Health monitoring of an Oregon historical bridge with fiber grating strain sensors

John Seim, Eric Udd, Whitten Schulz
Blue Road Research
2555 NE 205th Avenue, Fairview, Oregon, 97024 USA
Ph: 503-667-7772; Fax: 503-667-7880

Harold M. Laylor
Oregon Department Of Transportation
200 Hawthorne SE, Suite B-240, Salem, Oregon, 97310 USA
Ph: 503-986-2850; Fax: 503-986-2844

ABSTRACT

Twenty-eight fiber-grating sensors were used to instrument two reinforced concrete beams that were externally strengthened with composites on the historic Horsetail Falls Bridge in the Columbia River Gorge. Sensor assemblies were placed in the beams and mounted on the outside of the composite to provide performance data.

Keywords: Fiber Optic Sensors, Fiber Bragg Grating Sensors, Health Monitoring, Bridge Restoration, Composite Wrap Reinforcement.

INTRODUCTION

The historic Horsetail Falls Bridge (figure 1) is a 60-foot reinforced concrete slab span type, consisting of three 20-foot spans. The structure, built in 1914, is located on Crown Point Highway 125 at mile point 22.2, approximately 30 miles east of Portland, Oregon.

Figure 1: Horsetail Falls Bridge before the strengthening composite wrap was installed.

This bridge, as many of the older bridges in Oregon, was not designed to carry the traffic loads that are commonplace today. This bridge is on the historical register, and had to have its load carrying capacity increased. Fiber reinforced plastic (FRP) composite strengthening was selected as the method for upgrading the structure because the visual impact from the repairs would be minimized. This was the first FRP job on an Oregon bridge, so long-term performance monitoring was needed. Fiber optic Bragg grating strain sensors were selected for the monitoring since they potentially have a long service life and can be configured in long gauge lengths.

Fiber optic Bragg grating strain sensors [1] provide a practical method for implementing a cost-effective health monitoring system [2-4]. Traditional forms of instrumentation are harder to install at long gauge lengths and do not have good long-term performance records. With a health monitoring system installed on a structure, performance can be monitored and problems can be detected early and corrected. This saves maintenance time and money.

FIBER GRATING BASED HEALTH MONITORING SYSTEM FOR THE HORSETAIL FALLS BRIDGE

The Oregon Department of Transportation is using the Horsetail Falls Bridge as a pilot project to answer two key questions: 1) Can a bridge be repaired and strengthened with FRP composites on critical elements? and 2) How well does the composite perform in the long term? In an attempt to answer these questions, a sensor system was needed that could be embedded in the structural elements of the bridge and last for the remaining life of the structure. Fiber optic strain sensors were designed around Bragg grating sensors that are easily embedded into the structure and will give data that will help answer the above questions. The data will also be used to verify finite element models of the structure that are currently under development.

Several innovations were demonstrated in the design of the sensors for the bridge. Very small flexible tubing was used to support and protect the Bragg gratings while being placed into small grooves (figure 2) in the concrete beams as well as directly onto the composite. Small size was important to avoid altering the appearance of the bridge while allowing both the concrete beam and composite to be independently monitored.

Figure 2: Installation of long gauge length bragg grating sensors into a beam.

The sensors used on Horsetail Falls Bridge are Bragg gratings written on standard single mode fiber with a center wavelength near 1300nm. The Bragg equation for a fiber grating is [1]

$$\boldsymbol{\lambda = 2*n*\Lambda}$$

where $\boldsymbol{\lambda}$ is the center wavelength of a narrow reflection peak, **n** is the index of refraction of the core, and $\boldsymbol{\Lambda}$ is the grating period. This equation indicates that for a broad spectral source such as an ELED, the wavelength reflected from the grating depends only on the index of refraction of the core and the grating spacing. The index of refraction is known to be a function of the wavelength, but for typical applications of fiber Bragg gratings, such as strain or temperature, a scalar approximation works well. Changes in the fiber induced by stretching the fiber optic element containing the grating or by a temperature increase (thermal expansion of the material) cause the grating period to increase which forces the reflected peak to shift towards longer wavelengths. Compression and cooling of the fiber cause a spectral shift towards shorter wavelengths.

The actual gratings have a gauge length on the order of a centimeter. Sensors with an effective gauge length of 70cm and 100cm long were desired. The fiber Bragg gratings were mounted in capillary tubes, cut to 70cm and 100cm lengths, with an outer diameter of 1.6mm and inner diameter of 250µ. The tubing is made of a polymer called PEEK, poly-ether-ether-keytone. During fabrication the grating was placed approximately in the center of the tube and epoxied at one end. When the epoxy was cured, a known mass was attached to the opposite end so as to pre-strain the Bragg grating by approximately 1000µstrain. After the free end of the grating was epoxied to the tube, the fiber was then spliced to a rugged simplex single-mode patch cord. Shrink tube and splice protectors were used to cover any bare fiber. A picture of one sensor is shown in figure 3.

