THE ◆ BRIDGE

The Magazine of IEEE-Eta Kappa Nu

Lasers, Optics, and Photonics

Laser Safety for Electrical Engineers ◆

Quantum Optics for the 21st Century Electrical Engineer ◆

Smart Bridges using Fiber Optic Sensors ◆

A Brief History of High-Power Semiconductor Lasers ◆

March 2014 Vol. 110 / No. 1

Smart Bridges using Fiber Optic Sensors

Permanent Monitoring for Bridges

By Steve E. Watkins Gamma Theta Chapter

I. INTRODUCTION

Bridges represent an enormous infrastructure investment across the nation. Maintenance, repair, upgrade, and replacement of these structures are ongoing expenses. The management of these resources is particularly acute today. Many structures, especially those built in the first half of the twentieth century, are at or near the end of their service life and are carrying unanticipated traffic loads. [1] The possibilities of vehicular accidents, earthquakes, and terrorism add to the management difficulty. Engineers are turning to improved materials and techniques in conjunction with permanent instrumentation to decrease costs and increase service life in both old and new structures.

Effective structural instrumentation can be based around fiber optic systems. Initially a spin-off of optical telecommunication developments, fiber optic sensing technology has advanced and matured. [2] Many types of sensors have been developed with various characteristics. Common approaches use interferometry, Bragg gratings, scattering mechanisms, and fluorescence. [3] They all benefit from the low profile and low loss of optical fiber. The sensors can be placed in otherwise difficult locations and the information sent over long lengths of fiber. The result is a permanent, flexible capability for nondestructive testing.

Advanced instrumentation for civil engineering structures must address a wide range of interdisciplinary issues. Effective implementation requires the integration of sensor technology, advanced signal processing techniques, materials science, and structural mechanics. Also, field demonstrations are critical to developing practical protocols and to establishing confidence in long-term system performance. This article describes a smart structures approach to bridge improvements, introduces key technologies used in fiber-optic-based health monitoring systems, and gives an overview of three instrumented bridges. A sensing system in the first example bridge monitors general performance and health, the system in the second bridge interrogates the behavior of a major structural repair, and the systems in the third bridge verifies the performance of a bridge retrofit.

II. SMART BRIDGES

A smart structure is one in which integral sensors add control or interpretation attributes to a structure. In addition to the basic load bearing function, the structure will intelligently adjust or interpret its state with respect to environmental conditions similar to biological systems. [4] Figure 1 shows a typical system for fiber-optic-based smart sensing. The physical condition being measured, i.e. the measurand, interacts with the sensor to create an optical signal. The signal is transmitted over the optical fiber to the processing support instrumentation for demodulation and analysis. The resulting information can be used to control some physical aspect of the structure or to evaluate some management aspect of the structure. For instance, actuators could damp unwanted vibrations or managers could be warned of deterioration. With a smart system, an automated, fast response is possible and internal conditions that may be difficult to assess otherwise are detected.

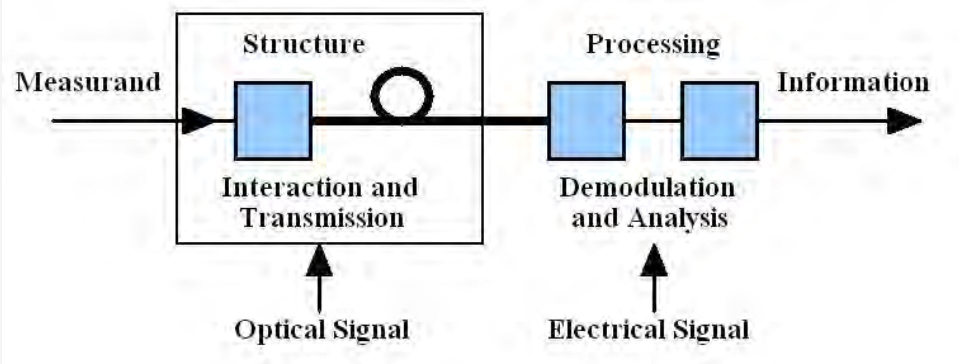

Fig. 1 Fiber-optic-based system for a smart structure.

The primary measurement needs for bridges involve management rather than control. Although, concerns such as damage mitigation during earthquakes would be addressed by a smart sensing and control system. Management concerns include [4]

- Verifying that the construction and the load distribution meets design expectations,
- Characterizing the extent and location of accidental damage,
- Determining the safe load posting after repair or upgrade, and
- Monitoring the remaining service life.

