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SMART BRIDGES WITH FIBER-OPTIC SENSORS

Permanent sensing instrumentation evaluates the structural, geometric, environmental, and health characteristics of bridges.

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COURTESY OF THE UNIVERSITY OF MISSOURI-ROLLA

Bridges represent an enormous infrastructure investment across the nation. Maintenance, repair, upgrade, and replacement of these structures are ongoing expenses. Management of these resources is particularly acute today. Many structures, especially those built in the first half of the 20th 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 can be sent over long lengths of fiber. The result is a permanent, flexible capability for nondestructive testing.

Advanced instrumentation for civil engineering structures addresses a wide range of interdisciplinary issues. Effective implementation integrates sensor technology, advanced signal processing techniques, materials science, and structural mechanics. Then effective implementation requires field demonstrations to develop practical protocols and to establish confidence in long-term system performance. This article:

- describes an approach to bridge improvements that uses smart structures
- introduces key technologies for health monitoring systems based on fiber optics

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- gives an overview of two instrumented bridges.

A sensing system in one application monitors general performance and health of the structure, while the system in a second application interrogates the behavior of a major structural repair.

Measurements are possible at hard-to-access locations, and the information can be transmitted over long lengths of fiber.

Smart Bridges

A smart structure has integral sensors that add control or interpretation attributes. In addition to the basic load bearing function, the structure will adjust intelligently or interpret its state with respect to environmental conditions similar to biological systems [4]. Figure 1 shows a typical system for smart sensing using fiber optics. The measurand, which is the physical condition being measured, interacts with the sensor to create an optical signal. The signal transmits over the optical fiber to the processing support instrumentation for demodulation and then 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 can damp unwanted vibrations, or managers can be warned of deterioration. A smart system provides an automated, fast response and detects internal conditions that may be difficult to assess otherwise.

Management concerns rather than control drive the measurement needs for bridges. Concerns, such as damage mitigation during earthquakes, would be addressed by a smart sensing and control system. Management concerns include:

- 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
- monitoring the remaining service life [4].

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

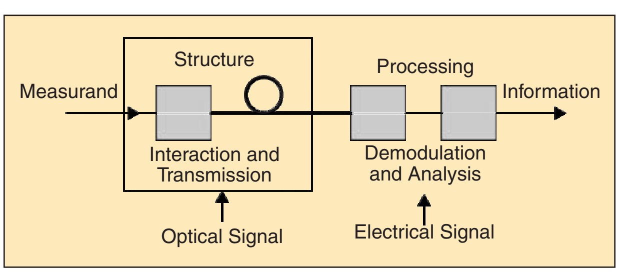

Fig. 1. Fiber-optic system for a smart structure.

A smart bridge requires understanding of the relationships between component technologies. 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, different sensing architectures may facilitate the system analysis. 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].

Fiber-Optic Strain-Sensing 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 choices 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. In particular, fiber-based Fabry-Perot interferometers are among the most successful sensor types. They can make point measurements and do not depend on a reference arm, as do Mach-Zehnder interferometers.

Fabry-Perot Fiber-Optic Sensors

The sensor interaction and design is classified as either intrinsic or extrinsic. An *intrinsic sensor* is one in which the sensing interaction occurs within the fiber itself. An intrinsic cavity can be formed by incorporating partially reflecting interfaces along the fiber. 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. Cutting the fiber and separating the ends can form an extrinsic cavity.

For intrinsic and extrinsic Fabry-Perot sensors, the gage length tends to be long and short, respectively. Strain is integrated over the gage length. Hence, a short gage length is best for point measurements.

An extrinsic Fabry-Perot fiber-based sensor is shown in Figure 2(a) [3]. 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 the returned signal varies periodically.

The extrinsic Fabry-Perot interferometric (EFPI) sensor has several desirable features. A single-ended sensor uses 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 length of the capillary tube rather than the cavity determines the gage length. 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 smart system provides an automated, fast response and detects internal conditions that may be difficult to assess otherwise.

Signal Interpretation

Interpretation of the signal occurs at 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.

The EFPI signal is periodic with strain and may extend through many cycles for typical strain levels. Various demodulation techniques exist for extracting the strain from this highly nonlinear signal. One common approach uses the response at several wavelengths to determine the absolute cavity displacement and hence the absolute strain. Figure 2(b) displays the schematic of this type of instrumentation. A broadband source excites the sensor, and a coupler and wavelength demodulator direct a set of wavelengths to a detector. The combined interference values uniquely determine the strain.

Smart Structure Integration

The application imposes diverse criteria on the sensing solution. The incorporation of the sensor system must not affect the structure adversely, the environment must not degrade the signal significantly, the demodulated information must be available readily, and the system cost must be less than 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 support instrumentation must satisfy the final two integration concerns. Performance and cost must balance; 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 for their capabilities in pattern recognition, classification, and prediction. These parallel processing architectures provide advanced processing and analysis functions accurately and robustly. The implementation of neural networks in smart structures is an active research area.

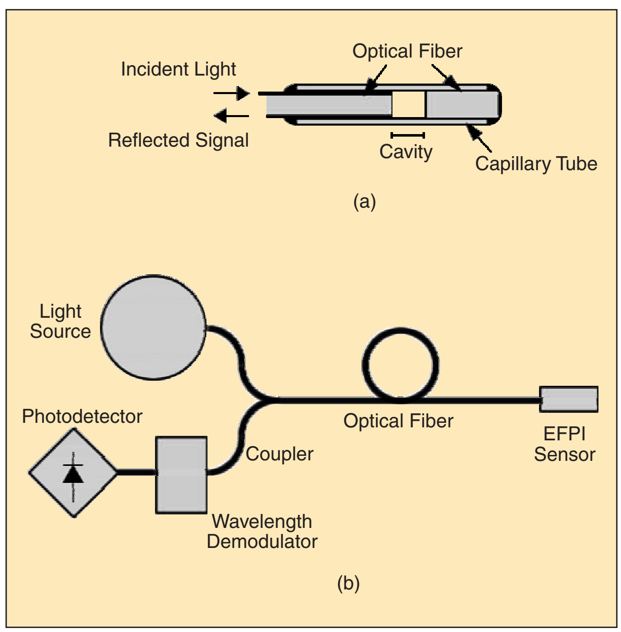

Fig. 2. Sensor system: (a) EFPI sensor with an external air-gap cavity between fiber end-faces; (b) EFPI fiber-optic sensor and support instrumentation for absolute strain measurement.

