A. Lower Cost Composite Materials for CNG Storage

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Objectives

- 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.

Approach

- Assess current state-of-the-art and identify potential improvements
- Evaluate these improvements in terms of structural performance and manufacturability
- Support the Gas Research Institute (GRI) contract award winner

Accomplishments

- Identified the major cost element of manufacturing composite CNG fuel tanks was the raw material cost of the carbon fiber. Cost analysis showed that this was 40% of the total tank cost.
- Identified large tow-size (50,000 filaments) carbon fiber as a potential improvement. The cost of large tow-size carbon fiber is approximately ½ the cost of conventional tow-size carbon fiber.
- Developed manufacturing processes and test procedures for large tow-size carbon fiber.
- The as-manufactured performance of large tow-size carbon fiber is currently being evaluated to ensure safe design margins.

Future Directions (Beyond this Contract)

- Complete performance evaluation of large tow-size carbon fiber composites for stress rupture of sub-scale pressure vessels.
- Provide results from completed durability test matrix on large tow-size carbon fiber composites to GRI contractees.

Introduction

Compressed natural gas (CNG) is an alternative fuel that is stored under high pressure (3600 psi) on the vehicle. The use of natural gas as an alternative fuel in automotive applications is not widespread primarily because of the high cost and durability of carbon fiber composite storage tanks. Carbon fiber composites are relatively expensive because of the raw material cost of the carbon fiber, which accounts for approximately 40% of the total tank cost. By introducing large tow-size carbon fiber in the tank design there is the potential for a tremendous cost savings. The cost of large tow-size carbon fiber is approximately one-half the cost of conventional tow-size carbon fiber. However, not all of this savings is realized in the final overall tank cost because of the lower fiber strength and lower strength translation that has been demonstrated in large tow-size carbon fiber composite structures.

Tank Manufacturing

Composite CNG tanks are typically fabricated using the wet-filament winding process. This is a process where the fiber tow is passed through a resin bath to impregnate the tow and then wrapped around a mandrel prior to curing in an oven at elevated temperature. The Akzo Fortafil 3(C) large tow-size carbon fiber was selected for evaluation based on the vendor reported impregnated strand tensile strength and the fiber's processing characteristics. It was determined from process trials that modifications to the manufacturing method were required when using the Akzo large tow-size carbon fiber. A typical process trial fabrication set-up is shown in Figure 1. The modifications consisted of increasing the fiber tension, pulley diameters, and bandwidth, and modifying the type of compaction used. The bandwidth is the amount of tow advance per one revolution of the mandrel. Composition data for fiber, resin, and void content from nine process trials were inconclusive and it was determined that additional process trials were needed to achieve the high fiber content and low void content that are achievable with the standard tow-size carbon fiber. Cylinder fabrications for machining the ring specimens were completed using the processing parameters of 25 to 30-lbs. of fiber tension, 20 lbs. of compaction, and a 0.442-inch bandwidth.

Performance Evaluation

Performance of the Akzo large tow-size carbon fiber was evaluated to determine any design impacts that would prohibit their introduction into the fabrication process of CNG storage tanks. The evaluation was based on completing a durability test matrix. The tests consisted of impregnated strand, composite ring, and sub-scale pressure vessel tests for static strength, fatigue, and stress rupture. The static strength data was needed to ensure that the design safety factor of 2.25 on burst pressure was met, whereas the fatigue and stress rupture data was used to estimate reliability over the lifetime of the tank for refueling cycles and time under constant internal pressure loads.

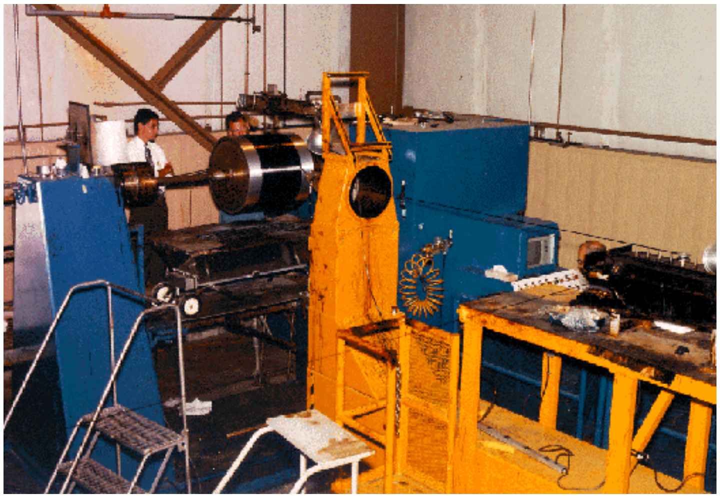

Figure 1. Process trial for wet-filament winding of large tow-size carbon fiber composite.