These functions are traditionally handled through conservative design, qualitative inspections, statistical analysis, risk-intolerant maintenance, and one-time testing. The weaknesses of the traditional approach, in addition to cost, are the difficulty of quantitative assessment and the slow use of innovations. Cost/performance optimization, new techniques, and new materials, such as fiber-reinforced-polymer (FRP) composites, cannot achieve widespread use without an assurance of safety and performance. Reliable monitoring can encourage the early use of innovations by decreasing risk and increasing confidence.

In a smart bridge, the relationships among component technologies must be understood. First, an embedded or attached sensor must be compatible with the host material. For instance, the performance of fiber optic sensors in concrete is a function of the fiber coating. [5] Similar considerations exist for metal and FRP composite materials. Second, the system analysis may be facilitated by different sensing architectures. Choices include detection of the measurand field at a single point, for an array of points, and along an integrated path. [5] Point detection resolves spatial variations or localized effects such as midspan strain and integrated sensing provides a view of global characteristics such as average temperature. Other interdisciplinary challenges are in the areas of constructability, system identification, data acquisition, information technologies, and field studies. [6]

III. FIBER-OPTIC STRAIN SENSOR SYSTEMS

The sensing process transforms a physical quantity into a useable signal. The characteristics of a fiber-optic sensor system are determined by the physical interaction, the sensor design, the signal interpretation, and the smart structures integration. The use of optical fiber as part of the system will influence most or all of these factors. In addition, one or more of these factors may recommend optical signals and optical fiber systems over other alternatives in a given application.

A key parameter of interest in structural applications is the measurand of strain. The dimensional deformation due to load, temperature, or other variables can be related to various performance, health, and safety issues. An optical strain sensor must encode this physical change on some aspect of the light wave. Phase changes and interferometric detection approaches are especially useful since they can resolve displacements and deformations on the order of an optical wavelength. Effective approaches that are based on interference include fiber-based Fabry-Perot interferometers and Bragg gratings. They can make point measurements and do not depend on a reference arm as do Mach-Zehnder interferometers. An alternate approach is Rayleigh scattering in the optical fiber. Information gained from Rayleigh scatter sensors provide distributed strain measurements along the optical fiber.

FIBER OPTIC SENSORS

The sensor interaction and design can be classified as extrinsic or intrinsic. An extrinsic sensor is one in which the sensing occurs outside of the fiber and the role of the fiber is only to transmit the data optically. An intrinsic sensor is one in which the sensing interaction occurs within the fiber itself. Three successful sensor types are Fabry-Perot sensors, Bragg grating sensors, and Rayleigh scattering sensors. The Fabry-Perot type can be extrinsic or intrinsic, while the Bragg grating and Rayleigh scattering types are intrinsic. For intrinsic and extrinsic sensors, the gage or interaction length tends to be long and short, respectively. Strain is integrated over this length. Hence, a short gage length is best for point measurements. A long interaction length can give integrated measurements.

An extrinsic Fabry-Perot fiber-based sensor is shown in Figure 2(a) [3]. An extrinsic cavity can be formed by cutting the fiber and separating the ends. (An intrinsic cavity can be formed by incorporating partially reflecting interfaces along the fiber.) Multiple-reflections occur between the two fiber end-faces. The total reflected interference signal varies in response to changes in the cavity spacing. A capillary tube is bonded to the two fibers and maintains the alignment of their end faces. The tube is bonded to a material under strain. As the material and attached tube is strained, the optical phase between reflections changes and returned signal varies periodically.

The extrinsic Fabry-Perot interferometric (EFPI) sensor has several desirable features. A single-ended sensor is given by use of the reflected signal (as shown), although the strain information is also in the transmitted signal. The sensor has little transverse coupling and effectively evaluates the axial component of strain. The reflection coefficient of the end-faces can be easily modified with a coating to enhance the return signal. The gage length is determined by the length of the capillary tube rather than the cavity. The tube length is typically limited to less than a centimeter. The fiber transmission path may be long, but the reflected signal is insensitive to environmental changes that could cause noise in other sensor systems. This sensor design can also measure temperature if attached to a material with a known thermal expansion characteristic.

