SMART ONBOARD INSPECTION OF HIGH PRESSURE GAS FUEL CYLINDERS

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ABSTRACT

The use of natural gas as an alternative fuel in automotive applications is not widespread primarily because of the high cost and durability of the composite storage tanks. Tanks manufactured using carbon fiber are desirable in weight critical passenger vehicles because of the low density of carbon fiber. The high strength of carbon fiber also translates to a weight reduction because thinner wall designs are possible to withstand the internal pressure loads. However, carbon fiber composites are prone to impact damage that over the life of the storage tank may lead to an unsafe condition for the vehicle operator. A technique that potentially may be a reliable indication of developing hazardous conditions in composite fuel tanks is imbedded fiber optics. The applicability of this technique to onboard inspection is discussed and results from preliminary lab testing indicate that fiber optic sensors can reliably detect impact damage.

KEY WORDS: composite materials, compressed natural gas (CNG), non-destructive evaluation (NDE)

1. INTRODUCTION

The promotion of alternative fuels in the transportation industry can reduce the United States dependence on foreign oil with the potential added benefit of reducing emissions. One alternative fuel is compressed natural gas (CNG) which is stored under high pressure on the vehicle. Factors that have inhibited the market growth of natural gas vehicles (NGV) have been the lack of infrastructure, limited range, high cost of the storage tank, and durability of the storage tank. CNG storage tanks are classified into four types depending on the type of materials used in the design: Type 1 tanks are all metal, Type 2 tanks are metal with a composite over-wrap in the cylindrical part of the tank, Type 3 tanks are metal-lined fully over-wrapped with composite, and Type 4 tanks are plastic-lined fully over-wrapped with composite.

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For weight sensitive and/or weight critical vehicle applications the Type 3 and Type 4 tanks are more commonly used. In these types of tanks the liner material is used for preventing gas permeation and the composite over-wrap is designed to carry the entire pressure loading. The reinforcement used in over-wrapping a tank is typically either a carbon fiber or glass fiber or a hybridization of these two fibers with an epoxy resin as the binding material. Fiber-reinforced composite CNG fuel tanks are desirable because of their low weight, corrosion resistance, and fatigue resistance. However, carbon fiber composites generally have poor resistance to damage caused by impact. Consequently, the durability of a fully over-wrapped tank that utilizes carbon fiber is a factor that has prevented significant NGV penetration in the automotive market.

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 over the life of the tank 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).

2. NDE TECHNOLOGIES

There has been a tremendous amount of research done on nondestructive evaluation (NDE) of composite materials primarily for quality assurance of fabricated components. NDE methods such as ultrasound, thermography (1,2), shearography (3), and acoustic emission (4,5,6,7,8,9) have been employed for detecting voids, delaminations, resin-rich areas, and low velocity impacts. Other NDE techniques include acousto-ultrasonics (10,11), vibro-acoustics, modal analysis (12,13), electrical resistivity, eddy current (14,15,16), and particle tagging (17,18). More recently, researchers have started using NDE techniques and sensor technologies for health monitoring of composite structures over their service life. Candidate technologies for “smart” on-board health monitoring of composite cylinders for high-pressure fuel storage must be cheap, reliable, and adaptable for field use. One potential NDE technology for in-service health monitoring of CNG tanks is embedded fiber optic sensors.

2.1 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.

Chang and Sirkis (19,20) used fiber optic sensors embedded into laminated graphite/epoxy composites for low velocity impact-induced damage assessment. The sensors used were in-line fiber etalon (ILFE) sensors because of their robustness, localization, and immunity to polarization fading and transverse apparent strain error. ILFE sensors are in the Fabry-Perot class of optical fiber sensors. Foedinger, et al (21,22) demonstrated the use of embedded fiber optic sensors for structural health monitoring in composite pressure vessels. Fiber optic sensors were chosen because of their immunity to electrical interference, corrosion resistance, and compatibility with composite materials and process conditions. Fiber optic sensor arrays were produced using Bragg gratings and ILFE and embedded in the standard ASTM 5.75-inch diameter composite pressure vessel. Huang, et al (23) developed and tested a distributed strain sensing technique using a fiber optic Bragg grating. A fiber optic Bragg grating is a periodic variation in the index of refraction along a certain length of the core of a single-mode optical fiber. This periodic structure makes the grating act as a wavelength-selective reflector that can be used as an indicator of applied strain in composite structures. Levin and Jarlas have addressed the issue of sensor reliability for embedded fiber optics in composite materials subjected to low-energy impacts (24). The limit of reliability of the sensor, in terms of the impact load, was determined by any DC anomalies in the fiber optic sensor response.