New test methodologies were developed for testing large tow-size impregnated strands and composite rings under tension-tension fatigue loading. The highest impregnated strand tensile strength was measured when specimens were fabricated using a 0.114-inch orifice and then potting the ends of the strand with a high elongation epoxy. This technique was also successful for conducting the strand tension-tension fatigue tests. Fatigue data for large tow-size carbon fiber is plotted in Figure 2 as a percent of characteristic strength versus cycles to failure. The characteristic strength was determined from the static tensile tests and a Weibull analysis of the data. The stress rupture data is presented in Figure 3 where the percent of characteristic strength is plotted as a function of time to failure.

In the characterization of filament-wound composite materials, rings are typically fabricated as test specimens for measuring the in-plane tensile strength in the hoop direction. Composite ring hoop strengths are commonly determined by using a method (split-d or NOL) that produces significant bending stresses in the specimen. In tension-tension fatigue these bending stresses become even more critical. To eliminate the bending stresses, a hydro-burst test fixture was designed for conducting the static and fatigue tests on the Akzo large tow-size carbon fiber composite rings. This fixture, as shown in Figure 4, loads the ring by internal pressure using hydraulic fluid. Work is in progress for completing the ring tests.

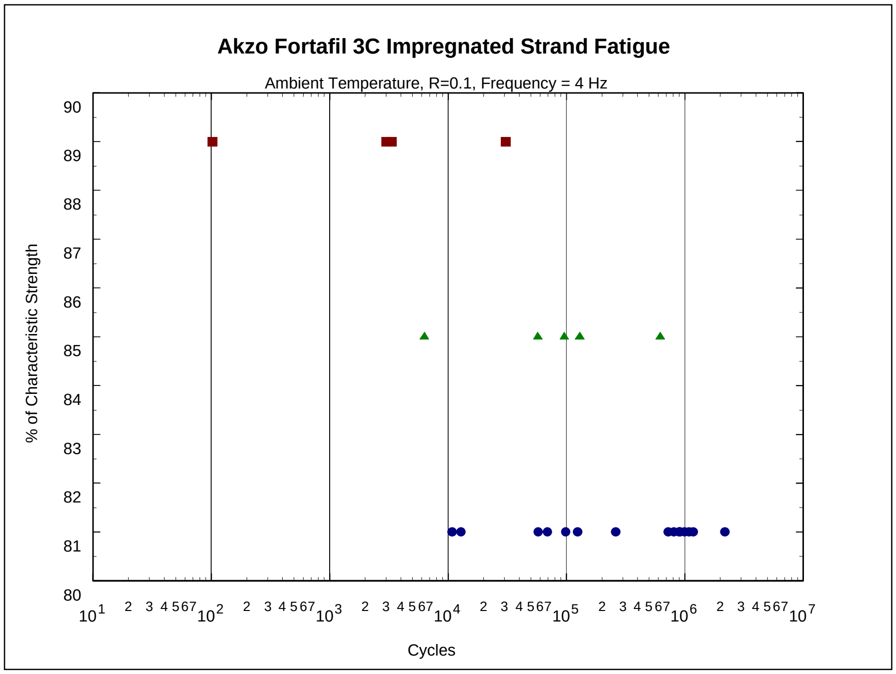

Figure 2. Large tow-size carbon fiber strand fatigue data.