A Bragg grating sensor is shown in Figure 2(b). Periodic index variations are incorporated along a length of the fiber. This Bragg grating structure will strongly reflect light of a particular wavelength, while other wavelengths have negligible reflections. As the interaction length is subject to strain, the period of the grating is modified and the reflect wavelength is directly modulated. Multiple gratings of different periods may be placed in the same optical fiber. A broadband optical input can excite all sensors along the fiber each of which reflects at a different center wavelength. Thereby, a single fiber can be used to

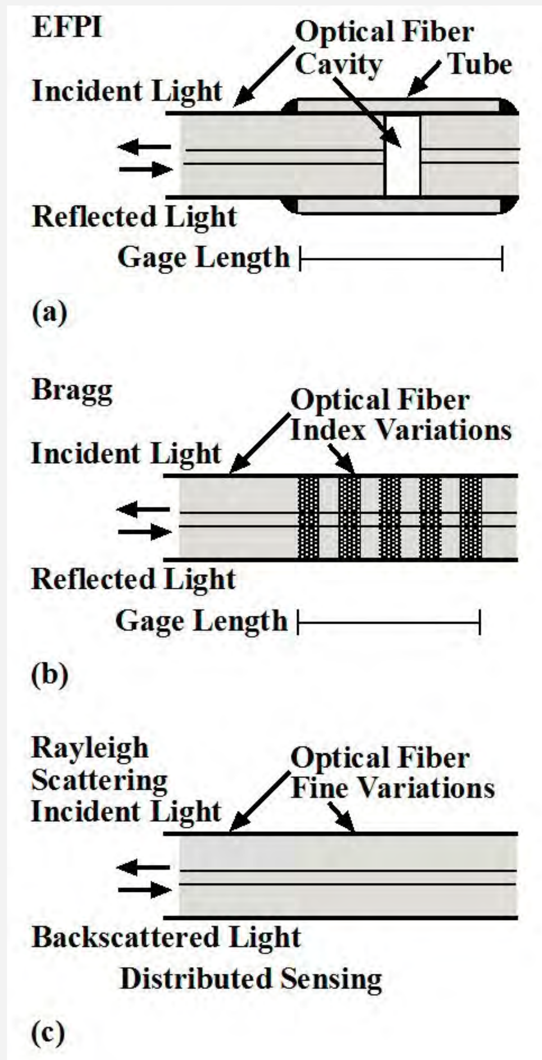

Fig. 2 Sensor Types: (a) Extrinsic Fabry-Perot interferometric (EFPI) sensor with an external air-gap cavity between fiber end-faces. (b) Bragg fiber optic sensor with periodic index variations within the fiber. (c) Rayleigh scattering sensor with distributed sensing capability.

perform multiple measurements as long as the spectral reflections can be resolved.

A Rayleigh scattering sensor is shown in Figure 2(c). This intrinsic sensor is based upon the local refractive index variations in the fiber glass and can measure distributed strain or temperature simultaneously along the fiber. These local variations are stable and produce a weak Rayleigh backscattered signature signal. As any point along the fiber is stretched or compressed due to load or temperature, the signature in the backscatter can be resolved and correlated to the strain or temperature. The spatial resolution of the measured depends on the capability of the data processing.

SENSOR DEMODULATION AND SMART STRUCTURE INTEGRATION

Interpretation of the signal has a number of levels. The most basic signal processing is to demodulate a strain value from a single sensor. More advanced signal processing may demodulate strain from a network of sensors and perform advanced analysis. Networking can be done simultaneously with dedicated instrumentation for each sensor or sequentially with a single instrument that connects to each sensor in turn. Also, optical wavelength-division multiplexing may be performed at the cost of wavelength-sensitive fiber couplers and connections. Advanced analysis depends on the application needs.

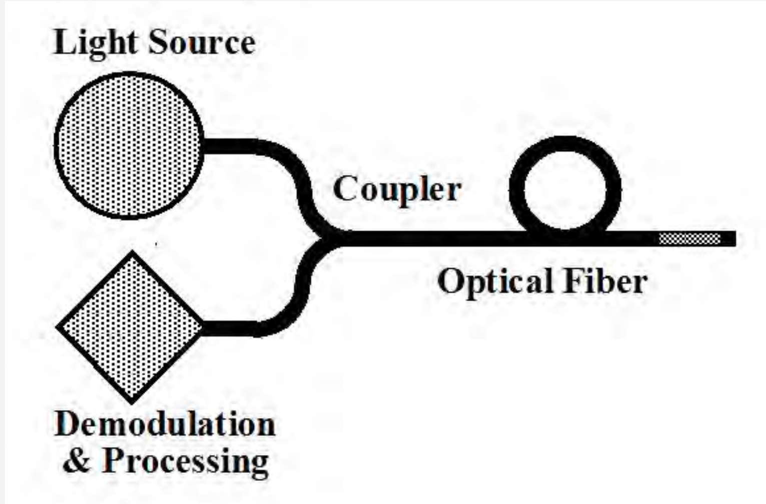

Fig. 3 Typical support instrumentation for fiber-optic sensor systems.

