Damage Evaluation and Analysis of Composite Pressure Vessels Using Fiber Bragg Gratings to Determine Structural Health

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ABSTRACT

With the augmented use of high performance composite materials in critical structures, it has become increasingly important for 'smart' systems to monitor these materials and provide rapid evaluation. Using fiber Bragg gratings embedded into the weave structure of carbon fiber epoxy composites allow the capability to monitor these composites during manufacture, cure, general aging, and damage. Fiber optic sensors allow greater insight into damage progression and can be used to verify analytical models. This paper emphasizes the results of recent work in which multiple arrays of Bragg gratings were wound into composite vessels and monitored while the part was damaged. Based on the response of these sensors, algorithms were developed to identify the location of damage impacts. Results were verified against eddy current and ultrasonic NDE methods.

Keywords: fiber Bragg grating, composite NDE, fiber optic strain imaging, structural health monitoring (SHM), embedded sensors, composite damage

1.0 INTRODUCTION

Composite materials are a high strength and low weight alternative to the use of traditional metallic parts. However, existing technologies are challenged by time and cost to accurately assess damage and its effect on each part. Damage assessment techniques capable of rapidly and accurately locating trouble areas in composites are needed for commercial, military, and industrial applications. Embedded fiber grating sensor technology offers the capability to locate and assess damage from fiber breakage and delamination that may occur in composites. Blue Road Research (BRR) and ATK Thiokol (ATK) demonstrated the ability of multi-axis fiber grating strain sensors to detect damage to composite articles through mapping changes in the three-dimensional strain fields, using data collected from multi-axis fiber grating strain sensors. Algorithms for damage mapping have been developed and are being refined in conjunction with the sensor readings to allow single and multi-axis fiber grating sensors to further refine the location and extent of damage to composite materials on a 3-dimensional and time-usage scale. A prototype system has been developed that is capable of locating and assessing damage in composites. This system has become available commercially and offers 3-D graphical views of damage as well as data for the analysis and evaluation of strain and damage fields.

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14. ABSTRACT
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2.0 DUAL-AXIS BRAGG SENSORS

Traditional Bragg sensing technology relies on the reflection of electromagnetic radiation at discrete Bragg wavelengths. Bragg gratings are written into the core of standard single mode optical fiber using a laser and photomask or interferometric techniques. As the fiber undergoes environmental effects such as strain or temperature change, the gratings on the fiber respond proportionally by compressing or expanding from their initial state. As this occurs and these gratings are illuminated through the core of the fiber, these same environmental effects shift the initial reflected wavelength to higher or lower values. These changes in wavelength are recorded and can be used to solve for strain (or temperature) according to equation 2.1:

$$\frac{\Delta\lambda}{\lambda_o} = \beta\Delta\varepsilon + \xi\Delta T \tag{2.1}$$

where

$\Delta\lambda =$ Sensor Wavelength Change (nm)

$\lambda_0 =$ Initial Sensor Wavelength (nm)

$\beta =$ Elasto-optic Coefficient for Fiber Grating Sensor

$\Delta\varepsilon =$ Strain Change

$\xi =$ Thermo-optic Coefficient for Fiber Grating Sensor (1/degree Celsius)

$\Delta T =$ Temperature Change (Celsius)

To manufacture a dual-axis fiber Bragg sensor, the writing of the grating is the same as outlined, except that polarization-maintaining (PM) fiber is used. The result is that the Bragg grating yields two orthogonal, independent spectral signals that can yield two independent parameters, such as strain in the transverse and axial planes, simultaneously.

3.0 EXPERIMENTAL SETUP

The 'strain imaging' system uses a series of optical subcomponents that collect data from the PM fiber optic sensors embedded throughout the composite structure. As scans are initiated the data is collected and processed through algorithms that compare changes from each region with historical data. The information is reduced and summarized through a graphical interface that helps the user locate damage. Raw data from damage signatures also showed differences between delaminations and broken tow damage, suggesting the ability to distinguish damage types, but implementation and refinement into the automated data reduction algorithms must still be completed.

