IV.D.5 Optimizing the Cost and Performance of Composite Cylinders for H_2 Storage using a Graded Construction

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Overall Objectives

- Develop 700-bar Type IV graded structure pressure vessel design incorporating low cost carbon fiber.
- Optimize composite performance of low cost fibers.
- Demonstrate performance of graded structure pressure vessel.

Fiscal Year (FY) 2016 Objectives

- Demonstrate fatigue performance of composite fabricated with a combination of Toray T700 and commercial low cost carbon fibers.
- Fabricate and test Type IV graded structure pressure vessels.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

(A) System Weight and Volume

(B) System Cost

Technical Targets

The overall goal of this program is to address the high cost of physical hydrogen storage in Type IV composite overwrapped pressure vessels (COPVs) with an overall cost reduction target of 25%. The cost of these COPVs is currently driven by the high cost of carbon fiber; this program aims to replace 40–60% of the high cost fiber with a low cost carbon fiber to achieve the cost reduction target.

A combination of finite element analysis driven composite design, experimental data, prototype construction, testing, and cost analysis will be used to demonstrate the approach.

FY 2016 Accomplishments

Accomplishments during the current project period include the following.

- Tensile strength retention of flat panels reinforced with a mixture of Toray T700 and Panex® 35 carbon fibers after 30,000 cycles to as high as 63% above the target operating pressure was in excess of 80%.
- A tank design was developed, using experimental data for Toray T700 and low cost Panex® 35 carbon fiber composites, allowing for 35–50% low cost carbon fiber.
- Type IV pressure vessels (Toray T700 control and graded structure) were fabricated and tested. One control tank burst at 21,925 psi, graded structure tanks did not burst, but leaked at the liner–boss interface after achieving pressures in excess of 13,000 psi. No visible damage to the composite was noted.

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INTRODUCTION

The challenges associated with bringing reasonably priced hydrogen fuel cell vehicles to market are numerous. One significant challenge is reducing the cost for onboard hydrogen storage tanks while continuing to provide a driving range of greater than 300 miles. COPVs have been designed and qualified for this application. However, as currently manufactured, these tanks are extremely expensive due in large part to the high strength carbon fibers (e.g., Toray's T700S) used; the cost of carbon fiber alone can constitute as much as 75% of the total cost of the vessel [1].

DOE's near-term goal is to reduce the cost of COPVs for high pressure hydrogen storage by 25%. CTD believes that this can be achieved by constructing the structural shell using a graded composite, in which a portion of the expensive, high-performance fiber is replaced with lower cost carbon fibers based on common textile fibers. Since the projected cost for these newer fibers is significantly lower than that for carbon fibers produced from higher grade precursors, their utilization in a significant portion of the mass of the composite material in the vessel will translate to a corresponding reduction in the cost of the raw materials for the vessel, thereby meeting DOE's target for cost reduction.

APPROACH

In this effort, CTD is investigating the use of a graded composite tank structure, in which a portion of the high cost T700S carbon fiber is replaced by lower cost fibers, such as the low cost carbon fibers being developed at Oak Ridge National Laboratory with DOE funding. The reduced strain requirements for the composite through the thickness of the pressure vessel enables the use of lower cost, lower performing fibers for a substantial portion of the composite structure. A design has been developed based on experimentally derived low cost fiber properties that would allow for replacement of a large fraction of the costly T700S fiber with a less expensive option.

Work during FY 2016 focused primarily on design, construction, and testing of Type IV COPVs using either Toray T700 carbon fiber or a combination of Toray T700 fiber and Panex® 35 carbon fiber.

RESULTS

Work during this period focused on further demonstration of the graded structure concept for reducing cost of 700-bar hydrogen storage tanks. Demonstration of graded composite fatigue performance as well as fabrication and testing of graded structure tanks is discussed in the following paragraphs.

Fatigue Testing

CTD conducted fatigue testing of the baseline fibers and resin system per ASTM D3479. To determine the stress levels for fatigue testing, finite element models were used to predict the maximum stresses that would be experienced by the fibers when pressurized to the target burst pressure of 23,852 psi. The maximum stresses would be 310,179 psi and 252,482 psi for the Toray and Panex® 35 fibers, respectively. The ultimate strength values for T700 and Panex® 35 are 320,000 psi and 265,600 psi, respectively. Using these values, starting stress levels were then determined for the fatigue testing (Table 1). CTD set a maximum number of cycles of 30,000 for this fatigue testing; ~5000 cycles would resemble weekly refueling for 10 years.

All of the specimens survived 30,000 cycles at both stress levels. Tensile testing to failure after fatigue showed excellent retention of properties; all specimens failed at >80% of the ultimate tensile strength after cycling. This indicates that the change in fiber properties at the interface between the T700 and the low cost carbon fiber should not result in any performance issues for the tank relative to one made with a single type of carbon fiber.