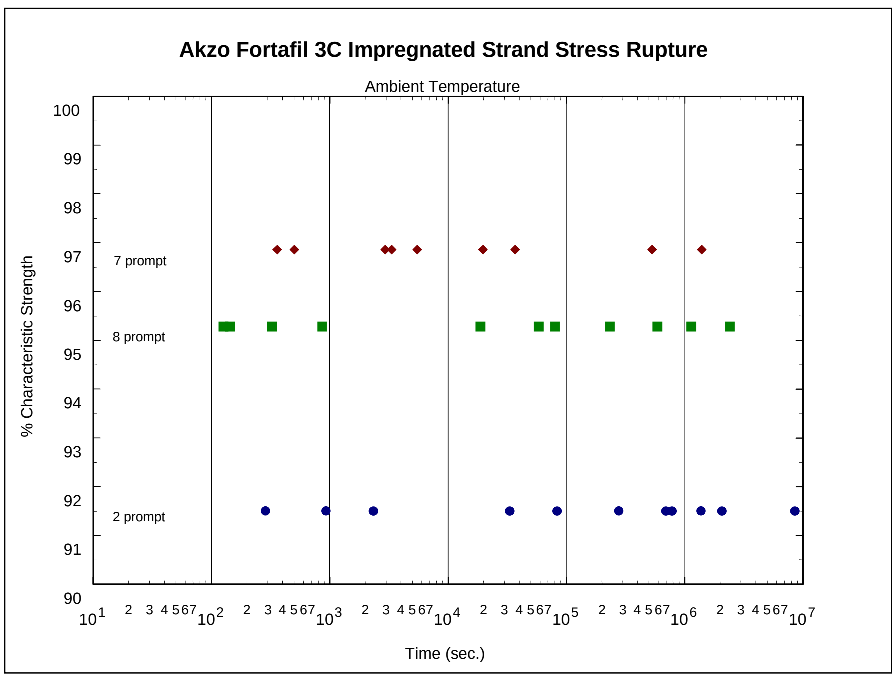

Figure 3. Large tow-size carbon fiber strand stress rupture data.

Figure 4. Hydro-burst test fixture for conducting composite ring fatigue tests.

B. Onboard CNG Storage Tank Diagnostic System

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Objectives

- Apply existing sensor technology for achieving cost-effective, in-service non-destructive evaluation (NDE) that is a reliable indicator of developing hazardous conditions in CNG composite fuel tanks

Approach

- Complete a review and evaluation of previous related work, including historical failures and inspection techniques for composite pressure vessels
- Identify the critical damage type and candidate sensor technologies
- Conduct laboratory demonstration tests

Accomplishments

- Completed literature survey and identified impact as the critical damage type
- Identified imbedded fiber optic sensors and modal analysis techniques as candidate technologies for in-service NDE of CNG composite fuel tanks
- Completed laboratory demonstration tests on a composite panel and a composite CNG fuel tank that was supplied by Lincoln Composites
- Successfully demonstrated two non-destructive diagnostic techniques that with further development have the potential for “smart” onboard inspection of NGV composite tanks

Future Directions (Beyond this Contract)

- Develop manufacturing processes for embedding fiber optic sensors.
- Determine damage criteria for an “unsafe” tank condition
- Manufacture prototype composite tanks and conduct field demonstrations

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Introduction

Carbon fiber composites are prone to impact damage that over the life of the CNG storage tank may lead to an unsafe condition for the vehicle operator. Normal degradation over time of a composite CNG tank, as it relates to structural integrity, durability, and expected service life, is accounted for by the design qualification standards. However, unexpected and/or unforeseen damage can occur that may render the tank unsafe for future refilling. To date, no reliable, cost-effective technique has been demonstrated for in-service NDE that could warn of a developing hazardous condition (this is commonly called "smart" tank technology). Two techniques that potentially may be a reliable indication are imbedded fiber optic sensors and modal analysis.

Fiber Optic Sensors

Several embedded fiber optic sensing techniques have been developed for composite structures where optical fibers act as transducers sensing changes in light amplitude, frequency, and time-delay. These changes can be accurately correlated to physical phenomena such as strain, pressure, and temperature, depending on the configuration and sensing technique employed.

