DESIGN ANALYSIS OF STEEL CONCRETE COMPOSITE VESSEL FOR STATIONARY STORAGE OF HIGH-PRESSURE HYDROGEN

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ABSTRACT
Design analysis is performed for a novel, low-cost, high-pressure, steel/concrete composite vessel (SCCV) for stationary storage of gaseous hydrogen. The SCCV comprises an inner, layered steel vessel encased by an outer pre-stressed concrete sleeve. The vessel design calculations are established based on engineering formulae from ASME Boiler and Pressure Vessel Code. A SCCV cost modeling tool is developed by considering the detailed bill of materials and labor costs for each of the vessel manufacturing steps. Using the vessel design calculations and cost modeling tool, the SCCV designs are studied for three pressure levels (i.e., 16, 43 and 86 MPa) relevant to the hydrogen production and delivery infrastructure. The effect of vessel dimensions on SCCV cost is discussed.

INTRODUCTION

Off-board bulk stationary storage of hydrogen is a critical element in the hydrogen production and delivery infrastructure [1]. Stationary storage is needed at locations such as fueling stations, renewable energy hydrogen production sites, central production plants, and terminals. Among the various hydrogen storage technologies, the compressed gaseous hydrogen (CGH_2) storage technology is most widely used [2,3]. According to recent data published by Fuel Cells 2000 in Aug. 2012, 98% of the hydrogen fueling stations in the U.S. use CGH_2 [2]. Worldwide (excluding those stations in the U.S.), 84% of the hydrogen stations use CGH_2 [3]. The current industry-standard CGH_2 storage technology [4] is largely the steel pressure vessel technology designed using ASME Boiler and Pressure Vessel (BPV) Code or other equivalent codes. As it provides the surge capacity to handle hourly, daily, and seasonal demand variations, the stationary storage vessel endures repeated charging/discharging cycles. Therefore, hydrogen embrittlement (HE) in structural steels, especially the accelerated crack growth during fatigue cycling, must be mitigated to ensure vessel safety. Nibur *et al*. [5] estimated that a crack in a pressure vessel made of AISI 4130X steel can reach the full critical flaw size in 3,500 cycles due to HE accelerated fatigue crack growth. Zheng *et al*. [6] demonstrated stationary flat steel ribbon wound vessels for CGH_2 with pressure up to 77 MPa.

This paper describes a novel, low-cost, high-pressure, steel/concrete composite vessel (SCCV) technology for stationary storage of CGH_2. In particular, the vessel design calculations are established based on pertinent engineering formulae from ASME BPV Code Section VIII-2. A SCCV cost modeling tool is developed by considering the detailed costs composed of bill of materials and labor for each of the vessel manufacturing steps. Using the vessel design and cost modeling tool, the SCCV designs and costs are studied for three pressure levels (i.e., 16, 43 and 86 MPa) relevant to the hydrogen production and delivery infrastructure. Opportunities in SCCV manufacturing and materials for further reducing cost while improving performance are discussed.

SCCV DESIGN CALCULATIONS

Figure 1 is a schematic drawing of the SCCV design which comprises an inner steel vessel encased in an outer pre-stressed concrete sleeve. The shell section of the steel vessel is a layered structure. The innermost layer directly exposed to the high-pressure hydrogen is made of an austenitic stainless steel clad (e.g., AISI 304L), which excels as a hydrogen embrittlement and permeation barrier. Such use of an austenitic stainless steel liner in SCCVs is similar to that in the flat steel ribbon wound vessels [6]. The other layers are made of high-strength low-alloy structural steel (e.g., ASTM SA 724-B), which is approximately 25 percent of the cost of stainless steel. Finally, the outer pre-stressed concrete sleeve used to bear the structural load costs even less when compared to structural steels.

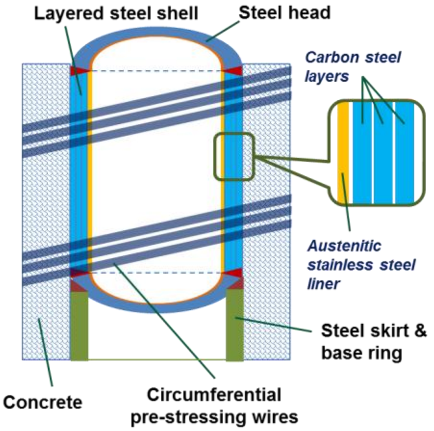


Figure 1. Schematic of a novel steel/concrete composite vessel (SCCV) design comprised of an inner layered steel vessel and an outer pre-stressed concrete enclosure.