Sensor demodulation depends on the sensor type and measurement needs. The typical components of these sensor support systems are illustrated in Figure 3. An optical source such as a laser diode or an LED excites the system, the sensing interaction in the optical fiber modulates a return signal, and the processing instrument converts the optical information into electrical form.

The application imposes diverse criteria on the sensing solution. The incorporation of the sensor system must not adversely affect the structure, the environment must not significantly degrade the signal, the demodulated information must be readily available, and the system cost must be less than alternative methods of inspection. The use of optical fiber addresses the first two integration concerns. Fiber advantages include small size, low weight, low loss, environmental ruggedness (e.g. to corrosion, temperature, and vibration), and immunity to electrical noise. Also, in laboratory and field tests, fiber sensors have been shown to function during and after catastrophic failure in reinforced concrete structures. The final two integration concerns must be satisfied primarily by the support instrumentation. Performance and cost must be balanced. For instance, the number and placement of sensors, the testing schedule, and the complexity of signal analysis are considerations.

Artificial neural networks are often coupled with fiber optic sensing systems due to their capabilities in pattern recognition, classification, and prediction. These parallel processing architectures have been shown to provide advanced processing and analysis functions accurately and robustly. The implementation of neural networks in smart structures is an active research area.

IV. BRIDGE IMPLEMENTATIONS

Permanent fiber-optic-based instrumentation in bridges provides capability for performance monitoring, health indicators, and warning functions. The following examples use EFPI strain sensor networks for long-term quantitative assessments. The on-site physical components are the sensors and a patch box. Data acquisition and processing equipment for the sensors are brought to the sites during tests. Initial testing gives base-line data for interpretation. Periodic measurements can be taken with little setup or disruption of traffic.

MISSOURI S&T SMART COMPOSITE BRIDGE

A nine-meter-span bridge and associated test articles were designed, analyzed, manufactured, and tested as a comprehensive research project. The structures are modular assemblies of fiber-reinforced-polymer (FRP) composite tubes. These pultruded square-tubes have standard 76-mm square cross-section and are reinforced with either carbon or glass fibers. Seven alternating layers of tubes form structural I-beam elements within the bridge. The approach results in an extended lifetime due to all-FRP construction and relative economy due to standard off-the-shelf tube elements. The strength and deflection of the bridge assembly was tailored by the balanced use of higher-cost, higher-stiffness carbon tubes and lower-cost lower-stiffness glass tubes. Although rated for highway loads, the prototype structure, the first all-FRP bridge in Missouri, is part of a pedestrian walkway located on the Missouri University of Science and Technology campus. The development was a cooperative development effort that was led by the university with industry and government partners (see reference [8] for details and partners). The project goals were to develop a novel FRP-composite approach for extended life-time highway bridges and to implement a permanent performance and health monitoring system as a long-term technological demonstration for industry and a field laboratory for engineering students.

The fiber-optic strain sensing system was incorporated as a primary feature of the bridge. Research issues included installation protocols, sensor accuracy, and sensor lifetime. The measurement objectives of the fiber optic instrumentation were:

- To monitor flexure strain during destructive laboratory tests of tube assemblies,
- To monitor flexure strain during near-rating load tests of the installed bridge,
- To record strain characteristics during dynamic and static load tests, and
- To provide a capability for field remote monitoring developments.

Sensors were embedded to monitor internal strain in the main load carrying layers, i.e. the top and bottom layers of carbon-FRP tubes. (1) A four-layer test article and a full-scale seven-layer structural I-beam element were loaded past failure to verify design strength and investigate failure characteristics. Fiber optic sensors along with companion electrical resistance strain gages and linear-variable-differential-transformers (LVDTs) monitored the tests. (2) The bridge was field loaded to near its design rating using the weighted dump truck shown in Figure 4. These tests are periodically repeated to document long-term bridge behavior. (3) The strain signals are analyzed for various loading conditions during academic laboratory exercises. (4) The instrumented bridge is a test-bed for remote monitoring developments.