The feasibility of using embedded fiber optics in composites as a NDE method for detecting impact damage in high-pressure natural gas fuel composite cylinders was demonstrated by a series of laboratory experiments. Two different structures, a nominal 35 cm by 35 cm, 24 layer, composite panel and a NGV Fuel Container supplied by Lincoln Composites, a Division of Advance Technical Products, Inc., were used to evaluate the various fiber optic techniques being considered.

An optical fiber was embedded in a serpentine pattern within the composite panel (see Figure 1) and the strain in the panel was evaluated using a simple low-cost light output and detection circuit as well as an optical time domain reflectometer (OTDR). Also, embedded with the composite panel was a fiber-optic Fabry-Perot strain gage system. The panel was tested in a cantilever beam set-up both before and after subjecting the panel to impact damage. Conducting a ram impact experiment produced the impact damage. The experimental set-up, as shown in Figure 2, consisted of a vertical-mounting fixture to secure the composite panel, and a ram device to impart an impact force on the composite panel. The ram device was designed such that it could be raised to some vertical height above the contact point on the panel then allowed to swing in a pendulum motion to contact the panel.

In Figure 3, the results from both the as built or baseline panel and the same panel after being damaged in the ram impact test are plotted. The data measured by the light output and detection circuit indicated a change in the system response due to the panel damage. A simple light input and detection circuit similar to this could be used to monitor the time history of a composite structure, in this case a NGV composite fuel tank.

The Lincoln Composite NGV all composite fuel tank was over-wrapped with approximately 110 meters of glass-on-glass 100/140 Teflon-coated optical fiber which mimicked the wrap pattern of the carbon composite. Two pressurization tests were completed where the fiber length was measured first at atmospheric pressure and then at incremental pressure increases of 3450 kPa (500 psig) until the maximum operating pressure of 24,820 kPa (3600 psig) was reached. The pressure was then reduced incrementally back to atmospheric pressure. Figure 4 shows a plot of the measured fiber length during each pressure cycle. Note that for each pressure cycle the slope remains essentially constant. Changes in the slope would be the indicator of any change in the condition of the NGV composite tank. Thus, by monitoring the slope of the pressure versus fiber length in association with structural tests on the tank, one can establish limits on the change in the slope allowed for maintaining certification of the vessel under operating conditions.

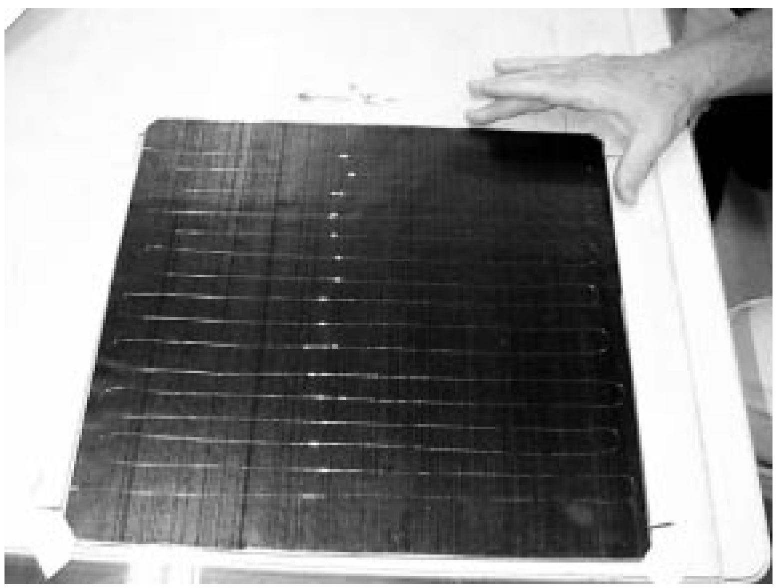

Figure 1. Pattern of fiber optic embedded in composite panel.

Modal Analysis

In the modal analysis technique, structural modal parameters are used as global indicators of complete structures including composite cylinders. The modal parameters such as natural frequency and damping can characterize the health or structural integrity of a component and may be used to detect defects in the material. Modal parameters may not be able to determine the exact location of the defect, but studies have shown that the defect size in composite materials can be correlated with changes in natural frequency and damping. These parameter changes (from baseline) are used to identify defects in the material.

