

Discrete Fiber Optic Sensing Techniques for Structural Health Monitoring of Bridges

Farhad Ansari

Synopsis: From the very beginnings of time mankind has been intrigued with the potential applications of light and the possibilities that it could bring about. The origins of optical fibers probably go back to mid 19th century when the scientists tried to guide, bend, and transmit the light from one location to another. Now, optical fibers have found widespread usage in telecommunications as well as in medical and sensing applications. This article provides a summary review of principles involved in sensing with discrete optical fibers such as Bragg gratings and specific methods more prevalently employed in monitoring of bridges. The focus will be in application examples including monitoring of the masonry vaults of the Brooklyn Bridge, deformation of cable stays, and fiber optic accelerometers for testing of bridges.

Keywords: Cracks; Damage; Fiber Optic Sensors; Structural Health Monitoring; FBG; Bridges; Stay Cables; Brooklyn Bridge;

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INTRODUCTION

Structures are monitored because of safety concerns, diagnostics and problem solving, forensic analysis, and condition assessment. In addition to routine visual assessments, survey of literature reveals the existence of many approaches for monitoring of structures including strain and deformation based techniques, vibration analysis, acoustics, and optical techniques. The practice of structural health monitoring (SHM) in mechanical and aeronautical systems has advanced to the stage where they now involve step-by-step text book procedures. However, the same is not true for civil structures and in particular for bridges. In comparison to mechanical systems, bridges are rather large and massive; exposed to ambient and environmental conditions; composed of several types of materials some inherently heterogeneous; possess many connections, splices, and expansion joints and less than ideal boundary conditions, manufactured while exposed to external elements, and under traffic or operation at the time of monitoring. Therefore, an effective strategy for monitoring of bridges requires a sound strategy for engineering analysis of the structural problems, economical placement of sensors and sensor types, interpretation of sensor data, quantitative analysis of the structure and correlation of the bridge issues with SHM results.

An important element in structural health monitoring is selection and placement of sensors suitable for measurement of key parameters that influence the performance, service requirements, and health of the structural system. In many recent applications, optical fiber sensors have emerged as sensors of choice. This is due to the fact that fiber optic sensors possess many attributes of interest in civil structural monitoring, including: single channel distributed sensing, geometric adaptability, immunity to electrical and magnetic interference, elimination of lead lines, optical transfer of information, high resolution, and high signal to noise ratio. Optical fibers transduce physical or ambient perturbations through intensity modulation, wavelength shifts, frequency changes, and interference of the optical signals. A number of sensor types have been developed based on these principles including Fiber Bragg Gratings (FBG), Fabry Perot (FP) and long gauge white light sensors (Ansari, 2007). However, other sensor designs such as those based on intensity modulations of light waves as well as Brillouin scattering distributed sensors have been developed and effectively employed in civil engineering applications (Glisic, et al, 2010, 2011, Gu, et al, 2000, Wu et al, 2010, Bao et al., 2002, Yuan, et al , 1997, Zhao et al, 2002). Over the years, FBG sensors have transcended from laboratory bench tops to full scale mass production for applications in bridges, tunnels, dams, high rise buildings and other types of structures. One of the practical advantages of FBG sensors is the capability for serial multiplexing of several sensors along a single optical fiber cable. This feature reduces both the number of lead cables necessary for transmission of the sensor signals as well the number of data acquisition channels in the optical interrogation instrument. These features render the sensor practical and cost effective for structural monitoring. This article focuses on some of the applications of FBG sensors in monitoring of bridges. Applications in three different bridges and measurement types are presented.

FIBER BRAGG GRATING SENSORS

The transduction mechanism in FBG sensors is based on the modulation of the wavelength of the optical signal travelling through the fiber. In essence, Bragg Gratings are produced by physical exposure of the optical fiber core to intense radiation of a UV laser. A mask is used to create a periodic change in the pitch of the grating in the optical fiber core. The pitch of the grating signifies the wavelength sensitivity of the grating. Bragg Gratings are typically 10 mm or so in length and the grating pitch can be selected to reflect specific wavelength components of the optical signal. Strain induced changes to the pitch of the FBG sensors result in proportionate variation in the wavelength of the signal (Fig. 1). The modulated light wave is then transmitted to an interrogation system for detection and demodulation. Calibration is required to convert the optical change into the measurand of interest, i.e. strain. In a manner similar to strain gages, calibration of optical fibers is related to the strain and temperature sensitivities of the fiber by appropriate gage factors. A complete review of theoretical basis for the establishment of strain and temperature sensitivities is given by Measures (2001). A brief description is given here for completeness.

The opto-thermo-mechanical process involved in fiber optic sensing relies on the optical path length, L_n , which is the product of the gauge length, L , and the core refractive index, n :

$$L_n = Ln \quad (1)$$

While L corresponds to the gauge length of the interferometric sensor, for FBG, L corresponds to the period of the Bragg and not the length of grating. FBG is sensitive to both changes in strain, $\Delta\epsilon$ and in temperature ΔT . In the case of uniaxial strain field and the absence of thermal gradients, the strain is related to the change in the optical path length by way of the gauge factor, G_ϵ :

$$\frac{\Delta L_n}{L_n} = G_\epsilon \Delta\epsilon \quad (2)$$

In Eq. (2) The change in optical path length is proportional to the wavelength change:

$$\frac{\Delta L_n}{L_n} = \frac{\Delta\lambda}{\lambda} \quad (3)$$

Where, λ and $\Delta\lambda$ are the Bragg wavelength, and the wavelength shift in FBG, respectively. Therefore, the gage factors for FBG sensor is defined as:

$$G_F = \frac{\Delta\lambda / \lambda}{\epsilon} \quad (4)$$

Eq. (4) is similar to the relationships for resistance strain gauges where the gauge factor, G_R defines the calibration factor relating the resistance change, $\Delta R / R$ to the strain, ϵ :

$$G_R = \frac{\Delta R / R}{\epsilon} \quad (5)$$

The calibration process for any of the FBG sensor is accomplished by mounting of the sensor to a calibration beam which is deflected to produce a known strain ϵ . The wavelength change is measured and the corresponding gauge factor is determined by Eq. (4).

APPLICATIONS

The Brooklyn Bridge

The Brooklyn Bridge approach structure on the Manhattan side of the East River was constructed over a series of increasingly taller and longer brick masonry vaults. The vaults that are the subject matter of this investigation are the two largest spans of the approach structure with span lengths of 10 and 10.4 m (32.8 and 34.1 ft), respectively. Longitudinal crown cracks covering the entire lengths of these cylindrical vaults were discovered during a routine inspection in 1996. The double-span vaults are seated on the walls of two 3-story masonry buildings. The structure to the west of these vaults is a steel truss and on the east is the bridge abutment as shown in Fig. 2. The bridge abutment is a masonry counterweight constructed on top of the steel anchorage for the main bridge cables. Visual inspection of the three floor levels and the basements in both structures also revealed existence of a vertical crack through the adjoining wall supporting the vaults. This crack was approximately halfway between the north and south ends of the structure, and ran from the seat of the vaults on third floor all the way to the exposed portion of the foundation in the basement (Fig. 3). In addition, other vertical cracks were present on the adjoining support wall as well as the support wall for the west vault, but they were confined to the upper levels of the structure. Details

regarding the instrumentation and SHM of the vaults are given elsewhere (Talebinejad, et al., 2011). Some of the SHM details are provided here.

Vaulted structures have been used throughout the centuries to support enormous structural loads. Because of the inherent geometric characteristics of the vaults, tensile stresses are eliminated and the loads are supported in compression. However, the vault thrust might push outward/inward as the bridge experiences overloading, foundation settlement or support displacement and thermal movements. As a result, cracks are formed in locations where line of thrust touches the boundaries of the vault (Fig. 4). The visual inspection observations were used in the decision making process in order to reduce the cost of the sensor installation and monitoring activities. In doing so, it was realized that the middle wall supporting the two vaults was considered most likely to have moved causing the vaults to crack. The cause for the formation of the main vertical crack in the middle wall could have been differential settlement of support following the construction of the bridge back in 1883, or excessive thrust from the vaults due to loads, and thermal gradients. The fact that the east wall was not cracked was attributed to confinement by the anchorage structure.

The sensor installation plan was based on the abovementioned considerations. The vault crown cracks were monitored by way of crack sensors, and to examine the movement of the walls, especially the middle vault, tiltmeters were used on all the floors. Temperature sensors were used on all the floor levels as well as at the vault locations in order to examine the effects of thermal gradients. Accelerometers were used for monitoring of traffic induced vibrations and the vibration of the wall in the basement adjacent to the anchorage. All the sensors were FBG based and a single optical interrogation unit was employed for the acquisition of sensor signals. Fig. 5 corresponds to the schematic front view of the vaults with sensor types and locations. Typical crack and tiltmeter sensors are shown in Fig. 6. For detailed analysis of all the sensor data and considerations leading to the conclusions provided here reference should be made to Talebinejad, et al. (2011). A typical result is shown in Fig. 7 which corresponds to the correlation between the vault crack sensors and the temperature sensor signals from the west vault over a twelve months period. These results and the results from the east vault indicate that the mid section of the vault went through a crack opening displacement cycle with crack opening displacement as large as 1.2 mm (0.05 in), commensurate with thermal fluctuations. The west vault controls the movements, because the mid section of the vault expands and crack opening displacements increase for rise in temperature and contract for falling temperatures. In essence, the crown cracks were developed due to the movement of the middle wall and the confinement of the vaults by the anchorage and the truss structures.

Lingotto Cable Stayed Pedestrian Bridge

The Lingotto pedestrian bridge was constructed in Turin, Italy for the 2006 winter Olympic Games (Fig. 8). The bridge construction was completed in late 2005. The bridge was designed to link pedestrian traffic from the Olympic village to the Lingotto commercial center by spanning over railroad tracks separating the two. The bridge was designed with a complex geometry. For example, the bridge deck is constructed on a radius, has a vertical rise and fall slope, and the elliptical arch is set on a diagonal with cables at various levels. Due to the unusual design of the bridge, it was decided that sensors should be installed to monitor the structural health of the bridge. The objective of the monitoring was to record the cable displacements and vibrations to evaluate the condition of the bridge.

The main structural component of the bridge is a large parabolic arch. The cross section of the arch is triangular and constructed of 15 mm (0.59 in) thick plates. The triangular cross section had 3m sides at the base and rotates toward the top. The arch has a 55 m (180.4 ft) footprint and stands up to a height of 70 m (229.7 ft). The main bridge superstructure consisted of two edge beams, and additional framing spans between the two beams. The deck is reinforced concrete. The total length of the bridge is 368 m (1207.3 ft) and the main span is 150 m (492.1 ft). Eight pairs of cable stays support the main span of the bridge from the arch. There are eight pairs of cable stays on each side of the arch. The cables on opposing sides of the arch work together to anchor the arch and support the bridge span. The cables are spaced approximately 18.5 m (60.7 ft) along the span of the bridge. The cables consist of twisted steel wires. The steel cables consisted of three diameters; 55 mm (2.2 in), 60 mm (2.4 in), and 75mm (3 in). The main sensors used for the structural health monitoring of the bridge consisted of specially designed Fiber Optic Bragg gratings (FBG). The FBG sensors were designed to measure dynamic deformations over a long gauge. Conventional sensors and accelerometers were also employed for monitoring of the deck. The fiber optic cable sensor used on the bridge is shown in Fig. 9. It includes a pre-tensioned FBG glued to angled supports at each end.

The FBG is protected by a PVDF (polyvinylidene difluoride) tube. After manufacturing, each sensor was installed on a cable to be tested and calibrated. During the calibration process, the sensor experiences several cyclic loads to assess repeatability, hysteresis, resolution and the sensitivity of the sensor. The induced changes in the wavelength of the sensor are calibrated against a high precision extensometer. The gauge factor for these sensors vary between 1.05 - 1.16. Fig. 10 shows a typical plot of the calibration test data. These sensors are capable of measuring strain and dynamic properties such as vibration frequency and damping ratios. The resolution of these sensors is typically rated at 1.2 $\mu\epsilon$.

Twenty sensors were installed on the cables of the Lingotto Bridge to continuously monitor the deformation and dynamic response of the cables. These sensors were installed on the cables near the end closest to the bridge deck. Fig. 11 shows a sensor mounted on one of the bridge cables. Data acquisition was accomplished by interrogator capable of acquiring the sensor data at a sampling frequency of 250 Hz and stored on an on-site computer.

In addition to monitoring the cable stays under ambient load conditions, static and dynamic load tests were conducted and the performance of the cables was recorded. Static load tests were completed by loading the bridge deck. Barrels were placed on the bridge deck and they were filled with water in sequence starting from the north side. Each of the 138 barrels was filled with 600 L (159 gallons) of water. After the tests, the barrels were emptied in the same manner. The strain in the FBG sensors was used to calculate the force in the cables and this was compared to the estimated design forces. Test setup for dynamic tests of the bridge included a 500 kg (1104 lb) concrete mass as a pendulum from a steel frame. The mass was hung at three different heights to excite the bridge at different natural frequencies. By swinging the pendulum mass, the bridge superstructure was excited. The pendulum setup was tested at three different locations along the span of the bridge.

Typical dynamic strain data as well as the frequencies computed from the cables are shown in Fig. 12 and 13. As shown in these figures the resolution of these types of sensors are extremely high and they were able to monitor the very low strain data from the measurements. The computer models found the first three natural frequencies of the bridge to be 0.454, 0.489, and 0.592 Hz. Because of the complex geometry of the bridge, almost all of the mode shapes are a combination of the lateral, bending and torsional deformations of the bridge. The first mode shape is lateral-torsional. In the second mode shape, the first bending mode shape is dominant. The third mode shape is the combination of lateral, bending and torsional deformation with more emphasis on the lateral movement.

Dynamic tests were done in both the longitudinal and transverse directions with different pendulum lengths. For the tests which were performed with pendulum oscillating in the transverse direction, nearly all of the sensors recorded a frequency of 0.54 Hz. Considering that the pendulum was swinging in the transverse direction, mode shapes which were dominated by the lateral deformation were more likely to be excited. So, it is evident that the third natural frequency of the bridge was captured with the fiber optic sensors.

Bridge Dynamics with Fiber Optic Accelerometers

Accelerometers are strategically placed in structures for the determination of dynamic characteristics and extraction of parameters such as natural frequencies and mode shapes. Typical sensing elements employed in the construction of accelerometers are piezoelectric and magnetostrictive materials. However, in recent years, fiber optic sensor accelerometers have become popular due to higher resolution and signal to noise ratios achieved in the applications. While the mass and spring systems form the basic structure of the accelerometers, various configurations have been employed for the construction of the fiber optic sensor accelerometers (Berkoff et al, 1996, Todd et al., 1998, Shi et al., 2003, Feng et al., 2011). A unique design was recently proposed by Talebinejad, et al (2009) where it utilizes a lumped mass and the stiffness of the optical fiber as the spring element. By employing this configuration, the FBG is always subject to uniform strain distribution along its length resulting in a sharp reflection with no broadening.

The simplest model of an accelerometer is a mass-spring system that is attached to an enclosing casing (Fig.14). The applied acceleration of the casing causes the mass to move, and this motion can be used to determine the magnitude of the acceleration. The equation of motion for the mass shown in Fig.4 is defined as:

$$m\ddot{x} + kx = -ma \quad (6)$$

Where, x is the displacement of the mass m relative to the casing, a is the ground acceleration and k is spring stiffness. Dividing both sides of the Eq.6 by the mass m and defining natural frequency of system by $\omega = \sqrt{k/m}$, result in:

$$\ddot{x} + \omega^2 x = -a \quad (7)$$

As shown in Fig.15, the design of the accelerometer involved stretching the optical fiber with FBG by a predetermined amount to achieve the required spring constant per accelerometer requirements. A lumped mass was attached to the fiber and guided through a precisely machined tube in order to eliminate the cross axis sensitivity. Modeling details and numerical simulation results for the evaluation of the sensor design are detailed in Talebinejad, et al (2009). The gauge factor was determined by the following relationship:

$$G = \frac{\Delta\lambda/\lambda}{a} \quad (8)$$

The calibration process was accomplished by mounting the FBG accelerometer along with a high-precision conventional piezoelectric accelerometer of known sensitivity on the cantilever beam. The wavelength shift due to the acceleration was measured during the experiments and employed in Eq.(8). Fig. 16 corresponds to a typical raw data from FBG accelerometer which is compared with the output of the conventional PZT accelerometer.

