EMBEDDED FIBER OPTIC SENSING FOR BRIDGE REHABILITATION

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Abstract: Instrumentation of a reinforced-concrete bridge subject to structural rehabilitation is described. This forty-seven-year-old bridge is located in Dallas County, Missouri and was upgraded using fiber-reinforced-polymer (FRP) sheets and rods. The permanent field instrumentation consists of an array of extrinsic Fabry-Perot interferometric fiber-optic strain sensors and co-located electrical resistance strain gauges. The sensors monitor flexural strain in the concrete, the original steel rebar, and the FRP reinforcement for the deck and beam in the central span of the bridge. The sensor system is designed for long-term health monitoring of the FRP-reinforcement with emphasis on field security and data acquisition. Implementation protocols for site preparation, installation, inspection, and use of fiber-optic sensors are discussed. The optical measurements will be compared to other measurements during the preliminary load testing. The motivation for this work is to demonstrate the implementation and use of fiber-optic-based sensing in field applications.

Introduction: Instrumentation of bridges in the Missouri Department of Transportation (MODOT) roadway system has been an ongoing effort for some time. As part of a study in the instrumentation of in-service structures, a bridge, known as P-0962, in Dallas County, Missouri, was instrumented with fiber optic and electrical resistance strain sensors. P-0962 serves a rural two-lane highway for local traffic in proximity to interstate access in MODOT District 8. P-0962 is subject to several types of strengthening and instrumentation efforts by the Center for Infrastructure Engineering Studies, the Civil Engineering Department, and the Electrical and Computer Engineering Department at the University of Missouri-Rolla. Bridge strengthening involves the use of Fiber Reinforced Polymer (FRP) and Steel Reinforced Polymer (SRP) and bridge monitoring includes smart sensing systems and other NDT methods to provide information as the P-0962 ages in field conditions [1,2]. P-0962 is one of a five bridges involving rehabilitation technology for transportation [3]. This paper presents the use of an Extrinsic Fabry-Perot Interferometric (EFPI) sensor array for detecting flexural strain at point locations in the structure. Conventional electrical resistance gauges are co-located with the network of fiber optic sensors as a check. This work is the first stage of a long-term effort to monitor structural changes with an integral system. Full bi-annual load tests are planned.

Instrumentation for health monitoring of civil engineering infrastructure has developed during the last decade [4-10]. Smart structures approaches use permanent, integral sensors to measure the condition of structures [8,11]. Benefits include enhanced understanding of in-service conditions, verification of repair or upgrades, and improved management of service life. A current area of research is field validation of sensing techniques using in-service structures. Fiber optic strain sensors (FOSS) are employed in several field applications [4,5,6] and have advantages of environmental ruggedness, low profile, and high sensitivity [8,9,12-14]. FOSS technologies are compatible with structural building materials such as reinforced concrete (RC) and FRP [10,15,16]. Embedded sensing allows for determination of the parameters in the future without re-installation, and invasive cutting procedures, that penetrate the concrete to expose rebar for installation. In the case of FRP reinforcement, the procedure for replacing sensors after repairs would compromise the strengthening procedures of the composites. FOSS systems must be investigated in the field environment to develop practical protocols and to establish confidence in long-term performance.

This paper documents the installation and preliminary testing of a smart health-monitoring sensor system. In particular, embedding of the sensing network into the RC and FRP structure to provide security and long term installation in weathered environments will be discussed. A description of the overall bridge and sensing system, the protocols for installation and testing of the embedded sensing component, and the installation of a modified fiber optic interface panel are included. Finally a discussion of future investigations will be presented

Description of the Bridge: Bridge P-0962 is a three-span structure with two lanes. The structure was aging at forty-seven years old and required rehabilitation to meet increased use and current traffic loadings. Repair and upgrade procedures used for the structure were conventional repair (involving steel rebar and concrete patches), FRP and SRP reinforcement, and health monitoring with in-situ sensors and other NDT approaches. Figure 1. shows the structure after instrumentation and repair work was completed. FRP reinforcement wraps are visible on the support girder. The sensing network was installed in the central span in parallel with the reinforcement. Note that the sensor network was embedded in the structure and was permanently covered by FRP fabric and concrete. An in-situ, permanent sensor network facilitates load testing for the life of the bridge.

Figure 1. MODOT District 8 Bridge P-0962

       Sensors and Data Acquisition Equipment: Strain is a key parameter for monitoring deformation in a structural component. Advanced FOSS and conventional ESG systems are used in this work. With an ESG system, the strain is detected by deformation in a resistive grid element. The change in resistance is used to determine the deformation and strain of the material. In an EFPI system, an optical interferometric relationship inside of an air cavity is related to the strain of the sensor [9,17]. Both systems have good directional properties and are effectively point sensors. Both sensors must be bonded to the structure to be measured. The FOSS can also be embedded within concrete or FRP materials.

