

# Single and Multiaxis Fiber Grating Based Strain Sensors for Civil Structure Applications

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## ABSTRACT

There are approximately 576,000 major bridges, 3.2 billion square feet of bridge deck, and 162,000 miles of highways making up a part of the civil infrastructure system in the United States<sup>1,2</sup>. Fiber grating strain sensors have the ability to play an important role in the health monitoring of these structures. The advantages of fiber optic sensors including EMI resistance, unobtrusive size, multiplexing/distributed capabilities, and environmental ruggedness, make them a logical choice for structural monitoring.

**Keywords:** fiber gratings, multiaxis strain, civil structures, bridges

## 1. INTRODUCTION

Many of the strain measurements made today are performed using electrical strain gauges. These devices cost about \$20 each and typically have gauge lengths of 0.5 to 1 cm. The vast majority of these devices are surface mounted and the procedure for mounting them involves preparing a flat surface, often with sanding, followed by cleaning, an acid wash, gluing the strain gauge to the surface and attaching electrical leads. The process with a skilled technician takes about an hour per gauge, adding perhaps \$25 to \$30 to the cost of each sensor. The electrical strain gauges are then attached to electronic demodulators such as a Wheatstone bridge, which costs anywhere from \$300 to over \$2000 per channel, depending on the performance and features of the unit. Issues associated with conventional strain gauges include (1) the strain gauges falling off or partially detaching from the surface on which they are mounted, (2) limited temperature ranges, (3) susceptibility to electromagnetic interference, (4) difficulties associated with embedding them into composite and metallic materials and (5) Multiplexing difficulties.

Currently fiber optic grating based strain sensors cost from \$150 to \$500 each in small quantities and are supported by fiber grating based demodulators costing about \$20,000 that can support 10 to 60 longitudinal strain and temperature measurements. The price of the fiber gratings is substantially lower in quantities of 100, on the order of \$100 to \$200 per item and as companies start to move toward mass production of these items, their cost should rapidly approach the \$20 target offered by electrical foil gauges. The reasons for these improvements include advances in preparing the fiber using such techniques as hydrogen loading as well as modifications to the fiber design. Strides have also been made in improving the quality of fiber gratings that are actually made as the fiber is being drawn. While additional work remains to be done to improve the reflectivity of fiber gratings made in this manner, there is the real potential of mass-producing fiber gratings while the fiber is being drawn.

While rapid progress is being made in improving fiber grating technology for the telecommunication industry, the introduction of fiber grating sensors into structures is likely to face significant competition from entrenched electrical strain gauge manufacturers in the near future. What is needed is additional differentiation from electrical strain gauge capabilities. Transverse strain and multiaxis single point strain capability are such differentiating items that can be realized for small cost premiums associated with polarization preserving fiber.

## 2. LONGITUDINAL STRAIN AND TEMPERATURE

Since the period of the fiber grating is written along its length, environmental effects that cause elongation of the fiber will change the period and the wavelength band that the fiber grating reflects and transmits. Two of the principle environmental

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effects that cause this change are temperature and longitudinal strain<sup>2</sup>. Other types of environmental effects can be measured such as magnetic field or pressure by designing coatings or transducers that will convert these effects into strain on the fiber.

The usual problem is to separate strain and temperature so that strain can be accurately measured. One approach<sup>2</sup> to this problem is to put two fiber gratings in close proximity to one another with one attached to the material on which strain is to be measured and the other nearby but not attached to the material so that it floats and is not subject to strain. Another method is to use fiber gratings in combination with another fiber sensor that measures temperature only. The Raman scattering based optical time domain reflectometer systems offered by York and Hitachi offer distributed temperature sensing along the length of the fiber<sup>3</sup>. The main issue associated with both of these approaches is that the temperature of the fiber grating making the strain measurement may be substantially different from that of the spatially displaced "floating" fiber grating or the temperature indicated by the Raman scattering based temperature sensor which may have spatial resolution on the order of a meter or more. To overcome these problems an alternative is to write two fiber gratings of widely separated wavelengths on top of one another<sup>4</sup>. By measuring the change in wavelength of both of these gratings with strain and temperature, one can establish two equations in two unknowns and solve for both quantities<sup>5</sup>.