3. FIBER OPTIC SENSOR DEMONSTRATION

3.1 Composite Fabrication 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.

The composite panels used for the experiments consisted of a quasi-isotropic lay-up of carbon/epoxy composite prepreg materials. The prepreg was manufactured by Akzo Fortafil Fibers, Inc. using Akzo's 3C 50k carbon fiber tow with a 8601 epoxy resin. Two panels were fabricated with the same arrangements of embedded sensors. Approximately 6.4 meters of glass-on-glass AFS 100/140 Thermocoat Polyamide coated optical fiber from Fiberguide Industries was embedded in between layers 4 and 5 of the panel lay-up. Figure 1 shows a photograph of the optical fiber serpentine pattern being installed in the panel lay-up. The two fiber ends from the serpentine fiber optic lay-up were connectorized using Type ST connectors. Four Fabry-Perot strain sensors were embedded in the center of the panel between layers 12 and 13. The sensors were located approximately 18 cm apart in a pattern shown in Figure 2. Two sensors were used to measure localized strain in one direction and the second two sensors to measure strain in a direction perpendicular to the first two sensors.

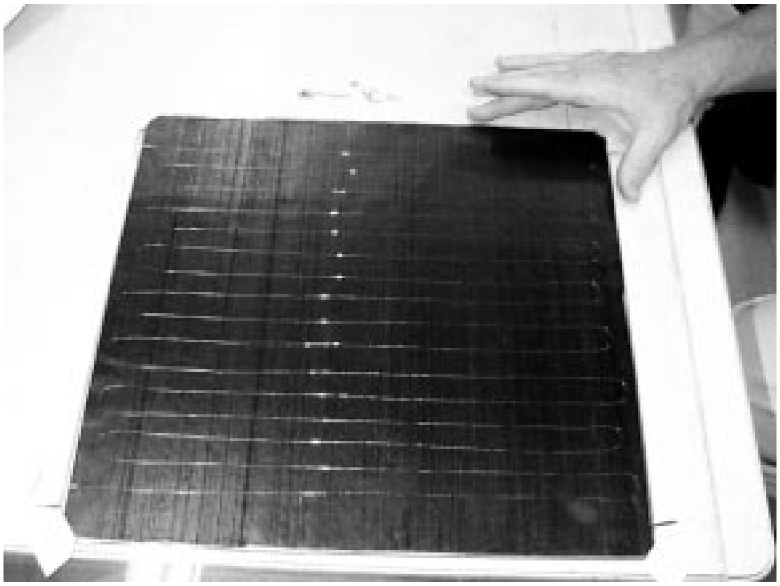

Figure 1. Pattern of fiber optic embedded in composite panel.

The optical fiber and Fabry-Perot sensors were laid directly on top of the layers, using the tack of the prepreg resin to hold the sensors in place. Lengths of the sensor leads were left protruding out of the laminate for later connectorization. After the lay-up was completed, the composite panel and all external sensor leads, connectors, etc. were carefully arranged on a metal plate and sealed within a vacuum bag. A sheet metal caul pad separated from the composite with a layer of release film was used to maintain flatness of the panel's upper surface during cure. The panels were cured for 2 hours at 120°C under vacuum (26-29 mm Hg).