The accelerometers were also employed in testing a single span slab on girders bridge located in a western suburb of Chicago, Illinois. The bridge is 20.27 m (66.5 ft) long and has an overall width of 16.00 m (52.5 ft). The beams were supported on fixed bearings at the west end and rockers at the east end. Prior to the field testing of the bridge it was modeled using a commercial finite element program (ANSYS) in order to extract the modal properties and for comparison with the experimental results. The bridge remained open to traffic during the tests and therefore the accelerometers were mounted on the sidewalks. Eight optical fiber accelerometers were serially multiplexed 4 per line for the opposing sides of the bridge across the traffic lanes as shown in Fig.17. This configuration only required two channels of data acquisition and two optical fiber lead lines for the eight accelerometers. Sensor configuration allowed for the acquisition of the first bending and first torsional mode shapes of the bridge. Eight PCB piezoelectric accelerometers with the sensitivity of 1000 mv/g were also employed for comparison with the fiber optic accelerometers. Talebinejad, et al (2009) analysis of data indicated that the conventional and the fiber optic accelerometers compared well with errors of less than one percent. However, results from their preliminary numerical model did not fare well with the accelerometer data.

CONCLUSIONS

A brief summary of discrete optical fiber sensors and their applications in structural health monitoring of bridges is given in this article. Basic principles of FBG sensors and formulations leading to their calibrations are described. In general, FBG provide flexibility for design of sensors with customized sensing capabilities beyond the limitations of the conventional sensors. The geometric flexibility of these sensors renders them suitable for infrastructure applications. Example applications that are provided in the present article include monitoring of the masonry vaults of the Brooklyn Bridge, and cable stays in LingottoLingotto Bridge. Development and testing of a fiber optic FBG accelerometer was also described, including their applications in testing of a bridge in Illinois. Irrespective of the sensor, engineering judgment and knowledge about structural behavior are prerequisites to every structural monitoring activity.

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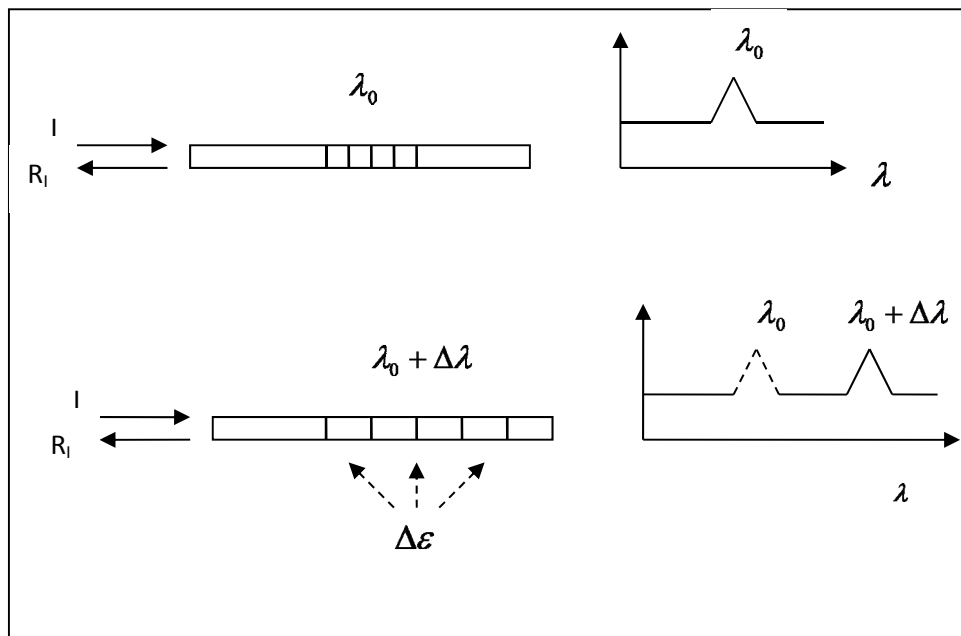


Figure 1 – Strain induced wavelength shift in FBG sensors.



Figure 2 – Masonry arch approach structures on the Manhattan side of the Brooklyn Bridge.

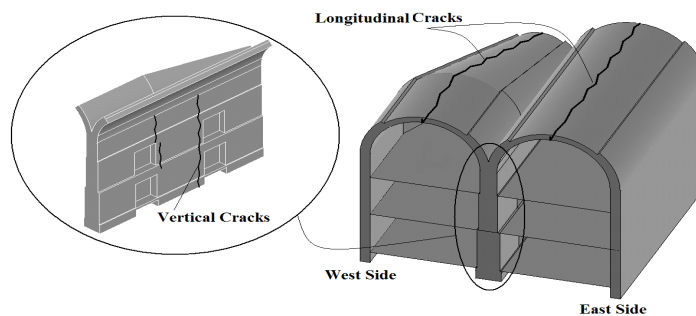


Figure 3 – Cracks in the masonry vaults and the support walls of the approach structure.

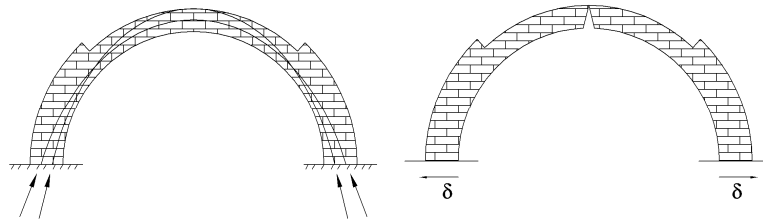


Figure 4 – Failure mechanism of the vaults.

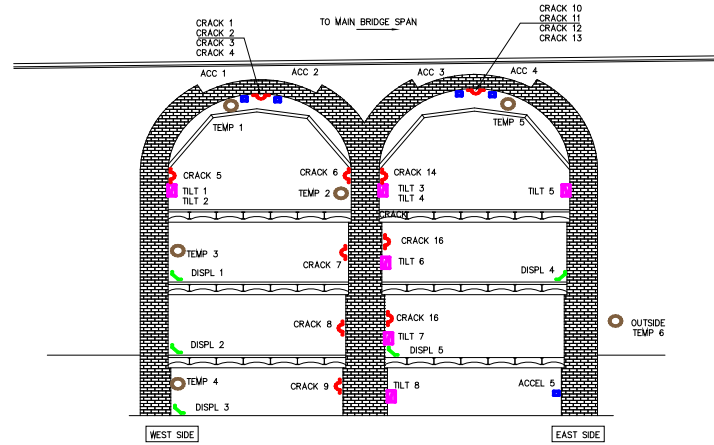


Figure 5 – Sensor layout for the double spam masonry vaults.



Figure 6 – Typical crack sensor at the crown crack and tiltmeter at the center wall

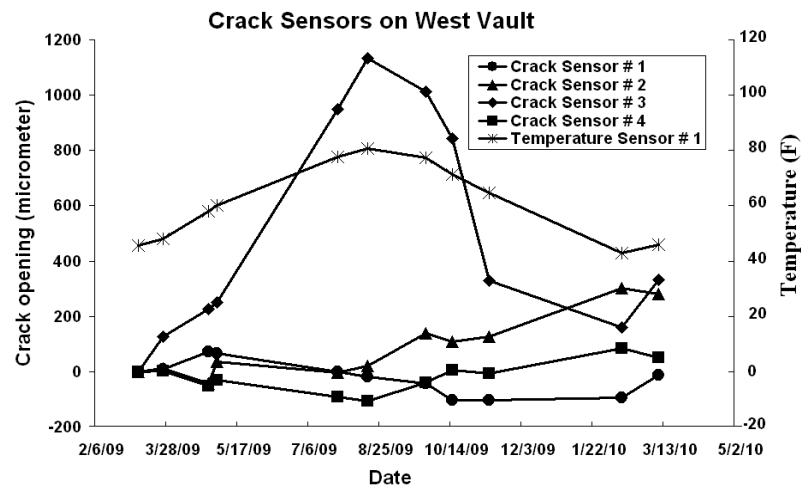


Figure 7 – Correlation of crack sensor and temperature data on the west vault over a 12 months period.



Figure 8 – LingottoLingotto Pedestrian bridge.

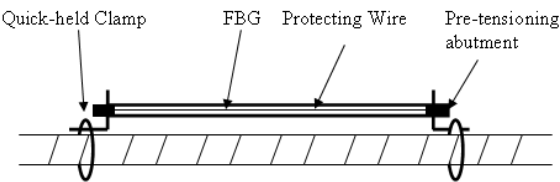


Figure 9 – FBG Cable Sensor.

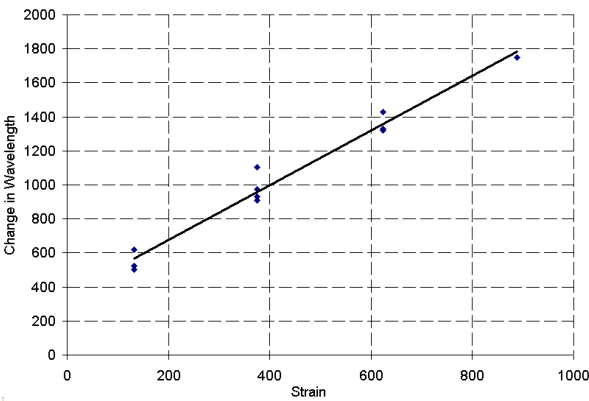


Figure 10 – Typical cable sensor calibration data.



Figure 11 – Typical field installation of FBG cable sensor (LingottoLingotto Bridge).

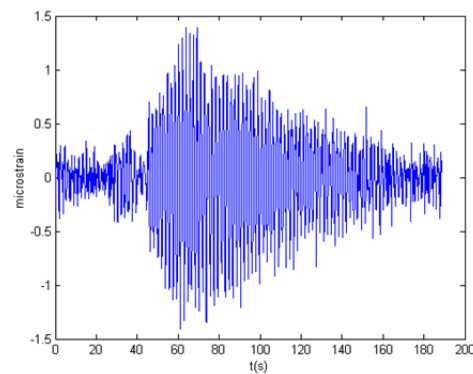


Figure 12 – Typical dynamic cable data from pendulum tests.

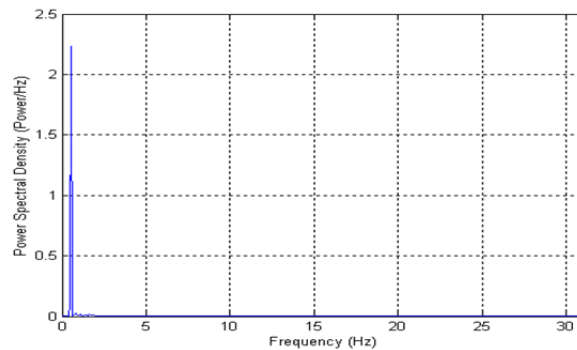


Figure 13 – Frequency domain analysis of the strain data for the cable stays.

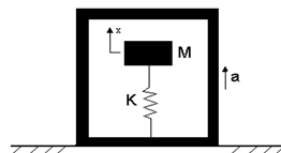


Figure14 – Basic spring mass system.

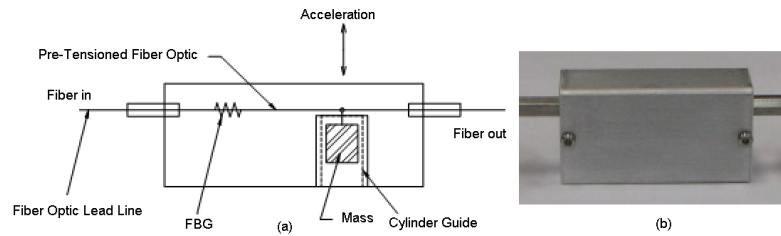


Figure 15 – (a) schematic design of the FBG accelerometer; (b) photo of the FBG

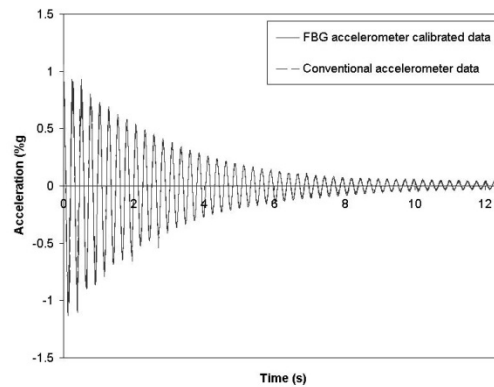


Figure 16 – FBG accelerometer calibrated data vs. conventional accelerometer data.

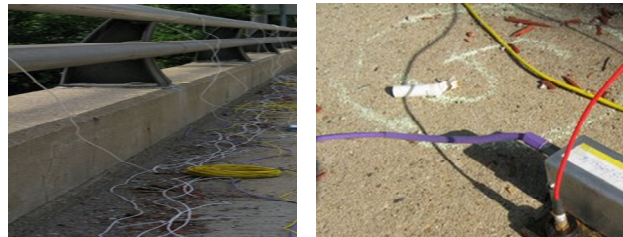


Figure 17 – Accelerometer locations on the side walk of the bridge.

Distributed fiber optic sensing technologies and applications – an overview

Branko Glisic

Synopsis: Needs for structural health monitoring in the last decades were rapidly increasing, and these needs stimulated developments of various sensing technologies. Distributed optical fiber sensing technologies have reached market maturity and opened new possibilities in structural health monitoring. Distributed strain sensor (sensing cable) is sensitive at each point of its length to strain changes and cracks. Such a sensor practically monitors one-dimensional strain field and can be installed over the entire length of the monitored structural members, and therefore provides for integrity monitoring, i.e. for direct detection and characterization of local strain changes generated by damage (including recognition, localization, and quantification or rating). The aim of this paper is to help researchers and practitioners to get familiar with distributed sensing technologies, to understand the meaning of the distributed measurement, and to learn on best performances and limitations of these technologies. Hence, this paper briefly presents light scattering as the main physical principle behind technologies, explains the spatial resolution as the important feature for interpretation of measurements, compares performances of various distributed technologies found in the market, and introduces the concept of integrity monitoring applicable to various concrete structures. Two illustrative examples are presented, including applications to pipeline and bridge.

Keywords: Distributed Fiber Optic Sensors, Structural Health Monitoring, Integrity Monitoring, Bridge Monitoring, Pipeline Monitoring, Brillouin Scattering, Overview of Technology

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ABSTRACT

Needs for structural health monitoring in the last decades were rapidly increasing, and these needs stimulated developments of various sensing technologies. Distributed optical fiber sensing technologies have reached market maturity and opened new possibilities in structural health monitoring. Distributed strain sensor (sensing cable) is sensitive at each point of its length to strain changes and cracks. Such a sensor practically monitors one-dimensional strain field and can be installed over the entire length of the monitored structural members, and therefore provides for integrity monitoring, i.e. for direct detection and characterization of local strain changes generated by damage (including recognition, localization, and quantification or rating). The aim of this paper is to help researchers and practitioners to get familiar with distributed sensing technologies, to understand the meaning of the distributed measurement, and to learn on best performances and limitations of these technologies. Hence, this paper briefly presents light scattering as the main physical principle behind technologies, explains the spatial resolution as the important feature for interpretation of measurements, compares performances of various distributed technologies found in the market, and introduces the concept of integrity monitoring applicable to various concrete structures. Two illustrative examples are presented, including applications to pipeline and bridge.

INTRODUCTION

Many large structures of critical significance to the US prosperity and economy are approaching the end of their lifespan and it is necessary to determine and observe their health condition in order to mitigate risks, prevent disasters, and plan maintenance activities in an optimized manner. Structural health monitoring (SHM) is an emerging branch of engineering with aim to address the assessment of structural health condition. The information obtained from monitoring is used to plan and design maintenance activities, increase safety, verify hypotheses, reduce uncertainty, and widen the knowledge concerning the structure being monitored. SHM helps prevent the adverse social, economic, ecological, and aesthetic impacts that may occur in the case of structural deficiency, and is critical to the emergence of sustainable civil and environmental engineering. Thus, the need for reliable, robust, and low-cost SHM is rapidly increasing.

The standard monitoring practice is based on the choice of a reduced number of points, supposed to be representative of the structural behavior, and their instrumentation with discrete sensors, short-gage or long-gage. However, reliability of detection and characterization of damage that occurs in the locations far from the discrete sensors is challenging, since it depends on sophisticated algorithms which performance is often decreased due to various influences that may “mask” the damage, such as high temperature variations and load changes, and outliers and missing data in monitoring results (Posenato et al. 2008). Denser network of sensors could improve the reliability of damage detection and characterization, but it will lead to significant increase of the costs associated to hardware (sensors and accessories), software (data management and analysis), and labor (installation, maintenance, and operation). These issues are especially emphasized in the case of large structures such as bridges, dams, tunnels, levees, and pipelines.

