REVIEW OF FIBER OPTIC SENSORS FOR MONITORING OF CONCRETE STRUCTURES IN THE NUCLEAR INDUSTRY

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Monitoring aging of concrete structures is necessary for the long term operation of nuclear power plants. Sensors attached or embedded in concrete can provide continuous data on the state of some of these structures. Excessive strain, temperature, moisture ingress, development of cracks, steel corrosion and stress relaxation in tendons are some of the parameters that can be monitored with these sensors. This paper provides an overview of Fiber Optic Sensors (FOS) configured for monitoring of concrete structures.

Fiber optic grating sensors, intensity-based and interferometric FOSs are used as distributed sensors or as a large number of multiplexed localized sensors. The ability to use these sensors in different configurations makes them very versatile for long-term monitoring of different degradation processes such as cracks, corrosion, chloride and water ingress, excessive strain and deformation in concrete structures. These sensors are stable, and can be used both as embedded and surface attached sensors for both new and existing structures. They are also very safe for the energy industry since there is no electrical current passing through them.

The uses of different types of FOS sensors are reviewed based on their application for monitoring different types of distresses in concrete structures, and their advantages and disadvantages are discussed.

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REVIEW OF FIBER OPTIC SENSORS FOR MONITORING OF CONCRETE STRUCTURES IN THE NUCLEAR INDUSTRY

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ABSTRACT: Optical Fiber sensors can be attached or embedded in reinforced concrete structures to provide continuous data on the state of these structures. This paper provides an overview of the state-of-the-art FOS sensors for monitoring of aging concrete structures in the nuclear industry. Cracks, corrosion, chloride and water ingress, excessive strain and deformation and stress relaxation in tendons are among the parameters that can be monitored using these sensors. Fiber optic sensors can be used either as distributed sensors or as a large number of multiplexed localized sensors. The ability to use these sensors in different configurations makes them very versatile for long-term monitoring of different degradation processes in concrete structures. The advantages and disadvantages of different types of FOS sensors are discussed in this paper.

1 INTRODUCTION

Concrete structures in civil engineering such as bridges, tunnels, dams, and nuclear power plants generally have long service life. However, some of these structures cannot reach to their expected service life because of severe cases of concrete degradation. Damages in concrete structures usually happens due to excessive loading, fatigue from long-term and cyclic loading, environmental corrosion, and catastrophic events. Accumulation of damages results in performance degradation and capacity reduction of these structures.

Continuous monitoring is a new way of tracking the degradation process of the aging structures over time. The degradation can result in a different response of the structure than the one it was designed for. This becomes especially important in the event of a large load or an accident. Many types of concrete structures including those in the nuclear plants often have areas with difficult accessibility. This poses an extra challenge to the inspection and monitoring process of these structures. Monitoring nuclear concrete structures using embedded sensors can help overcome that barrier by detecting damage locations and estimating the magnitude of the damage in almost real time.

This paper reviews current state of the technology both in practice and at a research stage for deployment of optical fiber sensors which can be used to address the specific problems of the nuclear industry. The reviewed literatures in this paper were focused to address problems such as monitoring cracks, corrosion, chloride and water ingress, excessive strain and deformation, and loss of pre-stress in steel tendons. While the application of interest is primarily the nuclear industry, the used examples of advances made for deployment of sensors are sometimes from other similar industries such as transportation, tunneling and building industries. The advantages and disadvantages involved in the use of different sensory systems are discussed. Also, their applicability for use in new and existing structures is investigated. The optical fiber sensors used for monitoring different types of distresses in civil engineering structures are discussed in the following sections.