The current approach to writing dual overlaid fiber gratings is to use a phase mask with two parts, one for each wavelength. Once the fiber is positioned, first one wavelength is written, then the other. It may be possible to write two gratings on the fiber with one exposure, reducing the intrinsic cost to that of a single fiber grating. Initial efforts indicate this may not result in as clean a fiber grating profile as the individually written fiber grating patterns. Further work remains on this problem.

To date, the reflectivity of the dual overlaid fiber gratings has been about 80%, a value chosen for good overall performance and reduction of sidelobes to low levels.

The intrinsic strength of these dual gratings is approximately the same as a single fiber grating which 3M Fiber Grating Technologies has demonstrated can be the same as the original strength of the optical fiber.

One additional consideration with respect to strain and temperature measurements is the ability of the fiber gratings to withstand long term operation at elevated temperature. This depends heavily on how the fiber grating is written and processed. Typically, fiber gratings that are written using side-imaging techniques either holographically or with phase masks will operate with very little change up to approximately 400 degrees C. By writing "strong" gratings that are essentially overexposed and annealed, this temperature range may be extended to 650 degrees C<sup>2</sup>. Fiber gratings that are exposed to short bursts of light that cause optical damage to form the fiber grating have survived temperatures up to about 800 degrees C. One major issue of operating at elevated temperatures for extended periods of time is that the glass may soften allowing for the possibility of creep. This may in fact be the limitation of using silicon dioxide based fiber gratings to measure strain at high temperature. The temperature issue is important to civil structures when fiber gratings are to be attached directly to structures using high temperature processes.