The SCCV design calculations determine the vessel dimensions (e.g., steel thickness, concrete thickness, and layers of pre-stressing steel wires) for the given inputs including the inner diameter and length of the steel vessel and the hydrogen pressure. The steel vessel dimensions are calculated first as follows.

The thickness of hemispherical steel heads (see Fig. 1) for the given hydrogen pressure is obtained from the ASME BPV Code - Section VIII-2 as:

$$t_h = R_i\left(e^{0.5P/S} - 1\right) \tag{1}$$

where t_h is the minimal head thickness, R_i is the inside radius, P is the internal hydrogen pressure, and S is the allowable stress of the head steel. The selected material for head construction is SA 537-CL2 and its key mechanical properties are summarized in Table 1.

Table 1. Mechanical properties of SA 537-CL2 and SA 724-B low-alloy steels selected for steel vessel head and layered shell construction, respectively.

Vessel component	**Steel**	**Allowable stress in BPV VIII-2**	**Yield stress**	**Ultimate tensile stress**
Head	SA 537-CL2	216 MPa (31.3 ksi)	379 MPa (55 ksi)	517 MPa (75 ksi)
Layered shell	SA 724-B	273 MPa (39.6 ksi)	517 MPa (75 ksi)	655 MPa (95 ksi)

Similarly, the thickness of the cylindrical steel shell can be obtained as:

$$t_s = R_i\left(e^{P'/S} - 1\right) \tag{2}$$

where t_s is the shell thickness, and P' is the effective internal pressure that is used to account for the reinforcement to the steel shell by the pre-stressed concrete sleeve. In the current SCCV design, the pre-stressed concrete sleeve bears 50% of the circumferential (hoop) stress due to internal hydrogen pressure, and thus $P' = 0.5 \times P$. As a result, the shell thickness is chosen to be the same as the head thickness. It is noted that the longitudinal stress in the steel shell is half the circumferential stress. In other words, the steel shell thickness, designed to carry 50% of the circumferential stress, is sufficient to bear the longitudinal stress. Moreover, as shown in Table 1, the steel for shell construction (SA 724-B) has about 27% higher allowable stress than the steel for head construction (SA 537-CL2), which provides additional safety margin. Therefore, no longitudinal reinforcement to the steel vessel is used.

Once the dimensions of the inner steel vessel are determined, the dimensions of the pre-stressed concrete sleeve are then calculated based on the deformation compatibility between steel and concrete vessels. The radial deflection, δ, of a cylindrical shell due to both internal and external pressures is:

$$\delta = \frac{R^2\left(P_i R_i^2 - P_o R_o^2\right)(1-2\nu) + \left(P_i - P_o\right)\left(R_i^2 R_o^2\right)(1+\nu)}{ER\left(R_o^2 - R_i^2\right)} \tag{3}$$

where R is the radius at any point in the cylinder, R_i is the cylinder inside radius, R_o is the cylinder outside radius, P_i is the inside pressure, P_o is the outside pressure, ν is the Poisson's ratio, and E is the elastic (Young's) modulus.

As illustrated in Fig. 2, the deformation compatibility at the steel/concrete interface under internal hydrogen pressure and external pre-stressing pressure is:

$$\delta_{so\_Pi} - \delta_{so\_Pf} = \delta_{ci\_Pf} - \delta_{ci\_Po} \tag{4}$$

where δ_{so_Pi} and δ_{so_Pf} are the deflections of the steel cylinder shell at its outside surface due to the internal pressure (P_i) and the interface pressure (P_f), respectively, and δ_{ci_Pf} and δ_{ci_Po} are the deflections of the concrete cylinder shell at its inside surface due to the interface pressure (P_f) and the external pressure (P_o), respectively. It is noted that the internal pressure (P_i) is the design pressure of stored CGH_2 and the external pressure (P_o) that is applied onto the concrete outside surface is 50% of P_i.

The interface pressure P_f can be calculated by substituting Eqn. (3) into Eqn. (4). With the knowledge of P_f, the circumferential stress in the concrete cylinder shell, σ_{c_θ}, is obtained as:

$$\sigma_{c\_\theta} = \frac{P_f R_2^2 - P_o R_3^2 + \left(P_f - P_o\right)\frac{R_2^2 R_3^2}{R^2}}{\left(R_3^2 - R_2^2\right)} \tag{5}$$

where R_1 and R_2 are the inner radius and outer radius of the steel cylinder shell, respectively, and R_3 is the outer radius of the concrete cylinder shell. Using Eqn. (5), the concrete thickness is determined so that the highest circumferential stress in the concrete is less than the concrete tensile strength. Light-weight concrete is used which has the following properties: elastic modulus = 22.8 GPa, compressive strength = 55.1 MPa, and tensile strength = 3.1 MPa.