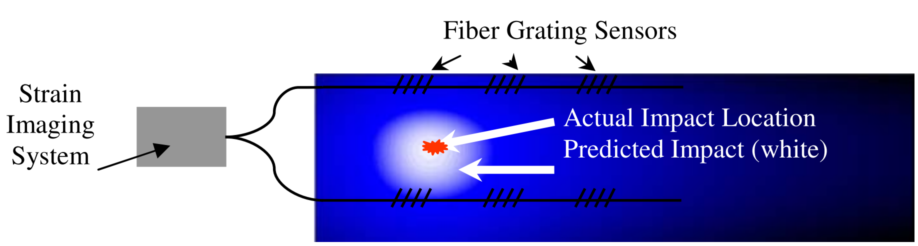

Figure 1. Strain imaging system scans fiber sensor arrays to locate damage

In the first of a series of tests, a brass weight attached to a pendulum was impacted into the side of a composite from specified heights that yielded a 5, 10, 15, and 20 ft-lbs. impact. Baseline and intermediate scans were taken to determine if the system was able to sense damage propagation. Figure 2 shows a photograph of the test. The impact occurred in an area among 4 Bragg sensors whose installation location was monitored during the manufacturing process.

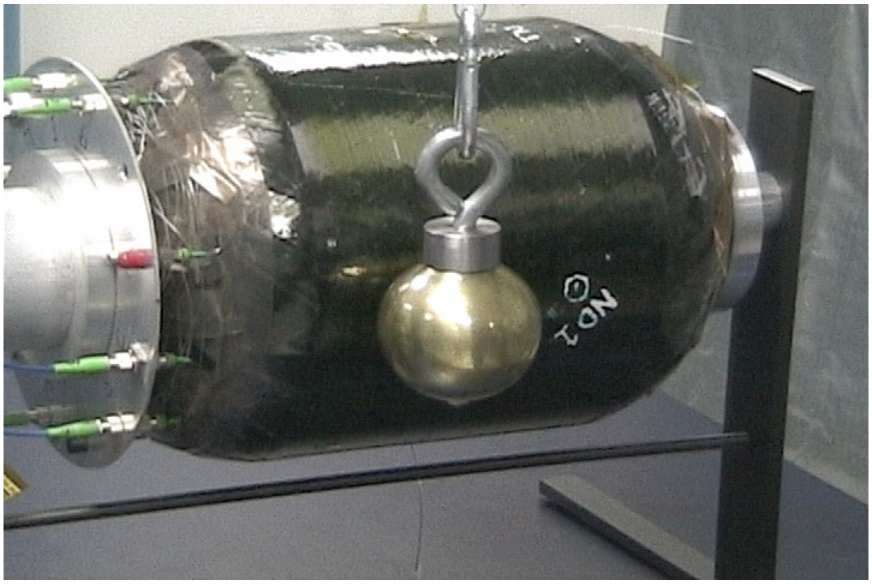

Figure 2. Photograph of impacts to a composite using a brass ball

In another test, the composite was randomly impacted using a rounded chisel point, dropped with forces ranging from 4 to 24 ft-lbs, as shown in Figure 3 below.

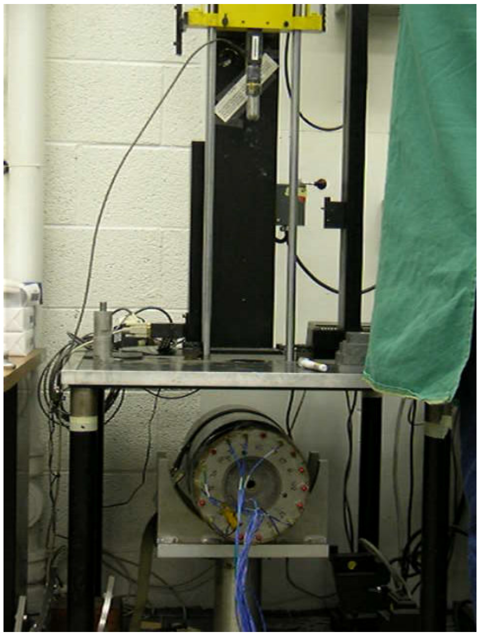

Figure 3. Fiber optic sensors embedded under the surface monitor impact damage

The impacts occurring from known forces were distributed randomly across the surface. A series of impacts followed by eddy current and ultrasonics scans were completed to allow for verification of the impact damage incurred with the data captured by the fiber optic sensors.