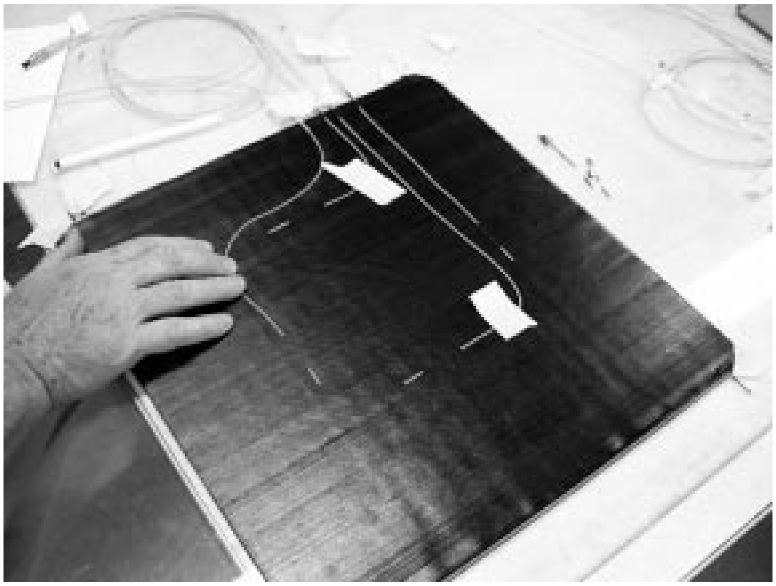

Figure 3. Fabry-Perot strain sensor position in composite panel.

Lincoln Composites has developed and supplied the Oak Ridge National Laboratory (ORNL) with two Type-4 fuel tanks used by the NGV industry. Glass-on-glass 10/140 Teflon-coated optical fiber was used to over-wrap the outside surface of the as-fabricated composite tank. The existing end fittings of the tank were removed and replaced with threaded steel shafts. The tank was then installed into an Entec 4-axis filament-winding machine.

A layer of room-temperature-curing epoxy was applied to the carbon fiber composite surface on the outside of the tank. The epoxy coating was allowed to set up for a period of time so that it was slightly tacky. The purpose of the coating was to smooth out the rough surface of the tank outer diameter and minimize possible abrasion of the optical fiber during the winding process. The slight resin tack also helped hold the fiber in place during winding.

A polar pattern was used that yielded a grid of optical fiber around the tanks outer circumference with nominal spacing between adjacent fibers of approximately 2.5 cm. The tank wrapping was accomplished with minimal (≈ ½-1 kg) winding tension. Nominal 0.6 to 0.9-meter lengths of optical fiber were left extending from both the beginning and end of the wrap pattern to be used for subsequent connectorization. After winding, the continuity of the optical fiber was evaluated by shining a HeNe laser light source into the end of one of the leads. The light traveled through the length of optical fiber in the wrap pattern and was visible exiting the other lead. This indicated that the winding process did not damage the optical fiber.

A layer of room temperature curing epoxy was then applied to the tank outside surface to bond the optical fiber to the tank body and to protect the exposed fiber from subsequent damage. Continuity of the fiber was again established and the exposed fiber leads were then loosely wrapped around the tank shafts and immobilized with masking tape. The tank was left to rotate overnight in the winding machine until the epoxy coating had cured. Examination of the tank the next day revealed that the lead adjacent to the tank boss had broken at the point that it exited the epoxy coating. Testing with the remaining lead indicated that there was still continuity throughout the entire optical fiber grid up to the point where the other lead had broken. The length of the continuous optical fiber was experimentally verified, using an optical time domain reflectometer (OTDR), to be 110 m. Figure 3 shows the Lincoln Composite tank with the optical fiber.

Figure 3. Lincoln Composite tank with optical fiber over-wrap.

The fiber used here was a test configuration that was known not to be ideal for future applications. The fragility of the optical fiber is expected to be less of a factor in a tank manufacturing process where the fiber can be either co-mingled or co-wound with the carbon fiber used to wind the tank. Furthermore, metal sheathed optical fiber can be used to provide a more rugged embedded system but this type of fiber was not available off-the-shelf at the time of the testing.

3.2 Experimental Setup The composite panel was tested in two different experimental configurations to evaluate different techniques for indicating potential impact damage within the panel. One detection technique evaluated light amplitude change as a function of overall strain. A second technique measured the actual localized strain in the panel as a function of load and also served as an active monitor during the impact tests. The first experiment consisted of measuring the strain in the panel as a function of the stress applied to the panel in a cantilevered configuration.   The second experimental setup employed a ram device with a 12.7-mm diameter tip which applied an impact to the panel at approximately the center point of the panel.