       ESG technology is mature and generally uses an instrumentation system based on a Wheatstone bridge and amplifier circuits. Equation 1. shows the relationship between the strain and the voltage detected on the electrical resistance strain gauge. The measured strain is

$$\varepsilon_{ESG} = \frac{\alpha \cdot \Delta V}{V_{ex} G_f} \qquad \text{Eq. 1.}$$

where the parameters are change in voltage ΔV, the excitation voltage V_{ex}, a gauge factor G_f, and an instrumentation gain α. Accuracy, reliability, and noise are dependent upon the quality of the gauges and the associated instrumentation. Filtering and other signal processing can also improve the system performance.

       For an EFPI sensor, Figure 2. and Figure 3. illustrate the physical construction and the detections setup, respectively. In the sensor construction, the cavity length and the gauge length (roughly the capillary tube length) determine the strain. Multiple-beam interference in the reflected optical signal is modulated by the cavity length and the associated strain. The sensor instrumentation consists of a light source, the optical fiber for transmission, and the detector. The strain can be demodulated by observing the reflected signal as a function of source wavelength. The instrumentation accounts for the periodic modulation and calculates the absolute strain.

Equation 2. uses the parameters of the reflected intensity I(d), cavity length d, and an operator that tracks the nonlinear periodic modulation function $f(\cdot)$. The strain is

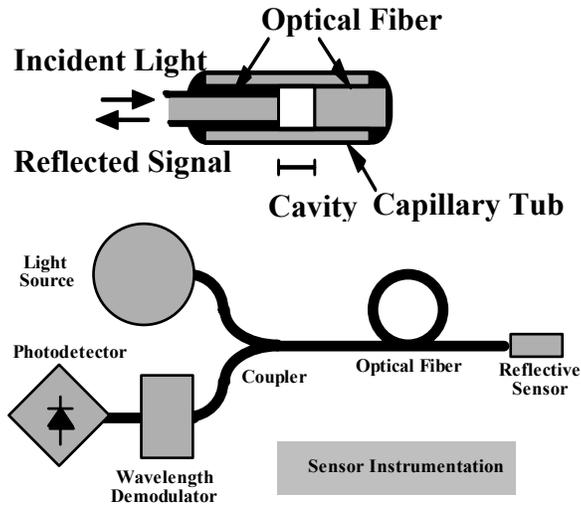$$\varepsilon_{FOSS} = f(I(d)) \qquad\qquad \text{Eq. 2.}$$

Figure 2. EFPI Cross Section Architecture

Figure 3. FOSS System

The sensors used in this work are Model EA-06-250BG-120 and EA-20CBW-120 electrical resistance gauges from MicroMeasurements Company and Model AFSS EFPI sensors from Luna Innovations. Data acquisition for the ESG gauges is based on use of a National Instruments data acquisition system. This field instrumentation system is shown in Figure 4. The multi-gauge box may be interfaced with instruments such as ESG's, LVDT's, and load cells. Data acquisition and demodulation for FOSS uses a Fiberscan 2000 optical sensing detection system from Luna Technologies. The Fiberscan is interfaced through a RS-232 communications port to the PC. Information received may be captured to a text file and viewed in several software environments such as Excel or Matlab.

Figure 4. ESG Data Acquisition System   Figure 5. FOSS Detection System

Application of the Sensors: Sensor location is a critical design choice that must be made early. Choice of key locations will allow the structure to be monitored reliably and may be minimized to help meet budget constraints. Six locations were chosen on the P-0962 installation. These locations were chosen to accomplish several tasks. First, the need to measure several locations in the same vertical alignment will allow for a three-point determination of the strain profile in the materials. Second, locations were chosen to compare the strain of concrete steel rebar, and other reinforcements as an indicator of bonding. Three sets of gauges and sensors, one on the steel rebar, one on FRP, and one on the surface of the concrete below the roadway surface were used in two locations on the bridge. One set was located on the western longitudinal beam on the mid-span. The other set is placed in the transverse direction of the road deck at mid-span. The next pair of figures shows the configuration of the sensors on the structure from below and the cross section of the structure. The sensors located in the deck plate of the structure were mounted to measure transverse strain.
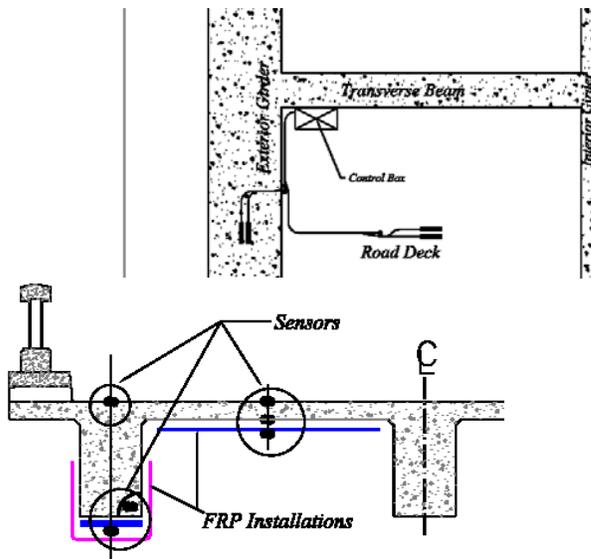
Figure 6. Bottom View of Sensor Array Location   Figure 7. End View of Sensor Array Location