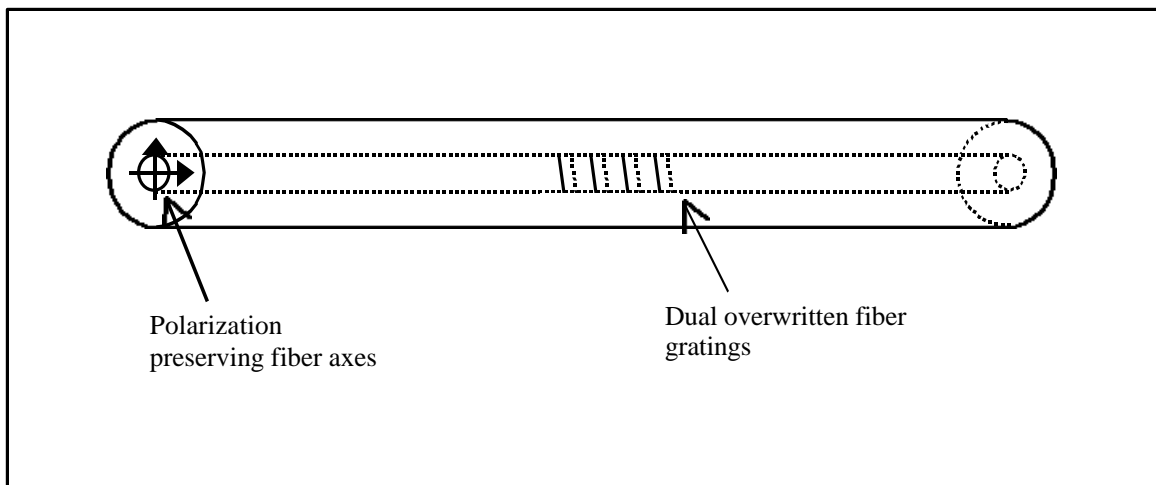
### 3. TRANSVERSE STRAIN

One exciting advantage of fiber optic grating sensors is that they can readily be embedded into a variety of materials to measure internal strain. Examples of application areas would include embedment into fiberglass structures, carbon epoxy, thermoplastics, concrete, and metals such as aluminum. When these fiber gratings are embedded into materials, transverse strain may arise that will also shift the period of the gratings. An initial design to attempt to solve the transverse strain measurement problem involved writing four overlaid fiber gratings, two of which were tilted so that transverse strain would change their effective period<sup>6</sup>. The idea is to use the four resulting wavelength shifts from the fiber gratings to generate four equations in four unknowns. A second approach is to use dual overlaid gratings written onto polarization preserving optical fiber. In this case, each fiber grating results in two effective fiber gratings so again there are four equations in four unknowns<sup>7</sup>. Fabrication of this fiber grating sensor is simplified since the two birefringent axes of the fiber provide automatic alignment of the transverse sensing axes and only two fiber gratings need to be written along the longitudinal axis of the optical fiber. It should be noted that polarization preserving fiber need only be used in the vicinity of the fiber sensor since information on all of the four effective fiber gratings is wavelength encoded.

One further issue with respect to using the fiber optic grating to measure transverse strain is the orientation of the fiber in the material or on a surface. Since many fibers are cylindrically symmetric, it would be necessary to mark the coating on this type of fiber and establish appropriate procedures for placement. An alternative approach is to use fibers that are shaped with flat sides. The D shaped fiber marketed by Andrew Corporation or the flattened sides of the ATT polarization preserving

fiber would be appropriate choices. These different fiber configurations will result in a different response to transverse strain and work is in progress in this area. When the fiber is drawn, it would also be possible to coat the fiber with an asymmetric coating that would simplify placement of an appropriately oriented fiber.

Figure 1 shows a diagram of a multi-axis fiber grating based strain sensor that is formed by writing dual overlaid fiber gratings on polarization maintaining fiber. This effectively establishes four gratings whose output wavelengths may be tracked. The result is four equations in four unknowns allowing the potential for three axes of strain and temperature to be measured. Recent experiments with dual overlaid fiber gratings written at 1300 and 1550 nm onto polarization preserving fiber made by 3M and Fibercore have shown that two axes of transverse strain can be measured when the longitudinal strain and temperature are known and that also three axes of strain may be measured when the temperature is measured independently<sup>8</sup>. Figure 2 shows the spectral response of a dual overlaid fiber grating when subjected to axial and transverse loads. With an axial load, the peaks will shift, and with a transverse load, the peak separation will increase.