Distributed sensing technologies based on fiber optic sensors offer solutions for improved and reliable, yet affordable damage detection in large structures. The qualitative difference between the monitoring performed using discrete and distributed sensors is the following: discrete sensors monitor strain or average strain at discrete points, while the distributed sensors are capable of one-dimensional (linear) strain field monitoring. Distributed sensor can be installed along the whole length of structure and in this manner each cross-section of the structure is practically instrumented. The sensor is sensitive at each point of its length and it provides for direct damage detection, avoiding the use of sophisticated algorithms. In this manner integrity monitoring of structure can be reliably performed.

Distributed fiber optic technologies have reached market maturity, and they have been applied in pioneer projects worldwide (e.g. Thevenaz et al. 1999, Glisic and Inaudi 2007, Bennett 2008, etc.).

However, distributed fiber optic sensing technologies have their limitations, and their application and the interpretation of measurements is not as straight-forward as in the case of traditional strain sensors. Lack of proper understanding of distributed technologies may lead to improper selection and implementation of the monitoring system, which can, in turn, significantly reduce the overall performance of monitoring system in that particular project.

The aim of this paper is to help researchers and practitioners to get familiar with distributed sensing technologies, to understand the meaning of the distributed measurement, and to learn about best performances and limitations of these technologies. The next (second) section of the paper deals with distributed fiber optic sensors. A general introduction to fiber optic sensors is made first. Follows the introduction to distributed sensing and physical principles behind distributed sensing. Various distributed sensing techniques are then summarized and their potential for the use in SHM and integrity monitoring is compared. In the third section, the general integrity monitoring principle for large structures is briefly presented. Fourth section presents illustrative examples of applications to pipeline and bridge. Paper finishes with conclusions and acknowledgments.

DISTRIBUTED FIBER OPTIC SENSORS

General

A glass optical fiber is made of fused silica and used for transmitting light over large distances with very small losses. It consists of core, cladding, and coating. The core is the part which transmits the light and it has outer diameter (OD) that can be as small as 5 to 10 micrometers (0.0002-0.0004 in., single mode fibers), or about 50 micrometers (0.0020 in., multi mode fibers). The core is surrounded by cladding made of silica with slightly lower index of refraction than the core. The purpose of the cladding is to keep the light in the core (e.g. by total reflection), minimize the losses, and also physically to support the core region as the light propagates in the fiber. Finally the coating is a layer applied around the cladding in order to provide with physical robustness and general protection. The coating is the most commonly made of acrylate, in some cases of polyimide, and for some special applications (e.g. harsh environments, high temperatures) of other materials (e.g. carbon, aluminum, gold, etc.). The outer diameter of the optic fiber is typically ranged between 145 and 250 micrometers (0.0057-0.0098 in., similar to that of a human hair). Optical fibers operate over a range of wavelengths; 1310 and 1550 nanometer is common for single mode fibers with minimal losses and 850 and 1300 nanometer for multi mode fibers. Typical components of an optical fiber are shown in Figure 1.

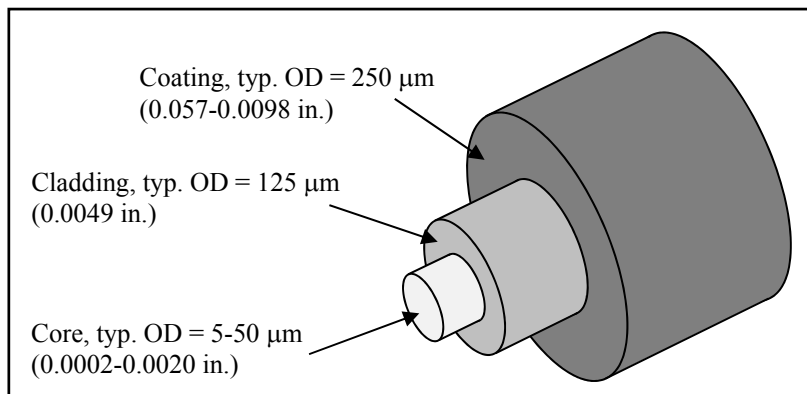


Figure 1–Typical components of an optical fiber.

Since 1990's, optical fibers are used in SHM of civil structures, and development and research is ongoing; existing technologies are improved and new products appear on the market continuously. The fiber optic sensors (FOS) are based on several different physical principles such as Extrinsic Fabry-Perot Interferometry (EFPI), Intrinsic

Michelson and Mach-Zehnder Interferometry (e.g. SOFO sensors), Fiber Bragg Gratings (FBG), and scattering of light. Clear and detailed descriptions over the different fiber optic technologies can be found in (Measures, 2001).

The high sensing performances of the FOS are intrinsically linked to the optical fiber itself. The optical fiber can be used for both sensing and signal transmission purposes. The silica of which the optical fiber is composed is an inert material, resistant to most chemicals in wide range of temperatures and is therefore suitable for applications in harsh chemical environments (Udd 2006). Various packaging especially designed for field applications made fiber optic sensors robust and safe to use even in very demanding environments (Udd 2006, Glisic and Inaudi 2007). The light used for sensing purposes in the core of the optical fiber does not interact with any surrounding electromagnetic (EM) field. Consequently, the fiber optic sensors are intrinsically immune to any EM interference (EMI), which contributes significantly to their long-term stability and reliability. The ability to measure over distances of several tens of kilometers without the need for any electrically active component is an important feature when monitoring large and remote structures, such as landmark bridges, dams, tunnels, and pipelines (Udd 2006).

Compared with conventional electrical sensors, fiber optic sensors offer two new and unique sensing tools: long-gauge strain sensors and truly distributed strain and/or temperature sensors. The former can be combined in topologies that allow for global structural monitoring while latter allows for one-dimensional strain field and integrity monitoring. Sensors that are generally used in civil engineering applications and their division based on gauge length, measurands, and the functional principle are presented in Figure 2.

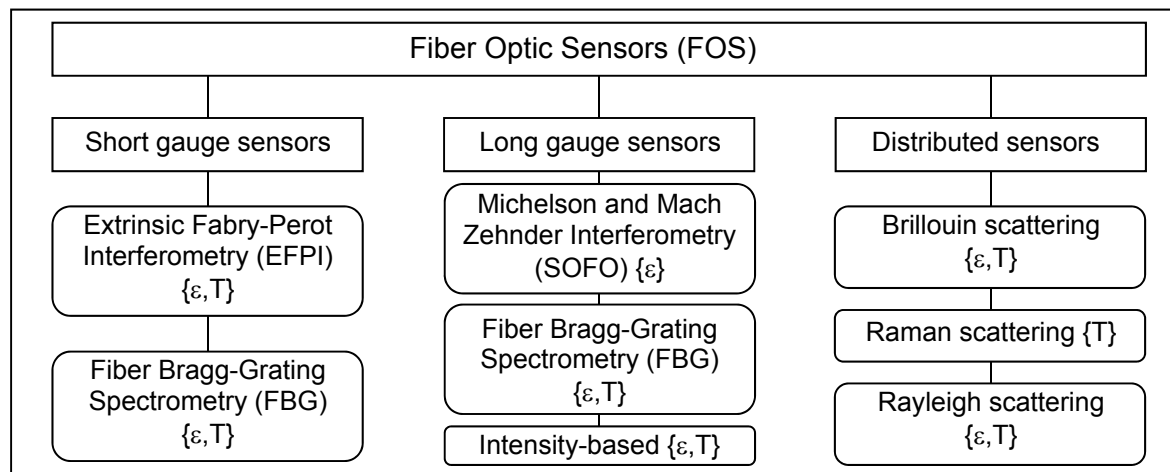


Figure 2–Division of FOS based on gauge length and functional principle; ϵ =strain, T= temperature.

The scope of this paper is limited to distributed sensors. More information concerning short- and long-gauge sensors can be found in literature (e.g., Measures 2001, Udd 2006, Glisic and Inaudi, 2007, Glisic 2011, etc.).

Recent significant developments in the optical telecommunications market helped reduce the cost of the FOS, which is still higher compared to conventional sensors, but however affordable and justified by superior long-term performance of the FOS, especially in the case of distributed fiber optic technologies applied to large structures.

Distributed sensing technologies

Distributed sensor (or sensing cable) can be represented by a single cable which is sensitive at every point along its length. Hence, one distributed sensor can replace large number of discrete sensors. Since the cable is continuous, it provides for monitoring of one-dimensional strain field. Moreover, it requires single connection cable to transmit the information to the reading unit, instead of a large number of connecting cables required in the case of wired discrete sensors. The reading unit is commonly placed on the structure or very close to it, but if necessary (e.g. if electrical power is not available at the structure) it can be placed as far as few kilometers from the structure. The data can be transmitted from the reading unit to the end-user using common wired or wireless telecommunication lines. Finally, distributed sensors are less difficult and more economic to install and operate. A schematic comparison between a structure equipped with distributed and discrete sensors is shown in Figure 3.

There are three main principles for distributed sensing: Rayleigh scattering effect (e.g. Posey et al. 2000), Brillouin scattering effect (e.g. Kurashima et al., 1990), and Raman scattering effect (e.g. Kikuchi 1988). Each technique is based on the relation between the measured parameters, i.e., strain and/or temperature, and encoding parameter, i.e., the change in optical properties of the scattered light, as shown in Figure 4.

Rayleigh scattering effect can be used for both strain and temperature monitoring. It is based on the shifts in the local Rayleigh backscatter pattern which is dependent on the strain and the temperature. Thus the strain measurements must be compensated for temperature. The main characteristics of this system are high resolution of measured parameters and short spatial resolution (see the next subsection), but the maximal length of sensor is limited to 70 m (230 ft., Lanticq et al. 2009). Thus, this system is suitable for monitoring of localized strain changes over relatively short distances. Best performances achievable in strain monitoring using the Rayleigh scattering effect are given in Table 1, at the end of this section.

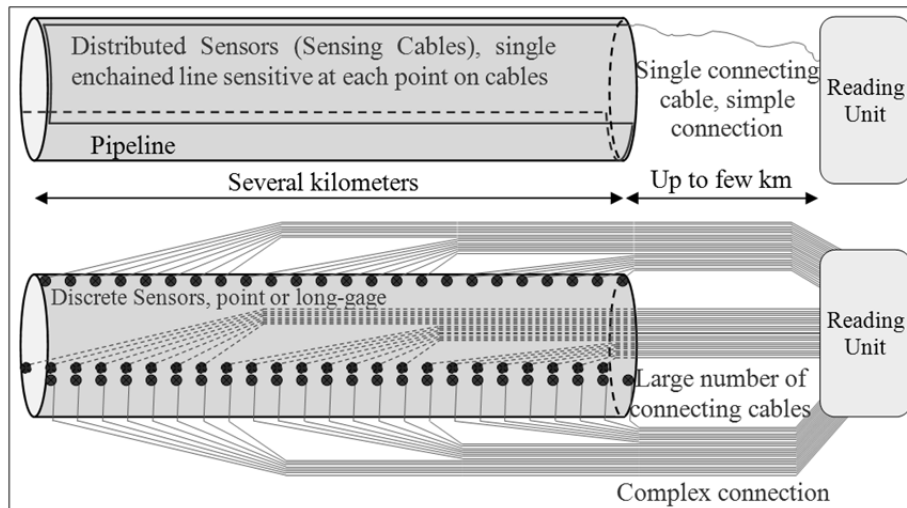


Figure 3–Distributed vs. discrete monitoring; schematic comparison (Glisic and Yao 2012).

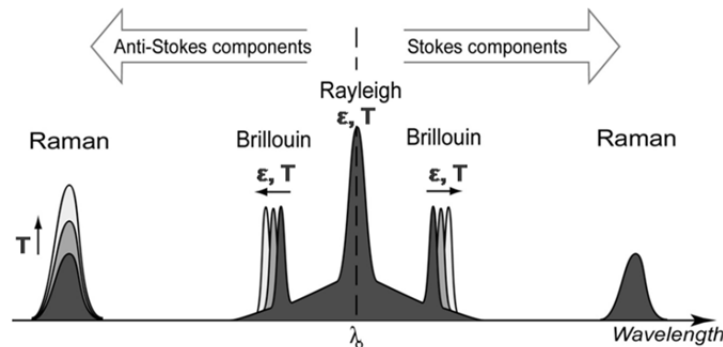


Figure 4–Scattered light properties as encoding parameter for strain and/or temperature measurements (Glisic and Inaudi 2007, courtesy of SMARTEC SA).

Brillouin scattering effect can also be used for both strain and temperature monitoring. It is based on the change in frequency of Brillouin scattered light which is dependent on the strain and the temperature. Thus, like in the case of the Rayleigh scattering, the strain measurements must be compensated for temperature, and temperature measurements are to be performed with sensors containing a loose (strain-free) optical fiber. Both spontaneous (Wait and Hartog 2001) and stimulated (Nikles et al., 1994, 1997) Brillouin scattering can be used for sensing purposes. Monitoring system based on stimulated Brillouin scattering is less sensitive to cumulated optical losses that may be generated in sensing cable due to manufacturing and installation, and allows for monitoring of exceptionally large lengths (Thevenaz et al. 1999), e.g. in the case of strain monitoring, a single reading unit with two channels can operate measurement over lengths of 10 km, while in the case of temperature monitoring, the lengths of 50 km can be reached. Remote modules can be used to triple the monitoring lengths. The measurement

specifications of Brillouin based measurements are not as good as these of Rayleigh based measurements, however the great advantage of Brillouin based systems is significantly longer length of the sensor (several kilometers). Thus, the Brillouin based systems are better suited for monitoring global strain changes over large distances. The best performances in strain monitoring achievable with Brillouin based systems are given in Table 1, at the end of this section.

Raman scattering is the result of a non-linear interaction of the light travelling in the silica fiber core and can only be used for temperature monitoring. It is based on the change in amplitude of Raman scattered light which is dependent on temperature only. The insensitiveness of this parameter to strain is actually an advantage compared with Rayleigh and Brillouin based temperature monitoring, since no particular packaging of the sensor must be made to make sensing fiber strain-free. Typical spatial resolution of Raman systems is 1 m (see the next subsection), and typical resolution is better than 1°C (1.8°F). Since the leakage of pipelines, dykes, dams, etc. often changes thermal properties of surrounding soil, beside the temperature monitoring the Raman based systems are used for leakage monitoring in large structures (e.g. Inaudi et al. 2011).

Spatial resolution and sampling interval

Although a distributed deformation sensor is sensitive to strain at every point of its length L_D , it measures at discrete points that are spaced by a constant value, called the sampling interval and denoted with L_{SI} , and the measured parameter is actually an average strain measured over a certain length, called the spatial resolution and denoted with L_{SR} , (Glisic and Inaudi 2007). Coordinates x_i of discrete measurement points (defined by the sampling interval) are defined as follows: $x_i = x_0 + iL_{SI}$, $i=1,2,3, \dots, n$, where x_0 is the coordinate of the first point on the sensor and $n=\text{integer}(L_D/L_{SI})-1$, unless x_0 coincide with the beginning of the first interval L_{SI} , in which case $n=\text{integer}(L_D/L_{SI})$. The spatial resolution can be considered as a gauge length over which the strain is averaged. Thus, the strain measurement values are given in discrete points with coordinates x_i which are spaced by sampling intervals L_{SI} . Value at each point x_i is actually an average strain obtained by integration over the length of spatial resolution L_{SR} . Both parameters are set by the user depending on project requirements, and in order to include entire length of the sensor in the measurements it is recommended for sampling interval not to be larger than a half of the spatial resolution (see Figure 5). These parameters and the principle of distributed sensor measurement are presented, in a simplified manner, in Figure 5.

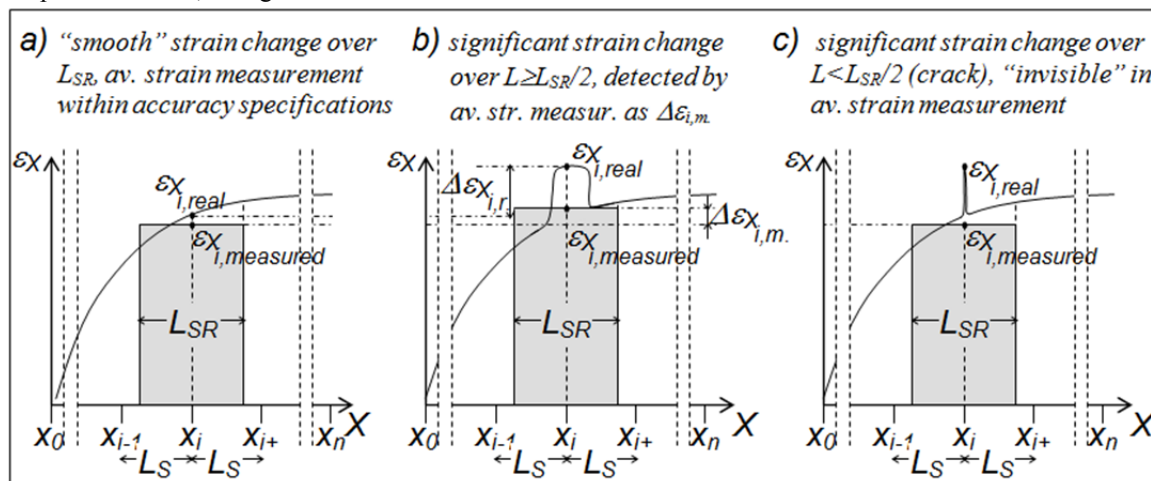


Figure 5–Simplified presentation of the principle of distributed sensor measurement (Glisic and Inaudi 2012).