In a third test, a modified system was used to scan composite vessels at 4 Hz, as they were being cycled to bursting pressures. Strain values were read from the fiber optic sensors and logged to disk where they could be dynamically viewed in 3-D after failure of the composite to locate weaknesses within the composite wall.

4.0 RESULTS

For the first test, multiple impacts of increasing force yielded an increase in the area of damage detected by the fiber optic sensors. Figure 4 shows the four nearest multi-axis sensors (one per chart) with plots of in-plane (lower wavelength) and out-of-plane (higher wavelength) spectra before damage (left) and after a 20 ft-lbs impact (right).

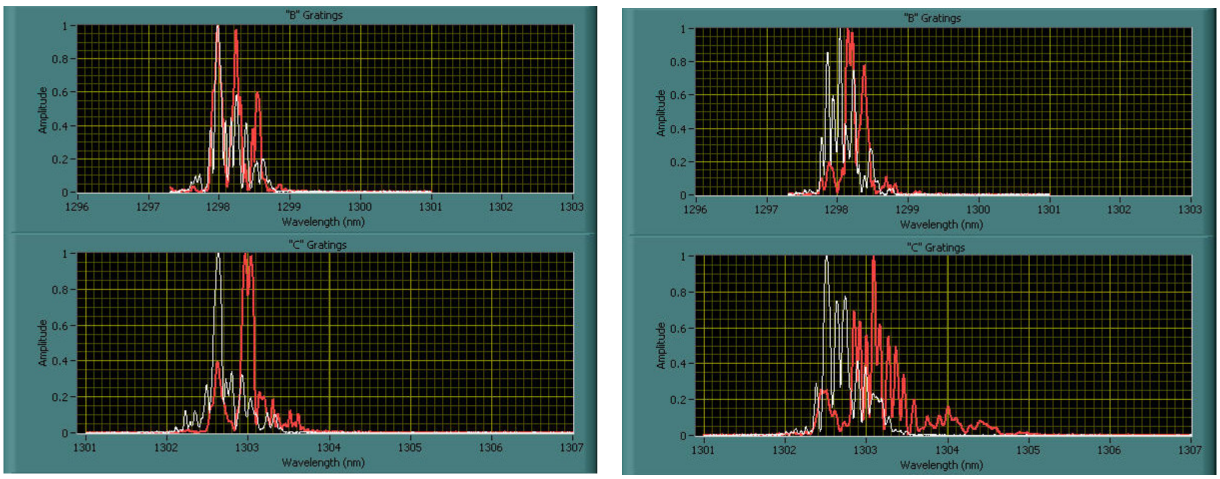

Figure 4. In-plane and out-of-plane spectra captured (left) before impacting and (right) after successive impacts to the composite surface

Experienced interpretation of these graphs indicates greatest out-of-plane damage nearest to the sensor graphed at the bottom right corner (sensor ‘c’). In order to process raw spectral data into results easier understood by non-technical end-users, an emphasis is placed on the generation of algorithms which can quickly determine and interpret location and damage information. When processed with software-created algorithms, the computer is able to simplify and enhance event data. Figures 4-6 show the end-result of the reduction of data to the composite impacted by a 5, 10, 15, and 20 ft-lbs force. The intensity scale is set to coincide with the maximum impact of 20 ft-lbs, while the y-scale shows location as a function of distance and the x-scale plots from 0 to 360-degrees.