In the cantilever configuration experiment the composite panel was clamped using an angle bracket along the entire length to a 2.8-cm elevated block on one end and the other end extended out into free space approximately 26.7 cm. On the unsupported end a second angle bracket and a screw down clamping mechanism were used to apply a bending force to the composite panels. Figure 4 shows a photograph of a typical cantilever experimental configuration. The allen wrench on the right was used to apply force via the cap screw clamping devise. The force applied was not measured but rather the output from the optical transducers were recorded as a function of the number of turns from unstressed (no pressure applied) to fully stressed (pressure was applied to the unsupported, free space end until it was forced against the table).   The panel was tested in the cantilever configuration test both before and after the ram impact test to determine if the impact damage was detectable. The results indicated the damage was detectable and the details are provided in Sect. 3.3.

The ram impact experimental set-up 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. The ram was instrumented with a laser timing mechanism to measure the velocity of the ram just prior to impact, and a force transducer on the ram tip to measure the impact force as the ram strikes the panel. The additional instrumentation used in the experiment were the Fiber Optic Support System I (FOSS I) which fed a digital oscilloscope to provide the Fabry-Perot strain reading for one of the four sensors. The experimental test set-up is shown in Figure 5.

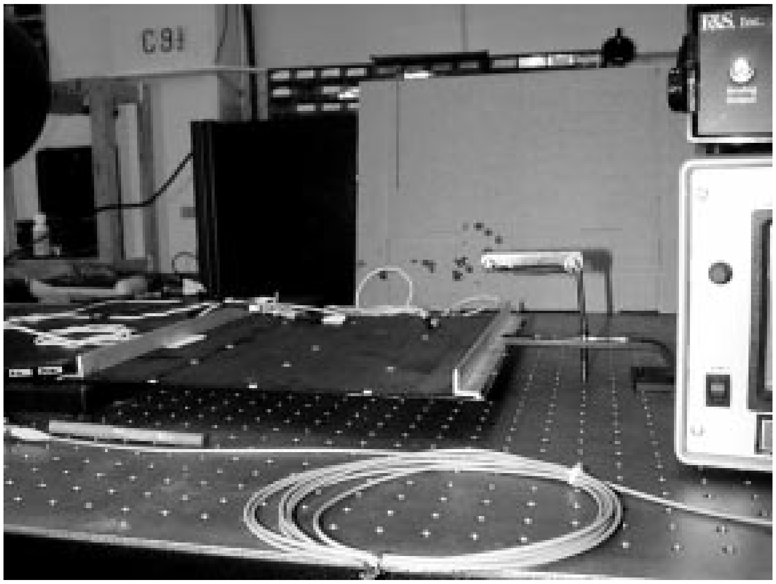

Figure 4. Typical cantilever configuration for bending stress evaluation.

