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## Simultaneous Monitoring on Corrosion-pH-Temperature using Multiplexed Fiber Bragg Grating Sensors Techniques in New RC Structure: A Review

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### ABSTRACT

Most recently, the use of Fiber Bragg Grating (FBG) sensors for monitoring and sensing the condition of structures in civil engineering applications has been developed significantly. FBG can be used for multi-point sensing through a single fiber optic and can be embedded inside the concrete. This paper is a review of current research and development of FBG sensor as a health monitoring system in concrete structure. FBG sensor offers the possibility of sensing due to different parameters like a strain, temperature, pH and displacement. In this paper, the advantages of FBG sensor in contrast to conventional electrical are reviewed. An introduction to fiber optic sensor technology and some of the applications which is still in its early infancy is presented. Two commonly used fiber optic sensors are briefly described namely corrosion sensor and pH sensor. Finally, shortcoming and deficiencies of existing corrosion monitoring technique are reviewed. Promising research efforts in multiplexed FBG sensor in-line one-fiber approach to realize simultaneous measurement of corrosion-pH-temperature monitoring for future research are discussed.

### 1. Introduction

Corrosion is a serious problem for many civil and defense structures. Currently, the ability to reliably quantify corrosion in the field is limited and became of great interest since late 80s and the early 90s (Castro et al., 1997; Sagüés, 1993; Page, 1985). An extensive literature and research reports describe a variety of effects that

influence the steel corrosion and has been debated until present (Yue et al., 2011 and García et al., 2010). pH change in concrete is the most important parameter influence the corrosion process (Song et al., 2012; Blumentritt et al., 2008) and it is hard to inspect visually (Song and Saraswathy, 2007; Sathiyarayanan et al., 2006). Indeed, corrosion also occurs due to effect of ingress of carbon dioxide (CO<sub>2</sub>) and

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chloride ions inside concrete (Junying et al., 2011).

Song and Saraswathy (2007) and Zhang and Lounis (2006) indicate it is important and preferable to monitor corrosion of reinforced concrete at an early warning system that potentially cause and directly affects the service life of the structure (Ismail, et al., 2006; Yeih and Huang, 1998). Traditionally, monitoring steel corrosion via conventional techniques available in market presently relies on physical deterioration of the reinforced concrete structure (Song, 2000; Yeih and Huang, 1998; Sagüés, 1993; Hanson, 1984). Some of the conventional systems also do not have possibility of remote monitoring and require costly maintenance (Duffó et al., 2009; Sathiyarayanan et al., 2006; Elsener, 2002; Andrade and Alonso, 2001).

However, with the rapid development of science and technology, optical fiber sensors were introduced in civil engineering applications and their development have grown significantly. Among the types of optical fiber based sensor that is extensively being studied, Fiber Bragg Grating (FBG) is one of the most exciting developments due to its superior to normal optical fiber thanks to its multi-mode ability and distribution system (Zhao and Liao, 2004). In this review paper in the literature on corrosion sensor, pH sensor based FBG and the uniqueness of multiplexed FBG will be discussed.

## **2. Conventional Corrosion Monitoring Methods**

Methods such as visual inspection, dye penetrant, qualitative thermal wave imaging, imaging microwave spectroscopy ultrasonic, X-ray techniques and reference cells have been developed to detect damages especially in steel corrosion monitoring. However, many of these methods suffer from distinct disadvantages when trying to successfully maintain the aging of steel in concrete (Song and Saraswathy, 2007; Kelly and Jones, 1999). These methods demonstrated lack of precision in visual inspection in early stages of detecting steel corrosion and weakness to hostile environments, susceptibility to electromagnetic interference and lack of capability for continuous

performance monitoring the steel corrosion in real time (Deng and Cai, 2007). Electrochemical technique also has been widely used in the corrosion monitoring (Angst et al., 2009; Qiao and Ou, 2007). However, in some cases unreasonable results were obtained and the high resistivity of concrete strongly dependent on the applied current or potential. Kelly and Jones (1999) reviewed on potential surveys to examine active corrosion areas by sending in open circuit potential when steel begins to corrode. But, the results only snapshots in time and generally coarse with respect to spatial variables. Meanwhile, Yeih and Huang (1998) monitored the corrosion damage in concrete structure using ultrasonic testing. They noted that this method is more significant to detect the size of steel bars in the beginning stage of corrosion processes.