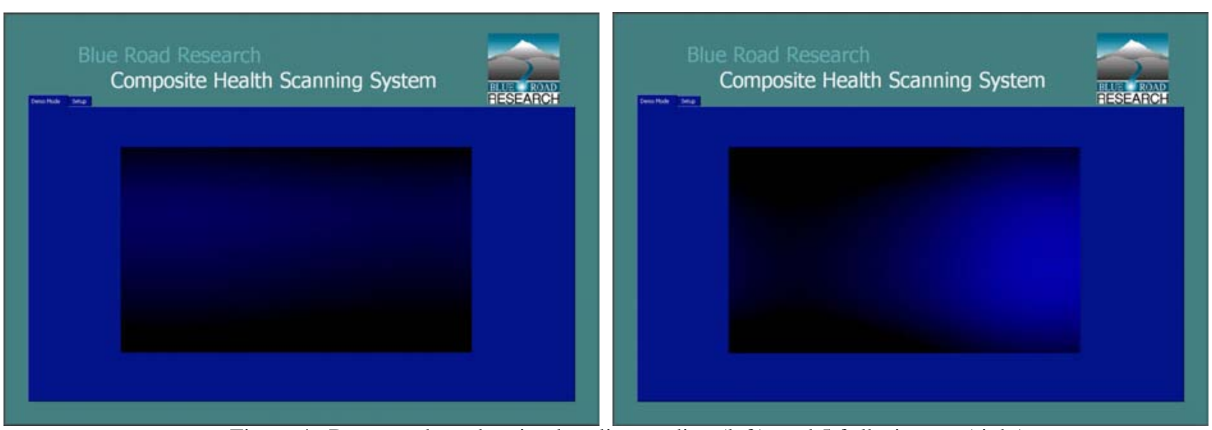

Figure 4. Damage chart showing baseline reading (left), and 5 ft-lbs impact (right)

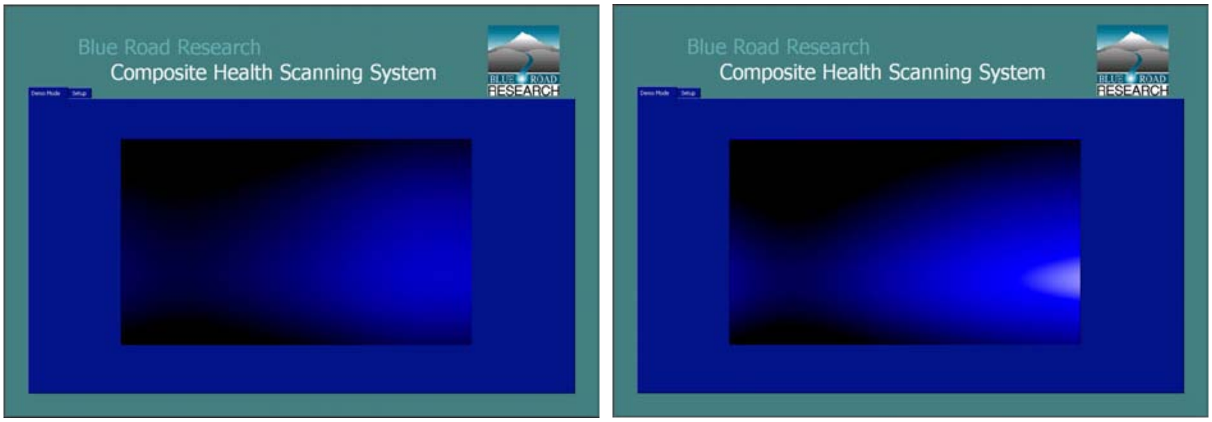

Figure 5. Damage chart showing 10 ft-lbs impact (left), and 15 ft-lbs impact (right)

Figure 6. Damage chart shows location and intensity of damage after an impact of 20 ft-lbs

Using the charts of Figures 4-6 to determine the ability of the system to distinguish damage of varying intensities easily show an increase in damage intensity with an increase in damage force applied.

The second experiment used a series of random/'blind' impacts of varying forces to determine if the strain imaging system was able to locate and chart damage accrued in multiple locations around the surface. After a series of impacts, the composite was scanned with eddy current and ultrasonics equipment to be able to verify the results. Damage greater than 5 ft-lbs coincides well with the traditional NDE methods, and to within a radial circumference of approximately 2.5 cm of measured impact locations. Figure 7 shows a comparison of the strain imaging developed by Blue Road Research with ultrasonic methods. Four impacts (impacts 3-6) were compared to the ultrasonic scans.

