weight, volume and cost of the containment vessel should be considered.

Most of finite element analyses (FEA) on composite pressure vessels are based on shell elements, which are generated using the classical lamination theory. Most FEA package like ANSYS provide a thick shell element to reflect the influence of shear stress, radial and hoop stresses.
1.2 Structure of Composite Pressure Vessels:

Cylindrical composite pressure vessels constitute of a metallic internal liner and a composite outer shell [5] as shown in Figure 1.1. The metal liner is necessary to prevent leaking, while some of the metal liners also provide strength to share internal pressure load. For composite pressure vessels, most of the applied load is carried by the strong outer layers made from filament wound composite material.

![Figure 1.1: Example of filament wound composite pressure vessels.](image)

1.3 Main Storage Techniques of Hydrogen Storage:

1.3.1 Compressed Gaseous Hydrogen storage:

Storing gaseous hydrogen under high pressure is an already used common technique as shown in Figure 1.2. High-pressure tanks for hydrogen storage are already available in the market, which can be pressurized up to 30MPa [4]. These are usually made of steel and their capacities are not big enough for fuel cell applications. It is reported that a tank of 320 L is capable to store 5 kg of hydrogen at around 25MPa [5]. To make them applicable to vehicular storage, their pressures have to be high, which results in increases in both the tank weight and the material cost. Even the use of lightweight materials such as carbon-fiber reinforced composites or stainless steel cannot
reduce the thickness to desired values [2]. Wall materials usually used are steel alloys (Yield Strength ($S_y$) 703MPa and density ($\rho$) = 7860kg/m$^3$), titanium alloys ($S_y$=924MPa and density $\rho=4430$kg/m$^3$) and carbon composite ($S_{ys\text{single}}=2070$MPa and density $\rho=1900$kg/m$^3$) [6, 7, 8]. Among these, stainless steel has been used mostly for pressure vessels. High tensile strength, low density and non reactivity with hydrogen along with low diffusivity, are the main, desired properties for hydrogen storage tanks.

Hydrogen as the smallest element has a very high permeability rate through many materials. For example, carbon composites have high yield stresses and low densities, but they do not offer any solution to hydrogen leakage. Therefore, hydrogen barrier coatings such as liners are required for carbon composites to stop the hydrogen escape and to keep the usable hydrogen capacity at hand. Other main tasks of the liners are to have low permeability of hydrogen, close stiffness to other wall elements to prevent cracking and low cost and weights [9,10]. Liners are usually compounds such as aluminum and copper alloys or polymers like cross-linked polyethylene covered with graphite fiber epoxy layer [9, 10, and 11].

![Figure 1.2: Compressed Gaseous Hydrogen storage [2]](image)
1.3.2 Liquid Hydrogen Storage:

At normal conditions, hydrogen is in gaseous form. At the atmospheric pressure; hydrogen can be transformed to the liquid state under 20.4° K, which is below the critical point temperature (33° K, 1.29MPa) [3]. This temperature is in the region of cryogenic temperatures which is defined as the range below 123° K (-150°C) [17,18]. To store hydrogen in liquid form has the advantage that the volumetric density is much higher than in gas form to give better storage capacities. Liquid hydrogen storage tanks are usually thin wall pressure vessels as shown in Figure 1.3 [11,12]. Some designs, have been proposed where hydrogen pressure vessels with a few adjustments can be adapted to liquid hydrogen storage technique [19]. Like in the pressure vessels, maximum useful volume is reached in tanks with cylindrical shape. The only concern here is the fitting of the tank into the available space inside the vehicle.

It is illustrated that trailers equipped with liquid hydrogen storage tanks are capable of carrying six times more hydrogen than those with compressed gas tanks [20, 21].

![Liquid Hydrogen (LH\textsubscript{2}) tanks](Figure 1.3: Liquid hydrogen (LH\textsubscript{2}) tanks [7])
1.3.3 Metal Hydrides:

The simple idea behind the metal hydride is to let hydrogen exothermically react with certain materials to build hydrides and, upon need, to extract it by heating [22]. A deeper observation in microstructure reveals that the idea of the technique is to play with the metal matrix and create interstitial sites. Hydrogen atoms are then placed into these interstitial sites, which have tetrahedral or octahedral molecular structures as shown in Figure 1.4.