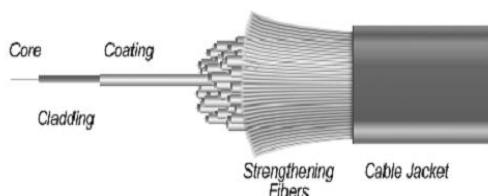
Alonso (2000) also reviewed on the corrosion potential via galvanic current and claimed that this technique is not in a 'free' corrosion potential but in anodic polarization conditions. Song and Saraswathy (2007) writes that reading on half-cell potential is not sufficient because it can be employed once any external sign of corrosion appears on the concrete. Embedded reference electrodes are very useful techniques for long term corrosion monitoring (Muralidharan, 2007). However, the problem with this technique is an embedded electrode should be placed as close to the steel surface, must be stable, invariant to chemical and thermal condition.

According the previous reports, most of the conventional techniques are not practical where ongoing corrosion studies are necessary. It has been proved that the conventional method lack to provide simultaneously information of the current and future performance of the structure. Therefore, it is the intention of the proposed study to establish the chloride and carbonation concentration, pH and corrosion potential simultaneously. In this case, fiber optic sensor could be a good alternative. In this present paper, the new monitoring system for steel corrosion detection at an early stage of corrosion will be developed. The proposed sensor will be embedded inside the concrete to measure simultaneously the corrosion potential, temperature and pH changes in concrete.

### 3. State-of-the-Art of FBG Sensors

An optical fiber is widely used as information carriers in the telecommunication industry and sensing applications. All optical fibers present a core surrounded by a cladding with index of refraction. Basically, an optical fiber is composed of three parts (i) the core (ii) the cladding and (iii) the coating or buffer. The basic structure of an optical fiber is shown in Figure 1.

A unique opportunity to install or embedded the fiber optic sensors (FOS) and gather data that will be useful for their whole lifespan offers an interesting means especially in structural health monitoring (SHM) for bridges (Rodrigues et al., 2010; Chan et al., 2006; Tsuda, 2006). FOS also well demonstrated for determining chemical and physical parameters in a variety of harsh environments due to chemical attack, temperature resistant, immune to electromagnetic interference, light weight, inherently small and have a flexible geometry (Caucheteur et al., 2006). Dakin and Culshaw (n.d) classified on three basis of FOS into (i) physical sensors: measurement of temperature, strain; (ii) chemical sensors: measurement of pH, gas analysis, spectroscopic studies; and (iii) biomedical sensors: inserted via catheters or endoscopes which measure blood flow, glucose content and so on.



**Figure 1:** Basic structure of an optical fiber (Jones, 1998)

A new corrosion monitoring system is needed in civil engineering to replace some outdated monitoring technique that responds better to today's necessities. It is shows that Fiber Bragg Gratings (FBG) sensor has been recognised as one of the most significant enabling technologies for fiber monitoring system. According to Hunt (2008) and Montanini and Pirrotta (2005), FBG sensor is spectral filters that present a resonance at the Bragg wavelength, whose value depends on the

effective refractive index of the core and on the grating pitch. Previous papers on application of FBG sensors have been published and reviewed in Majumder et al. (2008). They claimed simultaneous monitoring on strain, displacement, refractive index and temperature measurements constitute the most interesting parameters to be monitored (Tong et al., 2012; Liu et al., 2011; Lima et al., 2010; Meng et al., 2010; Lee et al., 2010; Dong et al., 2008b). In this case, it is proved that the FBG-based sensor on the whole used predominantly for monitoring physical parameters such as temperature, strain or pressure and it is capable and allowed to measure physical parameters simultaneously (Yeo et al., 2008). However, there is no research on simultaneous monitoring for combining physical and chemical parameters in civil engineering application using one single mode of FBG. Ideally, in this paper a new monitoring system for simultaneous on corrosion-temperature-pH measurement in reinforced concrete will be proposed.

An idea to monitor a wide range of environmental and chemical parameters such as humidity, moisture, chemicals, gas detection, salinity and several other environmental factors based FBG. According to Yeo et al. (2008) noted that to use FBG based chemical sensor, the selected material, for example, polymer-coated FBG should be sensitive and interacts to the chemical measurement and capable of inducing mechanical deformation. The outcomes of the various FOS techniques for humidity detection (Huang et al., 2007) have been summarized by Yeo et al. (2005). They claimed that, the relative humidity based FBG sensor shows the applicable responses but still fairly new. Then, numerous active research and development on FBG (Fidanboylyu & Efendioğlu, 2009; Mora et al., 2006; Sutapun and Azar, 2000; Takahashi et al., 2000) increase significantly whereas the works of various researchers have undoubtedly proven the suitability and reliability of these sensors not only in strain monitoring. Conversely, the applications of FBG sensor in chemical sensing are largely limited.