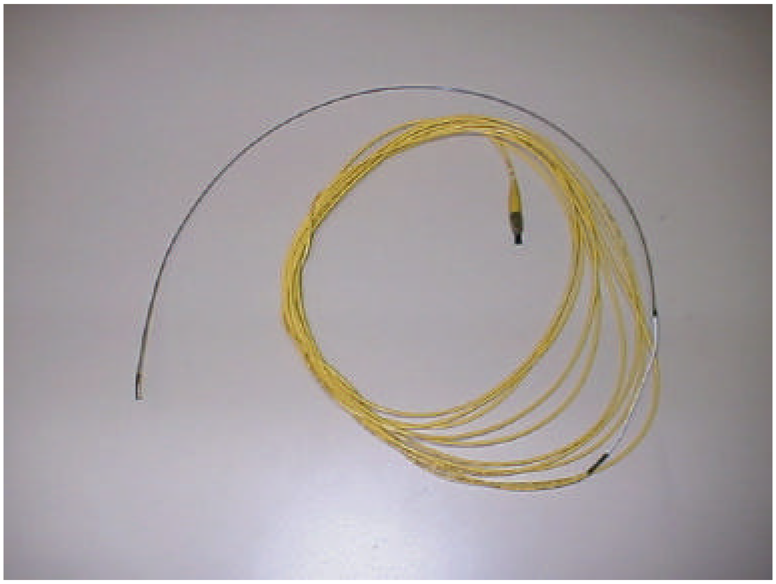

Figure 3: A 70cm gauge length fiber optic strain sensor and cable.

The bottom of deck and beams had many cracks, pits, and even some exposed re-bar. The first step in the repair was to fix these structural defects. Many gallons of epoxy was injected into the cracks and used to fill any area where concrete was missing. The surfaces of all the beams were prepared by repeated filling, grinding, and needle gun scaling. Grooves, approximately 3 mm wide and deep were cut into the concrete at predetermined locations on one longitudinal beam and one transverse beam. Four 70cm long sensors were mounted diagonally on the side of each monitor beam to measure shear strain. Three 100cm sensors were mounted on the underside of the two beams. The sensors and their respective cables were fit into the grooves and completely sealed in epoxy. When the epoxy cured, it was ground flush to the beam leaving a smooth surface.

Tests were conducted to verify that the sensors were functioning and to obtain a baseline. Traffic control was used while a 10 yard (26,000 pound) dump truck was parked at various locations on the bridge. Measurements were taken for various truck positions with a portable optical spectrum analyzer (Ando AQ6330 OSA). A spectrum was obtained for each of the 14 sensors for seven loading conditions. The data verified that all the sensors were functioning.

Carbon fiber sheets impregnated with resin were then adhered to the bottom and the lower part of the sides of all transverse beams on the structure for flexural control (shown in figure 4).

Figure 4: Installation of the Carbon-Epoxy Strengthening Material.

Impregnated Glass-epoxy sheets were placed over all of the beams for shear control. Once the glass-epoxy material had cured sufficiently, another set of 14 sensors were mounted on the outside of the two test beams with a fast curing epoxy (see figure 5). Sensor placement, gauge length, and number of

Figure 5: Sensors were mounted onto the glass-epoxy material after curing sufficiently.

sensors were identical to the set embedded in concrete. A special epoxy cosmetic coat (figure 6) was placed over the composite and sensors so that the appearance of the beams would closely match the appearance of the original concrete.

Figure 6: A cosmetic coat of epoxy was applied to the composites.

The patch cords to the sensor were then routed in a conduit to a breakout box. A k-type thermocouple was mounted in the concrete near the box to monitor the temperature of the concrete. The thermocouple data will be used for temperature compensation when load testing is performed. Load testing similar to the first tests are scheduled on a monthly basis for the next two years.

More extensive laboratory tests on full-scale model beams are scheduled. The beams have been outfitted with sensors and composite wraps identical to what was done on the Horsetail Falls Bridge for model verification. As of this writing, the control beam and one of the three test beams have been loaded to failure (figure 7) . The sensors were installed across the likely failure points – in this case the shear zone.

Figure 7: Shear failure in a full scale model concrete beam based on the Horsetail Falls Bridge beams.

The black material at the bottom of figure 7 is the carbon FRP used to strengthen the beam in flexure. The light gray lines perpendicular to the major cracks were fiber sensors placed to measure shear. These two sensors did not survive the beam failure. This reinforced beam failed under a 155 kpsi load while the control beam failed after 105 kpsi was applied.

The other two test beams are scheduled to be loaded April 1999. The results of these laboratory tests will be used in combination with data obtained from the Horsetail Falls Bridge (see figure 8 for sample data) to verify finite element models of the original beams and the composite strengthened beams.