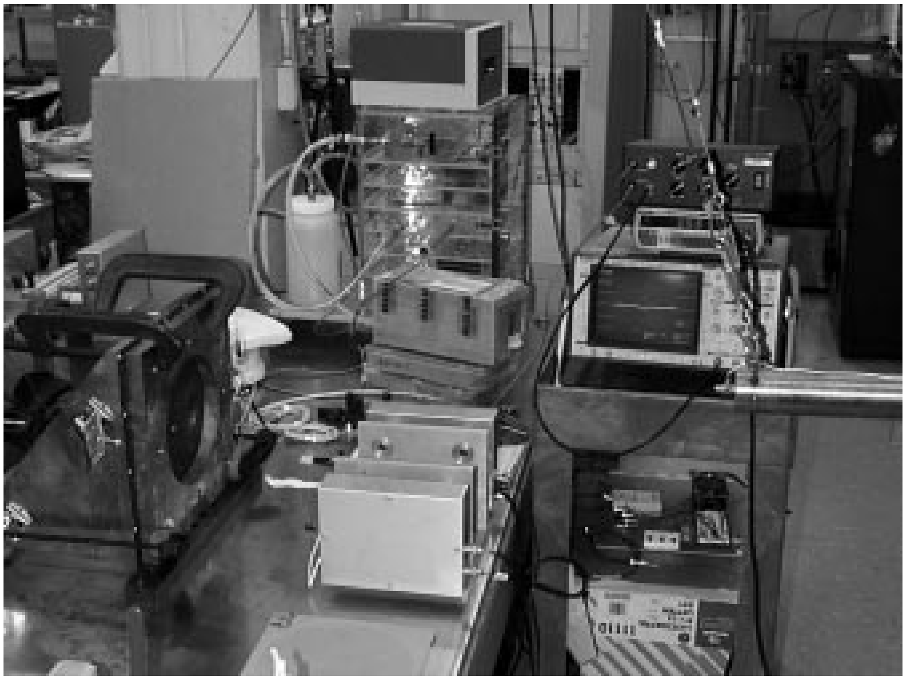

Figure 5. Ram impact experimental set-up.

The Lincoln Composite NGV Type 4 fuel tank was pressure tested hydrostaticly with loads varying from 0 to a maximum operating pressure of 24,820 kPa. The tank was pressurized in increments of 3450 kPa and at each pressure level an Optical Time Domain Reflectometer was used to measure the length of the fiber as a function of the pressure. The OTDR used was an Optical Fiber Monitor, Model OFM20-850 MM50, made by Opto-Electronics, Inc. This OTDR, under the conditions of the test set-up, can accurately measure the length to tenths of a millimeter. The experiments indicated that the fiber length was elongated approximately 4 cm for a pressure rise from 0 to 24,820 kPa.

3.3 Test Results Three pieces of test equipment were used to monitor the strain within the composite structures. The Fabry-Perot strain sensors along with a Fiber Optic Support System I (FOSS I) were used to measure the localized strain in the composite panel lay-up for both the cantilever configuration experiment and the ram impact experiment. The OTDR was used as a qualitative indicator of the overall strain exhibited in the Lincoln Composite NGV fuel tank. The final test hardware used was a simple light emitting and detection system which was built from standard of-the-shelve hardware and utilized a standard multi-meter to monitor the output of the detector.

Each of the three imbedded optical sensor techniques yielded useful data and showed excellent potential. The results are summarized in the following sections. Each technique has features that are most applicable to particular end goals. All three techniques could be used to monitor the pressure vessel as it is being filled at a refilling station. The OTDR technique and the use of the simple light input and detection circuit could each obtain an overall qualitative measurement of the vessel stress. In these two cases it will be important to determine winding patterns to provide suitable coverage of the vessel to detect impact damage at any given point on the vessel surface. The Fabry-Perot sensors could be used to continuously monitor the localized strain within the vessel and at the same time serve as a continuous impact monitor. Further research would be required to determine how best to locate the Fabry-Perot sensor to provide adequate coverage for the overall vessel.

3.3.1 Composite Panel Testing As discussed previously the composite panel was tested in two different experimental configurations to evaluate different techniques for indicating potential impact damage within the panel. The first experiment consisted of using the simple light input and detection circuit to measure the strain in the panel as a function of the stress applied to the panel in a cantilevered configuration, as described in Sect. 3.2. A second experiment used the same composite panel to evaluate the Fabry-Perot optical stain gage sensors as means of detecting impact damage. A ram device with a 12.7-mm diameter tip was used to apply increasing impact loads to the panel until visual evidence of failure was observed.

In the cantilever test, the simple light input and detection circuit was use to input light into the embedded serpentine optical fibers and observe how the output intensity changes as a bending force was applied to the unsupported end of the panel. An 850nm light emitting diode was used to launch light into the approximately 6.4 meters of glass on glass AFS 100/140 Thermcoat Polyamide coated fiber embedded in a serpentine pattern in the composite panel. The output light exiting the embedded fiber was routed to a silicon PIN diode that converted the light intensity to a current, which was then converted to a simple voltage output. This detection technique gives an overall or universal strain measurement verses a localized strain that would be typical of most commercial strain gages. A localized strain measurement would only be useful if the failure occurred in the near vicinity of the gage. Because the serpentine embedded fiber provides an output signal that represents the overall or universal strain in the panel, damage to any location on the panel was detected by the embedded fiber.