Now, FBG sensor in various sensing applications other than strain, humidity and temperature shows the potential of corrosion detection. Leung et al. (2008) presented a new FBG sensor for the detection of steel corrosion

in concrete structures. It is indicated that the sensor can detect the presence of chloride ions and the change in sensor output. Dong et al. (2006b) also investigated on the feasibility of an FBG corrosion sensor and metalized by physical vacuum deposition (PVD) to form Fe-C alloy film on a fiber core. It is found that electrochemical measurements by PVD demonstrated based FBG viable in practice. On the other hand, Hu et al. (2011) also developed the corrosion sensor based on FBG sensor fabricated by electroplating a Fe-C film. The results show that the spectra change, the wavelength shift and the occurrence of multiple peaks are related to the corrosion degree of the Fe-C film.

The development of techniques for detecting corrosion in concrete based FBG sensor growth rapidly until now. Gao et al. (2011) have designed FBG sensor and twin steel rebar elements. They establish the relationship between the reflected wavelength change from the grating and the weight loss rate of repair. Chen & Dong (2012) have been modified the wavelength-strain coefficient of FBG to predict the corrosion of steel embedded in concrete. They found that a new relationship between the Bragg wavelength shift and axial strain are significant for corrosion detection. Again, from the previous research it shows that the FBG sensor also capable of detecting the corrosion but there is still no studies on simultaneously between corrosion-pH-temperature changes in concrete have been done yet.

#### **4. pH Sensor based FBG using Sol-Gel Technique**

The monitoring of concrete corrosion relies upon correlation between chemical parameters such as chloride concentration, carbonation, pH changes and corrosion rate of the reinforcing steel. However, in recent times, many researchers have focused on developing a pH sensor itself. Since the pH in concrete may reach above 13, it is necessary for pH sensor to cover such high range. It is proposed to develop broad range fiber optic pH sensors and the effectiveness of using FBG for simultaneous monitoring of corrosion and pH changes under different corrosive induced environments.

Due to the viability and specialty of FBG, novel fabrication methods of FOS for monitoring pH in concrete structures have been developed progressively. Méndez et al. (2005) have designed a pH based FOS with pH sensitive dye. Blumentritt et al. (2008) improved the technique with producing a pH sensor based FBG consists of a pH-sensitive dye acting as optical transducer. The result indicated that it is possible to yield the pH but work is in progress to increase the reproducibility of sensor production and synthesis of the sensing materials.

Researchers have focused on developing broad range pH silica sol-gel sensor based on evanescent wave absorption (Ghandehari & Vimer, 2004 and Gupta & Sharma, 1998) and managed to do so by integrating three different types of dye namely chlorophenol red, cresol red and bromophenol blue. These dyes were selected because, in the porous glass matrix, a mixture of these three dyes covers a long pH range. Dong et al. (2008a) then improved the silica sol-gel pH sensors with the addition of triton capable to detect pH change in solution within the range of 4.5 to 13.0 and also repeatable response. However, works by these researchers only focused on sol-gel pH sensor performance in measuring pH in solution and limited to pH 13 since silica based sol-gel deteriorates at such pH.

Previous research that applied sol-gel based pH sensor in concrete did not manage to clearly distinguish pH changes (Ismail et al., 2005). The new techniques of producing tougher alkaline resistant sol-gel pH sensor using metal oxide, TiO<sub>2</sub> instead of polymer as a liquid precursor has been developed (Beltran et al., 2006). The method of developing pH sensor using TiO<sub>2</sub> sol-gel cladding is to be applied in this study. Pérez et al. (2006) improved the sol-gel technique using sol-gel deposited TiO<sub>2</sub> film doped with organic dyes based pH sensor. It was found that each dye is sensitive to different pH ranges so that with the combination of all of them it is possible to cover a dynamic range of pH levels that vary from 2 to 12. Furthermore, a research on pH sensor based on the cladding of TiO<sub>2</sub> sol-gel on fiber optic was done by Dong et al. (2008a). It is also found that the use of triton TiO<sub>2</sub> improve significantly the quality of the pH-sensitive sol-gel cladding and have great potential for pH range between 4.5 and 13.

Introduction of new pH indicator will increase the range of pH change detection for the sol-gel cladding thus allowing it detects pH beyond 13 in the highly alkaline environment inside fresh concrete. It is hoped that the new design of pH sensor may yield a better result in term of its pH sensing.

