IV.D.7 Optimizing the Cost and Performance of Composite Cylinders for H_2 Storage Using a Graded Construction

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Overall Objectives

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

Fiscal Year (FY) 2015 Objectives

- Optimize fiber property translation in filament wound composites utilizing 50,000 low cost carbon fiber tows
- Optimize design models utilizing experimental data to generate design for subsequent prototype construction
- Conduct preliminary cost analysis showing the potential cost savings realized through use of low cost carbon fiber

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section (3.3.5) 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 (COPV) with an overall cost reduction target of 25%. The cost of these COPV 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 (FEA) driven composite design, experimental data, prototype construction, testing, and cost analysis will be used to demonstrate the approach.

Fiscal Year (FY) 2015 Accomplishments

Accomplishments during the current project period include the following:

- Demonstration of high fiber property translation in composites that are filament wound using large tows of a commercial low cost carbon fiber
- Refinement of COPV designs based on experimental data obtained from low cost carbon fiber composite panels
- Preliminary cost modeling, based on refined designs, shows potential cost savings as high as 30% depending upon relative costs of Toray T700S and low cost carbon fiber candidates

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INTRODUCTION

The challenges associated with bringing reasonably priced hydrogen fuel cell electric vehicles to market are numerous. One significant challenge is reducing the cost for on-board hydrogen storage tanks while continuing to provide a driving range of greater than 300 miles. COPV have been designed and qualified for this application. However, these tanks are extremely expensive as currently manufactured, due in large part to the high strength carbon fibers used (e.g., Toray's T700S). 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 COPV 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 (ORNL) 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 targeted 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 2015 focused on gathering experimental data from commercial lower cost fibers with properties equivalent to those expected from newer textile-based fibers. These data were then used to refine the design and cost models for the program. Suitable low cost fiber options from ORNL were not available during this period.

RESULTS

One key factor for success in the application of low cost fibers to pressure vessels is fiber property translation, defined by rather than defined as how close the mechanical properties (strength, modulus, and strain) of the composite are to those of the reinforcing fiber itself. Fiber property translation in excess of 85% will likely be required if low cost fibers are to be used in any portion of the pressure vessel construction. Factors affecting fiber property translation include: fiber wetting, fiber consolidation, tow spreading, and resin cure conditions. Tow spreading is particularly challenging for low cost fibers where large tows (>50,000) are typical. Significant effort in FY 2015 was directed toward achieving high fiber property translation for large tows.

The initial large tow handling work was conducted using two commercial fibers, including Zoltek's Panex® 35 50,000 tow fiber. Both commercial fibers were selected because they had strength, modulus, and strain values that are very similar to those projected for the ORNL textile PAN-based low cost fiber candidates. Panex® 35 was also used during the Phase I effort and thus allowed for a direct comparison back to the previously acquired data relative to the reported translation values.

It was believed that to improve the translation numbers from the Phase I study and to provide consistent data across different test plates, it would be necessary to spread the 50,000 tow fiber to a larger width as it traversed the wetting mandrel. Thus, the fibers would achieve a better impregnation of the resin prior to being applied to the mandrel, as well as offering the potential to more thoroughly align the individual fibers within the tow. This improves fiber translation properties. To spread the fiber to a wider width, CTD evaluated effects of the fiber tension, span between the roll tensioner and the first roller, location, number and rotation of spreading rollers, as well as contact area with the spreading rollers.

Using the same resin system as was employed in Phase I, CTD manufactured five different test plates and created 30 different tensile test samples to observe if improved translation numbers could be obtained during Phase I. The average fiber property translation values for the five tested samples of each individual test plates are shown in Figure 1; a line corresponding to the data obtained in Phase I is included for reference.

A comparison of the Phase I and Phase II translation data is provided in Table 1.

TABLE 1. Improvement in Panex® 35 Average Fiber Property Translation

	Phase I	Phase II
Strain	78%	89.2%
Strength	65%	73.8%
Modulus	91%	91.5%

While the modulus translation remained relatively unchanged, an increase in the average strain and strength numbers of 14% and 13.5%, respectively, was achieved relative to Phase I, indicating that we have refined our process enough to greatly increase the translation numbers for the Panex® 35 fiber. Achieving this level of fiber property translation is critical for the success of the graded structure design for 700 bar tanks.