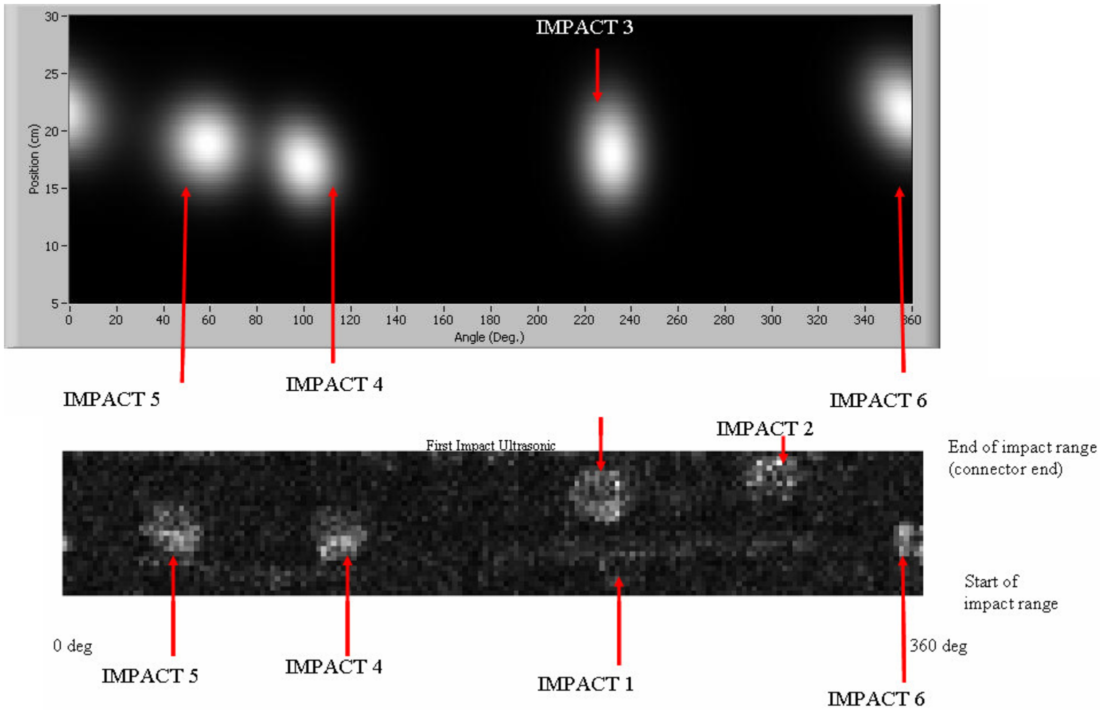

Figure 7. Ultrasonic (bottom) scans compare impact damage with strain imaging (top)

One of the impacts is shown below in Figure 8. The impact is plotted in 3-D and 2-D charts for better visualization.

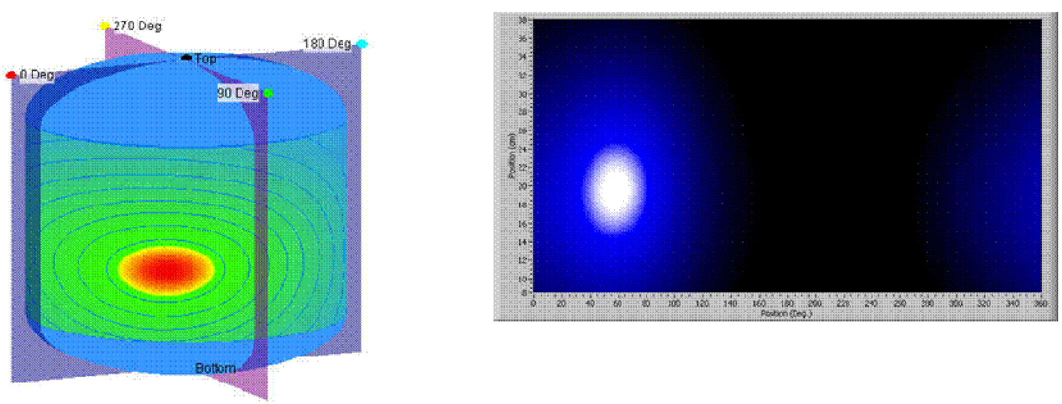

Figure 8. An impact is plotted in multiple charting formats to simplify damage visualization

