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CONTRACT REPORT

# HEALTH MONITORING OF POST-TENSION TENDONS IN BRIDGES

JOHN C. DUKE, Jr., Ph.D.
Professor of Mechanics
Department of Engineering Science
and Mechanics
Virginia Polytechnic Institute & State University

VIRGINIA TRANSPORTATION RESEARCH COUNCIL

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| Authors: John C. Duke, Jr. | | | | |
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Abstract

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This study was carried out to address concerns over the condition of PT tendons. The study included a literature survey of technologies that may have application for assessing and monitoring the condition of tendons. In addition, a limited assessment of promising technologies was conducted and follow-on efforts for development and application to post-tensioned tendons in Virginia was described.

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**John C. Duke, Jr., Ph.D.**
**Department of Engineering Science and Mechanics**
**Virginia Polytechnic and State University**

*Project Manager*
Gerardo G. Clemeña, Ph.D., Virginia Transportation Research Council

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## ABSTRACT

Post-tensioned (PT) concrete has been used in a number of bridge structures and is expected to be used more in future construction in Virginia. This type of detail offers unique advantages for improving the performance of concrete members. Recent problems in the United Kingdom and the State of Florida have increased concern over the condition of post-tensioned tendons in Virginia bridges. There is a need for efficient, cost-effective methods of assessing and monitoring the condition of aging tendons in-situ.

This study was carried out to address concerns over the condition of PT tendons. The study included a literature survey of technologies that may have application for assessing and monitoring the condition of tendons. In addition, a limited assessment of promising technologies was conducted and follow-on efforts for development and application to post-tensioned tendons in Virginia was described.

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## INTRODUCTION

Post-tensioned (PT) concrete has been used in a number of bridge structures and is expected to be used more in future construction in Virginia. This type of detail offers advantages for improving the performance of concrete members. These advantages are multiplied when combined with prefabrication so as to reduce on-site construction time. The nature of these applications makes it critically important that the condition of the tendons be maintained. Typically to ensure that the tendons remain in good condition, free from deterioration due to corrosion, they are placed in ducts, sometimes made of plastic, sometimes made of galvanized steel. Subsequent to installation of the components and tensioning of the tendons, these ducts are filled with a cementitious grout. Because of the grout and the extent, geometry, and orientation of the ducts, they may not be completely filled. If the ducts crack or corrode moisture and air might reach the steel tendons and cause corrosion. In other instances the grout material may deteriorate and moisture and air may infiltrate through the deteriorated grout and cause corrosion. Metal loss due to corrosion can result in partial or complete loss of tension, which in turn can lead to failure of the structure.

Recently the Florida Department of Transportation discovered "severe corrosion damage and strand separation near anchorages" of post-tensioned tendons.[1,2] In late December 2000, examination of PT ducts in the west approach of the east bound bridge of the Rte. 895 connector in Richmond, Virginia, suggested that regions of the duct may be devoid of grout.[3]

A program to inspect all of the PT ducts in Virginia bridges is being considered. In March of 2002, a "Post-Tensioning Tendon Assessment Workshop" was held at the FHWA Turner-Fairbank Research Center. David Cullington of Transportation Research Laboratory in the United Kingdom presented the results of an extensive study they performed. They determined that many voids existed in the PT ducts and no reliable method of nondestructive inspection was available for determining the extent of corrosive deterioration. Invasive examination of 100% of the critical areas was impractical, so statistical sampling was implemented. TRL further recommended that acoustic monitoring of strand failures be undertaken for those structures containing tendons in questionable condition. They noted that this approach could not establish the extent of deterioration prior to the start of monitoring.

The FHWA NDE Validation Center announced that they were starting a program to evaluate different NDE methods, in particular X-ray, with high-energy sources. Some work with this technique had met with success in France, but TRL indicated that health agency restrictions prevented such implementation in the United Kingdom.

There is cause for concern due to the critical nature and planned inclusion of the PT duct detail in near future bridge construction in Virginia in light of the lack of availability of proven NDE methods. This study is directed at identifying, and if necessary assessing, further development of reliable means for monitoring the health of PT tendons.

## PURPOSE AND SCOPE

The objectives of this study were to (1) survey what types of PT ducts are planned for near future use in Virginia; (2) identify from the literature, methods for health monitoring of PT tendons or like components that may hold promise for these specific applications; (3) assess, where possible, the capabilities of candidate technologies including embedded optical fiber sensors, embedded piezoelectric patches, and embedded wireless microsensor approaches; and (4) explore the possibility of incorporating promising health monitoring capabilities of a PT tendon in structure as part of future research.

## METHODS

The following tasks were performed:

1. Through consultation with the Structure & Bridge Division of the Virginia Department of Transportation (VDOT), all presently planned uses of PT ducts were identified.
2. A review of the technical literature was conducted, along with direct inquiries to other research groups, in order to identify health-monitoring methods capable of assessing the PT tendons.
3. After completion of task 2, the optical fiber sensors identified were subjected to a limited feasibility assessment.

## RESULTS

### Future Projects with PT Duct Detail

Through consultation with Julius Volgyi, VDOT Structure & Bridge Division, it was determined that only one structure was planned for construction in the next 2 years in Virginia involving PT ducts.