2 OPTICAL FIBER SENSORS

Optical fiber sensors have been historically associated with high speed telecommunication links because of their low attenuation and large bandwidth, but since there has been a growing interest over the years for their applications as sensors. These sensors have been used for measuring physical properties such as temperature, pressure, stress, rotation, strain, displacement, acceleration, chemical concentration, dosimetry, and moisture ingress. The interesting characteristics of the optical fiber sensors make them desirable for applications in civil engineering structures. Some of their important characteristics include:

- They are stable.
- They are small, and do not affect the properties of concrete.
- They can be used as distributed sensors or as a large number of multiplexed localized sensors in a large structure. If multiplexed, they do not need power at any individual sensor spot.
- They are light and yet rugged.
- There is no electric current passing through the optical fibers. As the result, they are not sensitive to electromagnetic interferences.
- If used for measuring strain, they have a lot larger signal-to-noise ratio in comparison with foil strain gauges.
- They can be surface attached or embedded in concrete structures.

Many researchers have investigated use of FOSs to measure different types of parameters in civil structures. Nanni et al. (1991), Alavie et al. (1994), Fuhr et al (1993a, 1993b) Hendrick et al. (1992), Inaudi et al. (1994) and Hable and Hillemeier (1995) were among the first people who performed laboratory testing to investigate the reliability of FOS as embedded sensors in concrete structures. One major finding from some of these laboratory studies was that a relatively stiff coating should be used for fibers to have a good bond with cement. This finding is important for strain measurement or crack detection problems especially when the fiber is embedded in concrete. Alavie et al. (1994) found that plastic jackets do not show a good bond behavior with cement in order to transfer the strain. The results of some of these studies also showed that if the FOSs survive during the embedment process, they will be possibly useful for long-term measurements. Fuhr et al (1993a, 1993b) installed the fibers under the steel bar reinforcement to increase chance of their survival during the construction process, and they mentioned that the fibers should be protected from being driven over, soaked in water, having things tied to them or dropped on them during or after construction process. Recently, Song and Peters (2011) have tried to overcome this weakness of FOSs by developing self-healing sensors which can repair themselves after damage.

All the above researchers and many others have tried to accommodate their specific sensing requirements based on the diverse physical properties that can be measured using the Fiber Optic Sensors. The Fiber Optic Sensors (FOS)s are configured in different ways to measure any parameter which can modify the intensity, frequency, polarization, or phase of light traveling through the fiber. Most Fiber Optic Sensors lie in one of the three major categories: Interferometric, Intensiometric and Fiber Bragg Grating (FBG) sensors. Interferometric optical sensors such as Extrinsic Fabry-Perot Interferometric (EFPI) and Low coherence double Michelson interferometer sensors are developed based on changes measured in phase of the passing lights. Intensiometric sensors have been developed based on measurement of the changes in the intensity of the passing light, and FBG sensors have been developed based on changes in wavelength of the reflected lights in the fiber. Fiber optic sensors can be also categorized as intrinsic or extrinsic sensors. If the effect of the measurand on the transmitted light takes place in the fiber, it is called intrinsic. On the other hand, if the fiber carries the light from the source and to a detector, but the modulation occurs outside, it is extrinsic. Although different researchers have configured their FOSs differently for the particular need of their application, the discussion of sensors in the following is presented based on their application type rather than their configurations. Some of the major distresses listed in this review study include water and chloride ingress, cracks, excessive strain and displacements, dosimetry and loss of pre-stress.

2.1 Water and chloride ingress

There are two main applications for sensors detecting moisture, ingress of water, chloride and otherchemicals: a) detecting the advance of an acidic front that can cause corrosion of embedded steel; and b) detecting leaks in tanks containing different chemicals normally found in plants. FOSs have been used in different configurations for both applications in concrete structures. Mitchie et al. (1997) developed a FOS sensor for detecting leaks in a concrete chemical tank. The configuration of this sensor is shown in Figure 1. The developed sensor is in the category of intensiometric FOSs. The sensor includes a carbon fiber core, a layer of hydrogel material which is placed on the surface of GFRP bar. The optical fiber and a dummy fiber are tightly held with the carbon fiber core and hydrogel surface. The hydrogel inflates wherever it is exposed to water. As the result of the inflation, the optical fiber is pushed against the thread and the fiber is bent. Intensity of light will be lost during this process. The backscattered power can be monitored using Optical Time Domain Reflectometry (OTDR). The location at which the power is backscattered can be determined by correlating signal loss to the time. The distribution of wet and dry regions can be monitored using this approach. Similar sensor configuration can be also used for monitoring other chemical reactions. The only difference would be using another type of gel which is sensitive to that specific type of chemical reaction.