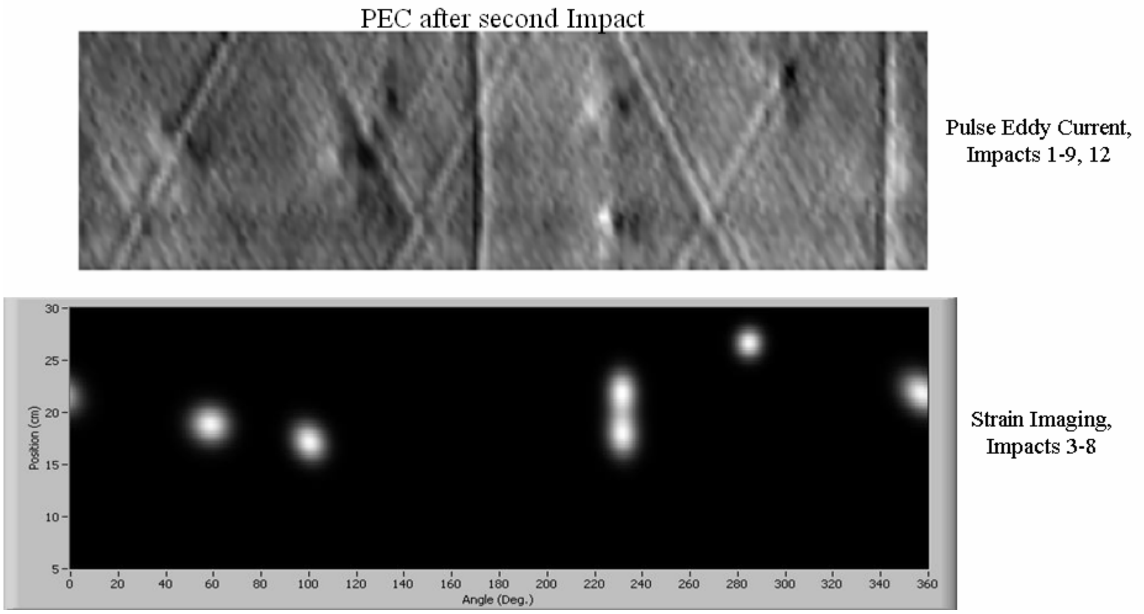

Figure 9. Strain imaging (bottom) compares damage with eddy current (top) NDE

Figure 9 shows a comparison of strain imaging to pulsed eddy current scans. The strain imaging scans were collected in approximately 1/10th the time of eddy current data.

In comparing the strain imaging data collected via fiber optic sensors with those of eddy current and ultrasonics, it can be determined that the information for those impacts presented coincides well among the three methods. Eddy current and ultrasonics hold a tradition of being among the reliable NDE methods, but strain imaging, on the basic level studied here, promises to be an effective and rapid alternative to non-destructive evaluation.

A commercial product that has recently been developed from this effort has the ability to log dynamic strain information while composite vessels undergo change, such as proof cycling or impacting.

Figures 10 and 11 display an example of a unit under a cyclic pressure test. Each display shows two 180-degree views of each composite. Fiber optic sensors may be surface-mounted or embedded, and offer the capability of predicting burst location.