Fig. 4 Missouri S&T Smart Composite Bridge during a near-rating load test with a weighted truck.

Fiber optic sensors were incorporated within the structure during assembly as shown in Figure 5. They were placed in small grooves on the tube surfaces to provide protection from impacts during assembly steps and to move the sensors away from the interface between tubes. The strain measurements by each sensor should be associated with only one tube and not complicated by possible interface effects. The sensors were tacked in place after cleaning the groove with acetone. The sensor leads were routed toward the end of the bridge along the interface between tubes. Then, the sensors and leads were covered with epoxy during the surface preparation of the next layer of tubes. A fiber optic sensor patch box is located at one corner of the bridge deck. The ends of the leads were carried inside transverse tubes to the sensor patch box.

SENSOR PERFORMANCE FOR SMART COMPOSITE BRIDGE

The EFPI sensor network performed well in the Smart Composite Bridge project with respect to monitoring of failure events, to agreement with other sensor measurements, and to sensitivity for small loads. [8] For a four-layer test article, the sensors survived the entire load test including catastrophic failure. For an I-beam test article, the sensors displayed excellent correlation to co-located electrical resistance gages. For the bridge tests, the fiber optic sensors differed from a finite element model prediction less than four percent (worst case). Also, the sensors recorded elastic behavior for loadings below the design threshold. Figure 6 shows the mid-span strain on the top layer as a Ford F150 truck drives across the bridge. The truck had a front axle weight that was 8.4 percent of the highway load rating of 142.4 kN (32,000 lbs.). Note that the unloaded strains before and after the test are the same. The maximum compressive strain occurred when the truck's center of mass was at mid-span. Load tests with heavier trucks, cf. Figure 3, produced strain measurements that fit a linear load-verses-strain relationship. Hence, the internal fiber optic sensors verified the elastic behavior expected for normal loading of the bridge.

Fig. 5 Fiber optic sensors are embedded in the bottom layer of the Smart Composite Bridge during assembly. The full-scale I-beam test article is shown in the background.

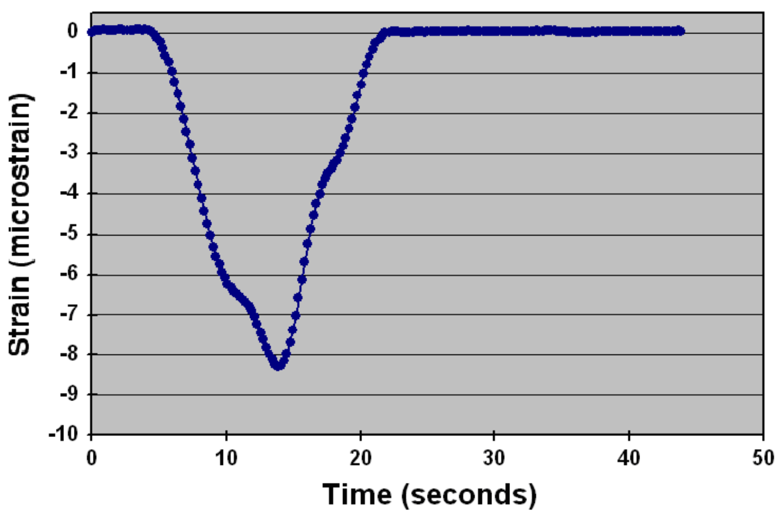

Fig. 6 Compressive strain in the top layer of the Smart Composite Bridge for a moving pickup truck. The front-axle load was 8.4 percent of the design load rating.

INTERSTATE OVERPASS REPAIR

A highway overpass on Interstate 44 in south-central Missouri was repaired following a major accident. The bridge is a reinforced concrete structure that is part of the Missouri Department of Transportation (MODOT) system. A vehicular impact severely damaged both piers in the median and the associated pier cap structure. The repair consisted of replacing the damaged piers, reconstructing the pier cap, injecting cracks with epoxy, and reinforcing the concrete with carbon-fiber-reinforced-polymer (carbon-FRP) composite sheets. A research aspect of the repair was the field demonstration of the ability of the carbon-FRP confinement to increase load carrying capacity. An effective repair was obviously less expensive and less disruptive than a total replacement of the bridge. However, there were concerns about possible degradation of the repair over time. Conventional testing and inspections involve considerable setup and time. The bridge was instrumented with fiber-optic sensors as a cost-effective means of confirming safety and an appropriate load rating.

