EMBEDDED SENSOR BASED PROCESS AND HEALTH MONITORING SYSTEM OF A COMPOSITE BRIDGE DECK

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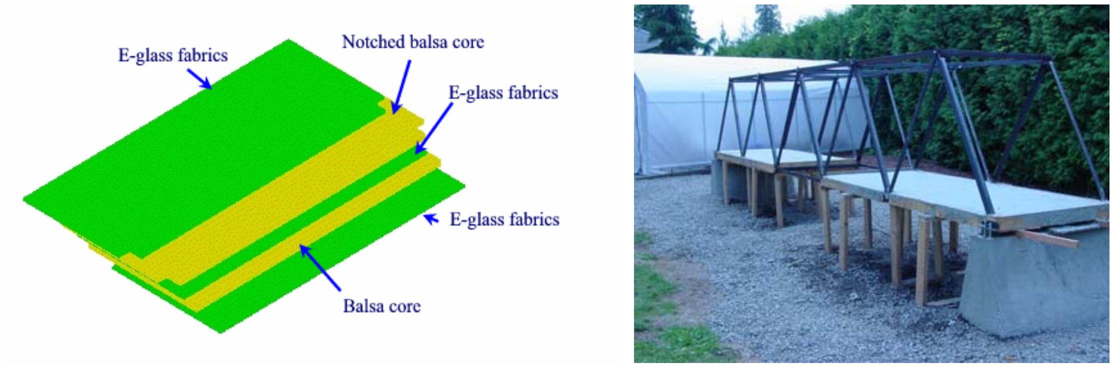
ABSTRACT

The paper investigates an embedded sensor system for composite bridge applications. It addresses the ingress/egress issues during a typical Vacuum-Assisted Resin Transfer Molding process and allows both process and in-service measurements. Three types of sensors have been integrated: 1)Fiber optic Bragg gratings are being used to measure strain applied during processing and in particular during cure as well as in-service monitoring of stiffness changes, 2) A Time Domain Reflectometry sensor system was used to measure cure and flow behavior during the VARTM process and 3) Embedded MEMS accelerometers were used in conjunction with vibration analysis for defect detection. Overall, the system allows monitoring of important process parameters and enables performance monitoring during the life of the component.

1. INTRODUCTION

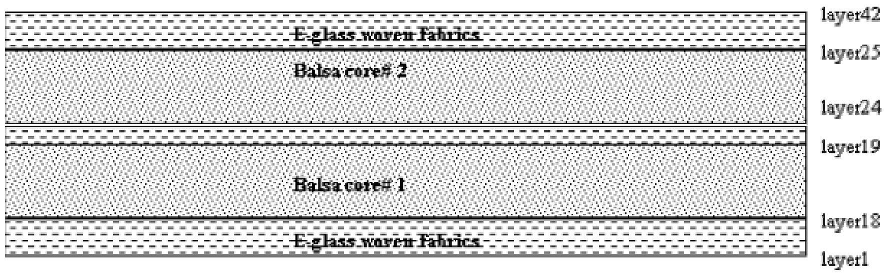
Composite materials are becoming increasingly used in civil engineering structures such as bridges due to lower lifetime costs and increased lifetime performance. Unfortunately, the lack of relevant monitoring data in composite bridges limits further implementations in the civil engineering arena. This paper discusses the development of a health monitoring system for a composite demonstration bridge in Oregon. The system consists of three types of embedded sensors: 1) single and multi-axis fiber optic Bragg gratings at several discrete locations, 2) Time Domain Reflectometry sensor to measure distributed strain and 3) MEMS based accelerometers for vibration testing. This article reviews the preparation and embedding of the sensors in the part, monitoring of the sensor response during production, non-destructive evaluation after manufacturing and mechanical testing in the laboratory prior to installation in the field. The bridge deck has been exposed to several defects including cut fiber tows and delaminations. This paper leads to a better understanding of critical fabrication and performance issues of integrated sensors, which could be used to optimize and reduce maintenance cycle times.

Two bridge decks have been fabricated in a sandwich construction to increase the stiffness at minimum weight of the slab (Figure 1a) using the Vacuum-Assisted Resin Transfer Molding approach. The decks are approximately 120cm by 60cm by 7.5cm in dimensions and bonded together with an adhesive joint replacing a concrete slab of a demonstration bridge located in Portland, Oregon (Figure 1b).