The output voltage was adjusted to a nominal 5 volts for the no load position and a bending load was applied to the unsupported end via a screw down clamping mechanism. The photo detector output in volts was recorded as a function of the force applied in number of turns of the screw down clamping device. The as-built composite panel was tested as a baseline and then the test was repeated on the same panel after the ram test was completed and there was visual damage to the panel. In Figure 6, 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 indicate 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 the natural gas vehicle composite fuel tanks.

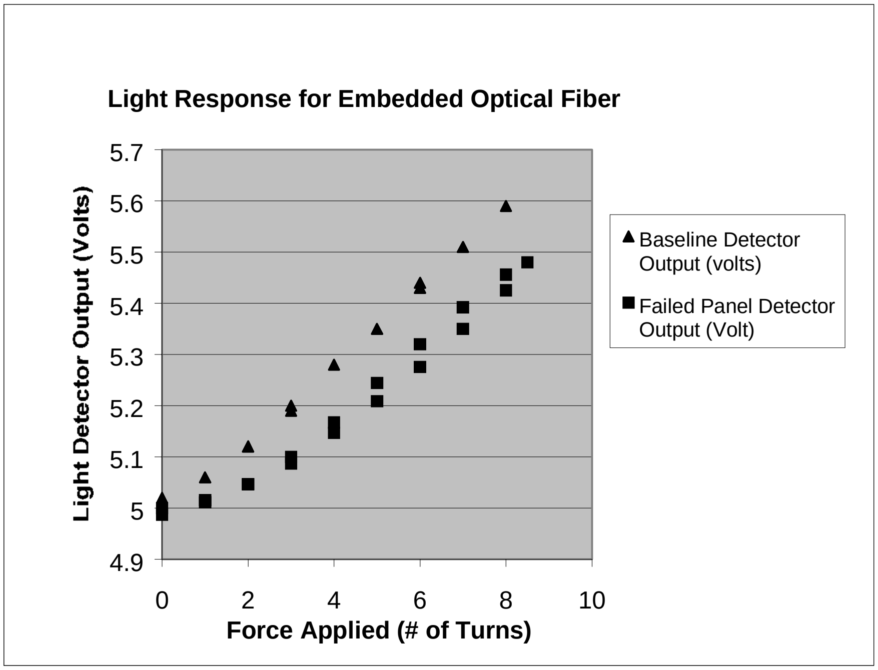

Figure 6. Detector response for baseline and failed composite panel.

In the ram impact experimental, the ram was raised to a predetermined vertical height above the contact point on the composite panel. The ram was then allowed to swing in a pendulum motion and impact the panel. Raising the initial ram height in increments of 2.5 cm increased the ram force. After each test run the panel was visual inspected for damage before proceeding to the next test run. There was no visual damage to the panel until after run 10, the second impact test run from a height of 15.2 cm. Upon visually inspecting the panel, a slight impact indenture was found on the front side of the panel where the impacts had taken place. The panel failed on run number 12 when the backside of the panel became partially delaminated. The test panel was then removed and returned to the laboratory to repeat the cantilever test.

The data obtained in the test included the run number, the ram height, the impact force applied (measured by a force transducer on the ram tip), the velocity of the ram prior to impact, the number of fringes detected by the Fabry-Perot optical strain gages and the calculated strain. The data is summarized in Table 1.

The Fabry-Perot optical strain gage sensors served as an excellent means of monitoring the panel impacts and identifying when real damage occurred in the composite structure. A typical output from the Fabry-Perot sensor when no structural damage occurred was a nearly symmetrical, mirror image, fringe pattern. When permanent damage occurred in the composite panel (run 12), the Fabry-Perot sensor tracked the strain through the entire event. At the point corresponding to permanent damage, the output signal from the sensor reacted to the failure in the composite structure. The signal departed from the near symmetry that was evident in the previous runs. The erratic output signal can thus be used as an indicator of failure. Figure 7 shows the Fabry-Perot sensor response to the panel failure that took place in run 12. These results indicate that simple Fabry-Perot sensors could be embedded in a composite structure, such as the NGV composite fuel tank, to continuously monitor the structure as an indicator of impact failure. Additional research and testing would be required to define where and how many such sensors would be needed to effectively monitor the entire surface of the tank.

