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Optical Fiber Sensor for Corrosion Detection and Evolution Monitoring in Reinforced Concrete Structures

S. ALI-ALVAREZ, P. FERDINAND, S. MAGNE
and R. NOGUEIRA

ABSTRACT

Corrosion of reinforced bars (rebars) in concrete structures is a major issue in civil engineering structures, being its detection and evolution measurement a challenge for applied research. In this project we present a new methodology to detect corrosion and its evolution monitoring, based on the direct rebar-concrete interface changes measurement by the use of Optical Fiber Sensor (OFS) either a Fiber Bragg Grating (FBG) network or Optical Frequency Domain Reflectometry (OFDR) interrogation technique providing distributed strain measurement. A built-in pre-strain profile makes possible the detection of general and pitting corrosion with the same sensor. Accelerated corrosion tests were performed in an electrolytic solution under both pitting and general corrosion. A clear correlation is observed between the evolution of the spectral shift and the corrosion progress thus demonstrating the feasibility of this technique.

INTRODUCTION

Corrosion measurements by the standardized methods are obtained from destructive analyses like concrete sampling for electro-chemical tests [1, 2], others involve an indirect measurement of corrosion, like impedance or ultrasonic measures [3, 4], and all are limited both in space and time [5], leading to tedious analysis and making decision difficult. Much effort remains to be done to survey the onset and the progression of corrosion processes in a reliable way. Corrosion attack to rebar surface depends on several physical, chemical and electrochemical parameters (temperature, pH, carbonation, presence of chlorides, presence of microbes, etc.), which lead basically to two types of mechanical changes at rebar-concrete interface. In the first

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case, metal oxidation products stay at the interface and increase internal pressure leading to a crack of the external concrete layer (general corrosion). In the second case metal ions are evacuated out of the structure without impact on internal strains [6], but reduce the rebar mass (pitting corrosion). By the combination of this newly developed OFS with the electrochemical and physical properties of rebar in a simplified pre-strained assembly, it is conceived to detect both types of corrosion development. This simplified manufacturing procedure proposes a low cost solution to Structural Health Monitoring (SHM) for a direct measurement of corrosion evolution, useful to implement or improve Condition-Based Maintenance (CBM) programs for civil engineering concrete structures. This work is based on a previous research [7].

SENSOR CONCEPTION

The sensor is based on the capabilities of the OFDR technique [8,9,10] to treat the optical fiber as a distributed FBG, as is shown in figure 1. The window and the gauge length (dx) can be adjusted in position and size, to increase both the measurement range and sensibility. It is possible to build a pre-strain profile based on high temperature epoxy curing and the difference in thermal expansion coefficients (metal – silica), able to follow both corrosion changes (pitting and general corrosion) at rebar surface. Pitting corrosion will release the strain whereas general corrosion will increase the strain applied to the fiber.

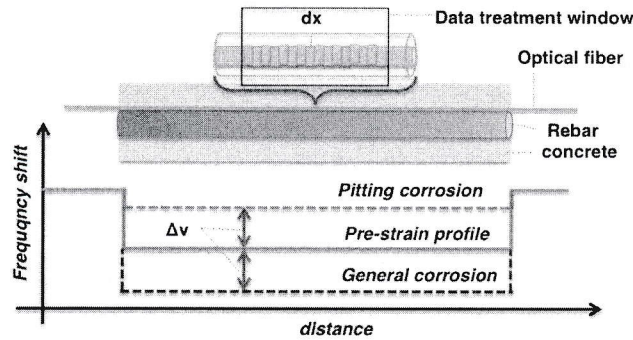


Figure 1. Operating principle of the corrosion sensor. The optical fiber measure changes at rebar-concrete interface surface. Blue line represents the pre-strain profile of spectral shift established by the manufacturing procedure. Red line represents changes of general corrosion and green line pitting corrosion. Optical fiber detail shows the virtual construction of FBG network for data treatment.

The OFDR frequency shift is defined by the following equation, similarly to FBG:

$$\frac{\Delta\lambda}{\lambda} = -\frac{\Delta\nu}{\nu} = K_T \cdot \Delta T + K_\varepsilon \cdot \varepsilon \quad (1)$$

where λ and ν are respectively the central wavelength and frequency, $\Delta\lambda$ and $\Delta\nu$ the spectral shifts, K_T ($\approx 6.45 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$) and K_ε (≈ 0.780) the temperature and strain coefficients, ΔT the temperature shift and ε the strain applied to the fiber [11].