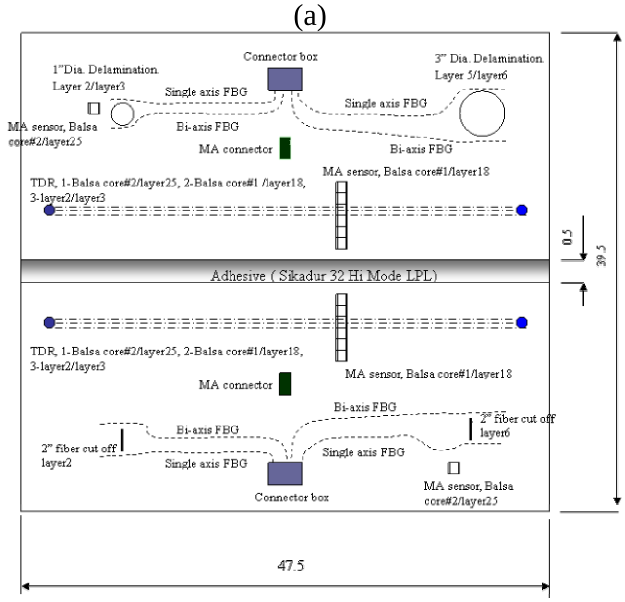


"**Fig. 1.** A sandwich construction of the composite deck is used to match the stiffness of the concrete slab replaced by the composite deck."

Two types of defects have been integrated into the sandwich: Two tows of the woven fabric were cut at separate locations as outlined in Figure 2, and two delaminations were created by integration of a large and a small Teflon film. During the lay-up of the preform and balsa core, 8 Bragg sensors, 6 TDR sensors and 15 MEMS sensors were integrated at various locations inside the part. All sensors were egressed during manufacturing through the vacuum bag on the bottom surface of the deck using connector blocks with integrated connectors to link the sensors to the various DAQ systems. A vinyl-ester resin system from DOW (Derakane Monemtum 411-350) was infused and the deck was hardened over a period of 24 hours.



(a)



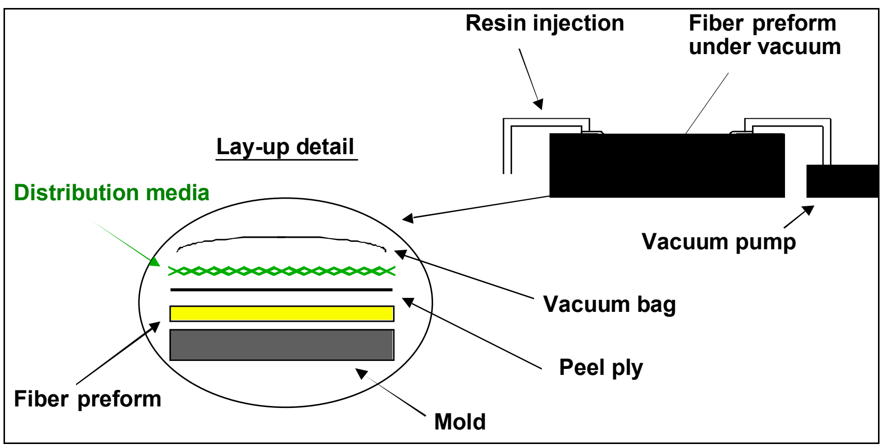
(b)

"**Fig. 2.** Map of the composite sandwich structure with defect and sensor locations."

The paper outlines the sensor response during manufacturing and during mechanical testing in 3-point bending mode. The MEMS accelerometers were used during a vibration test to evaluate shifts in frequencies and mode shapes. A novel damage detection technique using the vibration data has been applied and is compared to the embedded defect locations. Overall, the integrated sensors allow for repeatable and accurate measurement of strain and damage potentially resulting in a complete health-monitoring system for large-scale composite structures.

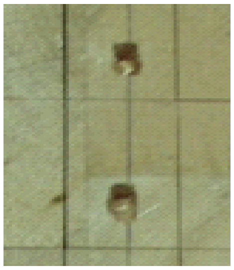
2. SENSOR INTEGRATION AND BRIDGE DECK FABRICATION

The Vacuum Assisted Resin Transfer Molding (VARTM) process has been used to fabricate the two bridge components. VARTM is a composites manufacturing process that involves the lay-up of dry reinforcing fibers in fabric, tape, or bulk form as a preform in a mold (Figure 3) and impregnation of the preform with liquid resin using negative pressure (i.e., vacuum), followed by cure and demolding. The advantages of the VARTM process include the use of a single-sided mold, which reduces tooling costs and other capital investments. In addition, large parts can be infused rapidly by applying a highly permeable distribution media as a surface layer into the preform. Upon opening of an inlet, the resin flows preferentially across the surface and simultaneously through the preform thickness. At the flow front, the surface leads the tool flow front. The lead length can be significant for thick preforms. In large structures, numerous inlets and vacuum ports are required and flow fronts become quite complex and are highly dependent on the sequence that inlets are opened.