*Figure 1. Dual overlaid gratings written onto polarization preserving fiber.*

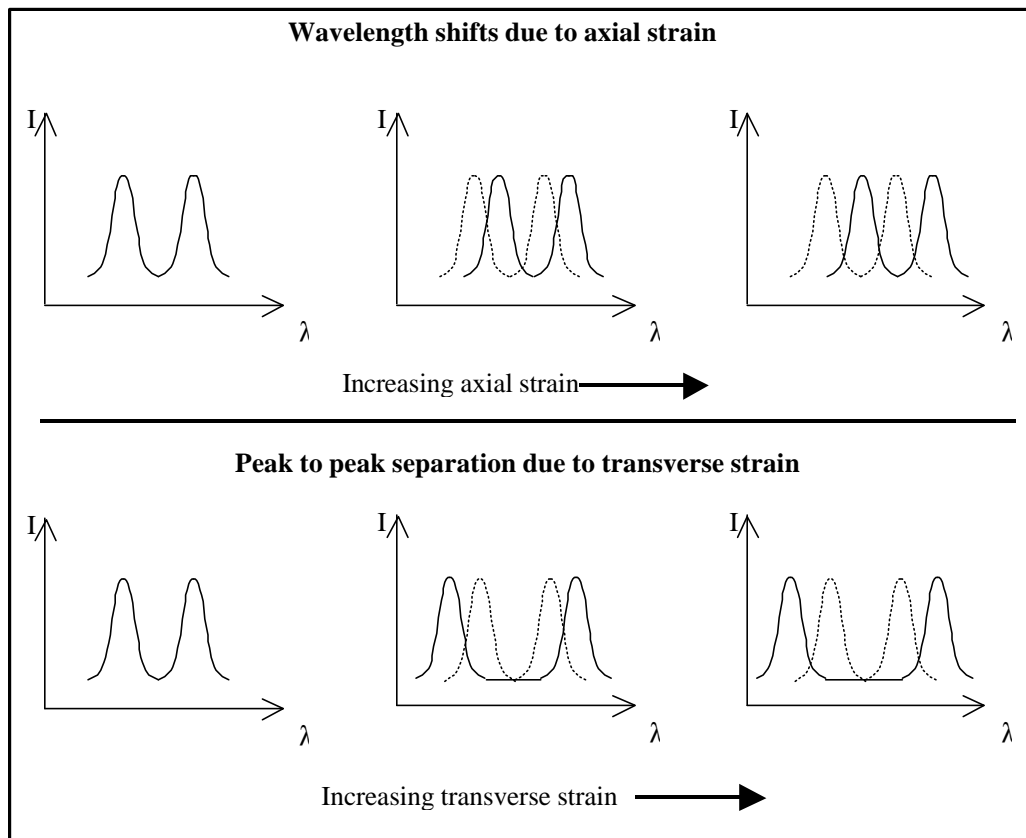


Figure 2. Peak shifts and peak separations due to axial and transverse strains.

It is difficult to measure temperature simultaneously because of the condition number of matrix associated with temperature for standard polarization maintaining fiber. Significant improvements can be expected by optimizing the thermal and dispersion properties of the fiber as well as the characteristics of the waveguide itself.

Figure 3 shows a system that has been used to track changes in a multi-axis fiber grating based strain sensor. Edge emitting diodes at 1300 and 1550 nm are combined using a wavelength division multiplexing element. The combined light beam is directed into a 50/50 beamsplitter and used to illuminate a dual overlaid fiber grating written onto polarization maintaining fiber. The reflected light beam is directed back via the beamsplitter into an Optical Spectrometer, which is controlled via a GPIB bus, and a PC. Blue Road Research has developed automatic spectral peak tracking software for this set of instrumentation that can be used to characterize the multi-axis fiber grating strain sensors.