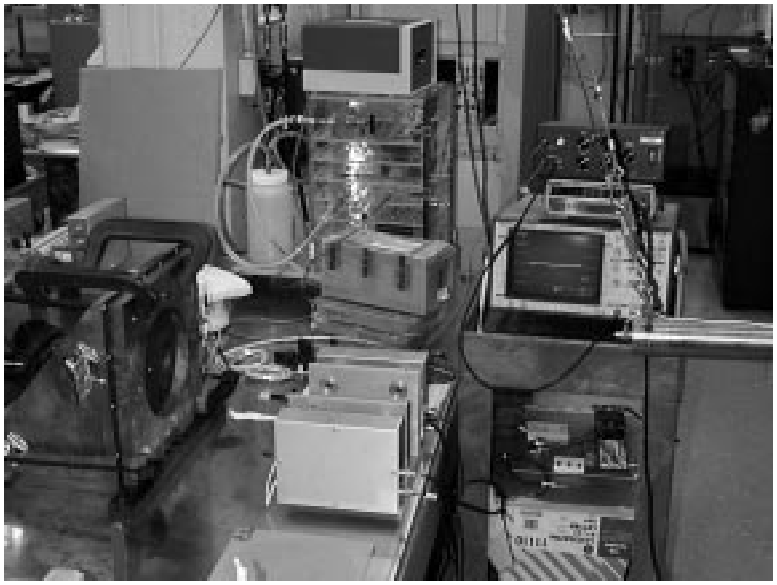

Figure 2. Ram impact experimental set-up.

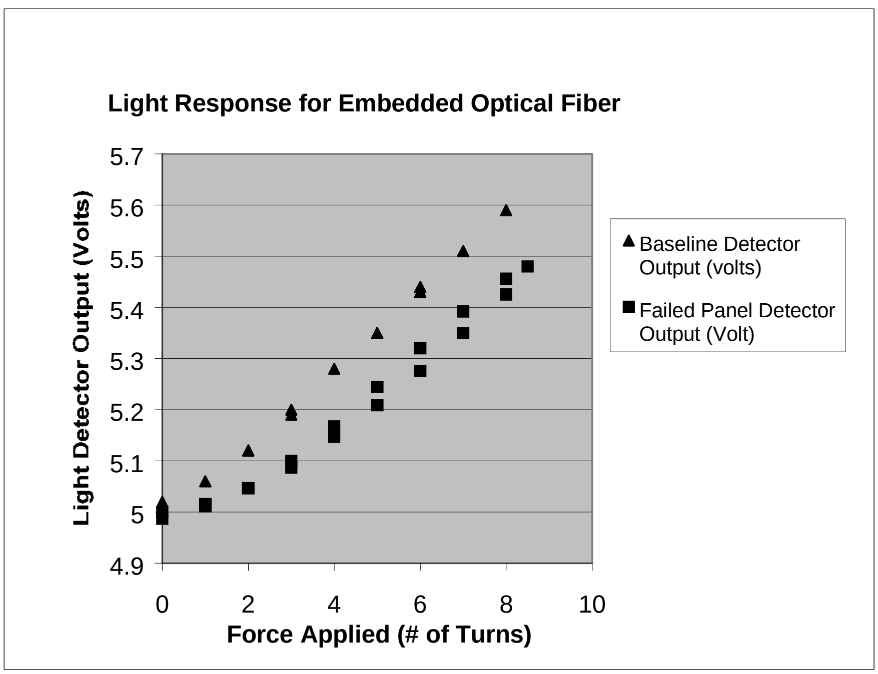

Figure 3. Detector response measured for baseline and failed composite panel.