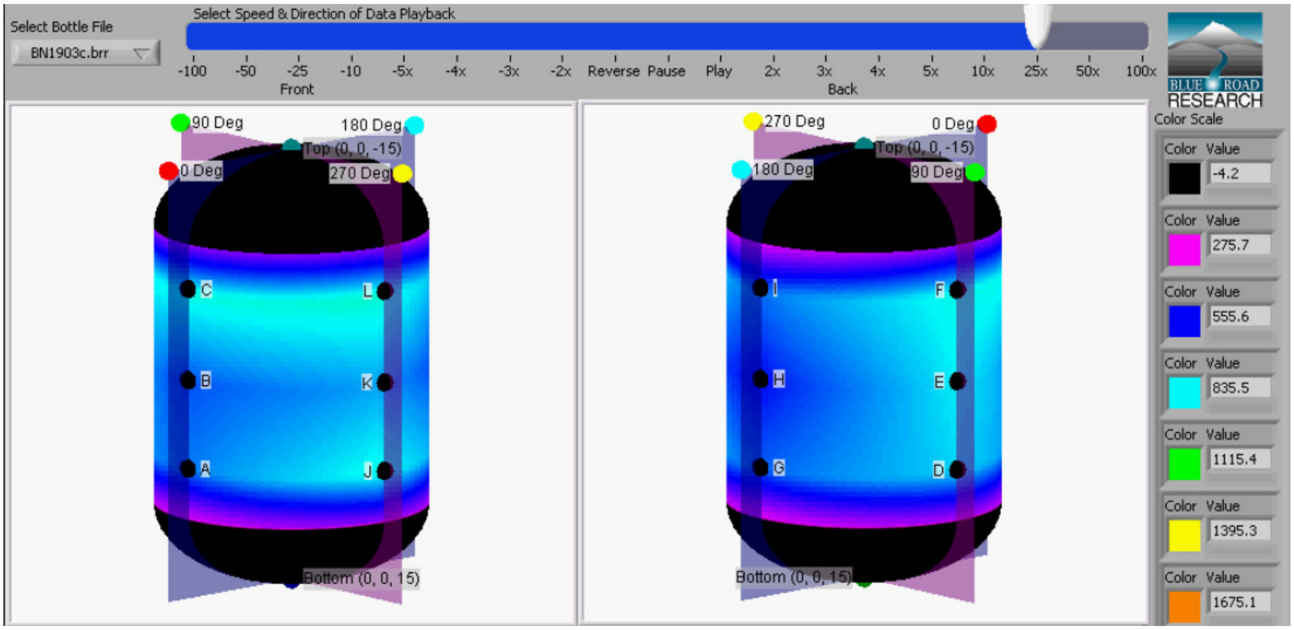

Figure 10. The strain fields on a composite vessel are monitored as the part nears 2000 psi

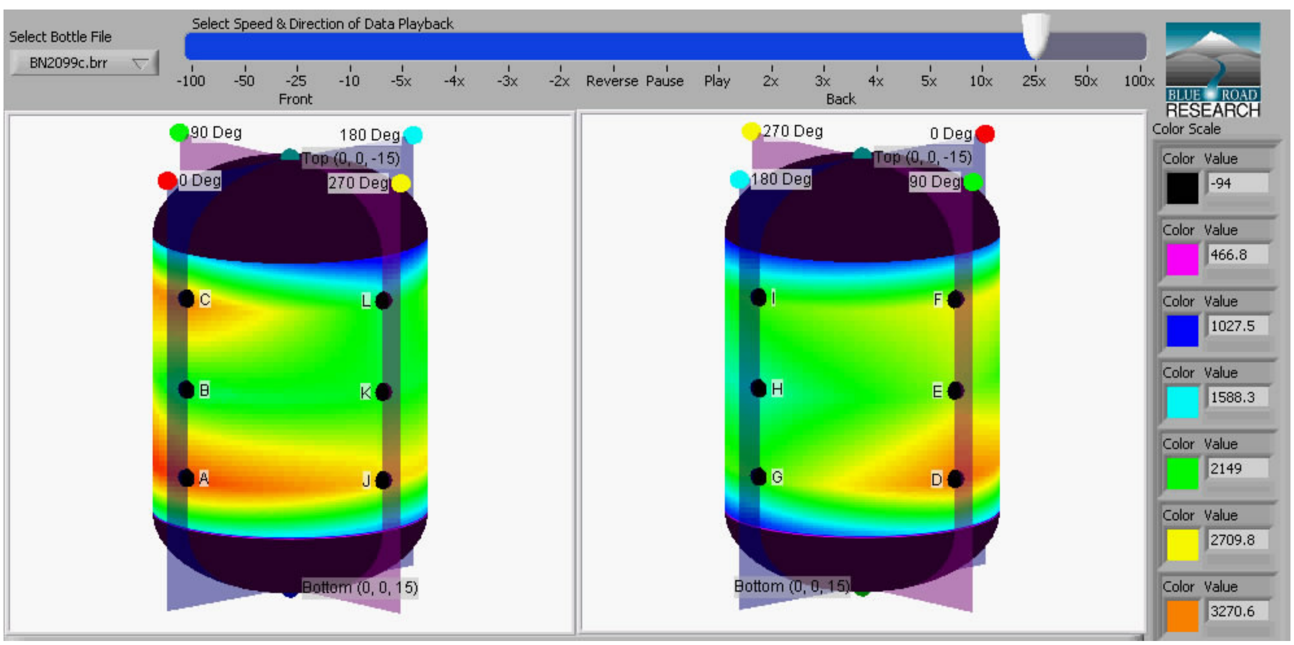

Figure 11. The strain fields on a composite vessel are monitored as the part is burst near 3000 psi

5.0 CONCLUSIONS

"Strain imaging" systems use fiber Bragg sensor arrays to locate and assess damage to composite parts. The results of these tests indicate that damage location and magnitude may be assessed with a fair degree of confidence, and that fiber optic strain imaging, although in its infancy, may be a viable non-destructive method to monitor and very rapidly locate strain field changes and/or damage.

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