**State-of-the-art Assessment of Structural Health Monitoring Technology**

After a review of the available technical literature, attendance at national technical conferences, and meetings and discussions with companies and researchers active in the technical area, the following technical assessment was developed. Because of the capital costs associated with manufacturing such technology, it was discovered that quite often the devices studied are either conceptual or prototypes that are not readily available commercially. Consequently, the assessment includes "concept" information distilled by the author. Where a specific device or instrument is available, a reference is provided.

Numerous federal agencies are exploring the potential for "structural health monitoring" with the expectation that mature technology offers the potential for considerable economic benefit as well as the potential for improved performance. Agencies such as NASA are considering such technology for flight monitoring; FHWA and AASHTO are considering it as part of an overall asset management program. To some extent, however, there exists an impediment to significant utilization in that little confidence has been developed because there is a hesitancy to utilize the unproven technology.

Those in positions of responsibility for managing large structures or systems would clearly benefit, if the promises of this technology were proven. However, the cost to implement this unproven technology is significant and is considered an unsafe gamble. In some instances, the managers, because of the rapid pace of electronic development, are likely to not fully comprehend the technologies and dismiss some of the technology as simple high-tech gadgetry. Nevertheless, there are an increasing number of applications where technology, if implemented, could have an enormous impact in the transportation infrastructure. For example, a number of different strain measuring systems that are battery powered with wireless data transmission capabilities are available. Installation of such devices attached to critical members would allow a direct assessment of cyclic loading, rather than indirectly through automated traffic counting. In other instances, appropriate location of such devices can provide information about foundations rather than indirectly assessing scour. Embedding, or incorporating, sensors during construction would allow for validating design assumptions regarding load distribution. In some instances, technology that is long since state of the art could be quite beneficial if utilized to collect information that is presently part of traffic, pavement, bridge, maintenance, and facilities management systems. However, the implementation of health monitoring for a single aspect of a structure, or system, is probably unlikely unless there is a crisis that cannot be mitigated by eliminating this particular detail.

Prestressed steel tendons, including those that are post-tensioned, are used to strengthen concrete structures but can be eliminated from bridge designs. Such a decision might be made if it is determined that problems with PT ducts are not worth the potential risk in the future. For example, the United Kingdom imposed a moratorium on post-tensioned tendons in the late 1990s. Use of coated or other "non-corroding" tendons apparently did not allay concerns at that time. Recently the moratorium was lifted as long as the duct is non-metallic in order to facilitate inspection for voids in the grout with a radar technique.

Economic comparisons of various alternatives to current practice may ultimately guide the bridge designer. In such comparisons it will be important to factor in the potential cost reduction that would occur if the technology, or alternative product, were produced in large volume. It is the working assumption in this report that PT tendons will continue to be used in bridge construction and that it will be important to assure that the condition of such tendons is adequate.

Technology determined to have potential for monitoring the health of PT tendons is described. As has been suggested, a decision to implement health monitoring of a structure is likely to involve a comprehensive strategy, while monitoring of a single component is unlikely. It is not feasible to discuss all of the details of these various comprehensive strategies. Some of the technology identified for PT ducts will be more appropriate for some strategies than others.

**Prestressed Steel Tendons**

Prestressed steel tendons are used to strengthen concrete structures by applying a large tensile load, which induces an elastic tensile deformation, to high-strength steel. In some instances the tendons are encased directly in concrete; the concrete then cures and the load is removed. The steel attempts to contract, but due to the constraint imposed by the cured concrete, it is only partially able to do so and remains in a state of residual tensile strain. The surrounding concrete is subjected to compressive stresses because the steel wants to contract further.

In other instances, the concrete structure is fabricated and provision is made to insert steel tendons through openings, or ducts. The ducts are composed of either galvanized steel or polymer material. The tendons, once inserted, are loaded in tension and elastically deformed. Gripping devices, supported by the concrete structure, are attached and the devices used to load the tendons are removed. The tendons try to relax but are constrained by the gripping devices, or anchorages, and remain in a state of residual tension; the concrete structure is correspondingly loaded in compression by the elastically deformed steel.

If the tensile load is applied to the tendon after the concrete structure has at least partially cured it is referred to as post-tensioned, otherwise as simply prestressed. Since it is necessary for the tendon to maintain the load on the concrete for many years of service, a steel alloy that does not experience significant creep deformation at high stress is used. The typical steels used, though, exhibit stress corrosion cracking, so efforts are made to prevent corrosion from taking place. For the PT tendons, grout is pumped into the ducts to protect the tendons from corroding. Voids entrapped in the duct, caused by either poor construction practice or problems with the grout materials, have been found. In addition, the grouting material may crack, and in some instances cracking of polymer ducts has been reported. As long as the tendon is not exposed to moisture or oxygen, voids in the grout are not problematic.

Generally the tendons are composed of six steel strands that are helically spiraled around a seventh strand, and many separate tendons are present in the same duct. If a strand fails the tensile stress (and strain) in the other strands increases, but the total load can never exceed that used to prestress the tendons (excluding external service loads). However, if the other strands have corroded, this increase in stress could cause failure. Since the grout has been formulated primarily to protect the tendon, it is not expected to transfer much load from the other strands back into the ends of the broken strands.

**Health Monitoring Considerations**

The health of the PT tendons in grouted ducts will depend on the environment to which the steel strands are exposed: chemical, mechanical, and thermal. The condition of the tendon at any time would depend on the condition of the strands that compose it.