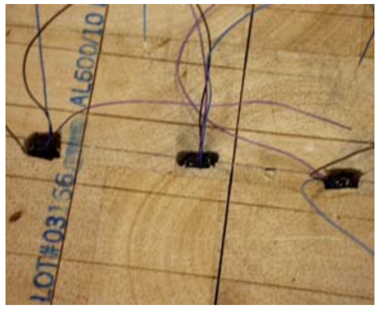


"**Fig. 3.** Schematic of the Vacuum Assisted Resin Transfer Molding Process"

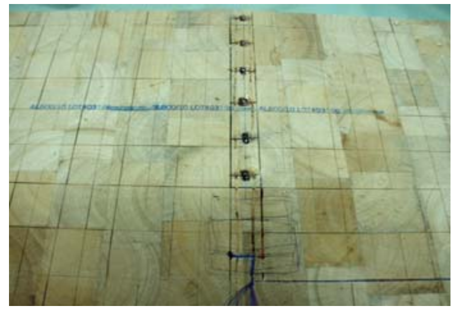
The core and reinforcement was precisely cut using a laser cutting machine. The MEMS sensors were integrated in the core surface to reduce any potential defect initiation due to the MEMS packaging. Holes were carefully drilled into the core and the MEMS accelerometers were placed by hand into the hole location (Figure 4). The MEMS sensors were permanently fixed using an epoxy adhesive. The wires were placed and bonded into the channels of the scored balsa wood. Then , the first layers of reinforcement was placed on the core material and the connecting wires were fed through the preform towards the connector system.



Holes for MEMS sensors



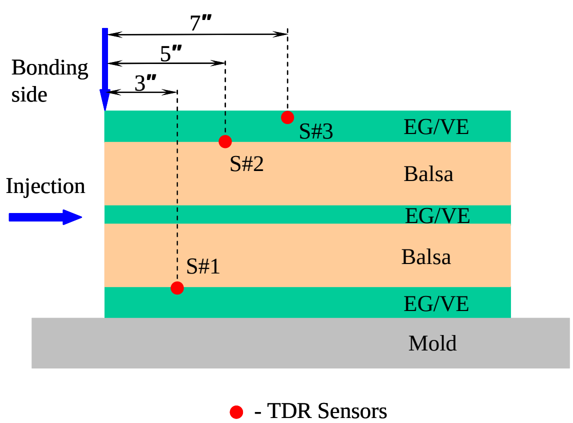
MEMS embedded in the holes and fixed with epoxy resin

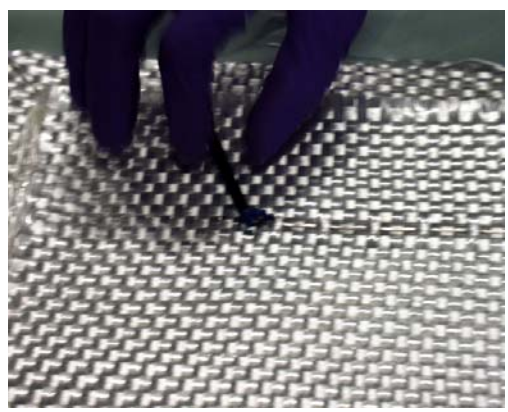


Wires were integrated inside scored balsa wood core

“**Fig. 4.** Integration of MEMS sensors into the core”