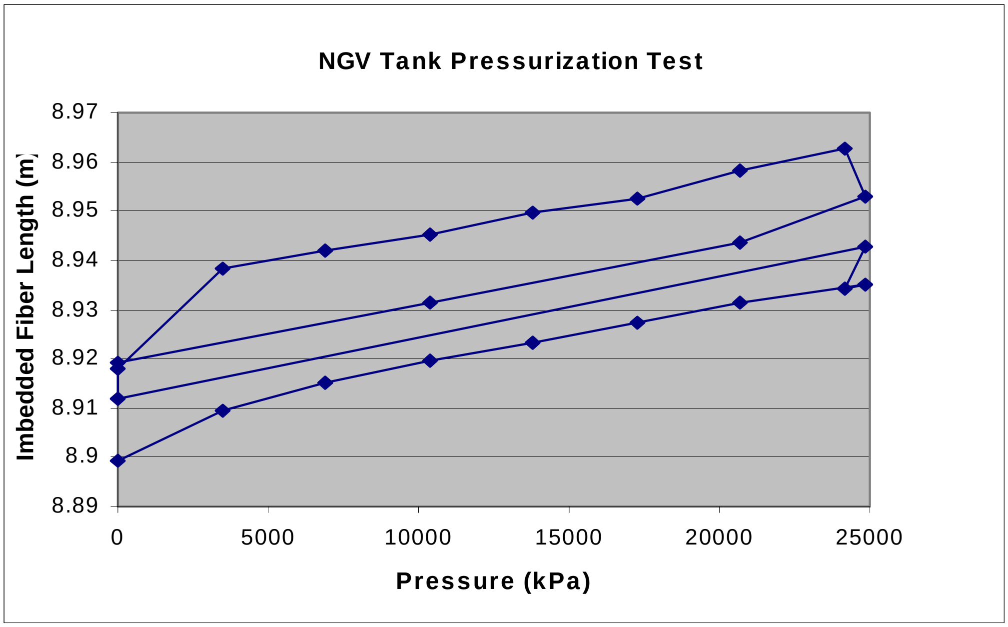

Figure 4. Plot of the measured fiber length during the tank pressurization test.

Modal tests and analyses were completed on the same undamaged and impact damaged panel used in the fiber optic sensor study. A plot of the frequency response function is shown in Figure 5 comparing the damage and undamaged responses. The resonant frequencies and damping were determined and the results indicated that the damaged panel had lower peaks for certain deformation modes and that the resonant frequencies shift downward with damage. Overall, the results showed that the damping parameter can be used to discriminate between damaged and undamaged panels for certain damage levels. However, the frequency shift was not a strong indicator of damage.

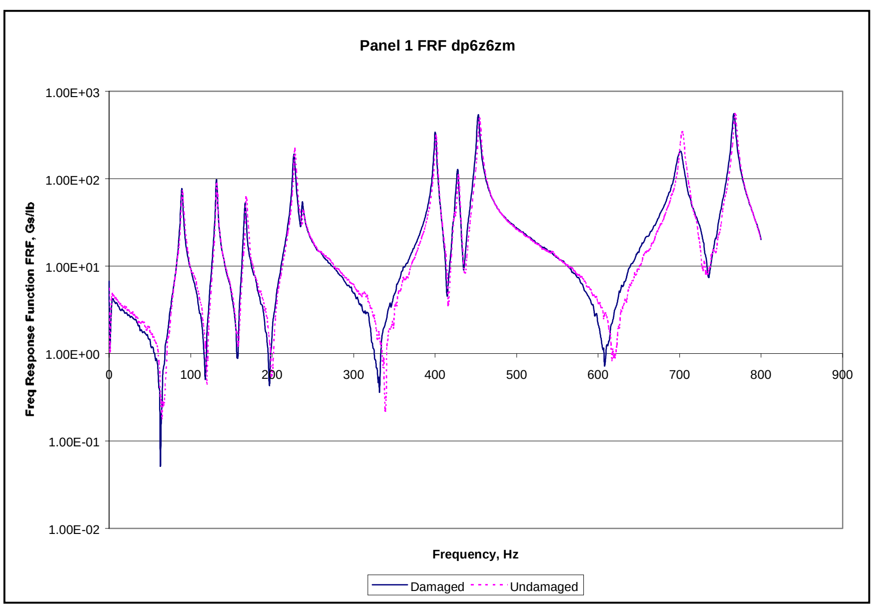

Figure 5. Modal analysis results for composite panel.

List of Acronyms

CNG – compressed natural gas
GRI – Gas Research Institute
NDE – nondestructive evaluation
NGV – natural gas vehicle
NOL – Naval Ordnance Laboratory
OTDR – optical time domain reflectometer