Ideally the condition of a PT tendon in a grouted duct would be that all the strands are carrying tensile load, identical to the load achieved after release from the post-tensioning load system, excluding external loads. Correspondingly the health of the tendon would be deemed excellent if the environment chemically was not corrosive, mechanically the structure was performing properly, and thermally the conditions were not conducive for deterioration of the steel alloy.

Monitoring of all, or a subset, of these condition or environmental parameters would depend on how the information obtained was to be used for decision-making. Maintenance decisions might be supported by monitoring the chemical environment in the vicinity of the tendon, such as the presence of moisture or chlorides, while decisions with respect to reducing the load rating might be supported by monitoring the strain in the tendon.

The extent of the monitoring will also depend on whether data are used to support some modeling or predictive simulation. For example, assumptions consistent with a model might require data from specific locations, while another model might simply require knowledge of the temperature near the bridge site in order to predict the temperature everywhere throughout the structure. The author is not aware of any models presently available for predicting the long-term behavior of PT tendons.

**Cost Consideration**

Assessing the cost for different structural health monitoring technologies is complicated by the impact of monitoring strategy on the overall cost determination. Whether sensors are installed during construction, or subsequently; whether monitoring is continuous, or periodic; whether the sensors report to hubs that in turn report to a central data analysis point, by wires or wireless; and whether the data are then locally processed or reported to a remote site can all significantly alter the cost.

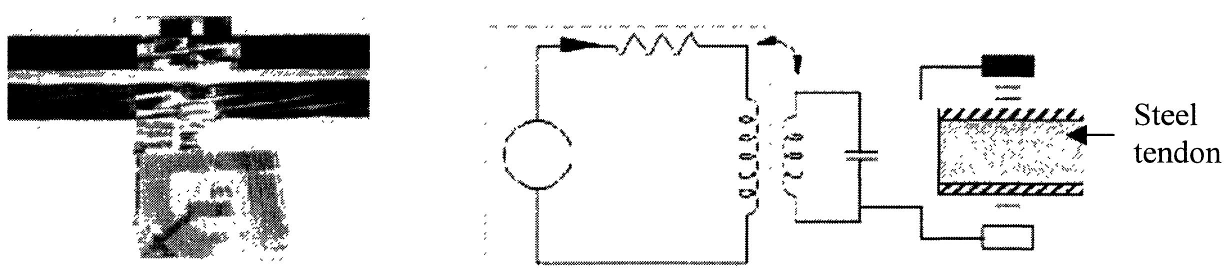
**Sensor Concepts**

Application of any sensor for health monitoring requires attention to the three important issues: construction survivability, sensor reliability, and sensor durability. A sensor must survive construction, and ideally the installation should avoid special handling. This requirement might be achieved by preparation of the sensor in a rugged or protected configuration prior to construction. Once the sensor has been properly installed, it must reliably sense or measure the parameter of interest at location(s) of interest. Finally the sensor must be durable and perform properly for the life of the structure. Consequently, in light of the rapid advances with microelectronics, postponing application for a few years might allow for newer and better sensors to be utilized. However, during the interim period, any structure built would be constructed without benefit of such health monitoring. If sensors that measure fundamental properties such as displacement, temperature, moisture, pH, etc., are used, concern can be allayed over whether delaying implementation might allow a "better" sensor to be installed. If the sensor survives construction and functions reliably for the life of the structure, the focus of development can be directed at improving how to use these fundamental measurements to predict the long-term performance of these critical structures.

*Wireless Sensors*

Wireless is a term generally used to suggest that communication with other systems does not involve the use of wires, although the device itself could be reasonably large and incorporate wiring. Some wireless devices are quite small (Figure 1), and the only wiring is conductive layers etched on a substrate. Here the electrochemical activity associated with corrosion is detected as it provides a voltage from the galvanic cell formed by separate sites on the same tendon.

Most conventional measurement instrumentation can be set up in a wireless configuration using battery power supplies, possibly charged with solar panels, and may communicate with a base station a short distance away using FM radio communication. Figure 2 is a unit that is commercially available from Campbell Scientific and is an example of a battery-powered unit for transmitting data from a measurement site.




(a) (b)

**Figure 1. (a) A wireless sensor for corrosion monitoring[4] attached to a steel tendon and (b) the schematic diagram**

**Figure 2. Campbell Scientific RF 400 Spread Spectrum Radio[5]**

Using such wireless technology, multiple measurement sites can report to one central processing site, avoiding the need to string wires long distances, which might require considerable effort as well as traffic control.

Other microelectronic wireless devices may incorporate no on-board power supply and are designed to be powered by the same device with which the microelectronic unit communicates measurement information. Such devices can be quite small and may be "interrogated" by a microwave communication device. Since these devices are so small and unobtrusive, it would be possible to incorporate large numbers into materials such as concrete. An implementation limitation, at this time, is that the orientation of the device is important, so placement might be time-consuming, and shielding will occur if a metallic material is placed between the device and the interrogating system. Consequently placement in metallic ducts would shield this type of sensor, but not for polymer ducts. In the latter case, the path between the device and the interrogating system would need to be unobstructed by the steel tendons.