## **5. Multiplexed FBG Sensor and Applications**

Any change in fiber properties such as strain, temperature or polarization which varies the model index or grating pitch, will change the Bragg wavelength. The grating is an intrinsic sensor which changes the spectrum of an incident signal by coupling energy to other fiber modes (Hill and Meltz, 1997). The promise of successful multiplexing schemes was one of the early features promoted as a major benefit of FBG sensor over conventional devices. Multiplexing of sensors offers the possibility of the use of a common source and detection system, and one of the advantages of optical fiber systems is the fact that for some sensors, multiplexing can be achieved in a relatively straightforward way.

The number of publications dealing with various aspects of multiplexing FBG sensor has increased markedly in recent years. To date, the practical application of FBG technique still necessitates further developments and the research on multi-axis (multiplexed sensor) measurement is still an active area of research (Chen et al., 2011; Zhan et al., 2009; Iadicicco et al., 2008; Men et al., 2008; Kang et al., 2006). The term of multiplexed sensor is referred as FBG can be written into a single optical fiber and simultaneously interrogated by one multi-channel instrument (Hunt, 2008). This finding agreed with Grattan & Sun (2000) who believed the success of multiplexing technique as a major benefit of FBG sensor over conventional devices.

Men et al. (2008) realized on the simultaneous measurement of salinity and temperature in one fiber sensor system, which consists of multiplexed polymer-coated fiber Bragg gratings. The proposed in-line one-fiber sensor system showed that the polyimide-coated grating responds to variations of both temperature and salinity. Meanwhile, Chan et al.

(2000) reported on multi-point strain measurement of composite bonded concrete beam using three FBGs multiplexed arrays. They demonstrated that the multiplexed FBG sensor proves the unique sensor for real internal strain monitoring and allow a large number of points to be monitored by the use of a single source or detector unit. In this research, the FBG interrogation system will be used as a detector unit for simultaneous monitoring that adopt multiple parameters.

The successful researches on development of multiplexed FBG for monitoring system are summarized in Table 1. It is shown that the multiplexed FBG sensors were realized as multi-point fiber sensing system (Li et al., 2012) and can be simultaneous sensing of multiple parameters in a single fiber optic (Kulchin et al., 2010).

As summary, it is clearly revealed that the capability of multiplexed based FBG sensor to measure multiple parameters with their flexibility to be used as single point or multi-point (multiplexed) sensing arrays make an ideal to be adopted for future research. The proposed monitoring system based corrosion-pH-temperature will be monitored using wavelength signal and the ease of multiplexing capabilities of FBG-based device (FBG interrogation system). Meanwhile, most of the studies focus on simultaneous sensing and a little attention have been paid to multiplexing capabilities of FBG sensor. In addition, no research has been done on simultaneous monitoring system for corrosion potential, pH and temperature changes in concrete using multiplexing sensor based FBG. Due to the uniqueness of FBG, integrating all the parameters in simultaneous monitoring system in single fiber will provide an effective early indication of corrosion initiation.

Table 1: Different approaches on multiplexing FBG sensor

Authors/ Year	Fiber Optic Approach	Parameters	Type of FOS
Silva et al., 2012	Reflective multimode interference based-fiber optic sensor	Refractive index with variation measurement	Single fiber
Schizas et al., 2012	Multiplexed FBG sensor	Monitoring of strains for delamination in composites	Single fiber
Chen et al., 2011	A parallel-multipoint FBG sensor	Simultaneous monitoring temperature-reflection index	-
Orr & Niewczas, 2010	Low-birefringence FBG sensor	Simultaneous measurement on strength-temperature	Single fiber
Herrera et al., 2010	Dual-FBG sensors	FBG interrogation for refractive in aqueous solutions	Dual fiber

Different approaches on multiplexing FBG sensor

Zhan et al., 2009	Combination of FBG and LPG with self-interrogation and self-discrimination	Strain, vibration and temperature	-
Suresh et al., 2009	Multi-mode FBG sensor	FBG based multi-component for force measurement	Dual fiber
Crunelle et al., 2009	Interrogated FBG sensor based optical time domain reflectometry	Reflectometry technique working for temperature sensor	-

## 6. Conclusion

Steel corrosion is one of the major reasons for severe concrete deterioration. A number of traditional detection methods available presently are not very effective and user-friendly comparing to the modified sensor based technologies. The development of Embeddable

sensor in corrosion monitoring system based Fiber Bragg Grating (FBG) technology and its potential applications are briefly reviewed.

It is shown that the capability of multiplexed based FBG sensor to measure multiple parameters with their flexibility to be used as a single point or multi-point (multiplexed) sensing arrays makes an ideal to be adopted in future research.

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