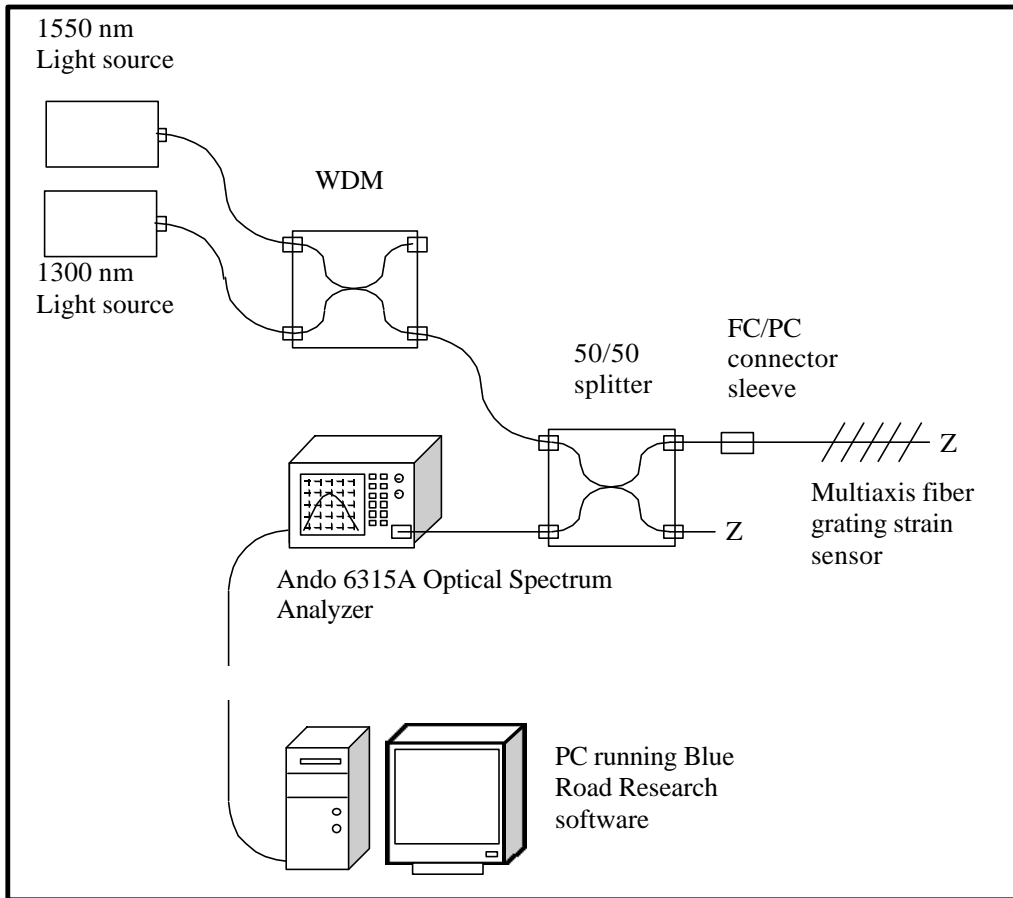


Figure 3. Demodulation system for a multiaxis fiber grating strain sensor.

#### 4. APPLICATIONS OF FIBER GRATING STRAIN SENSOR SYSTEMS

There are several smart structure applications of fiber grating strain sensor systems for civil structures and traffic monitoring/control<sup>9</sup>. This section covers current projects Blue Road Research and the Oregon Department of Transportation (ODOT) are working on in the area of civil structure monitoring.

The first project is monitoring the interface between a zinc spray coating and concrete with single and multi-axis grating sensors. Figure 4 shows the interface with an embedded sensor. The strain field information obtained from the fiber grating sensors can be used to determine the state of the interface between the concrete and the zinc coating. This information leads to a better understanding of the mechanisms affecting the outcome of the coating including spray thickness, number of passes, cooling time, residual stresses, etc. ODOT has performed a test where a length of standard telecom fiber was sprayed over with the zinc and then tested by using visible light. The fiber survived and the maximum temperature measured during the process was 200°C. As mentioned earlier, grating sensors can operate at 400°C.