EXPERIMENTAL SETUP

A standard rebar (FE500, $\varnothing = 12$ mm, $L = 6$ cm) was used to hold the optical fiber (ITU-G.652). A thin film of epoxy was applied on the fiber and the assembly was heated (for resin curing) (figure 2 - left). As the sensor is taken back at room temperature, a compressive strain results due to the difference in the thermal expansion coefficients of steel and silica. The pre-strained profile is 40 mm long (figure 2 - left). In order to recreate actual conditions in which corrosion products are prone to accumulate at the metal cement interface, the sensor was placed in the middle of a concrete cylinder, which was prepared with granulates (80 %) and Portland Type-1 cement (20 %) in a 0.6 proportion regarding a chloride-rich water (35 g.L^{-1}) so as to onset the corrosion. After 24 hours of drying in the capsule, the resulting cylinder was immersed in a NaOH 0,1 M + NaCl 35 g.L^{-1} solution for curing at open circuit conditions (pitting corrosion), which means without external biased polarization (figure 2 - right). The next step was to force corrosion by imposing a 100 mA.cm^{-2} current density until crack (general corrosion) occurs. The electrochemical measurements were made with a PGZ-100 potentiometer with Ag/AgCl electrode and frequency shift was recorded with LUNA 4600 Optical Backscatter Reflectometer (OBR).

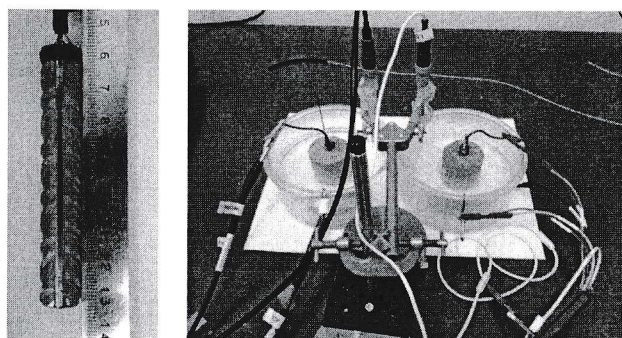


Figure 2. Left: image of the pre-strain sensor. Right: setup of corrosion test based on electrolyte solution.

RESULTS AND DISCUSSIONS

The sensor was assembled in a room air-conditioned at 22°C . A frequency shift of -1565 GHz ($10367 \mu\text{m/m}$) was recorded for a curing temperature of 84°C . After cooling down to room temperature, the fiber exhibits a permanent frequency shift of -1470 GHz ($9737 \mu\text{m/m}$), equivalent to a pre-strain of $\approx 630 \mu\text{m/m}$. This point is considered as the pre-strain of reference for the measurements. Room temperature variations (2.5°C) correspond to frequency variations of $\pm 3 \text{ GHz}$.

Pitting corrosion

Curing of the sample for 22 days (figure 2 - right) led to a frequency shift of -550 GHz ($3643 \mu\text{m/m}$), equivalent to a strain release of $6094 \mu\text{m/m}$. The recorded corrosion potential are below -500 mV , equivalent to a severe corrosion condition

according to ASTM 876 standard. The strain release is mainly due to loss of mechanical support by the metal oxidation at rebar surface, with low density of oxidation products.

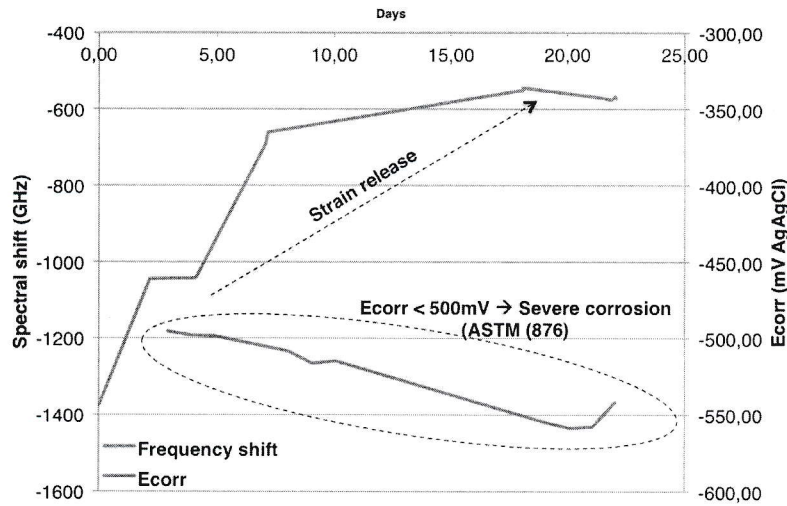


Figure 3. Evolution of the frequency shift and electrochemical potential (E_{corr}) of the sample during pitting corrosion process, showing clear correlation.

General Corrosion

The sensor that experienced pitting corrosion was then submitted to general corrosion by imposing a current of $100 \text{ mA} \cdot \text{cm}^{-2}$ during 17 hours. The frequency shift was -1795 GHz ($11890 \text{ } \mu\text{m}/\text{m}$) at sample cracking, being an increase of $8247 \text{ } \mu\text{m}/\text{m}$ in comparison with the lowest point during curing process. Figure 4 illustrates the optical and electrochemical variables evolution. The total charge applied to the sample, assuming no loss in the current path, is $Q=22640 \text{ C}$. Applying the Faraday law of electrolysis, the mass of metal transformed into rust is then:

$$m = \frac{Q}{q \cdot n} \cdot \frac{M}{N_A} = \frac{22640}{1.602 \cdot 10^{-19} \cdot 6.02210^{23}} \cdot \frac{55.845}{2} = 6.48 \text{ g} \quad (2)$$

where Q is the total charge, q the electron charge, n the valence of the metal, m the molar mass and N_A the Avogadro constant.