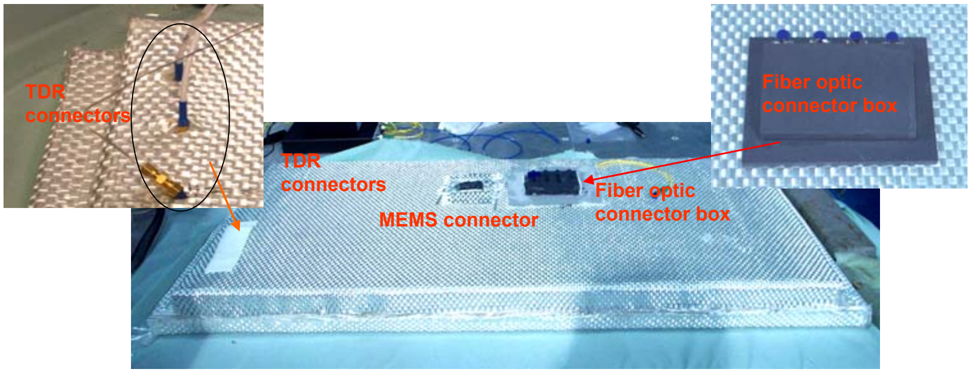
The TDR sensors were used to detect the flow, cure and any potential debonding at several interfaces in the composite during manufacturing. The benefit of the TDR system is that distributed parameters such as the resin arrival time on the complete sensor can be measured with an accuracy of up to 3mm. The transmission lines were placed by integrating two parallel conductive fibers (Aracon Kevlar from DuPont) into the woven fabric by replacing an existing glass tow bundle (Figure 4). Typically for a high-performance transmission line setup, highly conductive copper wires are utilized, but the use of a replacement fiber for the glass tow was to reduce any potential degradation of the final component.





“**Fig. 4.** Integration of TDR transmission line sensors”

Finally, single-axis and multi-axis Bragg gratings were placed on the fabric using F77 spray adhesive to complement the sensor setup. The sensors were all connected to multiple connection boxes integrated on the preform (Figure 5) ultimately becoming part of the composite component. A DB9 serial port connector was used for the MEMS devices and individually sealed using a barrier tape from any resin penetration. The process sensor (TDR and fiber optic) connectors were custom fabricated that they allowed sensor connectivity through the bagging of the preform. Sealing tape was applied around the flange of the connector block to attach the bag to the connectorization. Then, vacuum was applied and the sensor were checked.



"**Fig. 5.** Connectors allowed on-line measurements during resin infusion"

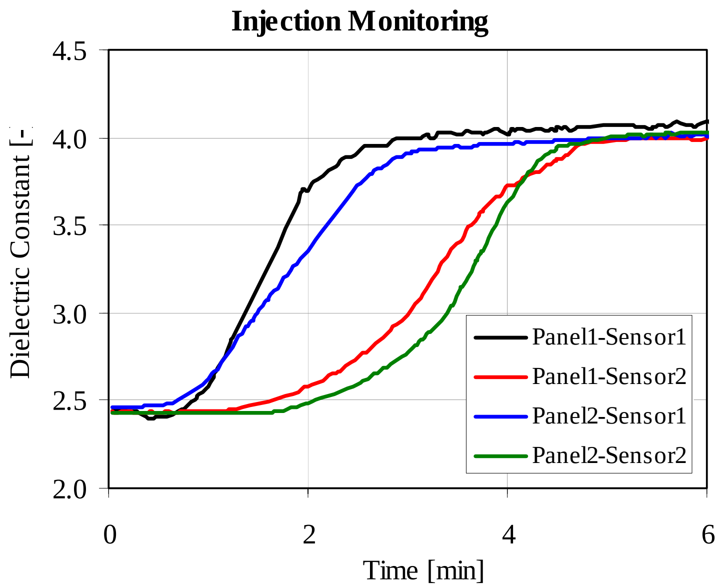
4. PROCESS MONITORING

TDR sensor 1 and 2 and fiber optic sensor 2,3 and 6,7 were monitored during manufacturing of the two decks due to the channel limitation of the acquisition hardware. The MEMS sensors measured only acceleration and were not monitored during resin infusion.

TDR sensors

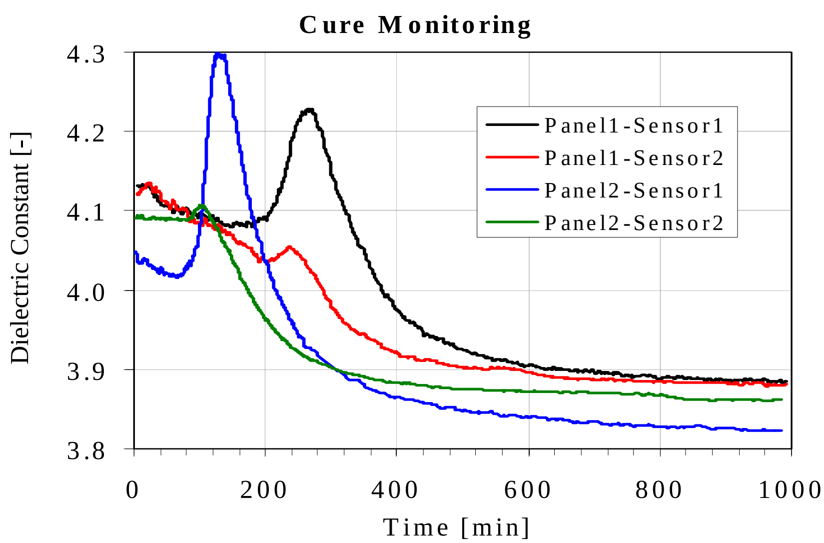
TDR is a method of sending the picosecond rise-time voltage step in a TL and detecting the voltage reflections resulting from the impedance discontinuities within the TL. TDR is extensively used in the testing of power lines, TV cables, computer networks, and in geological measurements . However, this technique is new in polymer composite applications. Dominauskas et al. have validated the parallel wire TDR sensor for the continuous resin flow measurement [1] and accurate cure measurement [2] comparable to FTIR and DSC during liquid composite molding. In these experiments an HP54750A (18GHz bandwidth) oscilloscope has been used as a sensor excitation and interrogation unit. It contains a TDR unit build in for high rise (35ps) EM step-pulse generation and data sampling. The oscilloscope has been connected to a computer through a GPIB card. During all experiments sensor signals were acquired with DAQ software written in LabVIEW.