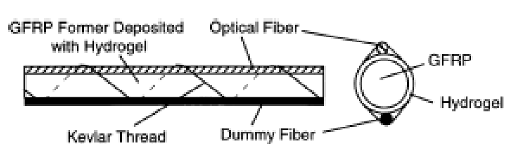

Figure 1. A distributed moisture/chemical sensor for detecting leakages (Mitchie et al. 1997)

Huston and Fuhr (1998) have developed a fiber optic chloride sensor. This sensor includes an input and output fiber which are separated with a small gap. The gap is filled with a sol-gel. When the gel is exposed to chloride, the intensity and wavelength of the light reflected through the sensor will be different. In another development, Laferriere et al. (2008) used a fluorescent molecule called “Luciegenin” along a sol-gel to hold the powder shape Luciegenin material for monitoring the chloride ingress in concrete. The gel was configured into an optode with a stack configuration. Along the optode, an excitation source and a detector was used to detect the intensity of the back propagated photons. The fluorescence intensity in this set up will be affected by chloride ions. The set up for the sensor is shown in Figure 2.

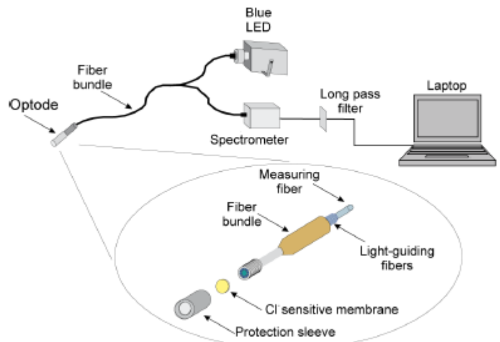

Figure 2. Experimental set up of the sensor (Huston and Fuhr 1998)

Blumentritt et al. (2008) noticed that a stack sensor could have some drawback for embedding in the concrete. During the pouring process and especially through the compression of concrete, the liquid cement could penetrate to every cavity in the stack configuration of the sensor. Alternatively, they developed a new planar sensor configuration to monitor pH in concrete structures. A schematic configuration for the developed planar sensor is shown in Figure 3. The sensing material which is a pH-sensitive azo-dye material acts as a transducer. The fiber guiding the signal is metallized at one end, and is glued to a ceramic substrate. Then, the fiber cut and the resulting slit is filled with sensing material. The amount of back propagated light from the sensing material is calibrated with the pH level in the concrete. The feasibility of the proposed configuration was tested in a lab setup.

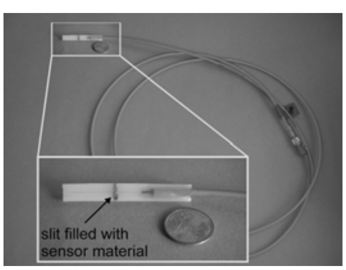

Figure 3. layout of the planar sensor (Blumentritt et al. 2008)

In an alternative configuration, Yeo et al. (2009) used a FBG sensor to monitor the water ingress to measure the porosity of concrete samples. The FBG-based sensor was based on the swelling of a moisture-sensitive polymer which was coated on the sensing region. The expansion of the polymer coating had a secondary effect on elongation of optical fiber. This will result in a shift in the wavelength of the FBG sensor. The amount of shift in the FBG sensor is calibrated vs. the amount of exposed humidity or the elongation on the fiber. This sensor is designed for embedding in the concrete.