Using special coatings, different liquids can be distinguished, but development is still needed to detect moisture on the surface of a steel tendon covered with grout.[6] Extensive use is being made of the radio-frequency identification chip (RFID) that can be embedded in credit cards, or inventory markers.[7] These devices can also be integrated with other microelectronic devices to create different types of sensors. The iButton is a similar type of device packaged in a tiny stainless steel "can" for situations requiring a rugged configuration.[8] Applying these devices will demand considerable engineering development that is unlikely to occur unless structural health monitoring is made a priority.

*Optical Fiber Sensors*

A considerable number of optical fiber sensors are now commercially available, and active development is underway for additional sensors. These sensors are lightweight, unobtrusive, insensitive to electromagnetic interference, and for cases where multiple sensors are placed on a single fiber, only a single point of egress is needed. Much of the present development is being driven by oil field or aerospace applications. Of particular relevance for health monitoring of PT tendons are sensors for detecting strain, temperature, moisture, and acoustic emission.

*Extrinsic Fabry-Perot Interferometer.* The configuration of fibers shown in Figure 3, where the light exits and re-enters the fiber to form an "extrinsic" Fabry-Perot interferometer. This optical fiber device can be used for displacement detection comparable to a resistance wire strain gage and with some special adjustment can detect transient displacements typical of acoustic emission. The sensor could be used to detect failure of tendon strands. Due to the nature of this configuration, only one such sensor can be placed on a single fiber. However, it is possible to also use this sensor to measure the temperature at the location of the sensor.

*Long-Period Grating (LPG).* Using a configuration (Figure 4) referred to as a long-period grating that incorporates an "intrinsic grating" and a specially modified surface coating, different chemical species can be detected. Luna Innovation, using funding from a NIST Advanced Technology Project,[6] has developed an LPG sensor that detects moisture level. It is possible to place as many as five LPG sensors on a single fiber; the spacing between sensors can be arranged to suit the application. As the specially modified surface coating absorbs moisture, the index of refraction of the fiber changes, which in turn changes the amount of light lost through the coating.

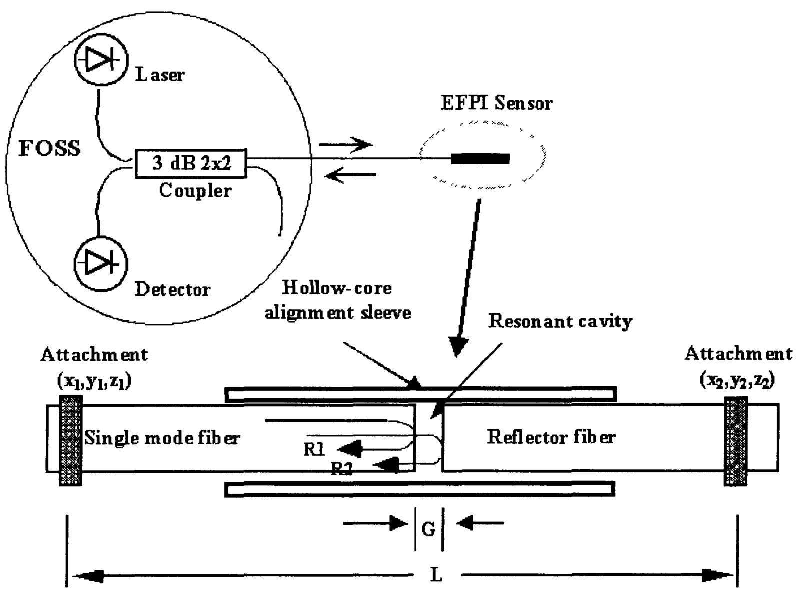



**Figure. 3. Extrinsic Fabry-Perot interferometric sensor for detecting displacement, temperature, or acoustic emission**

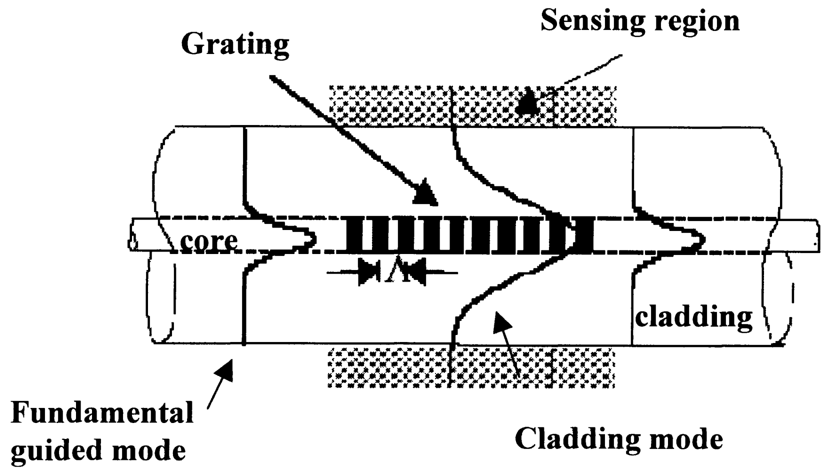



**Figure 4. Long-Period grating with sensing layer specially formulated for detecting moisture**

*Bragg Grating.* The Bragg grating sensor is intrinsic and involves an internal modification of the optical fiber that partially reflects light. The spacing of these modified regions and the interference that results can be used to determine the strain of the fiber in the area of the grating (Figure 5). It is possible to place very large numbers of Bragg grating sensors on a single fiber. Scientists at NASA developed a method for processing the optical signal in order to separate the strain data for, in theory, many thousands of sensors; this capability was demonstrated for a fiber with 800 separate Bragg grating sensors.[9]