Finite Element Modeling

A typical 700 bar composite pressure vessel requires a thick composite shell, in which there is a significant grading in the longitudinal (fiber direction) strain from the inside to the outside of the vessel wall (Figure 2). A COPV has been designed to the following dimensions, based on the use of Toray T700 high strength carbon fiber. The outer diameter of the pressure vessel was restrained in size to 500 mm (20 in) nominal because of the available space inside the automobile. The tank had the following dimensions:

- Inside diameter = 17.5 in
- Cylinder length = 27.5 in
- Thickness in the cylindrical section = 1.32 in

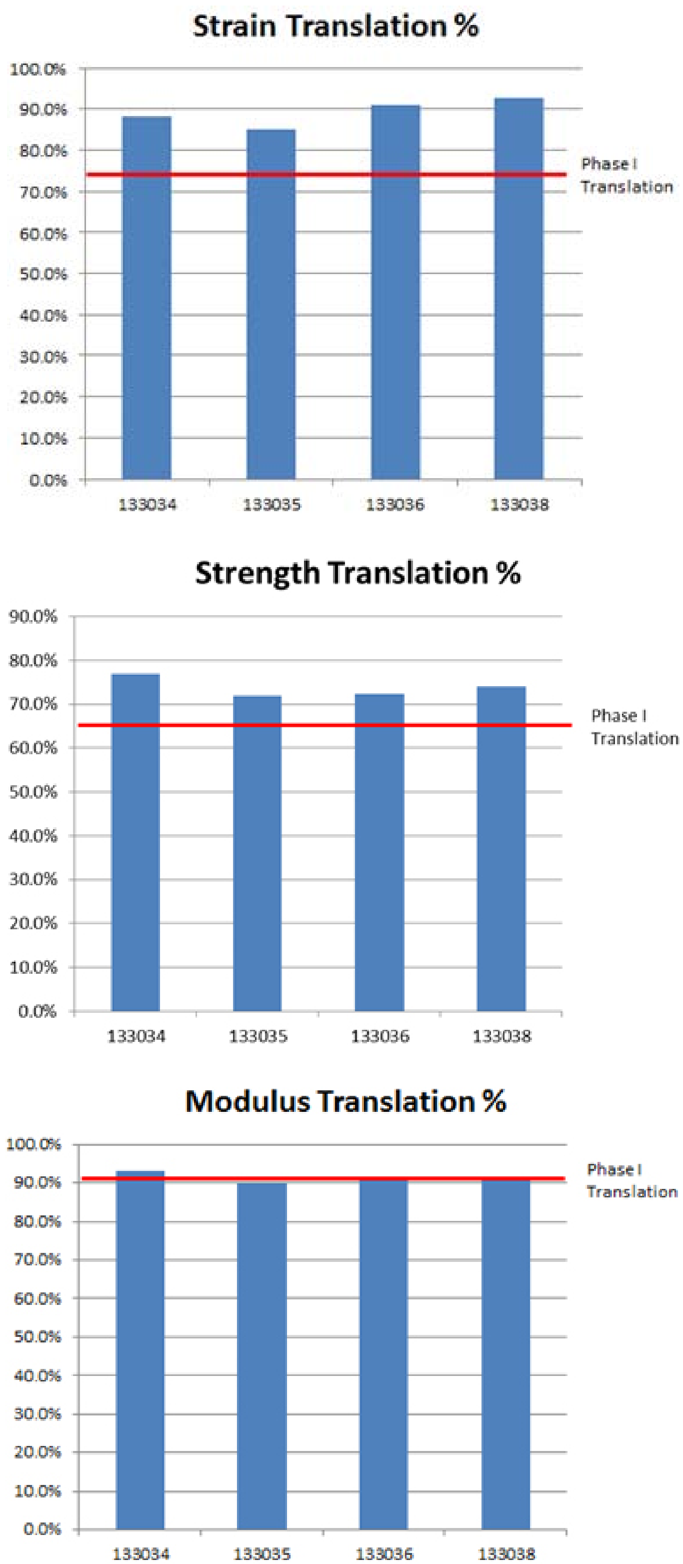

FIGURE 1. Average fiber property translation data (%) for Panex® 35 panels; five specimens each from four manufactured panels