Figure 6 shows the TDR data during the resin infusion of the two bridge decks for sensor 1 near the mold side and sensor 2 located near the surface. The distribution media placed on the surface results in a flow front which rapidly wets out the preform surface and then penetrates the thickness of the composite. Thus, arrival time of the resin is delayed in the lower layers. The TDR sensors clearly show this time delay of approximately 2 minutes between sensor 1 and sensor 2 for both infusions. In addition, the sensors were placed perpendicular to the flow direction, measuring the uniformity of the flow while it is filling the preform. A uniform flow would result in similar arrival along the complete width of the sensor and the TDR system would increase rapidly to the steady-state behavior. The slope decreases rapidly after less than two minutes for all sensors showing uniform fill of the preform. A slight increase of the wet-out time of the lower sensors can be attributed to variability in the through-thickness permeability of the reinforcement and due to flow variations induced by the scored balsa core.



"**Fig. 6.** TDR sensors are monitoring the resin arrival and through-thickness flow variation"

The TDR system also monitors the cure behavior of the resin after complete fill of the preform. During Panel 1 infusion an inhibitor was added to increase the gelation time to ensure full infusion of the preform. During Panel 2 fabrication the inhibitor was reduced by 80% decreasing the gelation time. Figure 7 shows the TDR sensor response during cure. The cure behavior of the two panels is dramatically different. A peak exothermic reaction is observed at 260 minutes for Part 1 and 130 minutes for Part 2. Nevertheless, the total dielectric change after full cure is identical for all 4 sensors showing uniform cure throughout the parts. It also can be seen that the surface sensor does measure a weaker exothermic reaction due to the heat loss on the surface reducing the overall temperatures in the upper layers.

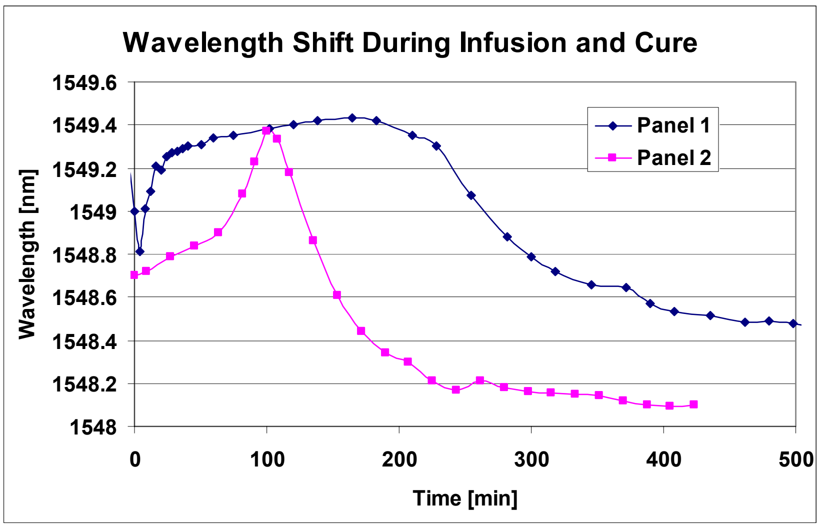


"**Fig. 7.** TDR sensors accurately measure cure variations during liquid molding"