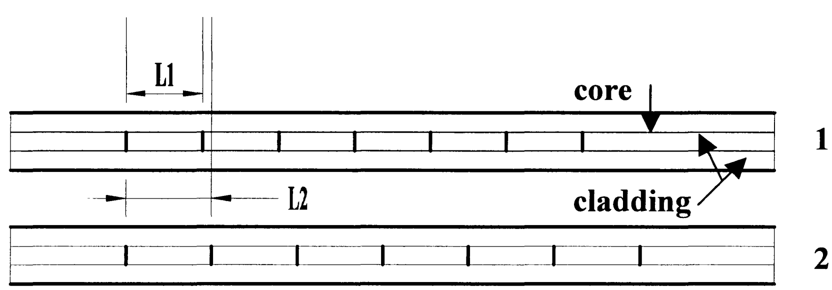



**Figure 5. Schematic of how a fiber Bragg grating is used for detecting strain. 1 and 2 represent the optical fiber containing the Bragg grating in different states of elongation. The optical interference is different for these different conditions and allows the spacing of the deformed grating lines to be determined. The spacing for the two different situations can then be used to determine the change in strain from condition 1 to condition 2, $\varepsilon = (L_2 - L_1)/L_0$.**

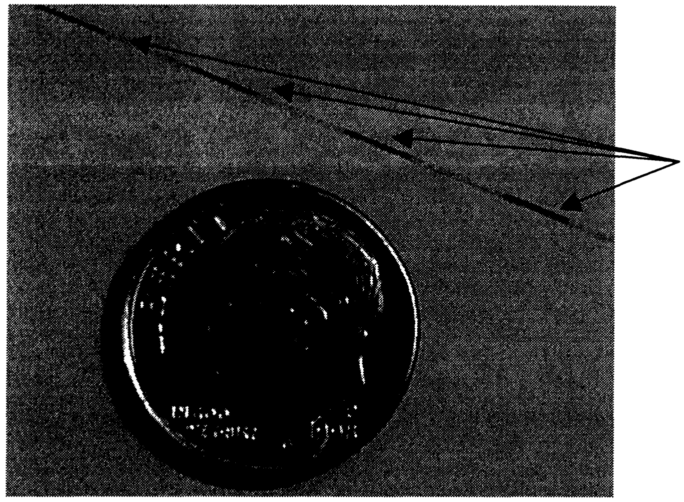



**Figure 6. Image showing a segment of optical fiber with Bragg grating sensors every centimeter, dark regions, in comparison to a dime**

Figure 6 shows a segment of optical fiber with Bragg gratings separated at a distance of 1 cm to provide the reader with a sense of the size. Despite the number of Bragg grating strain sensors on a single fiber, only one point of penetration, or attachment, is required. This offers enormous benefits for installation and, of course, cost savings over conventional strain monitoring instrumentation. For conventional instrumentation, at least two wires and a separate strain gage amplifying unit are required for each gage along with whatever instrumentation is needed to collect and store the data.

## Feasibility Assessment of Optical Fiber Sensors

Due to the short period of performance of this project, only a limited assessment of feasibility of certain of the most promising sensor technologies was performed. In particular, the EFPI AE sensor capability for detecting tendon breaks and the fiber Bragg grating sensor capability for distributed strain sensing were evaluated. It was not possible to assess the construction survivability or durability of these sensors. It is reasonable to assume that the issue of construction survivability is primarily an engineering challenge, while durability can only be assessed through field trials or validated accelerated testing.

### Feasibility of EFPI AE Sensor for Detecting Strand Breaks

Corrosion will in some cases cause PT tendon strands to fail suddenly. This failure causes a sudden reduction of load in that strand that has associated with it a transient displacement that travels along the tendon. Since the strand is touching other strands and may be surrounded by grout, shear transfer will cause a displacement transverse to the tendon. Conventional acoustic emission monitoring can be performed to detect such breaks using transducers that are predominantly sensitive to out-of-plane displacement. For safety considerations, a series of tests was performed as an analog to the tendon strand break that did not result in the large load release associate with the strand failure.

To demonstrate the capability of the EFPI AE sensor for detecting strand or fiber breakage, a test configuration used by other investigators, Prosser et al.,[10] for which actual displacements due to the sudden release of energy could be predicted was used. The test configuration involved a 330.2 x 330.2 x 3.175 mm 6061 aluminum plate. A long glass fiber was bonded to the center of the edge face of the plate, loaded in tension, and then cleaved to initiate a simulated break. The EFPI AE sensor was located on the surface of the plate in-line with the fiber (Figure 7). The locations were selected to try to provide as long a time interval as possible without reflections from the lateral boundaries. In addition, this configuration was selected because the disturbance is dominated by in-plane displacements, as would be a strand break if detected at a position along the strand away from the break point. Figure 8 shows the signals detected using the EFPI AE sensor and the conventional AE sensor. The EFPI AE response is much stronger, as was expected because of its in-plane displacement sensitivity. Although the conventional AE sensor detects the event, in a post-tension structure, the sensor is normally attached to the concrete structure and relies on mode conversion of the in-plane energy or structural vibrations excited by the strand break to provide a disturbance it can detect. However, detection of the in-plane displacements initially triggered by a strand break should provide the highest probability of detection.