Let the real strain distribution along the sensor without crack be as presented in Figure 5a. For each point with coordinate x_i the strain is averaged over the segment $[x_i - L_{SR}/2, x_i + L_{SR}/2]$ as presented in Figure 5a (gray area represents equivalent average strain), and the value of the measurement is attributed to the point x_i . The difference between real and measured strain at point x_i is small ($\epsilon_{x_i,measured} \approx \epsilon_{x_i,real}$) and depends on the strain change along the length of the spatial resolution.

Significant strain changes that occur over lengths shorter than the spatial resolution (e.g. strain concentrations at locations of geometric imperfections, change in cross-sectional properties, or at locations where a concentrated load

is applied), but not shorter than its half, are detected and localized, but not accurately measured, as shown in Figure 5b ($0 < |\Delta\epsilon_{x_i,m}| < |\Delta\epsilon_{x_i,r}|$).

This principle, however, is not valid for abrupt strain changes or concentrated strains in sensing optical fiber such as those generated by cracks, see Figure 5c. In these cases the measurement resulting from a distributed sensing system can possibly lead to important measurement errors. Even very high strain changes that occur over lengths shorter than one half of the spatial resolution are practically “invisible” for the system in common mode of functioning, as shown in Figure 5c. In addition, high local strains can lead to physical rupture of sensing optical fiber.

In order to deal with these issues two important improvements are made: (1) advanced algorithms allowing detection of events that occur over length shorter than one half of the spatial resolution and (2) appropriate sensor design and installation procedures, allowing for controlled strain redistribution over a length compatible with algorithm requirements and sensor mechanical properties, are developed. These improvements were for the Brillouin technology tested in laboratory and on-site, and presented in (Ravet et al. 2009 and Glisic and Inaudi 2012). To the best of the author’s knowledge, for Rayleigh based technology the improvements were not tested. Nevertheless, due to its small spatial resolution, the first improvement is probably not needed. The second improvement is independent on the sensing principle and dependent only on the sensor construction and installation procedures (that were essentially tested and validated with Brillouin-based technology).

The spatial resolution and the spatial sampling interval are usually determined based on the project requirements and set into the monitoring system by the user, through the user interface. Since the stability of the speed of the light in the optical fibers is very high and the stability of the light source (laser) as well, the error of the system in defining spatial resolution and spatial sampling interval is negligible. Table 1 summarizes currently best achievable spatial resolution and sampling interval of Brillouin- and Rayleigh-based strain monitoring systems.

Table 1–Comparison of best performances achievable in strain monitoring using distributed systems.

	Brillouin, stimulated	Brillouin, spontaneous	Rayleigh
Spatial resolution*	0.5 to 5 m (1’-8’’ to 16’-5’’))	1 m (3’-3 ³ / ₈ ’)	10 mm (3/8’)
Sampling interval	100 mm (4’)	50 mm (2’)	10 mm (3/8’)
Max. no. of sensors in network	16	N/A (1?)	N/A (1?)
Stability	N/A	N/A	N/A
Strain resolution*	2 $\mu\epsilon$ ($1\mu\epsilon = 10^{-6}$ m/m or in/in)	30 $\mu\epsilon$ (“accuracy”=2RMS)	1 $\mu\epsilon$
Repeatability	N/A	<0.02%	N/A
Instrument range	$\pm 30000 \mu\epsilon$	10000 $\mu\epsilon$	$\pm 7000 \mu\epsilon$
Max. length of strain sensor	0.25 to 5 km (0.16 to 3.11 mi)	N/A	70 m (229’-8’)
Temperature compensation	Needed	Needed	Needed
Measurement rate*	10 sec. to 15 min.	4 to 25 min.	4 seconds

* Spatial resolution, strain resolution, and measurement rate are mutually correlated

It is important to highlight that the spatial resolution, the strain resolution, and the measurement rate are mutually correlated, and improving one of these parameters will affect the others. Consequently, the best performances shown in Table 1 cannot be achieved simultaneously for a given technology, i.e., a trade-offs should be made (e.g. the measurement rate of 1 minute for stimulated Brillouin technology would require either larger spatial resolution or worse strain resolution, or both).

Distributed fiber optic sensor packaging

Optical fiber is fragile and has to be embedded in a packaging that provides for mechanical robustness, safe handling and durable installation. The strain transfer from the structure to the strain sensing fiber depends on strain transfer between the structure and the sensor packaging, and the strain transfer between the packaging and the optical fiber.

Thus, the quality of the strain transfer strongly depends on the packaging. Several types of packaging were found on market, and three typical examples are presented in order to identify advantages and challenges for each of them. These three packages are called “Tape”, “Profile” and “Cord”, and they are presented in Figure 6.

The Tape sensor consists of polyimide-coated optical fiber embedded within the thermoplastic composite tape in a manner similar to the reinforcing fiber integration in composite materials (Glisic and Inaudi, 2003). The typical cross-section width of the tape is in the range of 10-20 mm (0.4-0.8 in.) while the thickness of the tape can be as low as 0.2 mm (0.05 in.). The Tape sensor was applied to an underground pipeline, dam, and bridges (Glisic and Inaudi 2007). It had shown an excellent performance in terms strain transfer (i.e. strain measurement accuracy) and installation, but it features relatively large optical losses generated during the manufacturing process and consequently it suffices for monitoring of relatively short lengths, typically around 250 meters (830 ft.) per channel. The Tape sensor contains one sensing optical fiber, and cost is ranged between 15 and 20 US\$/m (4.5-6 US\$/ft.).

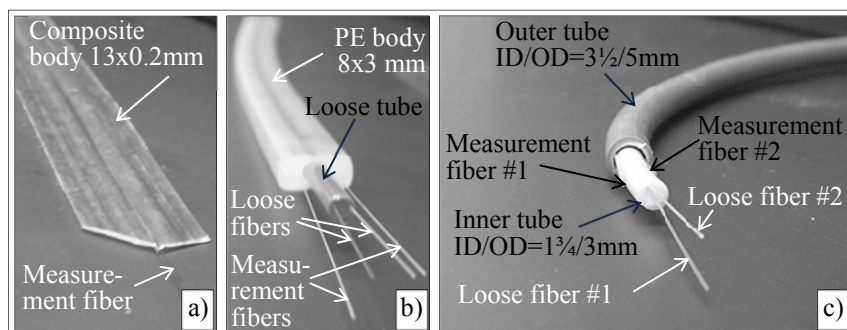


Figure 6—Examples of distributed sensor packaging: a) Tape, b) Profile, and c) Cord sensor (Glisic and Yao 2012).

The Profile sensor consists of two bonded and two free single-mode optical fibers embedded in a polyethylene thermoplastic profile. The bonded polyimide coated fibers are used for strain monitoring, while the free acrylate coated fibers are used for temperature measurements (limited range) and to bring back the optical signal to the reading unit (in the case of stimulated Brillouin scattering based technology). For redundancy, two fibers are included for strain monitoring. The size of the profile makes the sensor easy to transport and install by fusing, gluing or clamping. The sensor is designed for use in environments often found in civil, geotechnical, and oil and gas applications. The profile sensor was embedded in concrete (see further text) in order to monitor strain and in the soil to detect and localize settlements and ground movements (Belli et al. 2009). Profile sensor has a good sensing performance; however it is less accurate than the Tape sensor. The reason is lower quality of bonding between optical fiber and the packaging, so for higher levels of strain the former can slide within the latter. Profile sensor features significantly lower optical losses, and can be used for monitoring of considerably larger lengths, typically around 5 km (3.1 miles). Cost of this sensing cable is ranged between 25 and 30 US\$/m (7.5-9 US\$/ft.).

The Cord sensor consists of an inner and an outer tube, and four sensing optical fibers; two optical fibers are placed into the inner tube and two other optical fibers are placed between the inner and the outer tube. Fibers in the inner tube have an extra length and are loose (as in the case of Profile sensor), while the two other fibers are practically “squeezed” between the inner and the outer tube (we will call them “measurement” fibers). The optical fibers used are acrylate coated and manufacturing process is simple, which make the sensing cable cheaper to produce and easier to repair in case of damage. Since the strain is transferred from outer tube to the measurement fiber only by friction, localized strain changes due to damage in structure or displacement in soil will be distributed along longer lengths of the fiber, which slides in between the tubes. Thus the accuracy of measurement is lost, but it is still possible to conclude from the measured strain change where is the point of strain concentration (i.e., damage to structure), and redistribution of strain will prevent damaging of the fiber. The Cord sensor is rather damage indicator than real strain sensor, and it can be used in the cases where large deformations can occur (e.g. land sliding, ground movements, etc.). It features very low optical losses and can cover very long lengths (more than 10 km). The price is modest, 2-5 US\$/m (0.60-1.50 US\$/ft.).

Characteristics of Tape, Profile, and Cord sensor are summarized in Table 2. The performances of presented sensors will be better understood through the examples presented in the further text.

Table 2– Characteristics of Tape, Profile, and Cord sensor.

	Tape sensor	Profile sensor	Cord sensor
Strain transfer / accuracy of measurement	Excellent	Moderate	Poor
Max. measurable length range	~ 250 m (830')	4-5 km (2.5-3.1 mi)	> 10 km (> 6.3 mi)
No. of strain sensing fibers	1	4	4
Cost (1 US\$/m $\approx$ 0.3 US\$/ft.)	15-20 US\$/m	25-30 US\$/m	2-5 US\$/m

INTEGRITY MONITORING

By term “integrity” we refer to the quality of being whole and complete, or the state of being unimpaired. A distributed deformation sensor can be installed over the whole length of the monitored structural member, and therefore provide for direct detection and localization of local strain changes generated by damage. Thus, it provides for the integrity monitoring of the instrumented locations over entire length of the structure. The principle of integrity monitoring is schematically presented in Figure 7 (Glisic and Inaudi 2007).

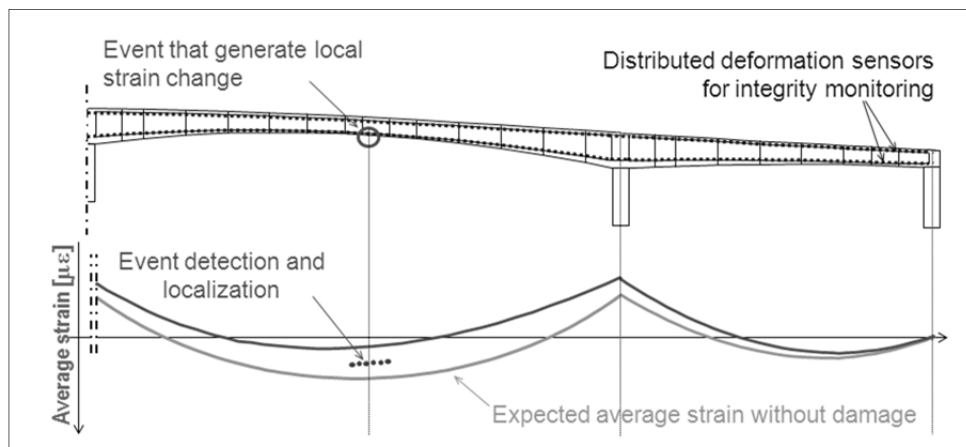


Figure 7–Schematic representations of simultaneous integrity monitoring and curvature monitoring (Glisic and Inaudi 2007).

In Figure 7 two distributed sensors are installed along the length of a bridge, one sensor at the top of the cross-section and the other at the bottom. If no damage is present on the structure, the distributed sensing cable will provide with average strain measurement at each point, where the strain is averaged over the spatial resolution. At the position of damage-induced local strain change, the sensing cable actually provides with the following information: (1) the average strain value over the length of spatial resolution without taking into account the local strain change and (2) strain concentration indication (based on special algorithms).

Let assume that the expected strain distribution due to some usual load (e.g. dead load) at the time of installation of sensors is as shown in the figure. This strain distribution cannot be measured by sensors (since generated before the sensor installations). Let assume that an event (e.g. crack) causes a strain concentration in the sensor installed at the bottom of the cross-section as shown by small circle in the figure. If the damage is small to cause the change in static system of the structure, then it will be identified by “crack spots” (as shown in the figure) or by very localized strain change detected by the main trace (as shown in Figure 5b). However, if the damage is big enough to cause the change in the static system of the structure, then the strain distribution along the bridge will change (e.g. as shown by dark gray line in the figure) and difference between two strain distributions will be measured by the sensors in addition to event (crack) detection.

Integrity monitoring was first applied at a relatively limited scale (Glisic and Inaudi, 2007) on dams (250 meters long joint). Good results led to the diversification of applications, and two examples are presented in the next section.

APPLICATION EXAMPLES ON CONCRETE STRUCTURES

Pipeline

A large scale test was performed on a pipeline with the aim to develop a method for implementation of a distributed fiber-optic system and to provide a reliable means for real-time, automatic or on-demand, assessment of pipelines subject to earthquake-induced permanent ground displacement. Beside the primary aim, the test helped evaluate the performance of distributed sensors in close-to-real conditions and their ability to detect damage. A detailed description of the test exceeds the scope of this paper and can be found in literature (Glisic and Yao 2012); only an overview of results relevant to the contents of the paper is presented.

An approximately 13 meter long concrete pipe with outer diameter of 30.48 cm (12 in.) consisting of five segments was buried in the soil, in the test basin, and exposed to shear ground movement. Topology of sensors depends on the expected pipe failure mode, which for a segmented concrete pipe occurs mainly by crushing of bell-and-spigot joints. Parallel topology is selected as the best feasible configuration. It consists of parallel sensors installed along the pipe as shown in Figures 3 and 8. Another set of sensors was embedded in the soil for detection of soil displacement and failure. The Tape, Profile, and Cord distributed sensor were bonded along the pipe, while Cord and Profile sensors were embedded in the soil. Position of all the sensors, as tested, is shown in Figure 8.

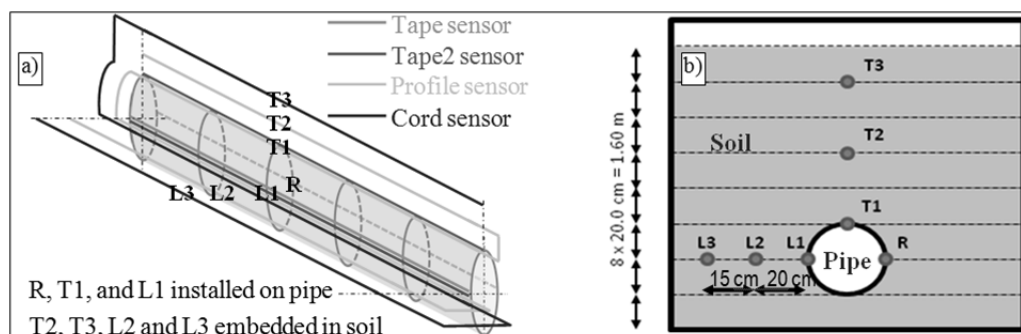


Figure 8—Topology of sensors used in validation test: a) global view, and b) in the cross-section (Glisic and Yao 2012).

Clamping the sensor to the pipeline would be time consuming and expensive as the full circumference of the pipe has to be accessible at large number of closely spaced points. Hence, it was decided to glue the sensors using appropriate adhesive, which was selected for each type of sensor in order to match with materials to be bonded. The installation of Tape and Profile sensors was challenging for several reasons: (i) they had to be handled without twisting in order to avoid the damage to the sensor; such a handling was not easy taking into account large length of the sensor; (ii) both the surface of the structure and the sensor had to be cleaned before gluing in order to provide for good bonding of the sensor to the structure; this happened to be time consuming especially in dusty environment of the pipe; (iii) sharp edges at the pipe joints (see schematic drawing in Figure 10b) had to be bridged with plastic supports in order to avoid concentrated optical losses in the sensors; this work was also time consuming; (iv) small bending radii of the sensor had to be avoided in order to ensure satisfactory strength of the optical signal and the durability of the installation. However, all these issues were not a real obstacle for implementation of the system. The Cord and Profile sensors have bodies that are physically robust, as opposed to Tape sensors that are relatively fragile, thus these two sensors were also embedded in soil. A photograph of sensors installed onto the pipe is given in Figure 9a and photograph of the sensors embedded in the soil in Figure 9b.