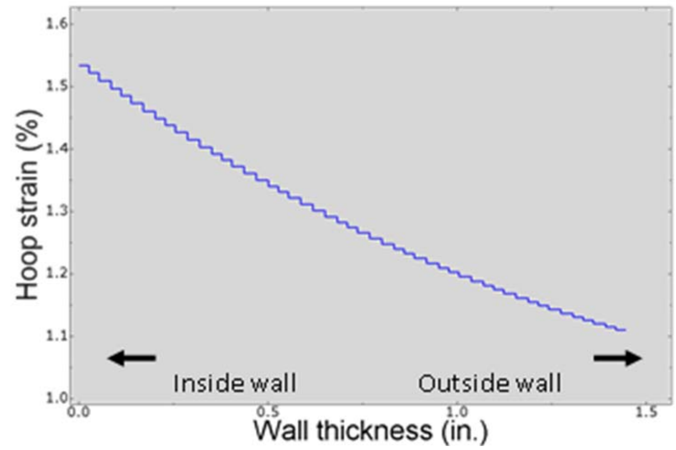

FIGURE 2. Distribution of hoop strain in composite wall of a 20-inch-diameter Type IV vessel designed for 700 bar operating pressure

- Length of the tank = 41 in

Since the outer layers are strained less than the inner fibers, the outer fibers can be replaced with fibers with lower strain capability and lower strengths (and lower cost) as long as the strain levels are maintained at acceptable levels (<1.8% for T700S carbon fiber and <1.5% for textile PAN fibers). Material properties of Toray T700S and Panex® 35 composites fabricated and evaluated by CTD (Table 2) were used in the finite element models (Figure 3) to determine how much of the Toray T700 fiber could be substituted with a lower cost variant.

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

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

Several analyses were conducted in order to find the amount of each material necessary to meet the design criteria. The analysis runs were used to vary the content of high strength Toray T700S fibers and Panex® 35 fibers. The layup sequence that was used was the same layup sequence used for the Phase I design; however, the number of layers of Panex® 35 fibers was varied as needed.

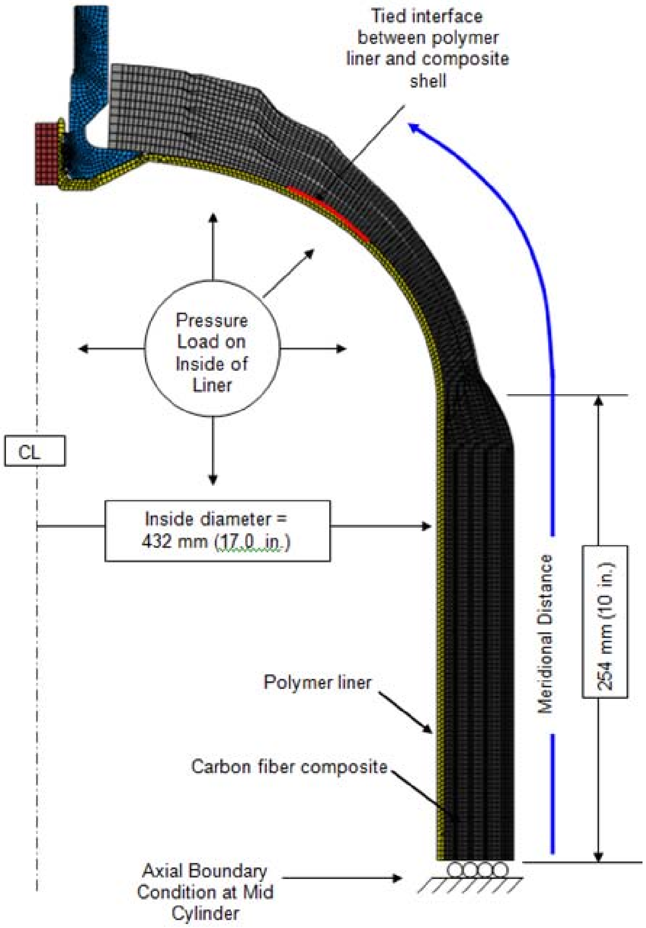

FIGURE 3. Finite element model of the COPV

The strain criteria were met in all layers consisting of Toray T700S carbon fiber regardless of composition. Figure 4 shows the hoop strain for the maximum allowable fraction of Panex® 35 fiber in the pressure vessel construction. This fraction is substantial and, should the fiber cost be low enough, would result in a significant cost savings.

Cost Analysis

As the first step in creating a cost analysis, a flow chart of the manufacturing process was generated. This allows the identification of any minor or major changes in the process flow that might result from using multiple carbon fiber types in COPV construction.

The only real changes in the process occur when purchasing two different fibers and having to change from one fiber to the next in the manufacturing process. The changes to procurement of the fibers are minimal and, other than the fiber cost, the largest change comes from any additional labor hours added to the process due to fiber change out.

A subsequent cost analysis was then used evaluate potential cost savings that might be realized by manufacturing a portion of the tank with a low cost fiber.