Subscale Tank Fabrication and Testing

Using the experimentally derived composite properties shown in Table 2, our previously developed finite element model was used to determine the amount of Panex® 35 fiber that could be used for tank fabrication. This amount, between 35% and 50%, was determined to be large enough to offer significant cost savings in tank production.

TABLE 2. Material Properties of Toray T700S and Panex® 35 Fiber Composites

Property	T700S Composite	Panex 35 Composite
Bandwidth (in)	1.69	1.69
Hoop Thickness (in)	0.027	0.027
Helical Thickness (in)	0.0164	0.0164
Longitudinal Elastic Modulus, E_1 (Msi)	18.5	19.05
Transverse Elastic Modulus, E_2 (Msi)	1.3	1.01
Poisson Ratio, ν_{12}	.28	.28
Shear Modulus, G_{12} (Msi)	0.5	0.5
Failure Strain in Fiber Direction (%)	1.8	1.34

High density polyethylene liners were rotomolded by RMB Products (Fountain, Colorado) to specifications provided by CTD. Tanks were filament wound at CTD; liners were pressurized during the winding process to avoid

TABLE 1. Stress Levels for Fatigue Testing of Composite Panels

65% of Ultimate:		Resulting Tank Pressure is:		% above OP
Stress T700 =	208000 psi	T700 =	15995 psi	60%
Stress Panex =	172640 psi	Panex =	16309 psi	63%

Using 30% above OP:		Tank Pressure:	% of Ultimate	% above OP
Stress T700 =	169056 psi	**13,000 psi**	53%	**Using 30%**
Stress Panex =	137610 psi	**13,000 psi**	52%	**Using 30%**

OP – Operating pressure

collapsing the liner. A total of five tanks (two control with T700 fiber only and three graded structure) were produced. Two control (T700) and two graded structure tanks were then subjected to hydrostatic burst testing. Results were as follows:

- Control 1: 21,925 psi, burst (Figure 1)
- Control 2: 18,833 psi, leak at the composite/liner/boss interface
- Graded 1: 15,831 psi, leak at the composite/liner/boss interface
- Graded 2: 14,377 psi, leak at the composite/liner/boss interface (Figure 2)

Since there was no visible damage to the composite structure in cases where leaks occurred, liner failures were assumed.

FIGURE 1. Type IV pressure vessel with Toray T700 carbon fiber after burst

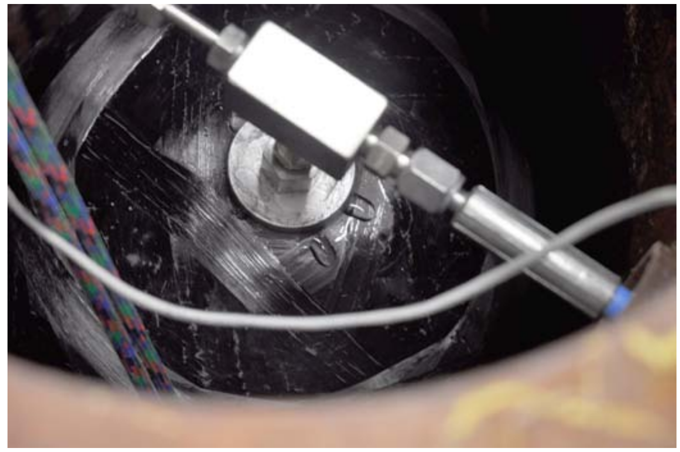

FIGURE 2. Graded Type IV pressure vessel (Toray T700/Panex® 35) showing leakage at composite/liner/boss interface

CONCLUSIONS AND FUTURE DIRECTIONS

This program has demonstrated the potential for using low cost carbon fibers in combination with Toray T700 for the production of thick wall, 700 bar pressure vessels. While burst of the graded structure tanks was not achieved, it appears that the graded structure has high potential to perform as well as a 100% T700 COPV in the absence of liner failure; pressurization in excess of the expected operating pressure was achieved in all cases. Further work will be required to unequivocally establish the performance in a situation where liner failure does not occur.

Whether or not cost savings can truly be achieved using low cost carbon fiber remains an open question. While fabrication using the Panex® 35 low cost fiber is possible, it is far from optimum. In contrast to the Toray T700, which unspooled and deposited onto the tank with no fuzzing, the Panex® fiber was extremely challenging with significant fuzzing occurring during the process. This resulted in frequent stoppages of the winder in order to clean deposited fiber from the rollers and resin bath. Significant improvement in handling of the Panex® fiber would be required in order for its use in production to be truly feasible. Impact of the added touch labor related to the fuzzing of the low cost fiber is currently being evaluated in the cost model.

REFERENCES

1. Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, Section 3.3 – Hydrogen Storage, updated May 2015.