**Feasibility of Distributed Bragg Grating Strain Sensing System for Monitoring Tendon Strain**

PT tendons are loaded to nearly 1 percent strain (10,000 microstrain) and then anchored in order to hold the concrete structure in compression. If for any reason, e.g., slippage or strand breakage, the tensile force provided by these tendons decreases and causes the compressive loading of the concrete structure to decrease, it may jeopardizing the integrity of the structure. Although the strain along the length of the PT tendon will be positive, it may vary in magnitude due to routing of the tendon or shear transfer due to friction between strands and grouting. Routing might cause some bending that will cause the strains in local regions to vary slightly. Also, if a strand fails locally, the strain will drop to zero due to elastic relaxation at the break, but since the strand is wound about the tendon bundle and encased in grout, shear transfer will keep the strain far from the break above zero. Consequently the strain detected by an optical fiber with Bragg grating sensors routed along a strand that spirals about the central strand would be expected to be reasonably similar while all strands in the tendon remain intact. As strands break, the strain will tend to increase in the remaining strands and other tendons and the sensing fiber as well.

To assess the feasibility of using an optical fiber with intrinsic Bragg gratings at 1-cm intervals to monitor the strains developed in a PT tendon, a test mock-up was devised.

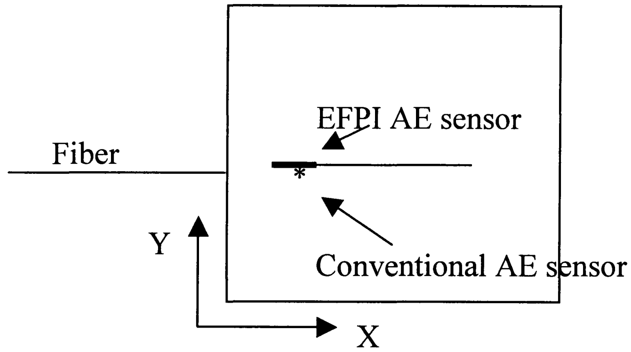



**Figure 7. Testing configuration of 330.2 x 330.2 x 3.175 mm 6061 Al plate with attached EFPI AE sensor and conventional sensor, and a glass fiber, used to simulate a strand break, bonded to the edge face of the plate**

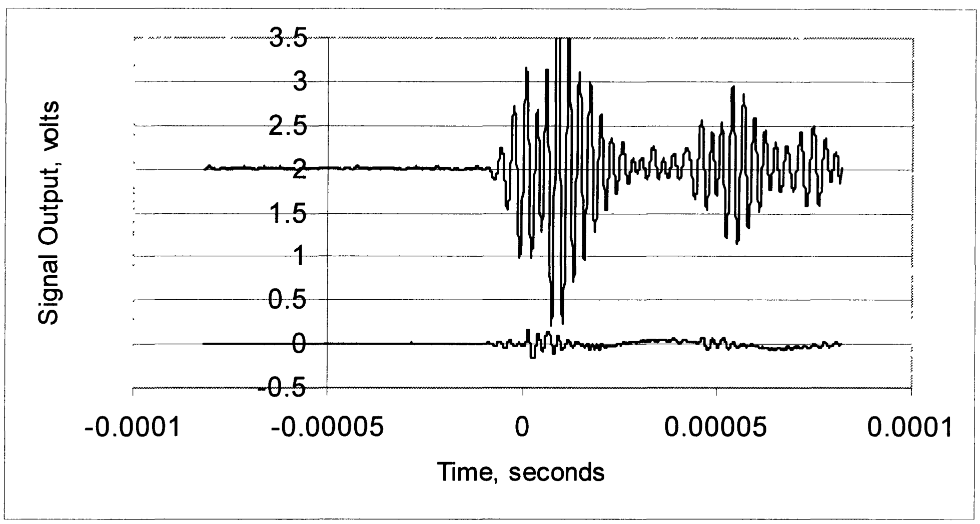



**Figure 8. The signal output for an EFPI AE sensor (upper, offset by 2 volts) and a conventional AE sensor (lower) excited by a simulated glass fiber break with the fiber attached to the edge face of an aluminum plate at a location expected to excite predominantly in-plane displacements at the location of the AE sensors**

A piece of optical fiber with 37 Bragg grating sensors at 1-cm intervals was bonded in the "valley" between two strands that spiral about the central strand of a 17-inch-long section (Figure 9). (It is anticipated that by bonding the fiber in such a position of a 7-strand tendon the fiber would be protected by the larger diameter strands as it is towed through the duct even if the tendon is scuffed by being dragged over piers or across duct unions. Once in place the tendon can be loaded in tension by the hydraulic jacks and the tendon, and the attached optical fiber, strained to an approximate 1 percent strain before the tendon is anchored and released in order to force the concrete structure into compression. An effective means of connecting the optical fiber sensor would need to be developed that could pass through the anchorage and survive the tensioning process.) The instrumented section was encased in a clear section of polymer tubing to allow for grouting of the tendon at a later time. Knuckle clamps at the ends and two eyebolts located in the central region were used to load the tendon in four-point bending.