Results of the cost analyses conducted to date are provided in Figure 5. Included in Figure 5 are three charts: one chart shows the weight of fiber used to make each tank, and the other two charts show the estimated cost savings for the two different graded structures (50/50 vs. 60/40) utilizing three different cost parameters for the T700 and the low cost fiber.

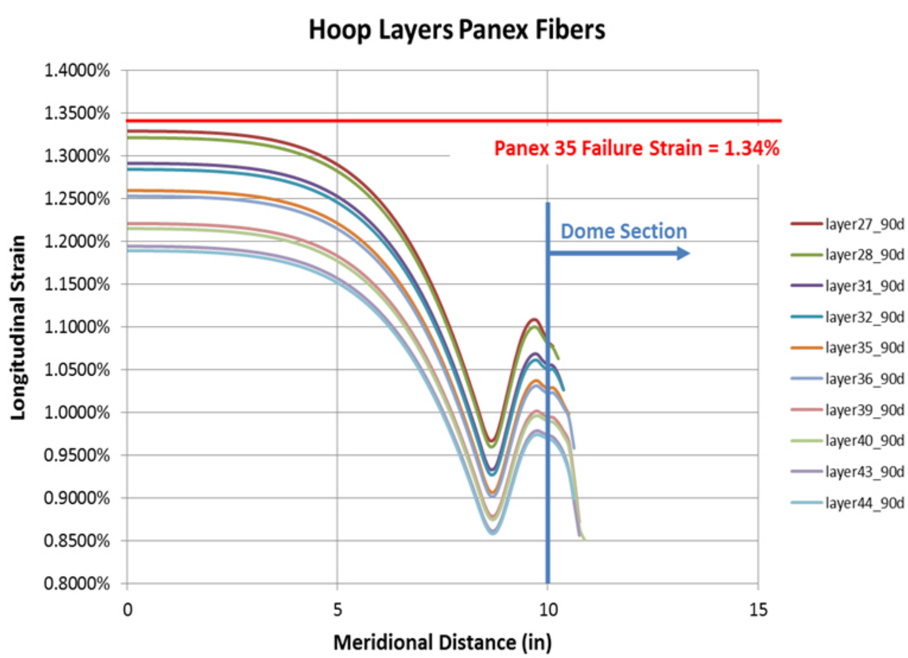

FIGURE 4. Hoop strain in Panex® fibers at the design burst pressure of 23,852 psi

T700 Price Range = $13 - $20
Low Cost Fiber Price Range = $7 - $12

These calculations come from a composite that has 50% fiber volume

50% T700 Toray/50% Low Cost Fiber				
		Low Cost Fiber ($/lb)		
		$ 7.00	$10.00	$12.00
T700 Toray ($/lb)	$13.00	20.4%	9.1%	1.6%
	$15.00	24.3%	14.5%	7.9%
	$20.00	30.6%	23.2%	18.3%

Weight of Fiber				
Percent	T700 lb	T700 kg	LC Fiber lb	LC Fiber kg
60/40	58.0	26.36	38.8	17.64
50/50	48.4	22.00	48.4	22.00
100	96.8	44.00		

60% T700 Toray/40% Low Cost Fiber				
		Low Cost Fiber ($/lb)		
		$ 7.00	$10.00	$12.00
T700 Toray ($/lb)	$13.00	15.9%	6.9%	0.8%
	$15.00	19.1%	11.2%	6.0%
	$20.00	24.3%	18.3%	14.4%

FIGURE 5. Results of cost analysis for two graded structure cases; potential cost savings are expressed as a percentage reduction over the 100% Toray T700 case

This cost analysis shows that the cost savings of a graded tank are between 0.8% and 30.6% depending on the price of T700 and the second fiber. This clearly demonstrates that there is potential for significant cost savings arising from the use of low cost carbon fiber, particularly if a cost on the order of $7.00/lb can be realized.

CONCLUSIONS AND FUTURE DIRECTIONS

Based on the results achieved during FY 2015, CTD will proceed with the construction and testing of a sub-scale prototype hydrogen storage tank based on the graded composite approach during FY 2016.

Additional work will be conducted in evaluating low cost carbon fiber options as provided by ORNL. Mechanical properties of unidirectional panels will be evaluated as was done for the commercial low cost fibers in FY 2015. The resulting data will be used in the finite element models to determine the amount of low cost fiber that can be used in a 700 bar hydrogen storage vessel. This composition, along with cost data provided by ORNL for the textile PAN-based carbon fiber options, will then be used in the cost model to predict the potential cost savings that may be realized through the use of graded composite structures in these pressure vessels.

REFERENCES

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