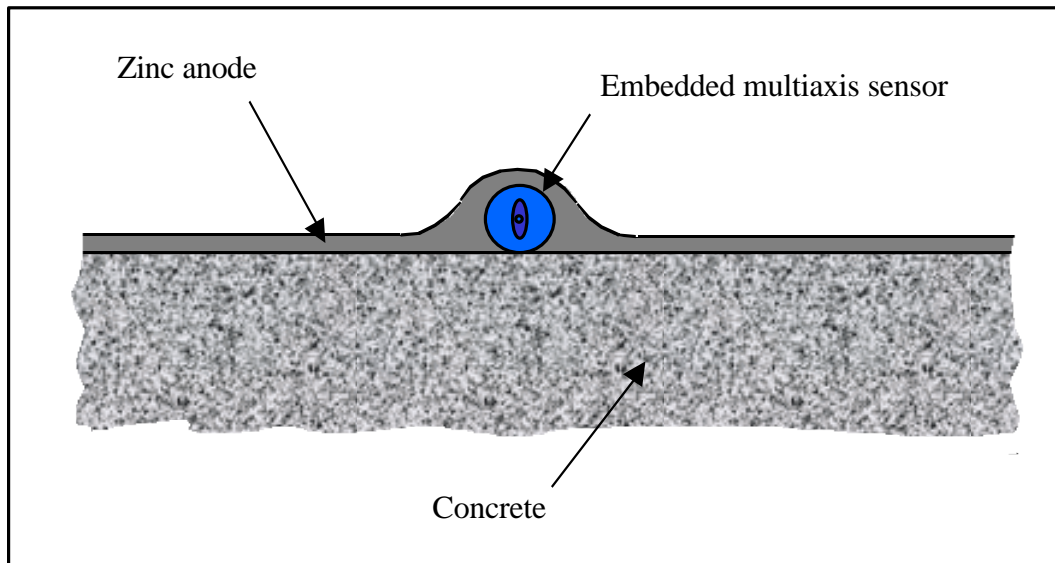


Figure 4. Monitoring the interface between a zinc coating and concrete with a fiber grating sensor.

The second project that Blue Road Research and ODOT are collaborating on is the monitoring of an historical bridge with fiber grating sensors. Horsetail Falls bridge; located in the Columbia River Gorge in Oregon was built in 1914 (Figure 5.) This bridge has been identified as having an insufficient load rating. To correct this problem, ODOT has instigated a plan to reinforce the bridge with composites and to use fiber sensors to monitor the bridge before and after reinforcement.



Figure 5. Horsetail Falls Bridge, Oregon, scheduled to be instrumented with fiber sensors in summer 1998.

Concrete beams with the same dimensions as the ones on the bridge will be instrumented and tested in the laboratory prior to reinforcing the bridge (Figure 6.) To surface mount the grating sensors to the structure, they are first attached to steel plates which are then placed between two steel pins that have been driven into the concrete. The spacing of the pins is such that the plate has to be bent to fit between them, thereby creating a friction fit and allowing both tension and compression to be

measured (Figure 7.) These “gauges” will be oriented to sense flexure and shear in both the concrete test beams and the beams on the bridges.

The sensors will be demodulated with a Blue Road Research Model BRR-3SA portable, hand-held, demodulator which can read strains at speeds up to 7kHz<sup>10</sup>.