Fiber optic sensors

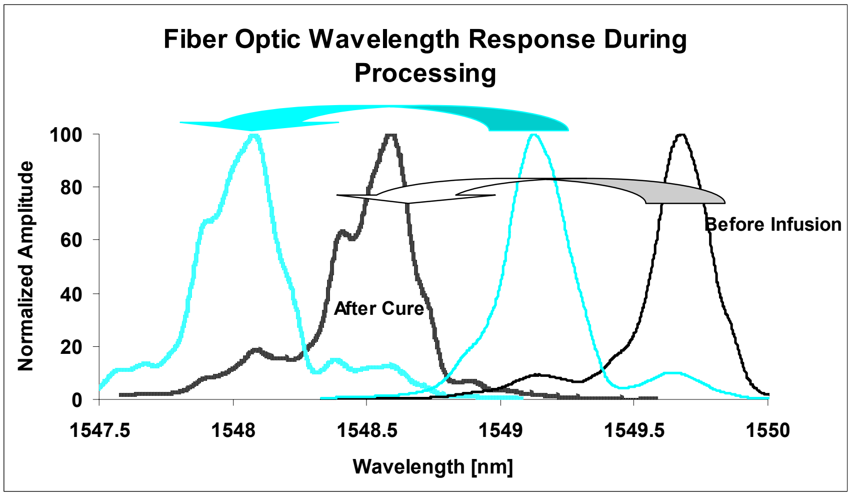
One birefringent fiber optic sensor response per panel was recorded every minute during the infusion and cure process. A birefringent optical fiber (such as commercially available

polarization preserving fiber) with a fiber grating written onto its core, is highly sensitive to transverse strain induced on the sensor. Two spectral reflection peaks correspond to the effective fiber gratings along each birefringent (polarization) axis which will move apart or together uniformly to provide a means to measure transverse strain [3,4]. Only one spectral peak was observed continuously due to equipment limitations and the second peak was measured after cure to calculate the transverse contribution to the wavelength shift.
Figure 8 shows the sensor response for Panel One and Two. Panel One sensor shows an initial wavelength shift from 1548.8nm to 1549.2nm after the resin reaches the sensor location. Here, the fiber optic may slide in the preform due to lubrication of the surrounding reinforcement and initial stresses applied during compaction. Slight increase in the wavelength response up to 220 minutes are a result of temperature variations and the start of gelation enabling bonding of the sensor to the composite as well as load transfer into the sensor. The wavelength starts to shift lower at similar time when the TDR sensor measures maximum conversion of the resin (>220minutes). Panel 2 sensor shows a similar behavior without the relaxation during resin wet-out and with a strong wavelength shift during gelation. A higher exothermic reaction also seen with the TDR sensor due to a reduced inhibitor concentration creates a higher temperature increase and residual stresses in the final part. The fiber optic feedback stays approximately constant after 500 minutes and 250 minutes indicating that the curing process and associated temperature changes are completed.



"**Fig. 8.** Fiber optic sensors measure cure and temperature variations during liquid molding processing"

Figure 9 shows the wavelength response of Panel 2 sensor before infusion and after cure. Two peaks can be seen for the two polarization axes. The overall wavelength shifts are similar, indicating a minimum transverse strain component. Nevertheless the shape of the sensor response has changed indicating a strain gradient applied on the sensor. This may be due to the fabric unit-cell geometry and resulting strain gradient from the residual stress component after cure. These strain gradients are small enough to limit the broadening effect and are not affecting the part performance.



"**Fig. 9.** Non-uniform strain distribution can be observed after cure"

5. MECHANICAL FATIGUE TESTING

A three-point fatigue load test has been set up after fabrication of the specimens (Figure 10). Panel 1 was loaded 2 million cycles at 600lb and Panel 2 was also fatigued two million cycles but at 8100lb. Before, during and after the mechanical tests, a vibration test and a fiber optic measurement was conducted to evaluate the part performance.

"**Fig. 10.** Bridge under mechanical fatigue test"

Vibration testing with MEMS accelerometers

Dynamic responses can be used to investigate structural irregularity of each panel as well as to check the structural integrity of two panels after installation in a field. Figure 11 shows pictures of the composite sandwich decks placed on two heavy steel tables simulating final installation and excitation of each grid points on the decks by an electronic instrumented impulse hammer during vibration testing. The number of total grid points is 96 (16 by 6 in the x- and y- directions) for each panel. The grid number starts from the left bottom corner (1 inch from the left edge and 1.5 inch from the bottom joint edge) and increase along the joint line (x-axis in the results). The grid step is 3 inch in both x- and y- directions. Structural responses and excitation signals were acquired by a FFT analyzer (OROS PC Pack) and modal parameters were obtained using a post-processing software (MEscopeVES).