2.2 Cracks

Cracks are usually considered as the most visible signs of degradation in civil structures, and their occurrence increase concerns regarding serviceability of the structure. However, as previously mentioned, there are large areas of concrete structures that are not accessible for visual inspection and where cracks can go unnoticed. Different types of FOS sensors have been reported to monitor cracks in civil structures. For example, an intensiometric FOS has been developed by Leung et al (2001) for purpose of crack detection in concrete. The concept for this sensor is demonstrated in Figure 4. The detection of the crack location is based on the sudden losses which happen in the power of the backscattered light. The light power is lost gradually as the light passes through the fiber. However, some sudden loss in power occurs at the locations of fiber bent. In addition, some sudden loss of power happens at the locations of crack. The location of the crack can be found by correlating the loss of power to the time using the concept of OTDR. The advantage of this method is that there is no need to know the location of crack *a priori*. The disadvantage of using this concept is that detecting the crack would be difficult if it occurs at the location at which the direction of the fiber changes. This concept can be used for both the new and existing concrete structures. The sensor can be also cast in the new concrete structures. The other disadvantage of this sensor is if a large number of cracks should be detected, the amount of loss of power per crack in the concrete should be controlled. This will result in a less sensitive sensor for crack detection.

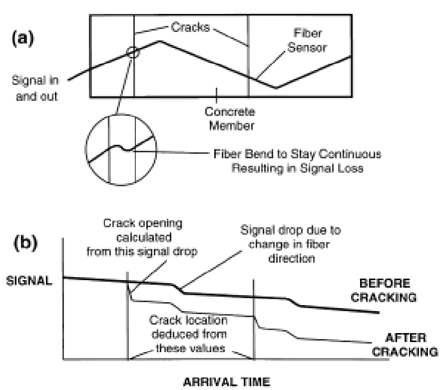

Figure 4. Description of the concept for crack detection using FOSs (Leung et al 2001)

In an alternative approach Imai et al. (2010) used an interferometric FOS setup for crack detection. Imai et al. (2010) used an improved Brillouin Optical Correlation Domain Analysis (BOCDA) system to detect early initiation of cracks in fiber reinforced concrete. The locations of cracks in concrete are unpredictable. Therefore, the best possible approach to capture this problem is using a distributed sensing system throughout the concrete structure. Using BOCDA sensing system will enable using a distributed sensory system throughout the structure. Although FBG sensors are usually more reliable than interferometric sensors, they can only provide quasi-distributed sensing configuration. In the proposed method, a synchronized pulse modulation is applied with a sinusoidal modulation to the injected light wave in order to stimulate the

Brillouin scattering. The Brillouin scattering occurs at a point at which the frequency difference is equal to the speed of the light wave. Information about the strain can be obtained at different locations by sweeping the frequency difference and monitoring the intensity of the scattered light. They demonstrated the ability of the sensing system by attaching the optical fiber to the surface of a Fiber Reinforced Concrete (FRC) test structure in the lab.

Brotzu et al. (2008) used FBG sensors to monitor crack growth in fatigue and corrosion-fatigue tests. They used a laboratory experimental setup in order to demonstrate the ability of FBG sensors for detection of crack growth in an aluminum plate under plain stress and plain strain conditions. They showed how the wavelength of the reflected lights changes by the length of the cracks. They calibrated the wavelength change in the FBG sensor by length of crack.

2.3 Excessive strains and displacements

Strains are monitored in some post tensioned containments structures of the nuclear plants by embedding vibrating wires in concrete. Fiber optic sensors embedded in concrete can be a good alternative for these types of measurements. Glisic et al. (2008) used a sensor system called SOFO (Surveillance d'Ouvrages par Fibres Optiques) to monitor the strain data on a bridge in Switzerland during a one year period including the time when the bridge was under construction. The SOFO sensor system is based on low-coherence interferometry. These sensors were installed to monitor the static responses at several locations along the length of the bridge. Cheng and Ni (2009) also investigated feasibility of applying SOFO optical fibers for long-term measurements in tunnels. They investigated the survival of these sensors under harsh construction environment. This study was performed by an experimental testing of a reinforced concrete beam with embedded SOFO sensors. The optical fiber sensors were attached to the steel rebars. Concrete was poured in the mold, and deformation of the beam was measured under bending in the lab. The installation of the SOFO sensors and field deployments of the sensors are shown in Figure 5.