![Figure 1.4: metal hydride storage](image)

1.4 Hydrogen Embrittlement:

The hydrogen permeation leads also to another problem with hydrogen storage vessels. Hydrogen migration into the metal can cause reactions within the structure and result in the phenomenon called the hydrogen embrittlement. Hydrogen embrittlement is an event, which occurs from long exposures to hydrogen. It leads to hardening of materials and serious reduction in ductility and then results in cracking and failures well below the normal yield stresses [1]. Deeper investigations on the hydrogen embrittlement revealed that cracking is driven by the tensile residual stresses near the outside diameter of the pressure vessel. These researches also assured that hydrogen is responsible for crack growth, but the final failures are due to mechanical effects of pressures creating stresses following plane strain condition [12]. Development
of hydrogen permeation resistant alloys has also been an interesting subject to suggest novel wall materials. Researches on this area [12] have come up with alloys with low hydrogen permeation levels. These can include various metals. One example is an alloys consisting of iron (37%), nickel (32%), cobalt (15%), chromium (10%), niobium (3%) and titanium (2.5%) together with aluminum and carbon contents less than 1% [15]. Here, the high number of materials leads to the observation that significant costs have to be expected for manufacturing. The main advantage of such alloys is that they provide both low hydrogen leakage and high strength. The above alloy is reported to have yield strength reaching 970MPa. Hydrogen permeation level can be adjusted by processing the alloy with different heat treatment operations. However, as the resistance to hydrogen permeation increases, the ductility of the material increases as well, accompanied by the strength reduction [15]. Advantages and disadvantages are summarized in the following Table 1.1.

Table 1.1 : Comparaisons Between Main Hydrogen Storage Techniques.

<table>
<thead>
<tr>
<th></th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compressed hydrogen</strong></td>
<td>Small weight</td>
<td>Large volume</td>
</tr>
<tr>
<td></td>
<td>Easy interfacing with fuel cells</td>
<td>Energy loss due to compressibility</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrogen permeation through walls</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High cost of materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hydrogen embrittlement in the wall</td>
</tr>
<tr>
<td><strong>Liquid hydrogen</strong></td>
<td>Small weight</td>
<td>H₂ embrittlement in the wall</td>
</tr>
<tr>
<td></td>
<td>Small volume relative to compressed H₂ technique</td>
<td>High liquefaction energy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High cost of materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Very low operating temperature</td>
</tr>
<tr>
<td><strong>Hydrides</strong></td>
<td>Very small volume</td>
<td>High weight</td>
</tr>
<tr>
<td></td>
<td>Low operating pressure</td>
<td>High operating temperatures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Slow charging/discharging</td>
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<tr>
<td></td>
<td></td>
<td>High cost of materials</td>
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</tbody>
</table>
1.5 Finite Element Technique:

Most of finite element analysis (FEA) on composite pressure vessels are based on shell elements, which are generated using the classical lamination theory. Most FEA packages like ANSYS provide a thick shell element to reflect the influence of shear, radial and hoop stresses.

The objectives of this study are to investigate the different ways of storing hydrogen via a literature survey (reported in chapter two). Then to design a pressure vessel consisting of aluminum liner wrapped with a filament winding glass fiber reinforced polymer matrix structure in the outer layer of vessel. The ANSYS FEM package is used to predict the mechanical behavior of different designs of the proposed pressure vessel as shown in the following chapters.
CHAPTER TWO
LITERATURE SURVEY

One of the most difficult issues in the development of alternative energy is in the storage of the gaseous fuel. Most often, the use of gaseous fuels, such as hydrogen and natural gas, can provide outstanding operating benefits and efficiency improvements over conventional fuels. However, the most expensive and complex component of the fuelling system is in the storage of these gaseous fuels.

2.1 Introduction to Composites:

A composite material [10] is made by combining two or more materials to give a unique combination of properties. The above definition is more general and can include metals alloys, plastic co-polymers, minerals, and wood. Fiber-reinforced composite materials differ from the above materials, in that, the constituent materials are different at the molecular level and are mechanically separable. In bulk form, the constituent materials work together but remain in their original forms. The final properties of composite materials are better than constituent material properties.