Bridge Implementations

Cost/performance optimization, new techniques, and new materials can be managed with greater safety and assured performance.

Permanent fiber-optic-based instrumentation in bridges provides capability for performance monitoring, health indicators, and warning functions. Both of the following examples use EFPI strain-sensing 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.

UMR Smart Composite Bridge

A comprehensive research project designed, analyzed, manufactured, and tested a 9-m span bridge and associated test articles. The structures are modular assemblies of 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.

The prototype structure, the first all-FRP bridge in Missouri, is part of a pedestrian walkway (although it is rated for highway loads) located on the University of Missouri at Rolla (UMR) campus. The development was a cooperative development effort that was led by UMR with industry and government partners. The project goals were to develop a novel FRP-composite approach for extended lifetime 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 at UMR.

Fig. 3. UMR smart composite bridge during a near-rating load test with a weighted truck.

A primary feature of the bridge was the fiber-optic strain-sensing system. 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
- monitor flexure strain during near-rating load tests of the installed bridge
- record strain characteristics during dynamic and static load tests
- 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.

- 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.
- The bridge was field loaded to near its design rating using the weighted dump truck shown in Figure 3. These

Fig. 4. 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.

tests are periodically repeated to document long-term bridge behavior.
- The strain signals are analyzed for various loading conditions during academic laboratory exercises.
- The instrumented bridge is a test bed for remote monitoring developments. A dedicated fiber-optic data line into the UMR Applied Optics Laboratory is currently planned.

Figure 4 shows how fiber-optic sensors were incorporated within the structure during assembly. 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 with other tubes. 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. Details and images of the manufacture, installation, and testing are available on the project Web site [7]. The site includes a live image of the final structure from a Web charge-coupled device (CCD) camera.

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, agreement with other sensor measurements, and 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 colocated electrical resistance gages. For the bridge tests, the fiber-optic sensors differed from a finite element model prediction less than 4% (worst case). Also, the sensors recorded elastic behavior for loadings below the design threshold. Figure 5 shows the midspan 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% of the highway load rating of 142.4 kN (32,000 lb). 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 midspan. Load tests with heavier trucks (Figure 3) produced strain measurements that fit a linear relationship of load versus strain. Hence, the internal fiber-optic sensors verified the elastic behavior expected for normal loading of the bridge.

I-44 Overpass Repair

A highway overpass on Interstate Highway 44 (I-44) in south-central Missouri was recently rehabilitated 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-FRP composite sheets. A research aspect of the repair was the field demonstration of the ability of

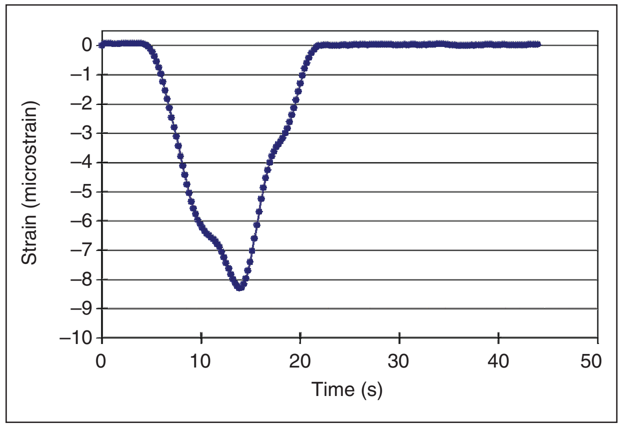

Fig. 5. Compressive strain in the top layer of the smart composite bridge for a moving pickup truck. The front-axle load was 8.4% of the design load rating.

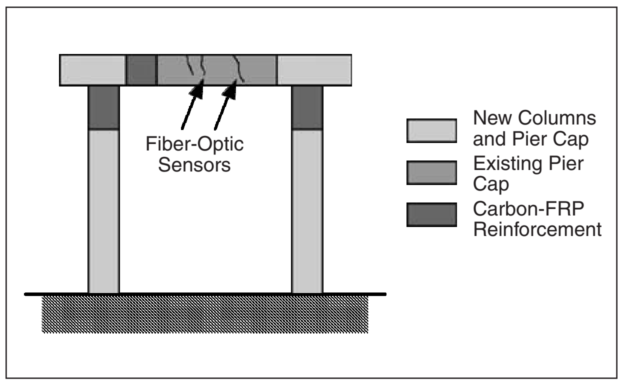

Fig. 6. Schematic of the piers and pier cap of an instrumented concrete bridge. Fiber optic sensors monitor cracks in concrete and delamination of FRP reinforcement.

Fig. 7. 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.

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 6 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
- monitor potential delamination of the carbon-FRP reinforcement
- record a signature strain during load tests.

All sensors were applied to the pier cap, as shown in Figure 7.

- 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.
- 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.
- 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 were 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. All sensors were operating for the baseline testing.

Greater Safety and Assured Performance

Smart bridges are possible in which permanent sensing instrumentation evaluates the structural, geometric, environmental, and health characteristics. 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. Instrumentation based on fiber optics 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.

Acknowledgments

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