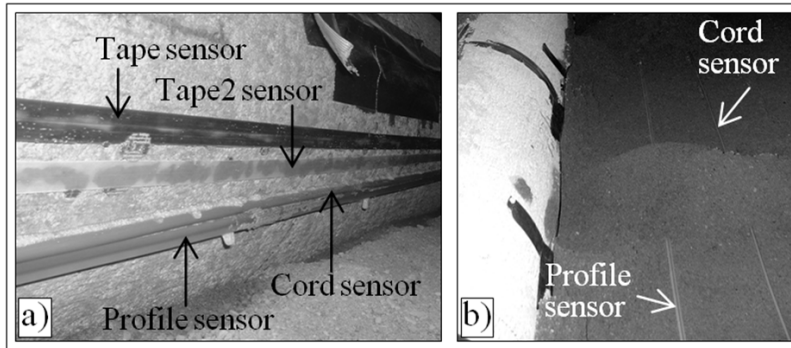


Figure 9– Installation: a) sensors glued to pipeline, and b) embedding in soil (Glisic and Yao 2012).

The pipeline was placed in a 3.4 m (11 ft.) wide and 13.4 m (44 ft.) long testing basin with two parts: the movable north end and the fixed south end. The movable part of the basin was attached to four actuators (see Figure 10a) anchored in massive concrete bearings.

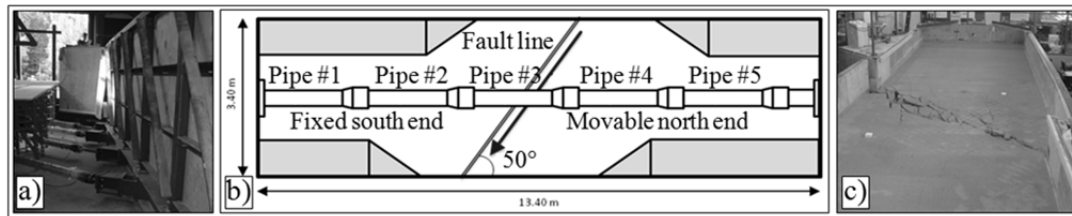


Figure 10–Validation test: a) actuators controlling movable end of the basin, b) schematic representation of the test, and c) failure of the soil during the test (Glisic and Yao 2012).

The joint between the two parts was oriented 50° with respect to the basin axis (see Figure 10b). Before the test started a reference (“zero”) measurement was performed. Then the movable part of the basin was displaced using actuators for 25.4 mm (1 in.) and one measurement is performed. This procedure was repeated until cumulative displacement of 304.8 mm (12 in.) was reached. The displacement introduced both shear and compression in the pipe and in the joint, and generated failure (cracking) of the soil (see Figure 10c). The segment #4 was built of fiber reinforced concrete and had much higher stiffness and resistance than other segments, made of ordinary concrete. This resulted in higher strain in ordinary pipes and early damage of joints, #2 and #3 that were the closest to the shear plane, and consequently the most loaded. The damage happened after the first 25.4 mm (1 in.) were applied. An illustrative example of results is presented in Figures 11 and 12.

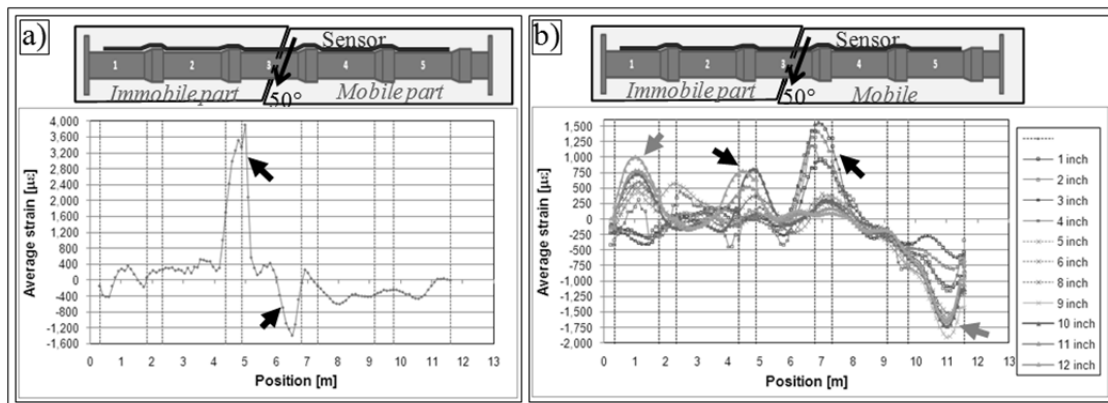


Figure 11– Results at location L1 (non calibrated, non compensated): a) Tape sensor, and b) Cord sensor (Glisic and Yao 2012).

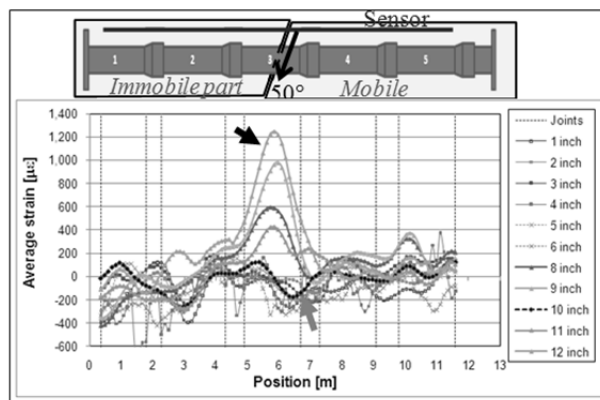


Figure 12—Results of Cord sensor at location L3 (non calibrated, non compensated), (Glisic and Yao 2012).

Tape sensor at location L1 functioned properly during the first step of the test when relative ground movement of 2.54 mm (1") was applied and damaged the pipe at the joints #2 and #3. The results in the Figure 11a) represent total non-compensated and non-calibrated strain distribution along the pipe. The temperature compensation was not necessary for damage detection purposes since it only translates vertically the diagram presented in the figure, and this does not influence data interpretation. Similar, the calibration was not necessary neither, since it "stretches" diagram with respect to vertical axis, with no influence to the data interpretation. Two unusual strain changes are observed, high tension close to joint #2 and high compression close to joint #3 (black arrows). They correspond to the locations of actual damage on the pipe. The results demonstrated the ability of the Tape sensor to detect damage in close-to-real conditions and in real-time.

Results of Cord sensor are presented in Figures 11b) and 12. In order to interpret the measurement of Cord sensor it is necessary to understand that the strain measured by optical fiber is not equal to the strain on the structure because the measurement fibers can slide inside the body of the sensor (for higher level of stress and strain). The part of Cord sensor installed on the pipeline registered the strain change due to damage in joints #2 and #3 (black arrows), but for displacements in the range of 25.4-203.2 mm (20 in.), it was difficult to distinguish it from the other strain variations (due to sliding of the fibers in the cable). For higher levels of displacement, the damage detection is performed more reliably, as the high strain in the diagram (marked by black arrows). Sliding of the fibers makes impossible to qualitatively evaluate whether damage increased or not. Two additional zones of a concentrated high strain are noted at extremities of the pipeline (gray arrows in Figure 11b). There was no damage at these locations and the observed pattern can be explained mainly by the sliding of the fibers transferred from the parts of the sensor embedded in the soil (see Figure 8a). Thus, Cord sensor can be used to detect and localize the damage, but only higher levels of the damage can reliably be identified by analyzing series of measurements.

The part of Cord sensor embedded in the soil at location L3 (see Figures 8 and 9b) successfully detected ground displacement and location of the shear plane, as shown in Figure 6 (black arrow). Besides the sliding of the fibers inside the sensor body, additional sliding of the sensor with respect to the soil was also possible. Due to sliding, a reliable detection and localization of the damage was possible only for higher values of ground displacement and by analyzing the time series of the measurements.

Profile sensor was broken during the test as well as other Tape sensors. The reasons were issues related to installation. These issues set directions for the improvements that were implemented in the next phases of the project (see Glisic and Yao 2012).

Bridge

Streicker Bridge, located on the Princeton University campus, was completed in the spring of 2010, see Figure 13. The bridge is 104 meters long (~341 ft.) and has a main span and four approach legs. Structurally, the main span is a deck-stiffened arch, thus the deck mainly carries bending moments and only secondary moments are expected in the columns and in the arch. The legs are curved continuous girders supported by steel columns. The legs are horizontally curved and the shape of the main span follows this curvature, resulting in a varying main span cross-

section. It is minimal at the middle of the deck and maximum where the legs join the main span. The leg cross-section is constant. The arch and columns are weathering steel while the decks are reinforced post-tensioned concrete. The slender and elegant deck-stiffened arch spans 34.75 m (~114 ft.), with a deck thickness of only 578 mm (~1.9 ft.) and arch diameter of 324 mm (~12.75 in.). The slender elements and varying deck cross-section create a geometrically complex structure, and structural health monitoring facilitates assessment of its performance.



Figure 13–Streicker Bridge. Right: Photograph. Left: Rendering, courtesy of Facilities of Princeton University.

The current bridge instrumentation is based on two monitoring approaches. The first: global structural monitoring using discrete long-gauge Fiber Bragg-grating (FBG) sensors, and the second: integrity monitoring using distributed sensing based on stimulated Brillouin distributed sensing (Brillouin Optical Time Domain Analysis – BOTDA). A detailed description of the project exceeds the scope of this paper and can be found in literature (e.g. Glisic et al. 2011, Sigurdardottir et al. 2011); only an overview of results relevant to the contents of the paper is presented.

Since the bridge is just about doubly symmetric in plan only half the main span and one of the legs, i.e. the southeast leg are instrumented. Two sensors parallel to the center line of the deck are installed close to the axis of symmetry of each cross-section, one sensor at the top and one at the bottom as shown in Figure 14. Parallel sensors are needed in order to capture and distinguish influences of normal force and bending moment. The instrumented area is also shown in Figure 14. The gauge length of all the discrete sensors was chosen to be 60 cm.

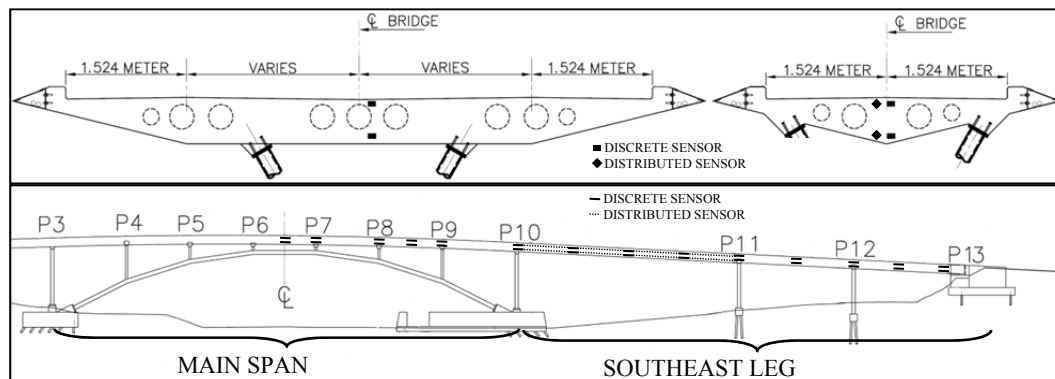


Figure 14–Top: Orientation of a typical pair of sensors within cross-section. Bottom: Bridge elevation, one approach ramp (leg) and half the main span are instrumented (Glisic et al., 2011).

The sensors installed in the southeast leg are of interest in this research, and they are presented in more details. The southeast leg is fixed to the deck of the main span on one end and simply supported at the other end. The deck consists of three spans shown in Figures 13 and 15. The most highly stressed sections – those above the columns and in the middles of spans – are monitored. In addition, both quarter-span sections of the longest span, P10-P11, are monitored. A Profile sensor (BOTDA sensing cable) was installed in the span P10-P11, at the top and at the bottom of the cross-section, parallel to the center line of the deck. Spatial resolution of the system was set to 1 m (39.4 in.). The distributed sensor was installed close to the discrete sensors in order to facilitate direct comparison of the two systems. All the sensors were loosely attached to rebars before the pouring of concrete using plastic ties. Thus, after

pouring, the sensors were practically embedded in concrete, and registered the strain during construction, including the early age of concrete and the post-tensioning of the deck. Figure 15 shows installation of sensors and Figure 16 shows the locations of the sensors.



Figure 15—Photographs taken during sensor installation. Top left: Student installing sensor. Bottom left: Students installing extension cable. Right: Parallel discrete and distributed sensors installed on rebar (Glisic et al., 2011).

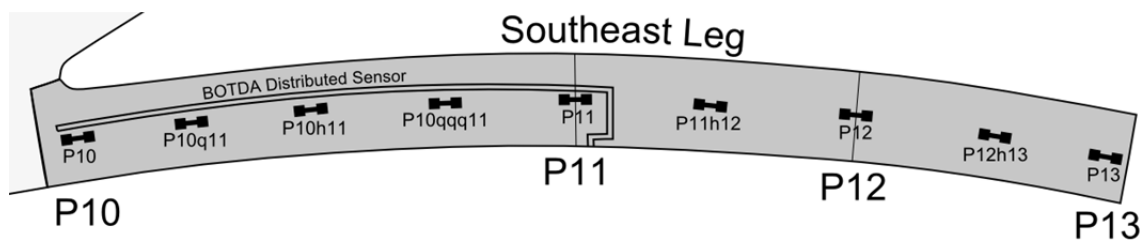


Figure 16—Plan view of the southeast leg showing the parallel and distributed sensor locations (Glisic et al., 2011).

At the early age of concrete, unexpected strain changes were noticed in the time histories of several sensors. FBG sensors at locations P10h11, P11, and P11h12 all show a distinct upswing in strain approximately three days after the concrete was poured, with location P10 showing a similar behavior five days later. This unusual behavior was confirmed by the distributed BOTDA system, see Figures 16 and 17. The analysis has shown that unusual behavior was produced by early age cracking generated by thermal gradients in the concrete (Hubbell 2011). The deck of the bridge was post-tensioned after 12 days in two phases, and measurements performed during post-tensioning are also presented in Figures 17-18.

The measurements performed by FBG sensors show in general significantly less noise compared with distributed sensor, which was expected since the former are about an order of magnitude more accurate than the latter. However, the noise of distributed sensor measurements exceeds the error limits and this variation is attributed to the mechanical action to which the sensor is subjected after the pouring of the concrete. These actions are lateral pressure and micro-bending of the sensor induced by the hardened concrete.

The agreement between two systems was in general qualitatively good (see Figures 17-18). Nevertheless, the quantitative comparison indicated some discrepancies, in particular during the very early age of concrete and at moments of occurrence of unusual behaviors. These discrepancies did not systematically occur between each pair of compared sensors. For example, quantitative agreement between the two systems is excellent at location P11 during the early age (see Figure 17), but it is less good after the unusual event happened. Contrary, agreement at location P10 was less good during the early age, but it was very good later on, even after the unusual event happened.

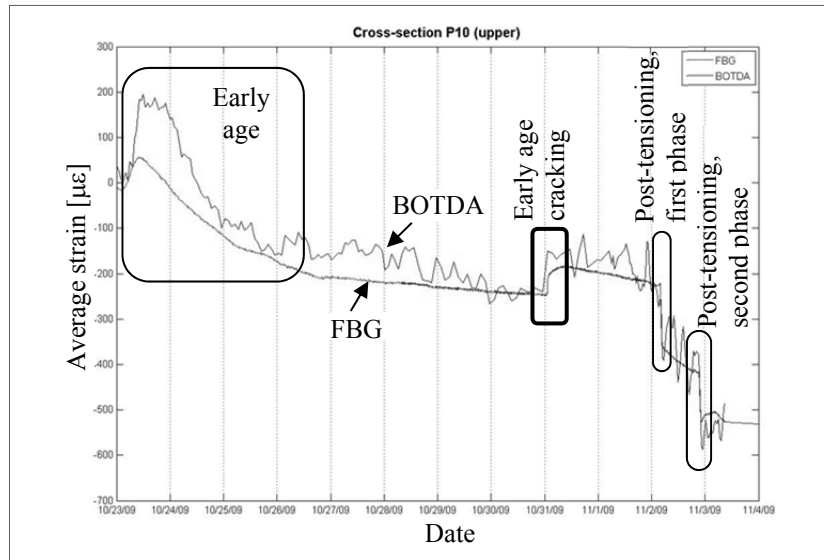


Figure 17–Early age cracking detected by discrete (FBG) sensor and distributed Profile (BOTDA) sensor at the cross section above the column P10 (Glisic et al., 2011).