The concept of composites was not invented by human beings; it is found in nature. An example is wood, which is a composite of cellulose fibers in a matrix of natural glue called lignin. The shell of invertebrates, such as snails and oysters, is an example of a composite. Such shells are stronger and tougher than man-made advanced composites. Scientists have found that the fibers taken from a spider’s web are stronger than synthetic fibers. In India, Greece, and other countries, husks or straws mixed with clay have been used to build houses for several hundred years. Mixing husk or sawdust in a clay is an example of a particulate composite and mixing straws in clay is an example of a short fiber composite. These reinforcements are done to improve performance.
The main concept of a composite is that it contains matrix materials. Typically, composite material is formed by reinforcing fibers in a matrix resin. The reinforcements can be fibers, particulates, or whiskers, while the matrix materials can be metals, plastics, or ceramics.

The fibers can be continuous, long, or short. Composites made with a polymer matrix have become more common and are widely used in various industries. This section focuses on composite materials in which the matrix materials are polymer-based resins. They can be thermoset or thermoplastic resins. The reinforcing fiber or fabric provides strength and stiffness to the composite, whereas the matrix gives rigidity and environmental resistance. Reinforcing fibers are found in different forms, from long continuous fibers to woven fabric to short chopped fibers and matrix. Each configuration results in different properties. The properties strongly depend on the way the fibers are laid in the composites. All of the above combinations or only one form can be used in a composite. The important thing to remember about composites is that the fiber carries the load and its strength is greatest along the axis of the fiber. Long continuous fibers in the direction of the load result in a composite with properties far exceeding the matrix resin itself. The same material chopped into short lengths yields lower properties than continuous fibers. Depending on the type of application (structural or non-structural) and manufacturing method, the fiber form is selected. For structural applications, continuous fibers or long fibers are recommended; whereas for non-structural applications, short fibers are recommended. Injection and compression molding utilize short fibers, whereas filament winding, pultrusion, and roll wrapping use continuous fibers.
2.2 Literature Survey:

J.C. Velosa and J.P. Nunes [23] 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 continues glass fiber. The ABAQUS 6.5.1 FEM package was used to predict the mechanical behavior of the cylinder in the range from 6 bars to 18 bars. Finally it was found that failure occur in some cross –ply internal layers having fibers oriented at 20% at lower vessel internal pressure.

Bryan C.Lung [24] 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. This work use low cost piezoafilm sensors selected to monitor the cylinder, where sensors were integrated into the carbon fiber structure.

Adali and Verijenko [25] discussed the optimization of multi-layered filament wound pipes with strength constraint. The suitability of shell theories for laminated circular cylindrical pipes has been discussed.

Salvador M.Aceves et al [26] developed an alternative technology for storing hydrogen fuel onboard automobiles. Insulated pressure vessels are cryogenic-capable pressure vessels that can accept cryogenic liquid fuel, cryogenic compressed gas or compressed gas at ambient temperature. They described the experimental and analytical work conducted to verify that insulated pressure vessels can be used safely for vehicular H\textsubscript{2} storage. It appears that aluminum – lined, composite wrapped pressure have the most desirable combination of properties for this application, due to low weight and affordable price.
Ben C. Odegard et al [27], provide quantitative information on tank failure and hydrogen release that can be used in the development of improved materials and environmental models. The structure of this cylinder consists of 5 mm thick fiberglass composite outer wrap over an 8 mm thick graphite fiber inner wrap. The liner was a 7 mm thick high-density polymeric liner. Only penetration tests were made in the modified test matrix and two different test sites were used. In Phase I, tests were conducted at a drop tower facility, which allowed better video diagnostic capability. All Phase I tests were made on tanks filled with nitrogen. In Phase II, a remote facility was used to allow measurements on the hydrogen plume ignition.

Parnas and Katirc [28] discussed the design of fiber-reinforced composite pressure vessels under various loading conditions based on a linear elasticity solution of the thick-walled multilayered filament wound cylindrical shell. A cylindrical shell having number of sub layers, each of which is cylindrically orthotropic, is treated as in the state of plane strain.