The in-situ system was designed to monitor possible degradation of the reconstructed pier cap and the carbon-FRP patch. Figure 7 is a schematic of the repaired piers, pier cap, and carbon-FRP reinforcement. The three objectives of the fiber optic instrumentation were:

- To measure potential propagation of cracks in the pier cap,
- To monitor potential delamination of the carbon-FRP reinforcement, and
- To record a signature strain during load tests.

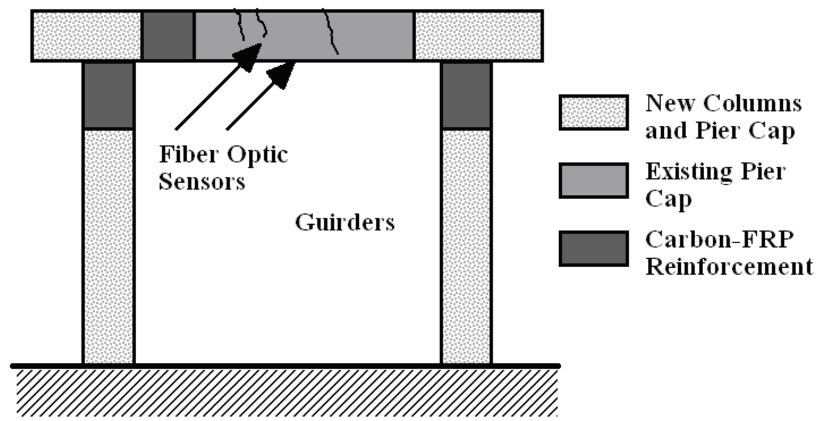

Fig. 7 Schematic of the piers and pier cap of an instrumented concrete bridge. Fiber optics sensors monitor cracks in concrete and delamination of FRP reinforcement.

Fig. 8 Fiber optic sensors installed on the reconstructed pier cap of an I-44 Overpass. The crack sensors and the patch box are visible on the face and the delamination sensors are placed on the blue reinforcing sheet on the bottom.

All sensors were applied to the pier cap as shown in Figure 8. (1) Three major cracks were present in the pier cap. A fiber optic sensor was attached at the base of each crack. Any further propagation of these cracks will produce a major change in the strain signal. (2) A sheet of reinforcement was placed on the bottom of the pier cap where it would experience maximum flexure strain. A circular bubble of diameter 12-cm was incorporated in the sheet. This intentional delamination reduces the effectiveness of the reinforcement. Sensors were surface-mounted on the delamination and at the edge to detect any spreading of the delamination. (3) The overall strain characteristics from all five sensors during a standard load test are an indication of the structural health. Changes from this signature could indicate a reduction in the bridge's load capacity.

The sensor installation consisted of preparing the surface and of routing the optical fiber to the patch box. The sensors were attached with epoxy and the fiber leads tacked in place. Sensors and fibers were covered with caulking for extra environmental protection. Also, the sensors mounted to the concrete were placed in small grooves to provide protection from impacts during testing. A sealed patch box was located on the pier cap to limit general access.

STATE HIGHWAY BRIDGE REHABILITATION

A three-bay bridge that serves a rural two-lane highway in Missouri was showing evidence of decay and was the object of a research collaboration between the Missouri University of Science and Technology and the Missouri Department of Transportation (MODOT). [9] The structure was 49 years old at the time of rehabilitation. This reinforced-concrete structure was strengthened by conventional repair using new steel rebar and concrete patches and by advanced techniques involving fiber-reinforced-polymer (FRP) composite sheets. The rehabilitation upgraded the bridge rating for higher traffic loads and extended the lifetime of the bridge. Fiber optic EFPI sensors were installed on the steel rebar and in the FRP wraps at various locations in the bridge deck and girders. Electrical strain gages were co-located with selected fiber-optic sensors to obtain a field comparison of performance.

Fig. 9 Fiber optic sensors and patch box installed on the rehabilitated highway bridge. Sensors monitored both the bridge deck and girders.

Figure 9 shows the underside of the bridge after installation with some of the fiber runs and the fiber patch box visible. The fiber runs were placed in grooves of the concrete and sealed to provide protection from weather and vandalism. The three objectives of the instrumentation were:

- To measure load-induced strain characteristics during dynamic and static testing,
- To correlate experimental measurements and theoretical modeling (including fiber optic sensors, electrical strain gages, and finite element analysis), and
- To monitor performance changes over time.