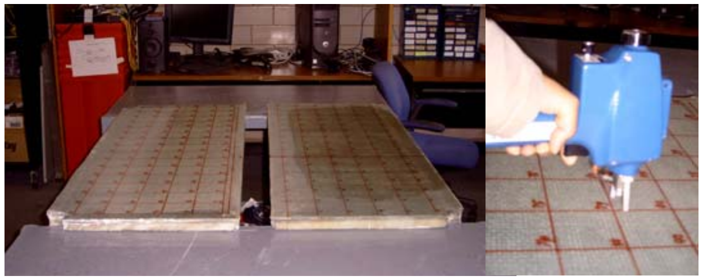
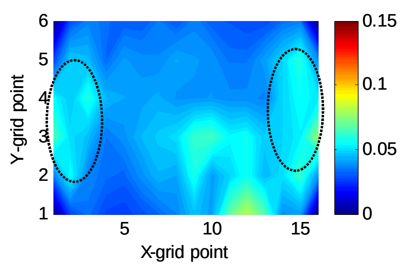
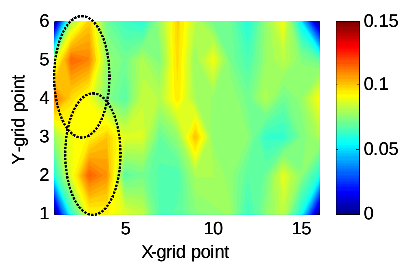


Fig. 11. Excitation of composite decks during vibration testing

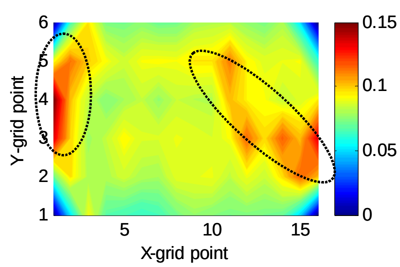
Since natural frequency data is very sensitive to the stiffness changes as well as the mass and geometry changes in structures, it can be used for QA/QC such as screening of the damaged parts by comparing to the baseline data. To increase sensitivity in damage detection, the two-dimensional gapped smoothing method (2D-GSM) was adopted to detect the spatial damage/structural irregularity indices [5]. The input data used was Operating Deflection Shape (ODS) data obtained from FRF. The 2-D GSM can identify structural variability in homogenous structures. Figure 12 shows the averaged structural irregularity indices (SII) and their differences from the bottom 4 MEMS sensors for the two parts before and after the fatigue tests. Effective frequency range was selected from 100 to 600Hz by taking the frequency region where the coherence functions were over 90%.



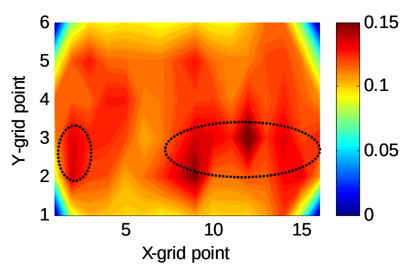
(a) Part 1 before fatigue test



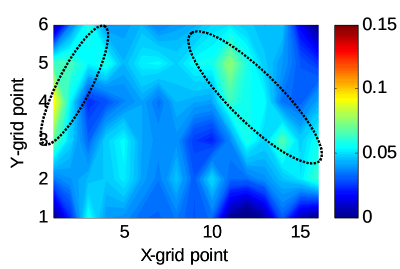
(b) Part 2 before fatigue test



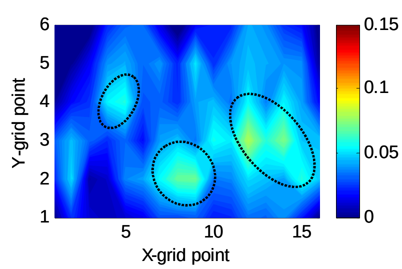
(c) Part 1 after fatigue test



(d) Part 2 after fatigue test



(e) Part 1 difference between (a) and (c)



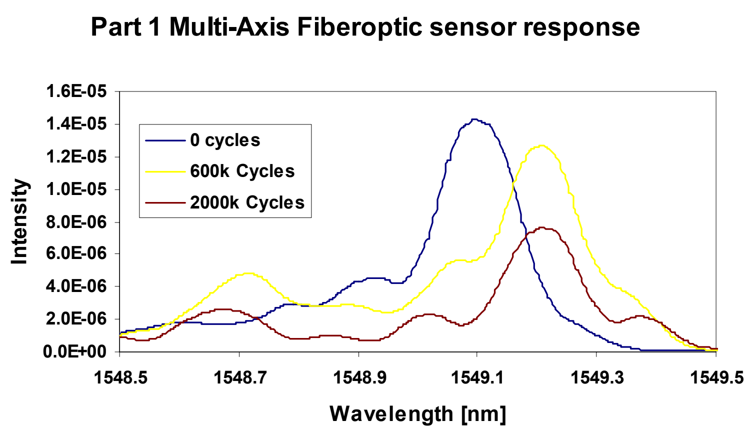
(f) Part 2 difference between (a) and (c)