Aziz ÖNDER [29] studied the optimal angle-ply orientations of symmetric and anti-symmetric shells designed for maximum burst pressure of filament wound composite pressure vessels under alternating pure internal pressure. A finite element method and experimental approaches were studied to verify optimum winding angles.

Park et al. [30] worked on the structural analysis of the filament wound composite motor case. They performed FEA using ABAQUS 10 software to predict the behavior of the filament wound composite structures and did water pressure tests to verify the analysis procedures. Tsai-Wu failure criteria was used to predict the occurrence of failure under various stress conditions. This motor case had a design pressure of 17.2 MPa and progressive failure analysis conducted to predict the burst pressure at 20.7 MPa.

Hwang et al. [31] manufactured composite pressure vessels made of continuous winding of fibrous tapes reinforced in longitudinal and transverse directions and proposed its use for commercial applications instead of traditional isotensoid vessels.
Kabir [32] worked on the numerical analysis of filament reinforced internally pressurized cylindrical vessels with over wrapped metallic liner. He modeled the structure as an elastic, ideally plastic liner reinforced with quasi-isotropic elastic composite. His primary objective in designing a fiber reinforced metal pressure vessel was to obtain maximum operating performance at a minimum weight. The applications of composites for weight saving give support to use composite material as material system for the mortar barrel.

John A. Eihusen [33] is a leading designer of high-performance vessels for Natural Gas Vehicle (NGV) and Hydrogen Fuel Cell Vehicle (FCV) systems. All-Composite fuel tanks consist of a durable plastic liner fully wrapped with epoxy impregnated carbon and glass fiber. The liner is formed from High Density Polyethylene (HDPE) and has two aluminum end bosses which provide the structural interface to the tank. The function of the liner is to provide a high-pressure gas barrier. The liner is able to transfer all loads to the structural shell of the fuel tank. The plastic liner eliminates the cycle life fatigue limitation of a metal liner. The boss/liner interface provides a leak-proof seal between the plastic liner and the metal end boss. The structural composite shell is produced by filament winding.

J. Michael Starbuck [34] aimed to develop and/or demonstrate technologies or methods that will reduce the cost and increase safety in composite over-wrapped compressed natural gas (CNG) fuel tanks for light duty vehicles.

R. Ansari, F. Alisafaei, P. Ghaedi [35] conducted the stress analysis of multi-layered laminate wound composite pipes subjected to cyclic internal pressure and temperature loading, based on the three-dimensional anisotropic elasticity. The pressure and temperature were considered to be symmetrical about the axis of the cylinder and independent of the axial coordinate. Each layer of the pipes was made of a homogeneous, anisotropic and linearly elastic material and it was assumed that the material properties don't change with increasing the temperature. Numerical results obtained from the model were compared with other published results and good agreement has been reported.
Parnas and Katırcı [36] discussed the design of fiber-reinforced composite pressure vessels under various loading conditions based on a linear elasticity solution of the thick-walled multilayered filament wound cylindrical shell. A cylindrical shell having number of sublayers, each of which is cylindrically orthotropic, is treated as in the state of plane strain.

Robert zalosh et al [37] described and analysis a various type of hydrogen fuel fire exposure test without any pressure relief devices. The objectives of the tests were to determine the tank time-to-failure and characterize the blast wave hydrogen fire ball, and fragment projectiles produced upon tank failure at nominal hydrogen storage pressure of 35Mpa.

Onder et al. [38] dealt with the influences of temperature and winding angle on filament wound composite pressure vessels. Finite element method and experimental approaches were employed to verify the optimum winding angles.

Spencer and Hull [39] discussed the effects of wind angle on the filament wound angle ply composite pipes. The pipes were tested to failure under the open and closed-ended conditions and the differences in their progress to failure were observed.

In the present study, different design parameters, of filament wound cylinder under internal pressure were considered to obtain a better design angle for such components.

1. Using four layers of high toughness glass fiber reinforced material with the same thickness.
2. Using four layers of low toughness glass fiber reinforced material with the same thickness.
3. Comparing high toughness glass fiber and low toughness glass fiber reinforced material of the above two cases.