Figure 5. Installing the SOFO sensor system on the cage bar

Perrone and Vallan (2008) developed a low-cost FOS for measuring displacement in civil structures. They proposed using a plastic optical fiber instead of glass optical fiber in order to decrease the cost of sensors. The basic premise of this method is based on interferometric interrogation. The tension or compression in the structural component will result in a change of the length of the fiber. This change will cause a change in the phase of the output signal. The experimental study showed that the developed sensing system is capable of measuring the displacement with resolutions in the range of several millimeters.

2.4 Dosimetery

FOS can be also used to measure dosimetry in nuclear industry. Luminescence materials can be also used in FOSs based on a concept called Optically Stimulated Luminescence (OSL). OSL materials trap excited electrons. These electrons will release light and produce a luminescence which is proportional to dose of radiation. A small amount of OSL material can be used at the end of optical fibers to measure the dose of radiation in the nuclear components and facilities. A prototype of an optical fiber sensor used for dosimetry applications has been developed at the LETI laboratory, and is tested in a nuclear zone. The developed sensor is able to develop both the dose and dose rate in the nuclear plants (Ferdinand et al 1998).

2.5 Pre-stress loss of steel tendons

Zonta et al. (2008) evaluated ability of a series of multiplexed SOFO interferometric sensors in detecting loss of pre-stress forces in a laboratory setup. They embedded a multiplexed version of the standard SOFO interferometer sensor, commercialized by Smartec SA. This sensor system works based on the concept of low coherence interferometry to measure the optical path imbalance between a measurement fiber, fixed to the structure, and a loose reference fiber. The setup for multiplexed SOFO sensors has been shown in Figure 6. They indirectly determined the loss of pre-stress in a pre-stressed concrete beam by measuring strain values of the pre-stressed cable.

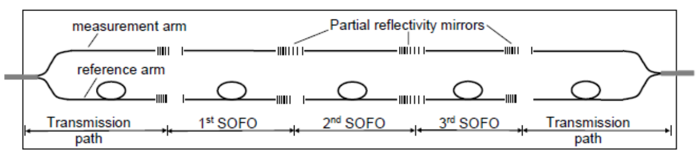

Figure 6. Scheme of the multiplexed SOFO (Zonta et al. 2008)

3 CONCLUSIONS

The applications of different types of Fiber Optic Sensors (FOS) are reviewed for monitoring of different possible distresses in the nuclear industry. The reviewed sensors have been developed with different configurations to address the monitoring requirements for different distresses such as water and chloride ingress, crack detection, monitoring strain and deflections, dosimetry and pre-stress losses. The ability to use these sensors in different configurations makes FOS very versatile for long-term monitoring of different types of distresses especially in concrete structures. The applications are discussed both as embedded and surface attached sensors for both new and existing structures. FOS sensors can be also used either as localized or distributed sensors in the structure. Using these sensors as distributed sensors makes them ideal for certain applications such as crack detection since the location of cracks are not usually known *a priori* in the structures. The ability of multiplexing a large number of these sensors in a single fiber is very advantageous for conducting localized measurements at different locations of a large structure; however there are disadvantages for using single fibers for monitoring at multiple locations. Damage at a single location of the fibers can lead to loosing data from a large part of the structure. The results of several studies have shown that FOS sensors are susceptible to damage during the construction process, but they can survive for a long time after embedment in the structure even in the harsh environment. Finally, versatility and stability of FOS beside the fact that there is no electric current passing through the FOS makes them ideal and safe candidates for monitoring of distresses in the nuclear industry.

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