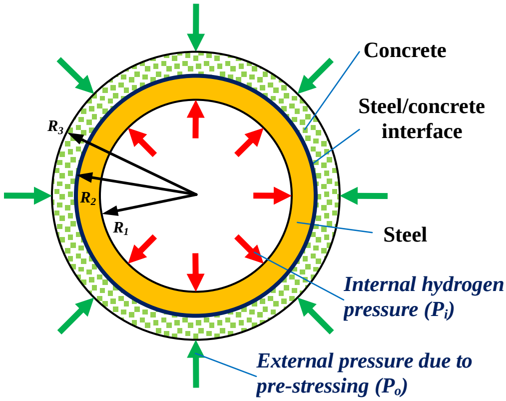


Figure 2. Cross-section view of a SCCV cylindrical shell. Pre-stressing wires are not plotted for clarity.

It is noted that the circumferential strength of the concrete enclosure results mainly from the high-strength steel wires wrapped around the concrete outside surface. The concrete itself serves as a medium for uniformly transferring the tensioning (or external pressure) to the inner steel vessel and protecting the steel rebars and pre-stressing wires from corrosion. The number of pre-stressing wire layers to achieve the specified external pressure is determined using the following procedure. First, the required pre-stressing wire area per unit length in the cylinder direction, A_s, is calculated as:

$$A_s = \frac{P_o R_3}{f_{ew}} \tag{6}$$

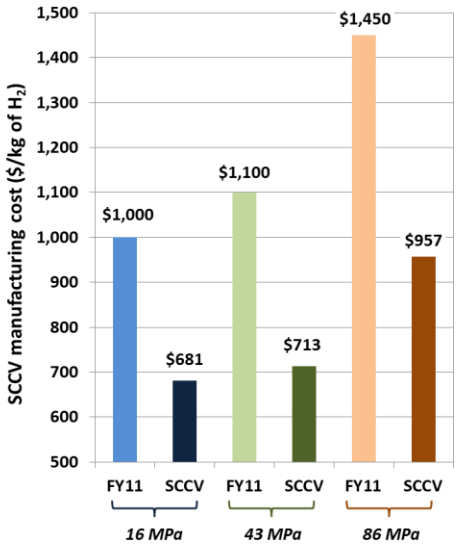
where P_o and R_3 are the external pressure and the outer radius of concrete cylinder shell (as defined previously), and f_{ew} is the effective strength (or allowable stress) of the pre-stressing wire. Then, the number of pre-stressing wire layers, N_s, is determined from $N_s = A_s / A_w$, where A_w is the cross-section area of a single wire. In this study, the pre-stressing wire has f_{ew} = 1,034 MPa (150 ksi) and A_w = 15.2 cm^2 (2.36 in^2).

Finally, two additional calculations are performed to ensure that (1) the inner steel shell does not buckle under the external pressure exerted by the pre-stressing wires, and (2) the SCCV passes the hydrostatic testing required by ASME BPV Section VIII-2. Details of the calculations are available elsewhere [7-9]. The steel thickness, concrete thickness and layers of pre-stressing wires are increased as needed to satisfy both the buckling and hydrotest conditions.

With the knowledge of the vessel dimensions, the SCCV cost is estimated based on a detailed, bottom-up approach which takes into account the material and labor costs involved in each of the vessel manufacturing steps. The major manufacturing steps include forming of hemispherical steel heads, cladding of stainless steel liner, wrapping and welding of layered steel shell, and pre-stressing of concrete shell, etc. Moreover, the cost study only considers an SCCV that can be readily manufactured in typical fabrication facilities without major capital equipment purchases/upgrades. Finally, a moderate production volume (24 identical vessels per order) is assumed in the cost study. More details of the SCCV cost modeling are available elsewhere [9].

RESULTS AND DISCUSSION

Figures 3 plots the SCCV costs at three pressures of 16, 43 and 86 MPa. For comparison, the costs of industry-standard steel pressure vessels estimated based on a recent industry survey [1,4] are superimposed in this figure. Key specifications of the three SCCVs are summarized in the inset table. As the hydrogen pressure rises, both the steel thickness and the number of pre-stressing wire layers increase as expected. Moreover, the steel vessel radius is further reduced to keep the steel thickness and pre-stressing wire layers from increasing beyond typical manufacturing capacity limits.