Fig. 12. Averaged structural irregularity indices for each composite part

For both components the SII is fairly low after fabrication indicating uniform part properties with Part 2 having slightly higher SII and thus higher property variations. After the fatigue test both component show a doubling of the SII, indicating reduced and varying stiffness in both panels. The dotted circles show suspected damage areas in the Figures 12(a-d) and stiffness changes before and after the fatigue tests in the Figures 12(e-f). The left and right circles correspond to the location of the fiber-cuts in the case of the Part 1 (See figures 12(a) and 12(c)). The delaminations of Part 2 in the Layer5 and 6 could not be detected after fabrication but can be detected after the fatigue test as shown in Figure 12(d). In addition, the fiber optic connector block location is shown as an area with reduced stiffness (Figure f center circle) indicating probable debonding of the connector.

Fiber optic sensors

The fiber optic sensor response of two sensors embedded in Panel 1 and 2 are shown in Figure 13 under full loading. The sensor response in all Panel 2 sensors reduced significantly compared to Panel 1 sensors. This may be due to the higher loading conditions during Panel 2 fatigue testing resulting in debonding of the connector block as indicated in the vibration test or due to losses in the fiber optic connections in the actual component. The dual-axis sensor indicates are higher change of the wavelength signal compared to the zero cycle baseline even under reduced fatigue loading. The sensor is more sensitive to transverse strain and thus indicates a higher change in the transverse stiffness of the panel compared to the fairly stable single-axis sensor response. Overall, the wavelength shifts do not indicate any significant strain changes in both panels and thus no real damage propagation of the defects affecting the overall stiffness of the bridge decks.



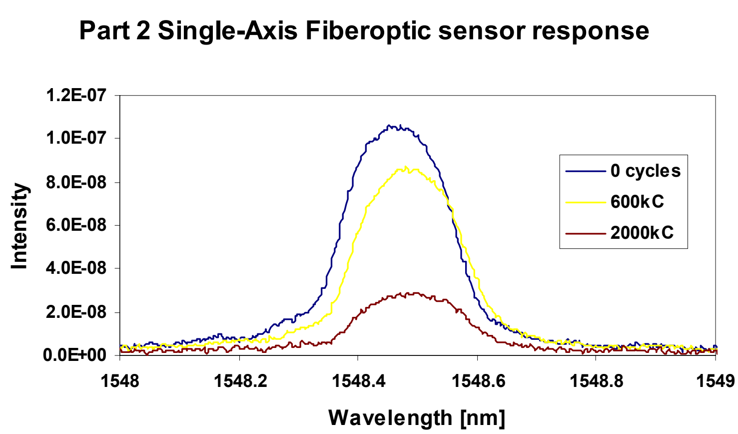


Fig. 13. Fiber optic response after fatigue testing of Panel 1 and 2

6. CONCLUSIONS

Two bridge decks with multiple embedded sensors have been fabricated using the VARTM process. The sensors survived the process and measures both processing and in-service conditions. The TDR sensor was able to detect the uniform infusion of the resin into the bridge component as well the degree of cure differences in Panel 1 and 2. The fiber optic sensors were used to measure the internal strain developed during cure, detected the onset of the exothermic reaction and allowed qualitative measurements of the end of cure. Vibration analysis using the 2-D GSM method identified some features near the fiber-cuts and delamination areas in Parts 1 and 2, respectively. After the fatigue test was completed the method also indicated a uniform stiffness reduction of the decks. The dual axis fiber optic sensors measured a small change in transverse stiffness after fatigue, but no indication of in-plane reduction was measured using the single-axis fiber optic system. Nevertheless, after increased fatigue loading the fiber optic connector blocks seemed to debond from the structure resulting in a loss or reduction of the sensor signals. Overall, the system is a first approach to have an integrated sensor system capable of measuring both process and in-service conditions. Connectors from the sensor in the part to the outside DAQ system have been developed but have to be improved to allow for robust in-service conditioning monitoring.

ACKNOWLEDGEMENTS

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