Preparation of the surfaces, and the area for installation, is critical for a proper installation. Removal of the concrete in areas to expose rebar must be accomplished along with marking and cutting of the cable lays to embed the sensor cables. Strain gauge surface preparation is crucial to the accuracy and the range of the sensor. Good bonding between the sensor and the surface transfers the material stresses to the sensor for detection. The surface itself must be clean and be level in the area that the sensor will be placed. For installation, the material area is ground flat and then the surface is chemically prepared for an adhesive. For the ESG and the FOSS systems, the installation process is similar. In the case of a concrete bond, an epoxy is used to build a bonding surface. In particular, the epoxy fills the porous voids of the concrete material.

Once a flat and chemically cleaned surface is available, the gauge or sensor is bonded with adhesive. ESG's must have the leads attached and insulated to ensure that no shorting occurs to compromise their operation. Use of a mastic material accomplishes this task. Next the leads are placed in the cable lays using the same mastic material to hold the leads until they are covered by concrete epoxy. FOSS installation is similar excluding the step of attaching leads to the sensor. FOSS's come with a specified length of fiber attached to the sensing head. The fiber will be laid into cable lays with the ESG leads and then the epoxy applied. Once the fibers are placed in the lays and the epoxy has dried, the FRP, concrete patch, etc. for that section may then be placed over the cable lays and the final surface sensors can be applied. Finally, the fiber interface panel is installed and the sensors are wound into the panel for permanent installation. The installation area and the optical fiber interface panel for the bridge are shown in Figure 8. and Figure 9., respectively.

Figure 8. Installation Area for Strain Sensors   Figure 9.   Fiber Interface Panel

A Lucent Technologies fiber interface panel is used to house and protect the fiber optic connections and ESG connections. The panel used is a modified Lucent 200B LIU enclosure. Several modifications are made to accommodate the application. A section of metal is removed from the rear of the enclosure in order to route the sensor leads into the panel without leaving the protection of the concrete, and epoxy, before coming into the panel. These minor modifications protect the optical fiber leads and the ESG leads from the environment and from vandalism. After the modifications, the panel cuts are covered by rubber tubing fixed to the rough edges in order to protect the sensor leads. Next the panel is mounted to the mid-span beam using masonry anchors. Once these steps have been accomplished the system is ready for a final check and then load testing

Calibration Issues: Calibration of the instrumentation is quite important for accurate readings of the strain sensors. ESG calibration is more complex that that for the FOSS system due the inherent noise content in the ESG system. The FOSS Fiberscan 2000 system from Luna Innovations is self calibrating. The Fiberscan system allows for zeroing of the strain gauges to be done in a few keystrokes from the unit or computer. ESG systems must be checked with a known reference in order to calibrate them. Using a calibration beam from Vishay Measurements Group, the electrical system is calibrated and the gain is determined at several points.   After the calibration procedure, the ESG instrumentation is ready to be used in the field.

FOSS system will be zeroed with a "no-load" state on the structure and the ESG sensors will have a zero point taken. Once these steps have been performed, the structure may be loaded in a pre-determined manner and readings taken. A load test will involve the measurement of initial strain, i.e. the zero point of the gauges and sensors. The load-induced measurements follow. The difference in the readings is then the net strain on the structure due to the loading. Either static load conditions or dynamic load conditions may be desired. The ESG box has a sampling rate of 2 Hz and the Fiberscan system has a sampling rate of approximately 67 Hz multiplexed across seven channels. When in use, the multiplexing will reduce the effective sampling rate on each channel.