The discrepancy at early age can be explained by the combination of difference in thermal expansion coefficient between the polyethylene body of the sensor and the concrete, and low interaction between these two materials at early age. As the thermal expansion coefficient of polyethylene is an order of magnitude higher than that of the concrete, the polyethylene tends to expand more than concrete, and the magnitude of the expansion depends on the goodness of interaction between the two materials. During this early stage the interaction between the materials is low and improves as the concrete hardens. The pouring of the concrete was performed from the P11 towards the P10 and the discrepancy during the early age increases in this direction, which supports our conclusion.

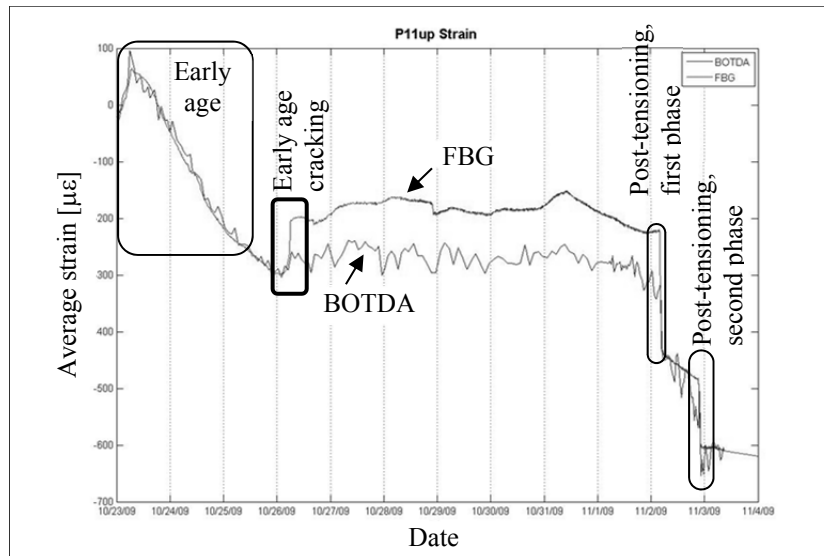


Figure 18–Early age cracking detected by discrete (FBG) sensor and distributed Profile (BOTDA) sensor at the cross section above the column P11 (Glisic et al., 2011).

The discrepancy at the times of occurrence of unusual events are attributed to the differences in the nature of the measurements performed with long-gauge and distributed sensors. Long-gauge FBG sensors practically average the crack opening over the sensor gauge length which was 0.6 m (2 ft.). The distributed sensor cannot detect an event

that is smaller than half of the spatial resolution (see Figure 5). However, the distributed sensor detected both events qualitatively. The reason for this is sliding of optical fiber within the sensor's body or sliding of sensor's body with respect to concrete, or both combined. The detected magnitude of the event depends on the size of sliding length (see Figure 5). A very good agreement is obtained regarding the deformation due to post-tensioning.

Qualitative agreement between two systems was good, and both systems were able to detect both unusual behaviors (early age cracking) and usual events (thermal swelling and shrinkage due to hydration and post-tensioning) on the bridge.

Quantitative discrepancies were observed during the early age of concrete and in measurement of magnitude of unusual events. The discrepancy at the early age was attributed to thermal incompatibility between the sensor body and concrete, and the poor adhesion between these two materials at this stage. Once the very early age was completed, the quantitative agreement between the systems was reestablished. The discrepancy in measurement of magnitude of unusual events is a consequence of a nature of distributed measurement and it attributed to the spatial resolution of the distributed system. Good agreement is obtained in the measurement of the final deformation induced by the post-tensioning because the cracks were closed.

CONCLUSIONS

Distributed sensing technologies have a unique capability of monitoring one-dimensional strain fields rather than the simple strain at a large number of discrete points. These technologies can be installed throughout a structure to provide for direct damage detection, localization, and quantification. In addition to their good measurement performance, they require a simple connection to the reading unit, which significantly simplifies the work related to cabling of the system.

Various distributed sensing technologies and advancements in the development of sensing cables are presented. Overall system performance and sensor cost analysis are included. Integrity monitoring based on distributed sensing in large structures is presented. Two successful applications, one on pipeline and the other on the bridge, illustrate how the integrity monitoring can be applied to existing and new concrete structures. In both applications the damage was successfully detected and localized. Besides applications to pipelines and bridges, integrity monitoring with distributed sensors was applied to dams and dikes, and recently to tunnels and sinkhole monitoring. This shows versatility and potential of this new technology for applications in large structures.

Distributed sensory systems are expensive, however their use is justified when a large structure is monitored, or when structural malfunction may have a large impact on the society, or where no other technology can satisfy the objectives of monitoring.

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Use of Electrical Impedance Spectroscopy and Conductive Surface Films to Detect Cracking and Damage in Cement Based Materials

Mohammad Pour-Ghaz, Mark Niemuth and Jason Weiss

Synopsis: This paper describes three electrically-based methods of damage detection in concrete materials. The first approach describes the use of EIS as an electrical sensing method for concrete. The results indicate that the electrical impedance spectroscopy of concrete can be used to detect cracks in concrete materials. Furthermore, this method can be used to obtain information on the geometry of the crack such as crack width and crack depth, however, the measurement are sensitive to the materials inside the crack. The second approach is the use of electrically conductive thin film that is applied to the surface of the concrete. The electrical resistance of this film increases due to cracking of the film and substrate. By monitoring the electrical resistance of this thin film, information about the time and location of cracking can be obtained. To evaluate the feasibility of using this method, it was used to detect cracking in restrained concrete elements while cracking was monitored with acoustic emission and strain measurements. The third approach presented in this paper describes the development and use of frequency selective circuit. A frequency selective circuit (FSC) has been developed to rapidly and simultaneously interrogate the response of multiple conductive surface elements. The response of the FSC is analyzed using numerical methods and the use of the FSC is demonstrated using a pilot study in which conductive films were used to simultaneously monitor the time of cracking of multiple restrained concrete rings

Keywords: Acoustic emission, Conductive thin film, Crack detection, Damage detection, Electrical impedance spectroscopy, Frequency Selective Circuit, Ring test, Sensor, Structural health monitoring,

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INTRODUCTION

The durability and service life of the concrete infrastructure can be influenced by the presence of cracks. Cracks provide preferential paths for fluid ingress, resulting in acceleration of degradation processes¹⁻³. Therefore, information about the location and the extent of cracking can be useful for the development of accurate service life prediction models for the concrete infrastructure.

The present paper provides a review of three recently developed electrically-based methods to detect and quantify damage in concrete elements. Electrical methods are typically fast, inexpensive and relatively easy-to-interpret. Electrical methods can be performed using either direct current (DC) or alternating current (AC) to monitor cracking in concrete material⁴⁻¹⁶. Electrical methods provide an alternative method to wave propagation methods and can be especially powerful if combined with wave propagation methods.

The first method is the direct use of electrical impedance spectroscopy to characterize the damaged/void in concrete by mapping the electrical resistance of the concrete. By measuring the changes in bulk resistance at various locations with various external electrode alignments the location and depth of voids in concrete specimen can be characterized. This method would enable in-situ measurements of damaged concrete.

The second method is the use of electrically conductive thin films that are applied to the surface of the concrete elements. The presence of damage can significantly increase the electrical resistance of the thin film. By monitoring the electrical resistance of this thin film the time and location of the damage can be obtained. This method can be applied to large geometries because of the low electrical resistance of the thin film compared to concrete material. To evaluate the performance of conductive thin films for crack detection a test case was constructed using restrained ring specimens.

The third method is the use of frequency selective circuit along with conductive thin films to monitor damage development in concrete elements. A frequency selective circuit (FSC) has been developed to rapidly and simultaneously interrogate the response of multiple conductive surface elements. The results of a pilot study in which conductive surface coatings were used to simultaneously monitor the time of cracking of multiple restrained concrete rings is presented and discussed. This technology could be extended to other resistance based sensors. This method enables simultaneous monitoring of damage at different locations on a single element or monitoring of damage on multiple elements.

USE OF IMPEDANCE SPECTROSCOPY TO DETECT DAMAGE IN CONCRETE ELEMENTS

Electrical impedance can be used to locate and determine the depths of cracks and voids in concrete. This method relies on the differences in the conductivity of the concrete and of the material in the void (i.e., air or water). The following contains data and information about this approach¹³.

Overview of the Method

Electrical impedance can be used to measure the electrical resistance of a specimen (i.e., the bulk resistance, R_b). The bulk resistance, which is geometry dependent, can be related to the resistivity (ρ), which is geometry independent material property as shown in equation 1.

$$R_b = \rho \cdot k \quad \text{Eq. (1)}$$

where k is a geometry factor, which is a function of specimen geometry, electrode geometry, and electrode alignment. In the specific case where the electrodes are parallel at a length, L , apart and the cross sectional area of the material and electrodes is, A , the equation is as follows:

$$\rho = \frac{R_b \cdot A}{L} \quad \text{Eq.(2)}$$

In other cases the geometry factor (k) can be determined from experiments directly or from numerical simulation.

In electrical impedance spectroscopy (EIS) an alternating current is applied to the specimen at different frequencies and the resulting voltage drop (V) is measured. Electrical impedance (Z) is determined using equation 3, Ohm's law in which V , I , and Z can be complex variables (real and imaginary components).

$$V = I \cdot Z \quad \text{Eq.(3)}$$

where Z is the impedance (measure of resistance), I is the alternating current (AC), and V is the voltage. The total impedance ($|Z|$) can be subdivided into a real component (resistance) and imaginary component (capacitance and inductance) defined in (4)

$$|Z| = \sqrt{Z'^2 + Z''^2} \quad \text{Eq.(4)}$$

where Z'' is the imaginary impedance and Z' is the real impedance. The complex electrical impedance ($|Z|$) has both a resistive and capacity component^{11, 17-20} while the true bulk resistance of a material does not have a capacitive component. The capacitive component can be seen in the bulk arc of the Nyquist plot. An example of a typical Nyquist plot is shown in Figure 1a and Bode plot is shown in Figure 1b.

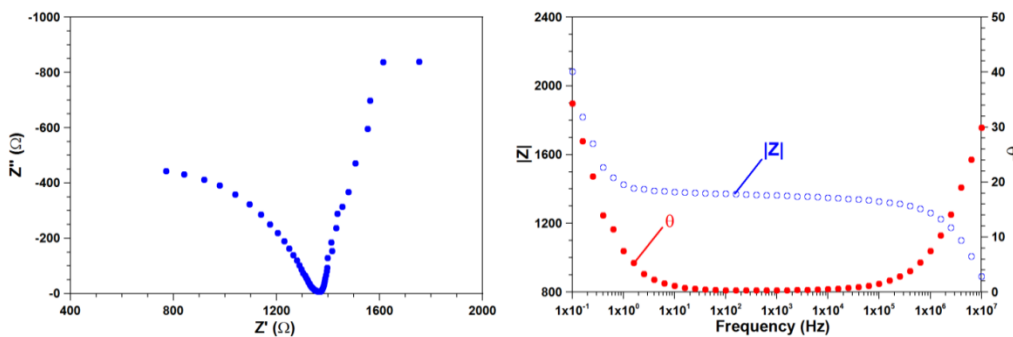


Figure 1 – Example of a Nyquist plot and Bode plot

The Nyquist plot is made over a wide range of frequencies, as seen in the Bode plot in Figure 1, since large errors in interpreting the bulk resistance may occur if one single frequency is used²¹. The bulk resistance is the real impedance, which occurs at the intersection of the bulk arc and the electrode arc (where the imaginary impedance is a minimum), which is equivalent to DC resistance. On the Nyquist plot, the electrode arc (the resistance due to the electrode) seen in Figure 1 occurs at low frequencies (generally kilohertz and lower) while the bulk arc (resistance due to specimen interference) occurs at high frequencies (generally kilohertz to megahertz). The bulk resistance is a measure of the purely resistive component (i.e., no capacitive component).

Materials and Experimental Procedure

Two external sensors or electrodes are placed on the surface of concrete with a conductive gel or soaked sponge used to ensure good contact. An impedance spectroscopy measurement is taken between the two electrodes using a Solartron Model 1260 impedance / gain-phase analyzer. The typical frequency range was 10 MHz to 100 Hz at 10 measurements per decade for each measurement. The electrodes are then moved around the surface of the concrete in question and multiple measurements are taken. The difference in the measured electrical resistance between different locations is used to determine when changes in localized resistivity (or conductivity) occur.

This method is assuming the conductivity of the bulk concrete is relatively homogeneous. Additionally consideration should be given to the contact area of the sensor and width between sensors. The sensor area and width between electrodes needs to be large enough so that the bulk concrete is relatively homogenous. In other words the electrical resistance is relatively consistent around the entire sample of concrete that does not contain voids.

Finite elemental analysis (FEA) was also done to verify results and show relationships in a more definitive manner. ANSYS University Advanced 7.1 (ANSYS 2002) software was used to create a finite element model for the specimens investigated in this study. This FEM considered the specimens, electrodes, and applied current loads. The load in this case was electrical current, in amps. The elements that were used were two dimensional, linear, plane three or four-node elements depending on the geometry. This permitted a temperature and voltage to be defined at each node. The temperature was considered to be constant throughout modeling and was assumed to be 23°C (73°F) while taking measurements. While modeling was performed in three dimensions, the solutions were adjusted to consider variations in two dimensions while the third dimension was one unit thick.

Results and Discussion

Take for example the case where the electrodes are linear and are placed parallel to a cut (see Figure 2a). At first the electrodes are placed so that the cut is not between the sensors ("cut outside electrodes" on Figure 2b) and electrical bulk resistance is low (100% on Figure 3). The electrodes are moved perpendicular to the sensors and the cut until the cut is between the sensors ("cut inside electrodes" on Figure 2b) and the electrical bulk resistance is high (> 100% on Figure 3). The difference in bulk resistance when the cut is between and outside the sensors is the indication that there is a discontinuity in the field that corresponds to a cut or crack. The bulk resistance is higher when a notch is between the 2 sensors since the path that the electrical signal is traveling for least resistance is longer and the notch is filled with air (a resistive element), which is not through the void, but through the concrete around the void. In the current experimental procedure it is implicitly assumed that no effect from moisture gradient is present. Presence of moisture gradient can significantly affect the electrical resistance measured at the surface of the material. Measurements on two-layer composites (with different electrical resistivity) have been made to more fully understand this effect and have been reported elsewhere²².

Multiple placements and alignments of those sensors near that "discovered" notch helps narrow down the location of the notch. As the electrode spacing is decreased the differences in bulk conductivity with and without a notch were more and more apparent (as seen in Figure 3). The same slab set up was shown where the experimental results are compared to the FEA results, both are normalized by the uncut specimen bulk resistance value, seen in Figure 4. Even as the electrodes are moved relatively close to the notch, while still having the notch outside of the electrodes the bulk resistivity increases as seen in Figure 5. Figure 5 is FEA results only since relationship between the FEA and experimental results was already established.