Specification	Design pressure of SCCV		
	16 MPa	43 MPa	86 MPa
Steel vessel inner radius	1.6 m	1.0 m	0.7 m
Steel vessel thickness	6.4 cm	10.8 cm	15.2 cm
Concrete thickness	53.3 cm	20.3 cm	20.3 cm
Number of pre-stressing wire layers	4	7	11
Steel shell height	5.3 m	5.3 m	5.3 m
Total vessel height	8.6 m	7.5 m	7.0 m
Storage capacity of CGH_2	707 kg	564 kg	416 kg

Figure 3. SCCV designs optimized for cost for three pressures. FY11 data represents costs of industry-standard steel pressure vessels [6].

The unit cost breakdowns for the three SCCVs are summarized in Table 2. The material cost of the steel vessel increases with the H_2 pressure, since a thicker steel wall is needed for higher pressure. Correspondingly, the labor cost also rises with the increased material usage. For the pre-stressed concrete enclosure, the pre-stressing cost goes up significantly with pressure due to the larger number of pre-stressing wire layers. For all three pressures, the steel vessel constitutes around 73% of the total SCCV cost. In other words, the pre-stressed concrete enclosure bears half of the total structural load at a cost that is only 37% of the steel vessel that bears the other half of the load. Hence, it is cost-effective to use the pre-stressed concrete enclosure to bear the structural load, when compared to the current industry-standard steel-only pressure vessel.

Table 2. Unit cost breakdowns for the three SCCVs in Fig. 3.

Item	Design pressure of SCCV		
	16 MPa	43 MPa	86 MPa
Steel vessel (unit price \$ per kg of stored H_2)			
Bill of materials	\$268	\$314	\$386
Labor	\$190	\$190	\$251
Consumables and others	\$50	\$35	\$33
Pre-stressed concrete enclosure (unit price \$ per kg of stored H_2)			
Concrete	\$42	\$13	\$14
Rebar	\$12	\$4	\$4
Pre-stressing wire	\$119	\$157	\$269
Total SCCV unit cost	**\$681**	**\$713**	**\$957**

The SCCV cost is further studied as a function of vessel dimensions (i.e., vessel shell height and radius) at the constant H_2 pressure of 43 MPa. The findings obtained are applicable to other pressures. In the following discussion, the reference vessel, shown in both Figs. 4(a) and 5(a), corresponds to the 43-MPa SCCV with key specifications defined in Fig. 3.

Figures 4(a) and (b) show the unit cost comparison between the reference SCCV and a shortened SCCV. Due to the shorter length, the SCCV in Fig. 4(b) has a CGH_2 storage capacity of 396 kg while that in Fig. 4(a) has a capacity of 564 kg. As the identical head (i.e., radius and thickness) is used for both steel vessels, the actual manufacturing cost of steel heads remains the same. However, since it stores much less H_2, the shortened vessel has a much higher unit cost (\$/kg of stored H_2) for steel heads. Overall, the unit cost of the steel vessel increases from \$539 to \$629/kg of stored H_2 as the vessel cylinder shell length is reduced from 5.3 to 3.4 m. For the pre-stressed concrete enclosure, the steel shell area on which it is wrapped is reduced in the shortened vessel. As a result, the pre-stressed concrete cost goes down slightly to \$156/kg of stored H_2 for the shortened vessel. Altogether, the rise in steel vessel cost outweighs the drop in pre-stressed concrete cost, resulting in a net 10% increase in the total vessel unit cost as the vessel shell is shortened from 5.3 to 3.4 m.

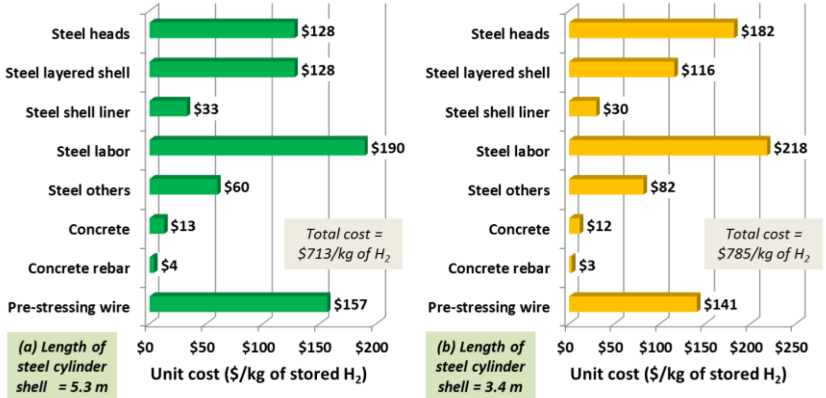


Figure 4. Effect of vessel shell length on vessel unit cost: (a) reference 43-MPa SCCV with shell length of 5.3, and (b) shortened SCCV with length of 3.4 m.