Table 1. Ram impact test results.

Run #	Initial Ram Height (cm)	Impact Force (N)	Velocity (m/sec)	Fabry-Perot Strain Sensor	
				Number of Fringes	Strain (microstrain)
1	2.5	1667	0.62	2.25	226.7
2	2.5	1700	0.63	2.27	228.7
3	5.1	2525	0.97	3.25	327.5
4	5.1	2666	0.97	3.25	327.5
5	7.6	3318	1.15	4.25	428.3
6	7.6	3400	1.18	4.30	433.3
7	10.2	4087	1.35	5.50	554.2
8	12.7	4721	1.51	6.35	639.9
9	15.2	5538	1.68	7.45	750.7
10	15.2	5604	1.69	7.45	750.7
11	17.8	6066	1.76	8.25	831.4
12	20.3	6636	1.97	9.00	906.9

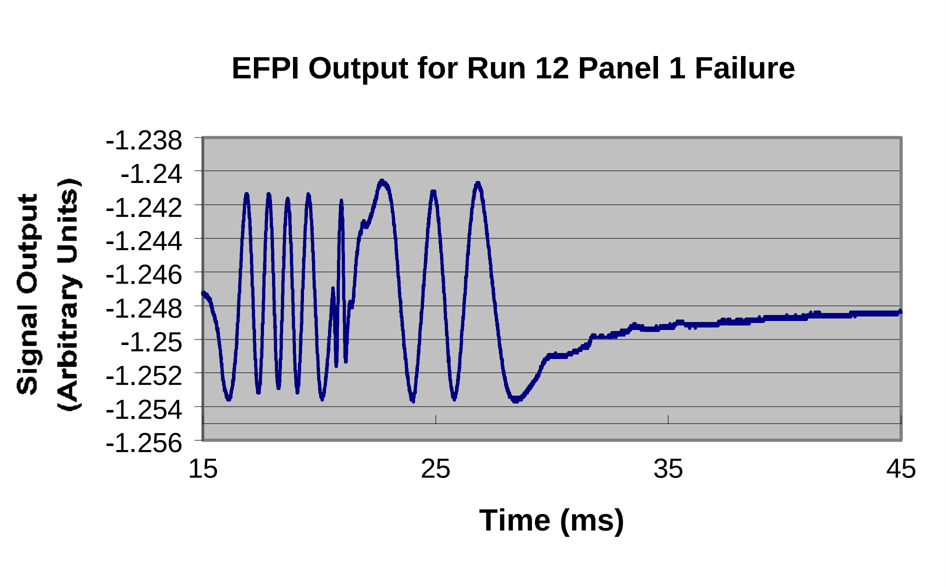

Figure 7. Output signal from the Fabry-Perot sensor for Run 12 panel failure.

3.3.2 Composite Tank Testing The concept employed in the pressurization tests was to overwrap the composite tank with a number of turns of optical fiber whose length could then be monitored during the filling operations. After overwrapping the tank with a suitable pattern one can monitor the overall change in length of the fiber during the filling operation. A baseline measurement of the pressure versus fiber length can be established before the tank is released for use. The tank can then be monitored during each refilling operation and limits of change established for both long-term service life and detection of damage due to external impacts. The testing described here indicates that the fiber length is a sensitive indicator of the overall stresses in the composite tank. The goal was to demonstrate the feasibility of the concept and help determine what some of the issues might be for future development activities. The experience gained will serve as a springboard for future developments in the general area of smart composite structures.

As described in Sect. 3.2 the Lincoln Composite NGV all composite fuel tank was overwrapped with approximately 110 meters of glass-on-glass 100/140 Teflon-coated optical fiber which mimicked the wrap pattern of the carbon composite. The fiber pattern was sealed to the tank surface by a coating with epoxy. After the winding operation was completed the overwrapped tank was moved to an optics laboratory where one end of the fiber was connectorized. The other end of the fiber was broken at the point where the fiber exited the composite, not allowing enough fiber length for a connector. It was found that the unprotected fiber on the exterior of the tank was easily damaged. The OTDR was connected to the optical fiber and a measurement of the fiber length indicated that the fiber had been broken at a point 11.0738 meters from the input connector. The composite tank was then transported to a second laboratory where the hydrostatic pressurization test took place. During the transportation and setup time the optical fiber was again damaged and we found that the length of the undamaged fiber on the connector end was 8.9182 meters indicating that the there were approximately 3 ¼ wraps of the tank remaining intact from the input connector.