A comprehensive set of strain measurements was recorded both one year after installation and two years after installation. Since the bridge was subject to traffic loadings that were not recommended for the original design, the field performance of the rehabilitation had to be verified for a new load posting. The testing confirmed that the bridge was stiffer than before strengthening. The performance of the sensor network over time was observed. The fiber optic and electrical resistance gages showed general agreement in the field environment. However, the fiber optic sensors exhibited less noise and better longevity. No fiber optic sensors failed during the two years of service, but multiple electrical gages failed. The sensitivity of the fiber optic instrumentation allows greater in-situ assessment of structural performance and insight into structural changes over time (or due to damage events).

V. SUMMARY

Smart bridges are possible in which structural, geometric, environmental, and health characteristics are evaluated with permanent sensing instrumentation. Cost/performance optimization, new techniques, and new materials can be managed with greater safety and assured performance. This interdisciplinary field addresses critical needs for maintenance, repair, upgrade, and replacement of structurally deficient or functionally obsolete bridges. Fiber-optic-based instrumentation is particularly well suited for civil engineering applications. Measurements are possible at hard-to-access locations and the information can be transmitted over long lengths of fiber. The optical sensors do not perturb the structure and can handle the environmental extremes while providing reliable, high-resolution information.

ACKNOWLEGEMENTS

This article is a revision of my earlier article of the same title that appeared in the *IEEE Instrumentation & Measurements* Magazine with the following citation and is reprinted with permission. © 2013 IEEE.
S. E. Watkins, "Smart Bridges using Fiber Optic Sensors," *IEEE Instrumentation and Measurement Magazine*, 6(2), 25-30, (2003).

IX. REFERENCES

1. American Society of Civil Engineers, *The 2001 Report Card for America's Infrastructure*, (2001). Available WWW: www.asce.org/reportcard.
2. E. Udd, "Fiber Optic Smart Structures," *Proceeding of the IEEE*, vol. 84(6), pp. 884-894, June 1996.
3. E. Udd, *Fiber Optic Smart Structures* (John Wiley and Sons, Inc., New York) 1995.
4. W. B. Spillman, Jr., "Sensing and Processing for Smart Structures," *Proceedings of the IEEE*, 84(1), 68-77, (January 1996).
5. C. I. Merzbacher, A. D. Kersey, and E. J. Friebele, "Fiber Optic Sensors in Concrete Structures: A Review," *Smart Materials and Structures,* 5(2), 196-208 (1996).

Students test the health of the Missouri S&T Smart Composite Bridge. Photo Credit Missouri S&T

6. A. E. Aktan, A. J. Helmicki, and V. J. Hunt, "Issues in Health Monitoring for Intelligent Infrastructure," *Smart Materials and Structures*, 7(5), 674-692 (1998).
7. D. K. Gifford, A. K. Sang, S. T. Kreger, and M. E. Froggatt, "Strain Measurements of a Fiber Loop Rosette using High Spatial Resolution Rayleigh Scatter Distributed Sensing," *Fourth European Workshop on Optical Fibre Sensors*, Proc. SPIE 7653, 765333, 2010, 8 September 2010, Porto, Portugal.
8. S. E. Watkins, J. F. Unser, A. Nanni, K. Chandrashekhara, and A. Belarbi, "Instrumentation and Manufacture of a Smart Composite Bridge for Short-Span Applications," *Smart Structures and Materials 2001: Smart Systems for Bridges, Structures, and Highways*, Proceedings of the SPIE 4330, 147-157, 2001, 4-8 March 2001, Newport Beach, CA.
9. S. E. Watkins, J. W. Fonda, and A. Nanni, "Assessment of an Instrumented Reinforced-Concrete Bridge with Fiber-Reinforced-Polymer Strengthening," *Optical Engineering*, 46(5), 051010, (2007).

About the Author:

Steve E. Watkins is Director of the Applied Optics Laboratory and Professor of Electrical and Computer Engineering at Missouri University of Science and Technology (formerly the University of Missouri-Rolla). His research interests include fiber-optic sensing, smart-structure field applications, and engineering education. He is active in IEEE, IEEE-HKN, SPIE, and ASEE. He received a Ph.D. from the University of Texas at Austin in 1989.