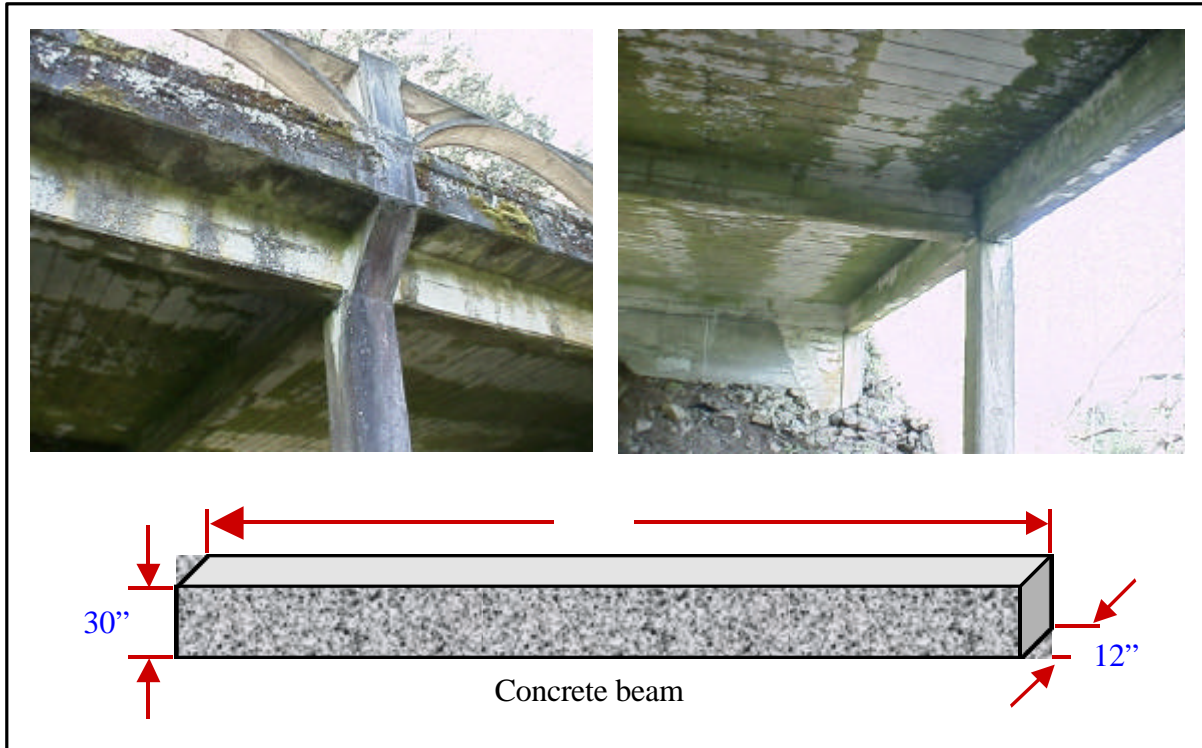


Figure 6. Concrete test beams are to be instrumented and tested in the laboratory prior to reinforcing the bridge.

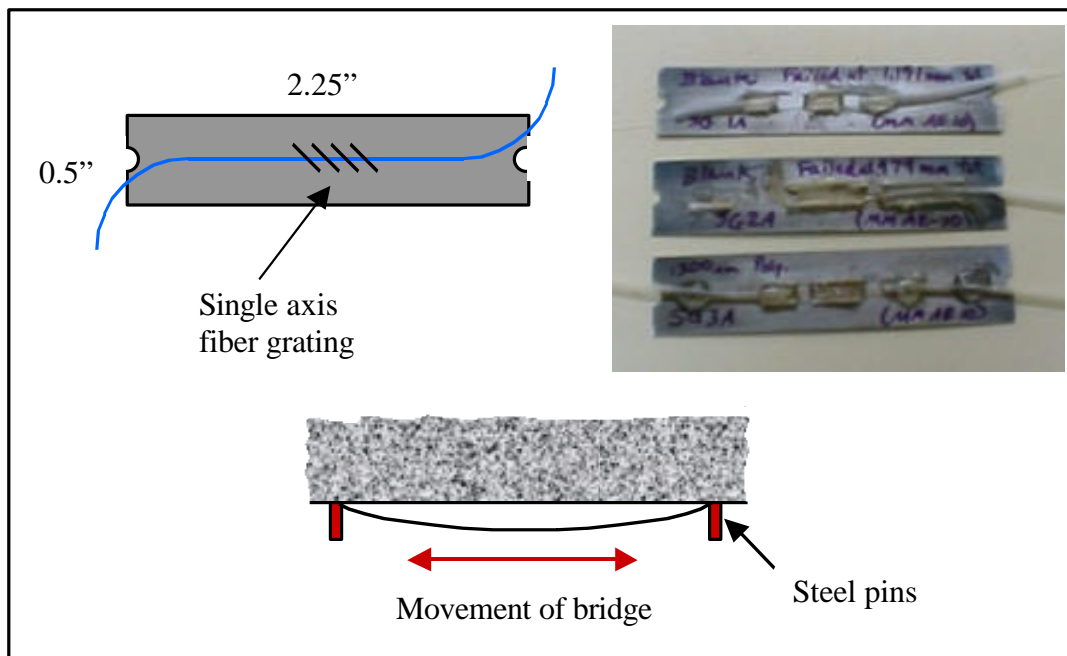


Figure 7. Surface mounted fiber grating sensors.

## 5. SUMMARY

Fiber grating strain sensors have been successfully used to monitor civil structure applications and they will play an important role in future infrastructure monitoring. The advantages of fiber grating sensors include size, multiplexing capabilities, environmental ruggedness, and the ability to support demodulation up to several kilometers away using standard telecom fiber. For these reasons, fiber grating sensors are strong candidates to replace and provide new capabilities over standard electrical strain gauges in civil structure applications.

## 6. ACKNOWLEDGEMENTS

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