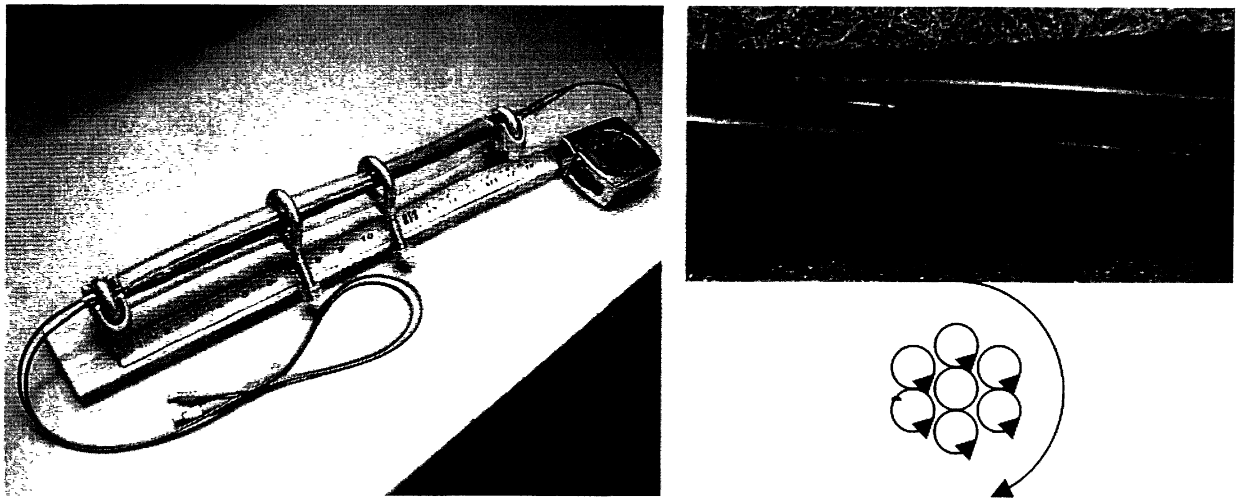


**Figure 9. A small section of 7-strand tendon instrumented with an optical fiber with 37 Bragg gratings sensors every centimeter. The fiber is bonded with epoxy in the "valley" (arrow) between two strands that spiral around the central strand. [The diagram shows that care needs to be exercised so that the fiber (solid small dot) is attached to a strand so it will rotate away from the "pinch" point when the strands straighten during tensioning. The large arc indicates the orientation of the spiral, while the small arrowheads indicate the direction of rotation of the strands as they straighten.] Knuckle clamps at each end and two eyebolts are used to load the section in four-point bending. A clear polymer tube surrounds the tendon to allow for grouting at a later time. Note: the gages in the constant moment section experience different strains because they spiral about the neutral axis.**

Figure 10 displays the strains measured by each of the 37 Bragg grating sensors that spiraled about the tendon subject to four-point bending. Strains were collected at two different deflections. The assembly was set aside overnight, and then the strains were collected again (Figure 11). Most of the deflection of the tendon had relaxed because the epoxy attaching the optical fiber, not optimized for this application, had deformed viscoelastically during the intervening time.

## Follow-on Field Testing of Selected Post-Tensioned Tendon Health Monitoring

The potential cost benefits of successfully implementing reliable health monitoring technology were recognized when the original work plan was formulated. At that time it was envisioned that the Innovative Bridge Research and Construction Program (IBRCP) was a potential source of resources for field-testing the health monitoring technologies identified through this study. Unfortunately at the time appropriate for developing a proposal for the IBRCP no bridge project involving PT tendon details was scheduled for Virginia in the near future that could serve as a testbed. As a result, no IBRCP proposal was submitted.

[The optical fiber with Bragg grating sensors and the instrument and software necessary to collect and analyze the signals to determine the strain at each of the grating locations are based on technology developed by NASA and licensed by Luna Innovations, Inc. Luna provided the fiber and Luna technicians collected and processed the signals for the data displayed. The DDS monitoring unit has 4 independent channels and costs ~$100K; the telecommunications grade optical fiber costs ~10¢/meter and the sensors are typically spaced 1 cm apart, so each meter would include 50 sensors.]

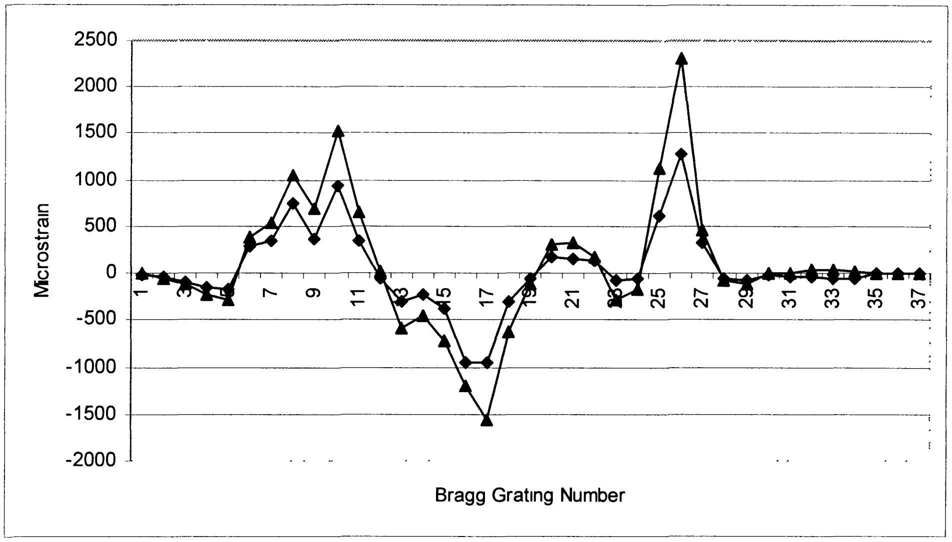



**Figure 10. Display of strain values collected for each of the 37 Bragg grating sensors at two different deflections caused by different amounts of tightening of the eyebolts. The peak positive values are from grating sensors in the vicinity of the eyebolts.**