On day one of the pressurization tests the fiber length was measured first at atmospheric pressure and then at incremental pressure increases of 3450 kPa until the maximum operating pressure of 24,820 kPa was reached. The pressure was then reduced incrementally back to atmospheric pressure, allowed to remain at atmospheric pressure for 3 ½ hours, then re-pressurized to 24,820 kPa. The tank was left pressurized at 24,820 kPa overnight. Overnight the pressure leaked down to 24,130 kPa. Again the fiber length was measured as a function of the tank pressure. The pressure was increased back to 24,820 kPa and then incrementally reduced in 3450 kPa increments back to atmospheric pressure. Figure 8 shows a combined plot of the two-days of testing. 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.

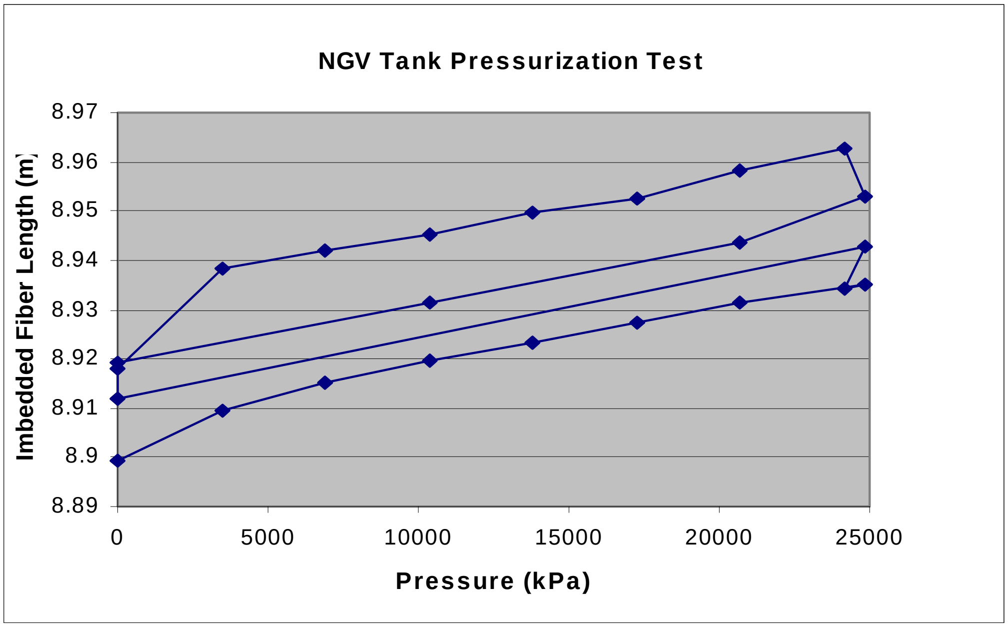

Figure 8. Plot of the combined results for the two-day tank pressurization test.

4. CONCLUSIONS

A preliminary investigation based on laboratory testing has demonstrated the potential use of embedded fiber optic sensors as a “smart” tank technology. Impact tests were conducted on a composite panel and pressurization tests were conducted on a composite NGV fuel tank for the lab demonstration. For the composite panel tests, both an optical fiber and a Fabry-Perot sensor were embedded within the quasi-isotropic composite laminate. The composite tank was supplied by Lincoln Composites and was over-wrapped on the outer surface with a glass-on-glass optical fiber. The three techniques used to monitor the strain within the composite structures were an OTDR, a simple light emitting and detection system, and a FOSS I (with the Fabry-Perot sensors). All three systems provided useful information and showed excellent potential for monitoring the structural integrity of the tank as it is being filled at a refilling station. Further research is needed for integrating the sensors into the tank manufacturing processes and for establishing appropriate damage criteria that would define an unsafe tank condition.

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