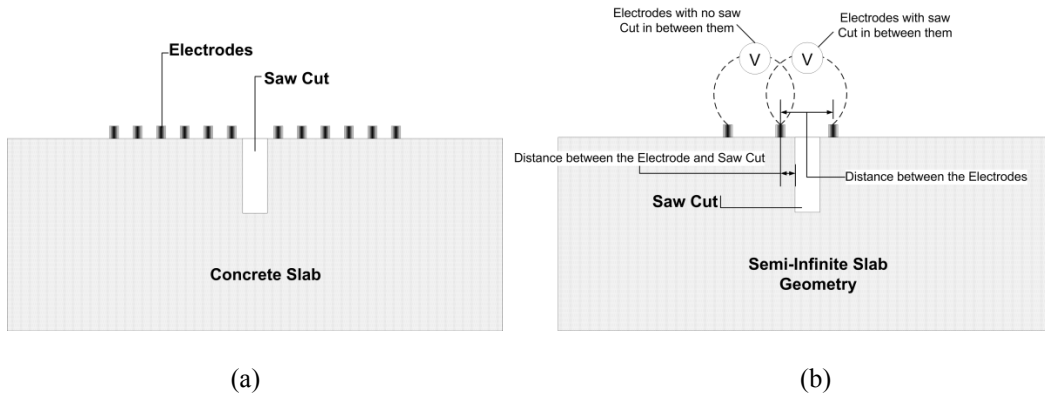


Figure 2 – Slab geometry and electrode position information

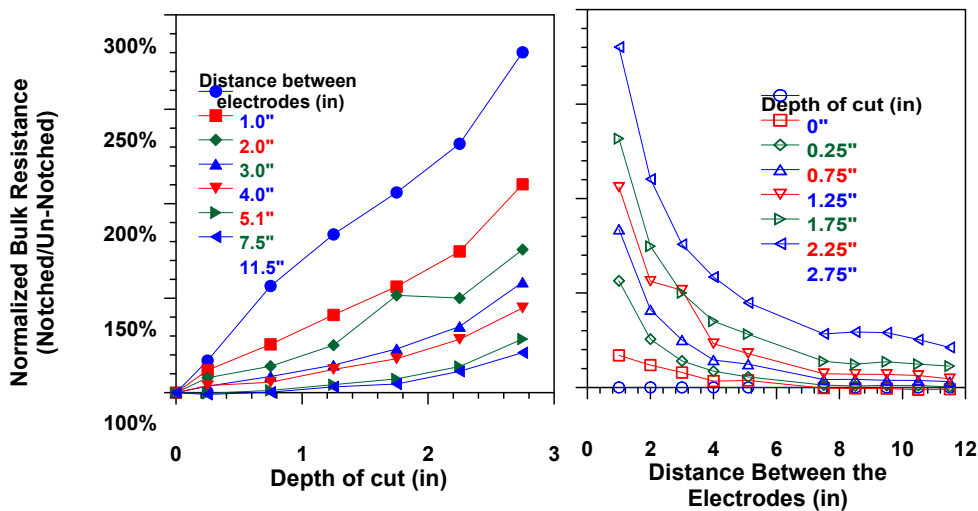


Figure 3 – Bulk resistance of 3” deep slab with various electrode spacing and cut depths

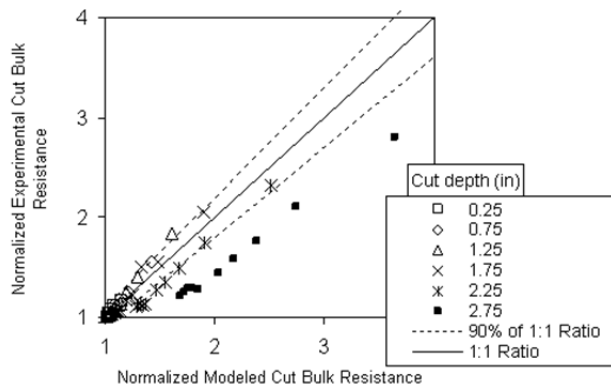


Figure 4 – Comparison of experimental and modeled slab specimen 3” deep. The linear fit line represents a perfect model of the experimental results. The 2.75” and 2.25” cuts have a relatively large offset from the line.

The 2.75” cut depth deviated from the 1:1 ratio because around the tip of the cut there was a relatively large concentration of current (analogous to stress concentration) for the same element size, similar to using a coarse element in FEA.

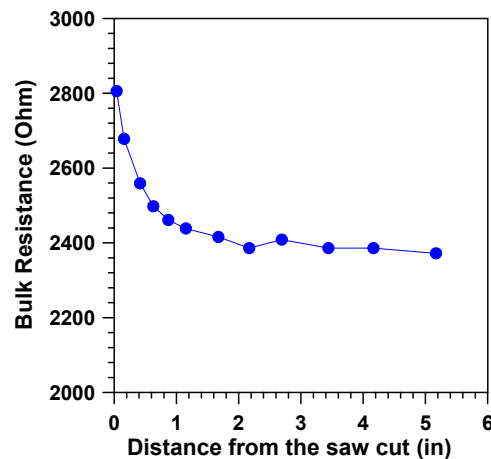


Figure 5 – Bulk resistance (Ohms) vs. distance from cut to closest electrode (inches) – FEA results. The cut is not between the electrodes.

As the void becomes deeper the bulk resistance will continue to rise as seen in Figure 3. Using the detour analogy again, the longer the crack the longer the distance traveled for the signal has to travel to reach the other sensor. Given that there can be huge differences in one concrete's bulk resistivity to another concrete, slab depth, electrode effects cannot be determined easily without calibration by another method or through FEA.

USE OF CONDUCTIVE THIN FILMS TO DETECT DAMAGE IN CONCRETE ELEMENTS

This section describes the use of conductive surface materials that are applied to the surface of the cementitious materials to detect the time and location of cracking⁹. In this section, conductive surface materials, acoustic emission, and strain gages are used to monitor cracking in restrained ring specimens.

Overview of the Method

By monitoring the electrical resistance of the conductive surface materials that are applied to the surface of concrete materials, an increase in resistance can be related to cracking. When the cementitious substrate cracks, the conductive surface materials stretches and ruptures, resulting in a large increase in the electrical resistance of these materials. This method has been previously used to detect the time and location of cracks and to study the effect of boundary conditions in partially restrained concrete slabs^{9, 23}. Conductive surfaces have also recently been used to detect the location and extent of damage in buried concrete pipelines²⁴.

Materials and Experimental Procedure

Materials

Plain mortar mixtures with a water-to-cement ratio (w/c) of 0.30 and 55% aggregate by volume and fiber reinforced mortars with the same w/c, 2% steel fiber and 53% aggregate by volume were tested (keeping the paste volume content of 45% for both plain and fiber reinforced mortar). The steel fibers were 25.4 mm (1 inch) long and had an aspect ratio (i.e., length/diameter) of 42. Specimens were subjected to top and bottom drying by placing the specimens on an open grate. Specimens were moved to an environmental chamber at $50 \pm 1\%$ relative humidity and $23 \pm 1^\circ\text{C}$ ($72 \pm 2^\circ\text{F}$) temperature until the time of cracking.

Restrained ring test specimens

The restrained ring test consists of casting an annulus cement-based material around a steel ring. The steel ring resists the volume change of cement-based material due to shrinkage causing stress development in the cementitious

material which can result in cracking²⁵⁻²⁹. The development of strain in the steel ring is a function thickness of the steel ring (degree of restraint that steel ring provides).

All the restraining steel rings had an outer steel radius (R_{OS}) ($R_{OS} = R_{IC}$, the inner radius of concrete ring) of 15.24 cm (6.0 inch). The mortar ring that was cast around the steel ring had a wall thickness of 5.08 cm (2.0 inch) resulting in the same mortar outer radius (R_{OC}) for all ring specimens. The thickness of the restraining steel ring was 0.95 cm (0.37 inch). The height of the restraining steel ring was 7.62 cm (3.0 inch). Figure 1 schematically illustrates the geometry notations (i.e., R_{IS} , $R_{OS} = R_{IC}$, and R_{OC}) of the rings.

Instrumentation: strain gages

A total of four strain gages were installed at the inner surface of each steel ring at 90° with respect to each other and the strain measurements were started immediately after casting (between 30 and 60 minutes of the time water and cement came in first contact) and continued until the time of cracking. The average value of the strain is reported in this work.

Instrumentation: conductive surface coating

Two strips of conductive surface materials were applied to the outer circumference surface of the mortar specimens. The conductive surface material used in this work was colloidal silver paint^{9, 23}. The conductive surface materials were applied using a thin paint brush. The width of the conductive surface materials strips was approximately 3 mm (0.12 inch). The width and uniformity of the applied paint can affect the results measurement both in terms of sensitivity and increase in resistance after cracking³⁰. The conductive surface material strips were applied on the outer circumference parallel to the top and bottom surface of the rings. The strips were applied 2.54 cm (1.0 inch) away from the top and bottom of the specimen and the distance between the two strips was 2.54 cm (1.0 inch). Figure 6 schematically illustrates the instrumentation of the ring specimens. Copper electrodes were used to facilitate the electrical connection between the conductive surface strips and wires that were connected to the electrical resistance measurement unit³¹.

Instrumentation: acoustic emission

A Vallen AMSY 5 acoustic emission system was used in this investigation. A total of three AE sensors were installed on each ring specimen. Sensors were installed at 120° with respect to each other on the top surface of the mortar ring (Figure 6). A silicon based coupling agent was used to install the sensors on the top surface of the ring specimens. Elastic rubber tape was used to press the sensors against the mortar surface during the experiment. A noise threshold of 34.0 dB was used in this work to minimize the noise from the surrounding environment.

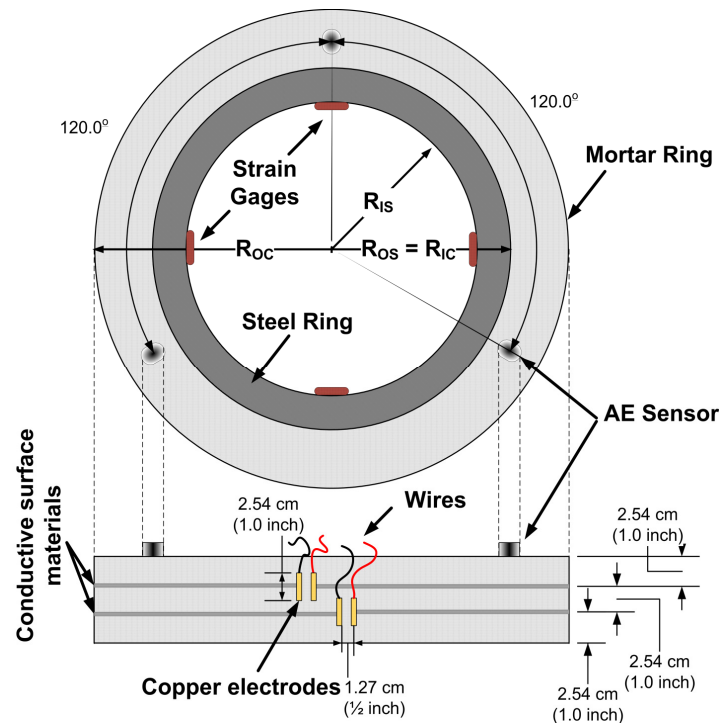


Figure 6 – Schematic illustration of an instrumented restrained ring specimen after instrumentation (after Pour-Ghaz et al. 2011⁸)

Results and Discussion

Figure 7 illustrates the cumulative acoustic energy, average measured strain at the inner surface of the steel ring, and the electrical resistance of the conductive surface materials for mortar ring specimens. The insert inside Figure 7a illustrates a magnified portion the acoustic energy plot to better illustrate the increase of acoustic energy at the time of through the depth cracking. The initial decrease in the resistance of the conductive surface materials (Figure 7b) is due to shrinkage of the substrate and drying of the colloidal silver paint⁹.

The time of cracking using strain gage method is captured by sudden strain release, using conductive coatings the time of cracking is captured with sudden increase in electrical resistance, and using acoustic emission technique the time of cracking is captured with sudden increase in acoustic energy. In both Figures 7a and 7b the time of cracking captured with all three methods corresponds well with each other.

Comparing Figure 7a with Figure 7b it can be seen that with the addition of steel fibers the time of through the depth cracking is significantly delayed and larger stains (i.e., 80 $\mu\epsilon$) develop in the fiber reinforced ring before through the depth cracking compared to plain mortar ring (i.e., 60 $\mu\epsilon$). Furthermore, after the through the depth cracking occurs all the strain in the plain mortar is released while residual strain remains in the fiber reinforced mortar. These effects are due to presence of fibers which results in stress transfer across the crack. The stress transfer across the crack results in smaller crack width.

In Figure 7b only one of the two conductive coatings shows resistance increase at the time of through the depth cracking while in Figure 7a both conductive strips capture the through the depth cracking. Note that the electrical resistance of the conductive coatings (after the through the depth cracking) increase more in plain mortar specimen compared to fiber reinforced mortar ring specimens. This is because presence of fibers results in significantly smaller crack with and as a result detecting the cracks using conductive coating becomes more difficult in fiber reinforced mortar specimen. Also, the resistance increase of the conductive coating due to through the depth cracking is smaller since the crack width in fiber reinforced mortar is smaller.

In both plain and fiber reinforced mortar, damage and micro-cracking using is captured acoustic emission significantly earlier than through the depth cracking is captured by strain gage and conductive coating. The amount of acoustic energy due to damage and cracking prior to through the depth cracking is much higher in fiber reinforced mortar ring specimen compared to plain mortar specimen. This can be attributed to the role of fibers in arresting cracks and elongating the path of the cracks which results in more micro-cracking.

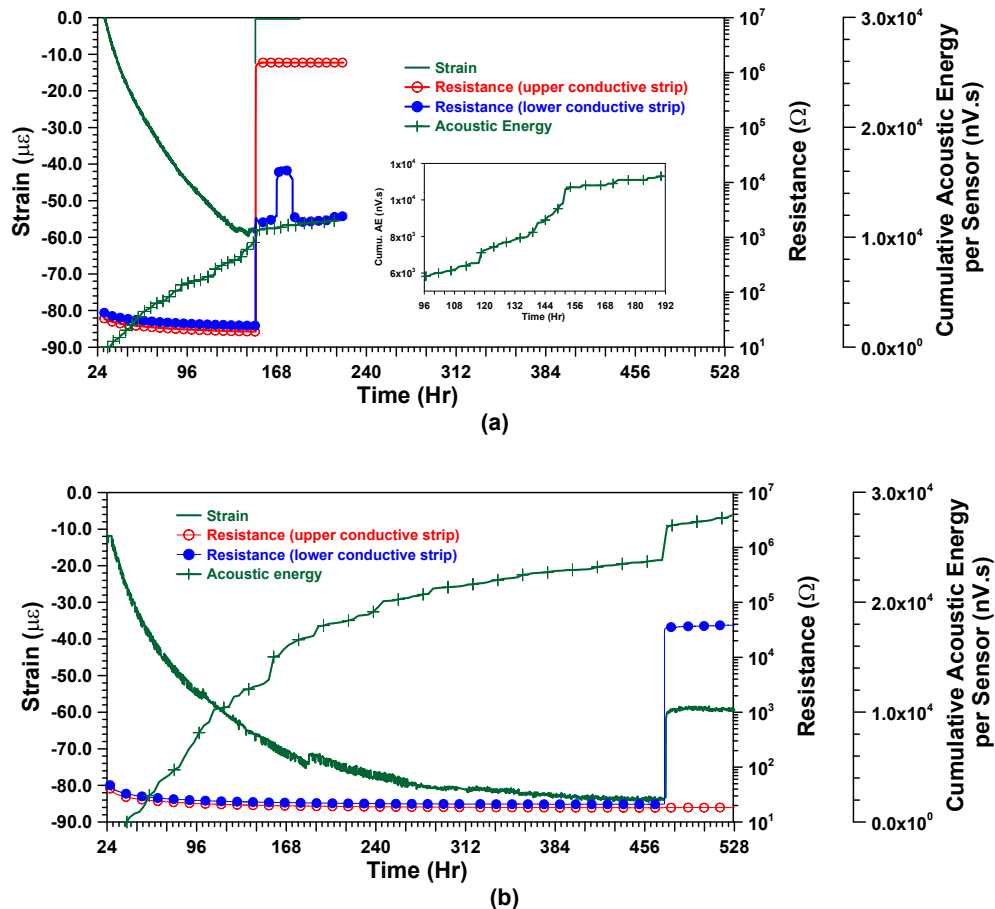


Figure 7 – Cumulative acoustic energy (per sensor), strain at the inner surface of the restraining steel ring, and resistance of the conductive surface strips (a) the plain mortar ring specimens, (b) fiber reinforced specimen

Summary of Conductive Thin Film Method

Three experimental methods were compared for detecting cracking in restrained ring specimens. These methods include monitoring the strain at the inner surface of the restraining steel ring, using passive acoustic emission, and monitoring the electrical resistance of conductive surface materials that are applied to the surface of the mortar. The time of through the depth cracking was detected by sudden strain release in steel ring, discrete increase in the acoustic energy, and a sudden increase in the electrical resistance of the conductive coating. The time of through the depth cracking (visible cracking) that was detected by each method corresponds well with one another.

Detecting the time of through the depth cracking is more difficult in fiber reinforced mixtures due to the role of fibers in decreasing the crack width. The conductive surfaces used in this paper enabled cracking to be detected as long as crack was larger than 0.02 mm (0.0008 in) in width at the surface. The electrical resistance of the conductive coatings increases orders of magnitude once through the depth cracking occurs. By monitoring acoustic emission

passively, micro-cracking could be detected well before through cracking or visible cracking is observed. Acoustic emission provides information about micro-cracking that is not provided by the other methods (the strain gage or conductive surfaces).

The time of through cracking is delayed significantly in restrained fiber reinforced specimens due to crack arrest and significant stress transfer across the crack. Detecting the time of through cracking in the fiber reinforced mortar becomes more difficult using strain measurements and monitoring the resistance of the conductive surface material at the surface of the mortar due to smaller crack width. Although the time of through cracking is delayed with in fiber reinforced specimens, the acoustic activity (e.g., micro-cracking) captured was higher.

FREQUENCY SELECTIVE CIRCUIT

This section describes the design and use of a frequency selective circuit (FSC) to simultaneously monitor response of multiple conductive surface sensors. In this work the FSC is used along with conductive surface coatings to detect cracking in concrete elements. The use of FSC with conductive surface coatings enables simultaneous crack detection on different samples or at different locations throughout the same sample. The FSC can be used to monitor damage development in large structures such as buried pipelines where direct inspection of the pipeline is not possible. In the following sections the physical principles of operation of the proposed FSC are discussed. The frequency dependent response of the proposed FSC is physically measured and simulated (using numerical methods). The FSC is used to simultaneously detect the time of cracking in restrained concrete elements.