The dependence of SCCV cost on the inner radius of steel vessel is illustrated by the results shown in Fig. 5. As the inner radius decreases from 1.0 to 0.85 m, the storage capacity drops significantly, from 564 to 398 kg. In other words, a 15% drop in the steel vessel inner radius amplifies into a 29% decrease in the storage capacity (since the storage volume depends on the square of the radius). It is noted that as the radius shrinks from 1.0 to 0.85 m, the steel wall thickness and the number of pre-stressing wire layers also decrease from 10.8 to 8.9 cm and 7 to 6 layers, respectively. However, as shown in Fig. 5, the drop in storage capacity outpaces the decrease in the manufacturing cost due to thinning of the steel vessel and the pre-stressing wire layers, resulting in an increase of 8.3% in the unit storage cost ($/per kg of stored H_2).

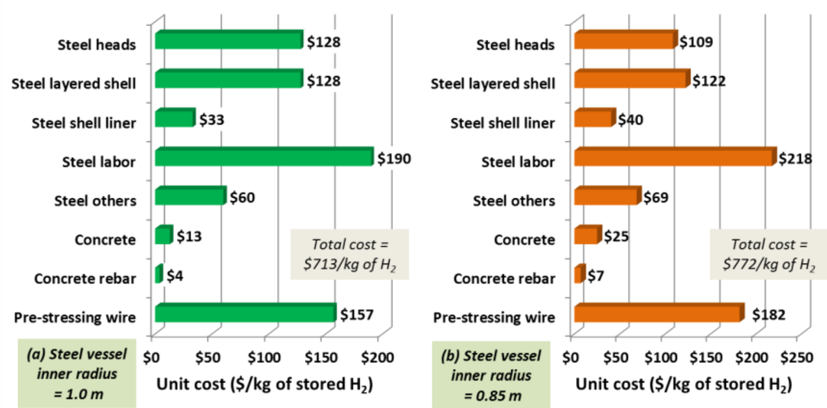


Figure 5. Effect of steel vessel inner radius on vessel unit cost: (a) reference 43-MPa SCCV with radius of 1.0 m, and (b) smaller SCCV with radius of 0.85 m.

OPPORTUNITIES IN SCCV MANUFACTURING AND MATERIALS

As described previously, an austenitic stainless steel clad liner is placed on the steel vessel's inner surface as the hydrogen embrittlement and permeation barrier. Moreover, such stainless steel clad, which is metallurgically bonded to its substrate carbon steel, can have a significantly better tolerance to the temperature rise due to pressurization of H_2, when compared to a polymer based liner. The performance of a stainless steel clad liner comes at a premium price: the liner costing $101, $68 and $60/kg of H_2 for the 16, 43 and 86 MPa SCCVs in Fig. 3, respectively. A lower cost liner material with performance comparable to stainless steel represents a significant opportunity for SCCV cost reduction.

The inner steel vessel constitutes the majority (about 73%) of the total SCCV cost. Further SCCV cost reduction can benefit from the development of advanced steel vessel fabrication technologies. One such potential technology is solid-state friction stir welding (FSW). In recent studies, FSW was demonstrated to weld a 6.4-mm-thick low-alloy high-strength steel pipe in a single pass [10]. Also, scaling-up of FSW for thicker steel structures in a multi-pass, multi-layer configuration has been achieved [11]. Compared to conventional arc welding, the low heat input in FSW results in minimal distortion and refined microstructure with superior mechanical strength. ExxonMobil estimated that FSW offered about 25% and 7% construction cost savings for offshore and onshore construction, respectively [12]. Hence, FSW for layered steel vessel fabrication can potentially further reduce the vessel cost.

CONCLUSIONS

The novel, low-cost, high-pressure, steel/concrete composite vessel (SCCV) design is studied for storing CGH_2 at three pressures (16, 43, and 86 MPa) relevant to the hydrogen production and delivery infrastructure. The SCCV technology utilizes commodity materials (e.g., structural steels and concretes) to cost-effectively bear the structural load exerted by CGH_2. Austenitic stainless steel liner is used as a hydrogen embrittlement and permeation barrier, ensuring vessel durability and safety under repeated charging/discharging cycles common to CGH_2 storage application. When compared with the industry-standard steel pressure vessel, the SCCV has significant cost advantage. Future opportunities in friction stir welding for layered steel shell fabrication and alternative liner materials are discussed for their potential in further SCCV cost reduction.

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