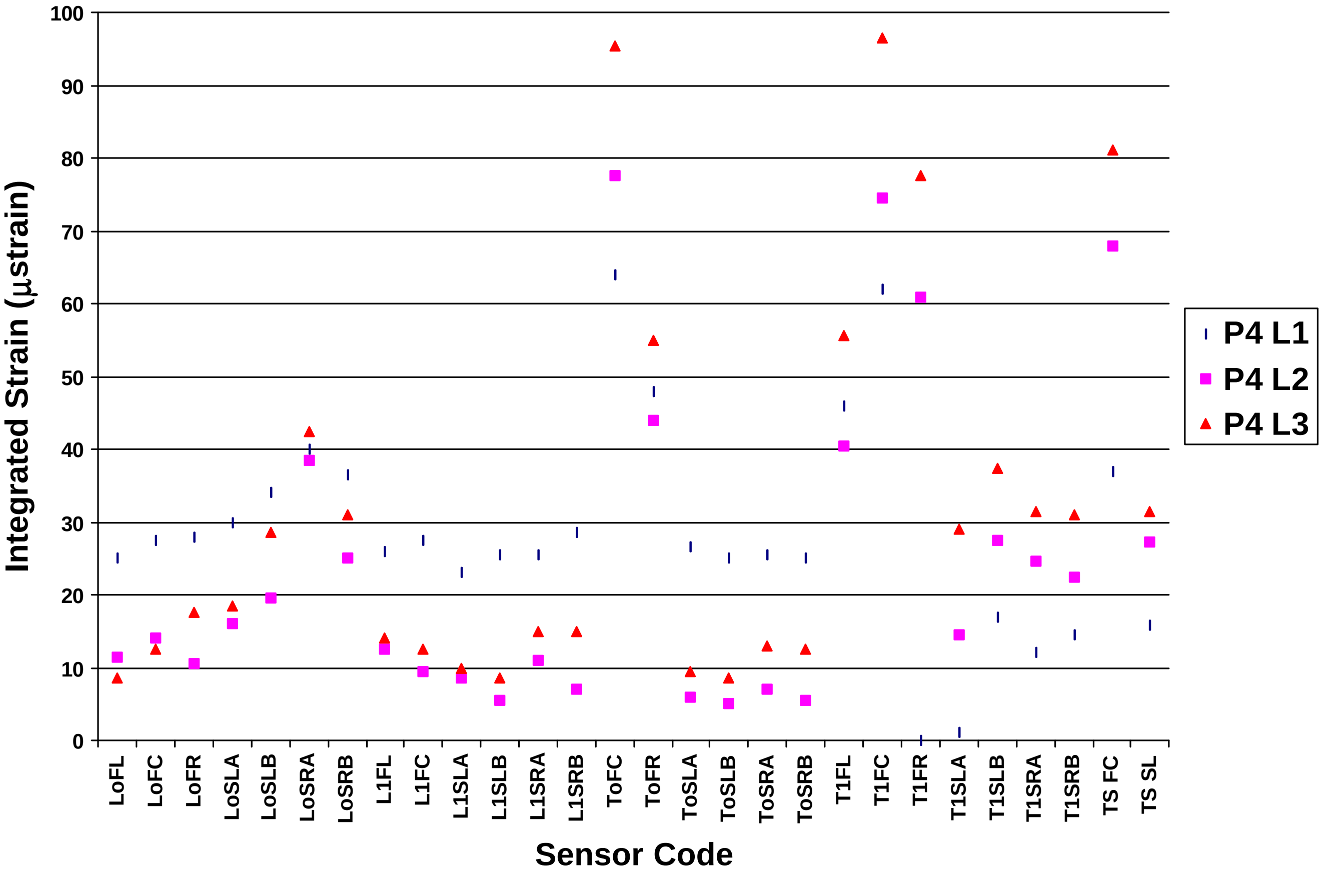

Figure 8: This particular set of data shows that the sensors are measuring strains for three different load levels. In the legend **P4** is the position where the loading truck is placed such that the rear axles are directly on top of the transverse beam outfitted with sensors. The three load levels were: **L1** (the empty truck) = 11,900kg, **L2** = 16,700kg, and **L3** = 19,900kg.

SUMMARY

Twenty-eight fiber-grating sensors were embedded into composite wrapped concrete beams used to reinforce the historic Horsetail Falls Bridge without altering its appearance significantly. Preliminary data has been obtained and the bridge will be monitored for the next two years. Full scale model beams have been manufactured to verify the FRP strengthening properties and will be tested to failure for model verification.

REFERENCES

1. W. W. Morey, “Fiber Optic Grating Technology,” Proc. of SPIE, Vol. 2574,p. 22, 1995.
2. D. Inaudi, S. Vurpillot and E. Udd, “Long-Gage Structural Monitoring for Civil Structures,” Proc. of SPIE, Vol. 3489, p. 93, 1998.
3. D. R. Huston and P. L. Fuhr, “Fiber Optic Smart Civil Structures,” *Fiber Optic Smart Structures*, edited by E. Udd, Wiley, 1995.
4. M. A. Davis, D. G. Bellemore, A. D. Kersey, M. A. Putnam, E. J. Friebele, R. L. Idriss and M. Kodinduma, “High Sensor-Count Bragg Grating Instrumentation System for Large Scale Structural Monitoring Applications,” Proc. of SPIE, Vol 2718, p. 303, 1997.