Overview of the Method

The physical principle of operation of the FSC can be explained using the element circuit shown in Figure 8. Each branch of the circuit consists of a capacitor (C_i) and a resistor (R_i) that are placed in parallel (where i is the branch number). It is assumed that the capacitances are placed in ascending order (i.e., $C_1 < C_2 < C_3$). While three elements are shown in this example, this concept can be extended to a larger number of elements. The frequency dependent response of the circuit is schematically illustrated in Figure 8b using a Nyquist plot.

At high frequencies all the capacitors in the circuit “short-circuit” the current and provide a path with a negligible electrical resistance (i.e., Path A) and current preferentially flows through this path. The resistance of the circuit, therefore, is essentially zero. The frequency dependent response of the circuit at high frequencies corresponds to point A. In Figure 8b, the real component of impedance (Z') at point A is zero.

As the frequency of the current decreases, the equivalent resistance (capacitive reactance) of the capacitor C_1 increases to the point that it blocks the current and the majority of the current flows through resistor R_1 . However, since capacitance of C_2 and C_3 are larger than C_1 , they still allow flow of the current and therefore current passes through Path B. The real component of the impedance of the circuit therefore is equal to R_1 . This is shown as point B (cusp B) in Figure 8b. With further decrease of the frequency, capacitor C_2 also blocks the flow of current forcing the current to pass through Path C. Therefore, the real component of the impedance is the sum of resistances of resistors R_1 and R_2 . The resistive response of the circuit corresponds to cusp C in Figure 8b.

The resistance of each branch can be calculated using the value of the real component of the cusps in Figure 8b. For example the equivalent resistance of branch No. 1 is equal to real component of impedance at cusp B (Z'_{cuspB}), the equivalent resistance of branch No. 2 is equal to ($Z'_{\text{cuspC}} - Z'_{\text{cuspB}}$) and the resistance of branch No. 3 is equal to ($Z'_{\text{cuspD}} - Z'_{\text{cuspC}}$).

By measuring the impedance of the circuit between point M and N, the resistance change of the all resistors in the circuit can be obtained. Each resistor in Figure 8a can be replaced with a conductive surface coating (or a conductive surface coating can be placed in series with each resistor in the circuit). The conductive surface coating can be used to monitor cracking.

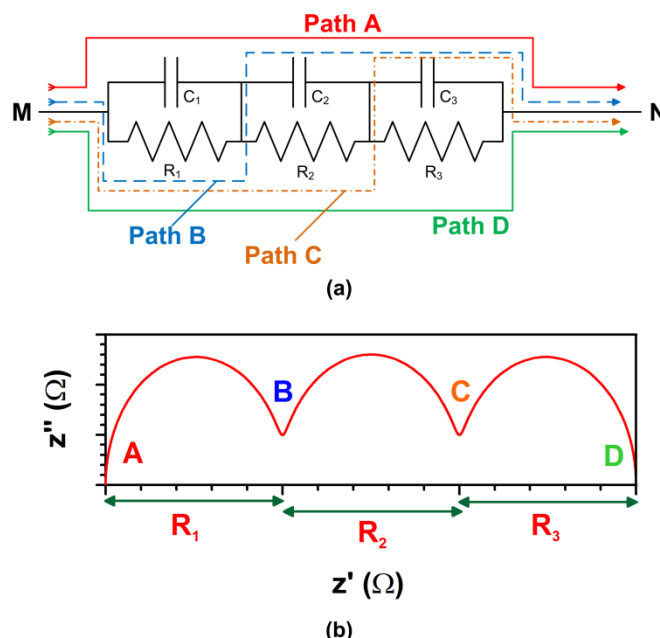


Figure 8 – (a) Schematic illustration of the frequency dependent response of a three-branch frequency selective circuit, (b) Schematic illustration of frequency dependent response of the three-branch frequency selective circuit (After Pour-Ghaz and Weiss 2011⁹)

Physical measurements performed on FSC show deviation from the shown response in Figure 8b at low frequencies. This deviation is due to the non-ideal behavior of the passive components of the circuit³². To minimize this effect an additional resistor is placed in parallel with the first resistor in each branch, and therefore in the modified circuit each branch consists of three passive components (i.e., one capacitor and two resistors). The secondary resistor can be a resistance-based sensor such as conductive coating. For example, if the resistance of the conductive coating becomes infinitely large the equivalent resistance of the branch equals the resistance of the first resistor (R_i) in the circuit.

Materials and Experimental Procedure

Two experiments were performed in the present work. In the first experiment a FSC was used to monitor the response of conductive surface coatings (sensors) applied to the surface of polymeric material. In this experiment ‘cracking’ was simulated on each sensor by intentionally cutting the conductive surface sensor. In the second experiment three conductive surface sensors were applied to the surface of three restrained ring specimens and a FSC was used to simultaneously monitor the cracking of the ring specimens.

Conductive surface sensor on polymeric substrate

Three strips of conductive coatings were applied to the surface of a polymeric sheet. Colloidal silver paint was used as conductive material. Each strip was 152.4 mm (6.0 inch) long and 5.0 mm (0.2 inch) wide. A small piece of conductive copper tape was used at each end of the conductive strips to connect the conductive materials and wires. The wires were in turn connected to the circuit so that the conductive coatings were placed as sensors (S1, S2, S3) in the circuit.

The resistance of each of the conductive coatings (sensors) was smaller than 1.0 Ω . To simulate cracking the conductive coating was cut using a sharp knife. The width of the simulated crack was approximately 0.2 mm (0.08 inch). Each branch of the FSC used for monitoring the response of conductive surfaces on polymeric substrate had one capacitor and two resistors. The capacitors used had capacitance of $C_1=0.01$, $C_2=1.00$ and $C_3=100$ μF and all the resistors used in the circuit had resistance of 100 Ω .

Ring specimens

A total of three restrained ring specimens were cast. Ordinary portland cement (type I) and natural river sand with fineness modulus of 2.71 was used in the mortar mixture. Plain mortar mixture with 0.50 water-to-cement ratio (w/c) and 55% aggregate volume was used. The mixing was performed according to ASTM C192-06³³. The dimensions of the steel ring used in the present study were according to the specification of ASTM C 1581. Four strain gages were installed at the inner surface of the steel ring at 90° with respect to each other.

Specimens were covered with two layers of plastic sheet during the first 24 hours to minimize the evaporation of water. Specimens were instrumented with conductive surface sensors at 24 hours (detailed in following section). During the instrumentation specimens were kept sealed. Specimens were subjected to circumferential drying. The top surfaces of the rings were sealed using aluminum tape. Specimens were placed in an environmental chamber at $50 \pm 1\%$ relative humidity and $23 \pm 1^\circ\text{C}$ ($72 \pm 2^\circ\text{F}$) temperature until the time of cracking.

Instrumentation of ring specimens

The conductive surface material (colloidal silver paint) was applied to the outer circumference surface of the mortar using a thin paint brush. The width of the conductive surface materials strips was approximately 3 mm (3/25 inch). The conductive strip was applied 7.62 cm (3.0 inch) away from the top and bottom of the specimen. Copper electrodes were used to facilitate electrical connection between the conductive surface strips and wires that were connect to the impedance gain/phase analyzer. The copper electrodes were mounted 1.27 cm (1/2 inch) away from each other. The impedance of the circuit was measured in 30-minute intervals with an automated impedance measurement unit. Figure 9a shows a photograph of an instrumented ring specimen, and Figure 9b illustrate a photograph of the experimental setup.

The longer length of the conductive sensors in this experiment resulted in a slightly higher resistance of these sensors. Each conductive sensor installed on the ring samples had $20 \pm 2 \Omega$ resistance. Therefore slightly different resistors were used in each branch of the FSC for this experiment. In all the branches the primary resistor had a resistance of 50Ω and the secondary resistor with was in series with the conductive strip was 30.0Ω resistor (i.e., $R_{1-2} = R_{2-2} = R_{3-2} = 30.0 \Omega$). This resulted essentially in an identical circuit with the circuit used for polymeric substrate experiment (previous section). All the other components of the circuit were identical to those used in the experiment described in the previous section.

Results and Discussion

Conductive surface sensor on polymeric substrate

Figure 10a illustrates the Bode plot of the circuit when all the sensors are in normal condition (i.e., no crack is simulated). In Figure 10 the solid lines represent the numerical simulation while the discrete points represent the physical measurements of the response of the FSC. The equivalent resistance of each branch of the circuit is 50Ω . Figure 10b illustrates the Bode plot for the circuit after a crack is simulated on sensors S_1 (i.e., it is assumed that a crack has an infinite resistance in the numerical model). Since a conductive coating on a polymeric substrate is used in this study, after a crack is simulated on a sensor the resistance of the sensor increases drastically (since the polymer is essentially nonconductive) and equivalent resistance of the branch increases to 100Ω . Note that the resistance of the other two branches remains constant. Figures 10c illustrate the Bode plot of the response of the FSC when two cracks are simulated on two conductive surface sensors (S_1 and S_3) and Figure 10d illustrates the response of FSC when cracks are simulated on three sensors.

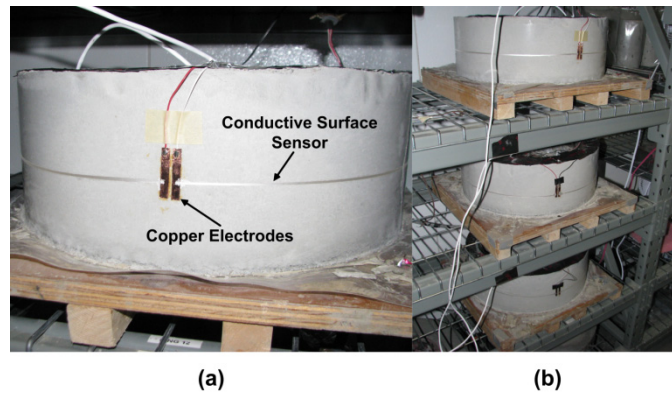


Figure 9 – (a) Instrumented restrained ring with conductive surface sensor, (b) three instrumented ring specimens monitored simultaneously with a frequency selective circuit

Application of frequency selective circuit to detect cracks in restrained ring test

Table 1 reports the time of cracking captured by FSC and strain gage method. The equivalent resistance of each branch is calculated by subtracting the real impedance of the circuit at consecutive cusps as described previously. In the strain gage method, the time of cracking is captured by sudden release of strain²⁵⁻²⁸. The cracking time captured using FSC corresponds well with the time cracking captured by the strain method.

Table 1 – Time of cracking (in hours) of the concrete ring specimen captured using strain gage and frequency selective circuit

Ring No.	Strain Gage (hr)	Frequency Selective Circuit (hr)
1	75.29	70.41
2	62.82	63.07
3	70.35	76.36

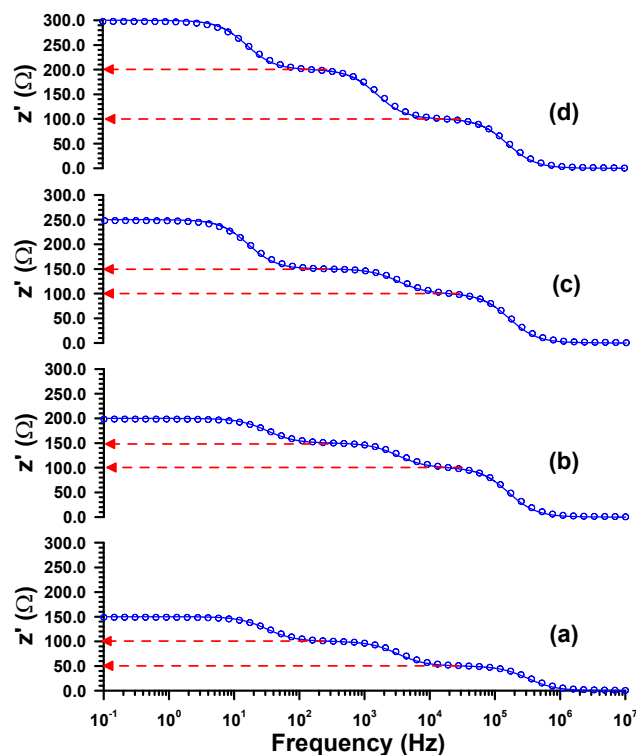


Figure 10 – Bode plot of the response of the frequency selective circuit (numerical (solid line) and experimental (symbols)): (a) no simulated crack, (b) cracking simulated on S_1 , (c) cracking simulated on S_1 and S_3 , (d) cracking simulated on S_1 , S_2 and S_3

Summary of Frequency Selective Circuit Method

The present work introduced the concept of a frequency selective circuit (FSC) for monitoring the response of resistance-based sensors. The design of the FSC is based on frequency selectivity of passive circuit components. The proposed frequency selective circuit provides a fast and inexpensive method for simultaneous monitoring of a large number of resistance-based sensors. In this work the proposed frequency selective circuit was used along with conductive surface sensors to monitor cracking in concrete elements.

The results indicate that the frequency selective circuit can be used to simultaneously monitor cracking of different concrete elements or different locations on a single element. The frequency selective circuit is potential for damage detection in large structures where a large number of sensors need to be installed at different locations.

The frequency selective circuit was used to monitor the resistance change in resistance based sensors; therefore, the capacitors in the FSC were constant components. Alternatively, the FSC can be designed with constant resistive components (resistors) and can be utilized to monitor the capacitance of capacitance-based sensors. This has implications for monitoring other properties of concrete materials such as internal relative humidity and depth fluid penetration. Further investigations in this direction are currently ongoing by authors.

SUMMARY

This paper reviews three recently developed methods for detecting damage in concrete materials using electrical measurements. The first approach describes the use of EIS as a sensing method for concrete. This method can be used to obtain information on the geometry of the crack (notch in the present work) such as crack width and crack depth. The presented data shows the very simply case of a notch from the top surface of a concrete slab with electrodes placed on the top surface. This method is easily be applied to different geometries¹³ and could be to the specific cases of cracks in concrete emanating from the top surface of the concrete where the electrodes would be placed.

The second approach is the use of electrically conductive thin film that is applied to the surface of the concrete. The electrical resistance of this film increases due to cracking of the substrate. By monitoring the electrical resistance of this thin film, information about the time and location of cracking can be obtained. The electrical resistance of the conductive coatings increases orders of magnitude once through cracking occurs. The conductive surfaces used in this paper enabled cracking to be detected as long as crack was larger than 0.02 mm (0.0008 in) in width at the surface. Detecting the cracks becomes more difficult with decrease of the crack width.

The third approach presented in this work in the use of frequency selective circuit. A frequency selective circuit (FSC) can be used to rapidly and simultaneously interrogate the response of multiple conductive surface elements. The frequency selective circuit provides a fast and inexpensive method for simultaneous monitoring of a large number of resistance-based sensors. The results indicate that the frequency selective circuit can be used to simultaneously monitor cracking of different concrete elements or different locations on a single element. The frequency selective circuit is potential for damage detection in large structures where a large number of sensors need to be installed at different locations.

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Smart Technical Textiles for Structural Health Monitoring

Daniele Inaudi and Riccardo Belli

Synopsis: Distributed fiber optic technology offers the capability to measure strain and deformation at thousands of points along a single fiber up to tens of kilometers. This is of particular interest for the monitoring in geotechnical structures where it allows the detection and localization of ground movements. Fiber optic sensing system offers the ability to detect and localize deformation induced by geological assessments, allowing the monitoring of kilometers with a single instrument and localization of the event with a precision better than 1 meter. To improve and optimize the thermal, mechanical and water transport properties of the sensing cable, the optical fiber sensor can be integrated in different types of geotextiles. Geotextile may, for example, be used to increase the strain-transfer surface, to route leaking water to the sensing cable or to protect the cable from damage.

Another civil engineering application of textiles is in the reinforcement of structures with composites. In this case the textile is used to reinforce ageing structures, such as masonry walls in seismic regions, corroded concrete columns and beams or other structural elements that require an increase in load-bearing capacity. However, the retrofitting by means of composites covers the original structure and therefore restricts the possibility to visually inspect it. Furthermore, the bonding between the composites and the original structure plays a major role in the effectiveness of such repairs and it must be guaranteed over time. To address such uncertainties, optical fiber sensors are embedded in the textile and become integral part of the composite material when the resin cures. Once in place, those sensors provide information about the strain and deformation of the composite and of the underlying structure.

This paper presents several designs of smart textiles and their field applications.

Keywords: Distributed Fiber Optic Sensors, Structural Health Monitoring, Integrity Monitoring, Smart Textiles