The initial sample volume and mass were 6.8 cm^3 and 53.43 g respectively (iron density $\approx 7.874 \text{ g cm}^3$). A mass loss of 6.48 g ($\approx 13\%$) is equivalent to 0.56 mm of corroded steel thickness. From this value, one might estimate a corrosion rate of $0.033 \text{ mm} \cdot \text{hour}^{-1}$. In the optical domain, the slope obtained by linear approximations is $-375 \text{ GHz} \cdot \text{hour}^{-1}$, which permits correlative values between both physical domains.

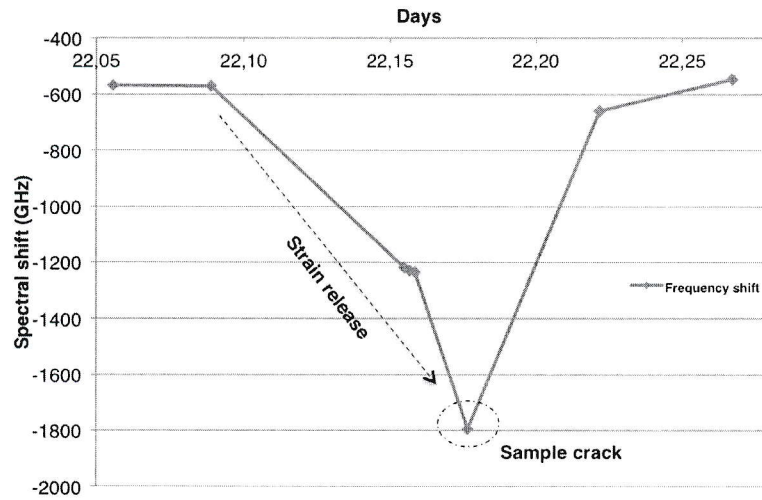


Figure 4. Evolution of the frequency shift of the sample during accelerated corrosion test.

Superposing all the optical strain distributions for pitting and general corrosion we can observe the behavior predicted during the sensor conception for both kinds of corrosion, as is depicted in figure 5. Presetting of threshold at different levels can be used in CBM programs for SHM systems.

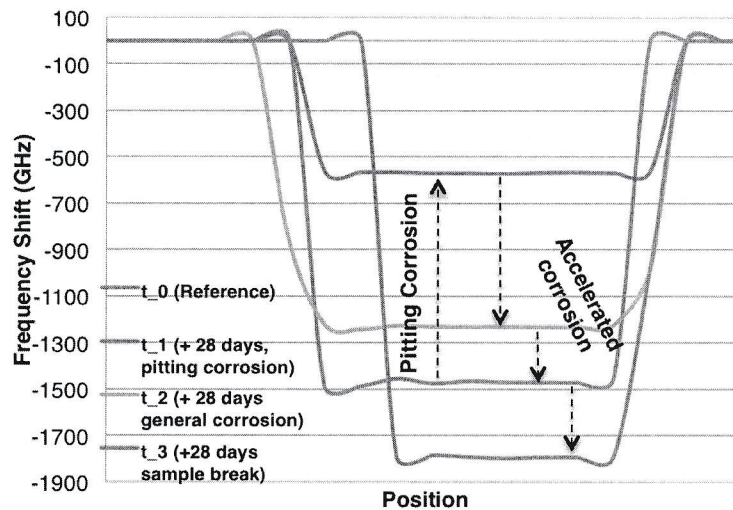


Figure 5. Synthesis of the test. The sample follows the sensor conception behavior (figure 1).

CONCLUSIONS

In this project we have demonstrated the feasibility of the OFDR technique in implementing a corrosion monitoring system devoted to concrete structures. Taking advantage of the OFDR technique and pre-straining method, it is possible to design a sensor sensitive to both main types of corrosion. The fiber pre-strain obtained by high

temperature epoxy polymerization, creates a reference point, which is not affected by temperature variation during the day and between seasons. Fiber sensor strain release indicates pitting corrosion, whereas a strain increase results from general corrosion. In accelerated corrosion test the system was able to follow corrosion evolution. Electrochemical measurements were used to calibrate the sensor and to check its proper behavior versus corrosion. The same assembly was used to firstly measure pitting corrosion, followed by general corrosion test, showing that the sensing technique is adaptable regarding the precedent state of the measurement. Owing to recent OFDR optical techniques, measurements were made in absolute frequency values. Further tests are programmed to validate the technique on field.

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