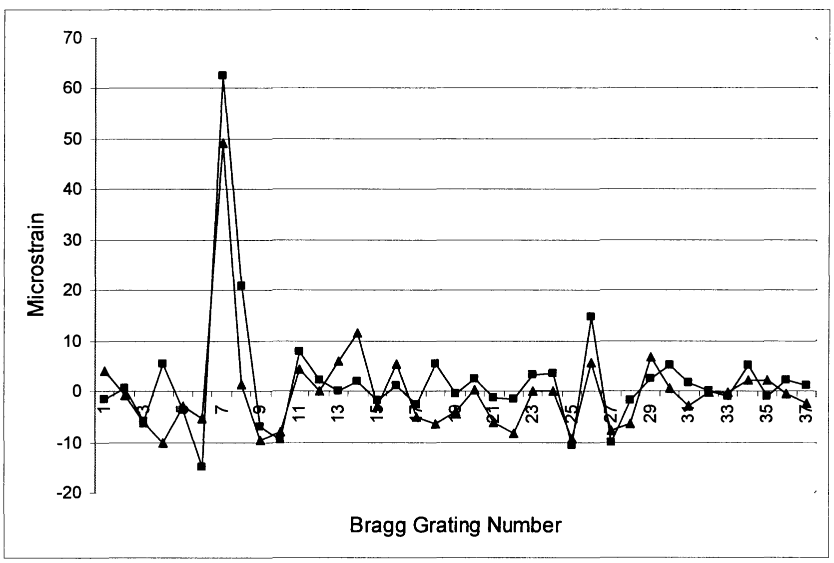



**Figure 11. Two different data sets collected at slightly different times display strain values 17 hours after the final data collection shown in Figure 9 for each of the 37 gages. Most of the deflection of the tendon has relaxed as the epoxy, not optimized for this application, used to attach the optical fiber had deformed viscoelastically during the intervening period.**

## DISCUSSION

Advances in microelectronic technology offer a vast variety of potential health monitoring technologies. Unfortunately many of these technologies are either only in the concept, or early development stage, or are not sufficiently mature for actual implementation. The choice of technology for feasibility assessment was made only of technology that was sufficiently mature as to be commercially available.

However, no technology was identified that has been tested subject to constraints associated with conventional bridge construction. Until such testing has been performed advanced development to address issues, e.g., environmental exposure, greater than 75-year desired service life, resulting from such application will not occur.

Although other possible applications of health monitoring were not carefully assessed, several that seem feasible include high mast lights, overhead sign structures, monitoring of slope stability, pavement strain monitoring at different levels, chloride ion diffusion near rebar in PCC, maturity measurements, and monitoring settlement in areas where scour is of concern. Recent interest in health monitoring and smart materials has attracted the attention of electrical engineers. These groups are exploring ways to construct embeddable sensors using off-the-shelf electronic devices. SRI International, working with Caltrans, is developing a Smart Pebble™ that utilizes an RFID chip integrated with a corrosion cell.[11] The Johns Hopkins Applied Physics Laboratory, working with Maryland DOT, is developing a "Wireless Embedded Sensor Platform" (that can be used with a variety of different sensing capabilities) into a unit called the Smart Aggregate.[12] They plan to develop capabilities to measure corrosion rate and chloride sensors with the devices, designed to last 50 years, for a cost of ~$50 each. Meanwhile, VTRC, in conjunction with FHWA and working with VDOT, has developed an embeddable corrosion sensor that is already installed in a bridge deck on Rte. 29 in Lynchburg.[13]

## CONCLUSIONS

Three technologies, all commercially available optical fiber sensors, offer capability for health monitoring of PT tendons for bridge construction. The identified technologies include:

1. long-period grating for monitoring the presence of moisture
2. optical fiber-based distributed Bragg grating strain sensors for monitoring tendon strain along the entire length
3. Extrinsic Fabry-Perot interferometric in-plane acoustic emission sensor for detecting strand breakage.

Limited assessment of feasibility of the distributed Bragg grating strain sensors and the EFPI AE sensor confirms:

1. Monitoring of axial strain at 1-cm intervals along the length of a PT tendon is possible with only a single optical fiber.
2. The EFPI AE sensor is selectively sensitive to in-plane displacements that are generated by tendon strand breakage with more than a factor of 20 greater response.

Development adapting these technologies to health monitoring post-tensioned tendons in bridge structures is warranted.

## RECOMMENDATIONS

1. The identified technologies should be developed for application to bridge structures.

2. Bridge management techniques that utilize the data provided by such technology must be developed.

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