Testing Results and Discussion: The field instrumentation and portable generator for the FOSS system is shown in Figure 10. Preliminary testing of the sensors to assure operation was done with a full-size pick-up truck, as shown in Figure 11. For both static and dynamic loading using the truck, the operation of sensors were checked for proper magnitude and direction and performance, e.g. noise. Note that the truck was a very light load with respect to the bridge highway rating. Static load cases 1 and 2 consisted of the front wheels of the truck directly over the sensor locations on the transverse beam and the exterior girder, respectively. Slow rolling load cases consisted of the truck repetitively moving a few feet to each side of the static load locations.

The operation of all ESG and FOS sensors were checked. Sensors on the rebar in the girder and sensors on the underside of the deck are used as typical examples and their locations are labeled A and B, respectively.

Figure 10. Test Equipment for the FOSS system   Figure 11. Load Vehicle

The static load averages for about 30 seconds are shown in Table 1. Zero strain corresponds to the unloaded condition. The two sensor types deliver good performance in terms of comparable readings. The dynamic load results are illustrated in Figure 12. and Figure 13. The ESG data for that location is shown as the solid line and the FOSS data is shown as the asterisks. Note that the least count on the FOSS instrumentation is 1 microstrain. Both graphs show the movement of the truck through the maximum strain points. Again, both sensor types show comparable measurements within about a microstrain. The FOSS system has less noise than the ESG system and has a greater expected service life. Sensors at the other locations showed similar performance.

	Loading Case 1	Loading Case 2
ESG Sensor at Location A	+9 με	+7 με
EFPI Sensor at Location A	+10 με	+6 με
ESG Sensor at Location B	+3 με	+8 με
EFPI Sensor at Location B	+3 με	+9 με

Table 1. Static Load Results in microstrain

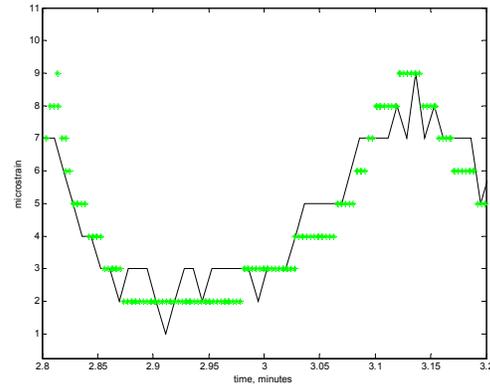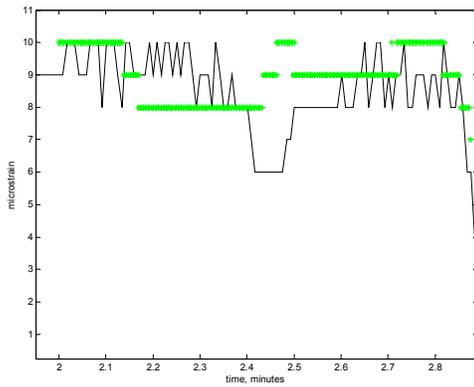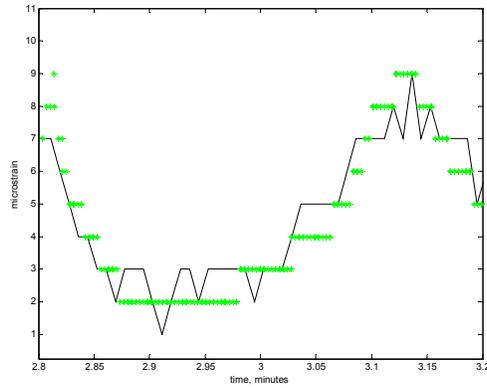Figure 13. Rolling Load on Sensor B

Figure 12. Rolling Load on Sensor A   Figure 13. Rolling Load on Sensor B

Conclusions: The instrumentation of MODOT bridge P-0962 with a fiber-optic sensor network was successful. This work is a field demonstration of a smart structures approach to a RC bridge structure for long-term health monitoring. A description of the structure, the installation of a sensor array, and the preliminary test measurements for load-induced strain have been shown. A comparison of FOSS and ESG sensors is given to verify system performance.   The sensor systems provide high resolution strain measurements. The information that is gathered from the instrumented structure is intended to monitor performance of the bridge and the FRP/SRP repair and rehabilitation. The bridge will be monitored for the long term and the FOSS measurements will be compared to other NDT approaches. Future improvements to the P-0962 bridge instrumentation are planned including signal processing and filtering capability, enhanced data acquisition technologies, and remote monitoring research. These efforts are aimed at developing a comprehensive structural monitoring system that can provide measurements and assessment of the bridge to management and maintenance personnel.

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