

Monitoring Localized Corrosion Distribution of Steel Bar in Concrete with OFDR Distributed Optical Fiber

Fujian Tang, Jialiang Hu, Hong-Nan Li, Liang Ren
School of Civil Engineering, Dalian University of Technology
No.2, Linggong Road
Dalian, Liaoning 116024
P.R. China

Els Verstrynghe
Civil Engineering Department, KU Leuven
Kasteelpark Arenberg 40
3000 Leuven
Belgium

ABSTRACT

This study aims to monitor the spatial distribution of pitting corrosion occurring in steel rebars in concrete structures using an optical frequency domain reflectometry (OFDR) distributed optical fiber sensor. A concrete slab was fabricated containing eight steel rebars. After curing for 28 days, the top surface of the slab was polished with a sand wheel, and then an optical fiber sensor was attached to the surface using epoxy resin. The direction of the fiber is perpendicular to the direction of steel bars, and a total of four loops were applied so that four intersection points are present between the fiber and steel bars. The slab was subjected to accelerated corrosion testing. During the test, open circuit potential (OCP) was measured, and the change of the surface strain induced by steel bar corrosion was recorded with the optical fiber. Results show that the OCP is affected by the presence of chloride, and the spatial distribution of localized corrosion of steel bars can be monitored with the OFDR fiber. An empirical equation was proposed between the corrosion-induced area loss of steel rebars and the measured OFDR strain, which can be used to monitor distributed steel rebar corrosion.

Key words: Reinforced Concrete, Corrosion, Cracking, Distributed Optical Fiber

INTRODUCTION

Steel rebars in concrete structures are usually protected from corrosion by a thin layer of passive film, which is formed due to the high alkalinity of concrete pore solution.¹⁻² However, this protective passive film could be damaged by penetration of chloride into concrete structures in marine environments or exposure to the use of de-icing salt for the removal of snow and ice in winter times.³ Penetration of chloride would impair the passive film locally and initiate pitting corrosion.⁴ Over time, the buildup of

corrosion products generates internal tensile stress in the concrete cover, and causes concrete cracking, delamination, spalling, and subsequently reduction in the carrying capacity and service life of structures.⁵⁻⁶

Half-cell potential is a well-established and widely used method to judge the corrosion status of steel reinforcement in a probabilistic manner, and it is easier and more economical compared with other techniques.⁷ However, it only provides a probability of corrosion activity instead of giving quantitative information such as the corrosion rate. Moreover, the potential reading is affected by many factors such as concrete cover, chloride concentration, rebar coating, and so on.⁸ Galvanostatic pulse measurement (GPM) is another electrochemical nondestructive testing method used for assessment of rebar corrosion based on the polarization resistance by using a small current pulse.⁹⁻¹⁰ This method provides more realistic measurement of the corrosion rate of steel bars compared with the potential measurement, but high concrete resistivity would lead to unstable measurements. Concrete resistivity is closely related to the corrosion rate of steel bars; therefore, it can also be used for assessment of steel bar corrosion.¹¹ Other electrochemical methods such as electrochemical impedance spectroscopy (EIS) and electrochemical noise have been used for corrosion measurement, but they are more suitable in the laboratory than for on-site measurement.¹²⁻¹³

In addition to electrochemical methods, steel bar corrosion can also be indirectly monitored with other physical techniques such as optic fibers,¹⁴⁻¹⁹ acoustic emission,²⁰⁻²² ground penetrating radar²³ and so on. Long-period fiber gratings (LPFG) coated with a thin layer of nano-iron or Fe-C film were proposed to monitor steel bar corrosion.¹⁴⁻¹⁵ Due to the limitation of the sensing range of the LPFG to the environment, they are more suitable for corrosion monitoring at early stages.¹⁶⁻¹⁷ By encasing the optical fiber or long period fiber grating in a steel straw, the corrosion can be monitored through the shift of the resonant wavelength or the change of the reflectivity.¹⁸⁻¹⁹ The accumulation of corrosion products generates tensile stress in the concrete cover and causes cracking, which can be indirectly detected with an acoustic emission instrument.²⁰⁻²² As chloride-induced corrosion happens on the steel bar surface, the properties of concrete cover change due to penetration of chloride, and accordingly the transmitted high frequency electromagnetic signal changes. Therefore, ground penetration radar has also been used to monitor steel bar corrosion as the reflected signal is affected the chloride in concrete cover.²³

However, both the electrochemical methods and the non-electrochemical techniques mentioned above can only monitor corrosion at a point or in a small area at a time. Highway or oversea bridges and other large infrastructures usually have a length of hundreds to thousand meters, therefore, it will be time-consuming and uneconomical to monitor corrosion with these point-by-point methods. Sensors or sensing instruments that are capable of monitoring distribution of corrosion over a large area would be more desirable than these point-by-point sensors.

In recent years, distributed optical fiber sensors have been proposed for continuous measurement of strain, deformation, temperature, and corrosion along the length of a fiber.²⁴ In general, distributed fiber optic sensing technology can be divided into two categories: time domain and frequency domain. Compared with time domain reflectometry such as the Raman optical time domain reflectometry (OTDR) and the Brillouin OTDR,²⁵ optical frequency domain reflectometry (OFDR) has more advantages such as high spatial resolution, high sensitivity and large measurement range. Therefore, it has been used for distributed sensing of temperature, pipeline leakages and strain.²⁶⁻²⁸

The purpose of this study is to monitor the spatial distribution of localized corrosion of steel bars embedded in concrete with OFDR distributed optical fiber. A concrete slab containing eight steel bars was fabricated in the laboratory and then subjected to accelerated corrosion testing. The evolution of localized corrosion was monitored with open circuit potential and OFDR fiber. A relationship between the mass loss of steel bar and the measured strain from the OFDR fiber is established.

EXPERIMENTAL PROCEDURE

Concrete Slab Specimen

A concrete slab with dimensions 300×670×100 mm was fabricated in the lab, as shown in Figure 1. It contained 8 steel bars with a diameter of 16.0 mm, and the embedded part of the steel bar has a length of 300 mm. The concrete cover on the top surface has a thickness of 20 mm.

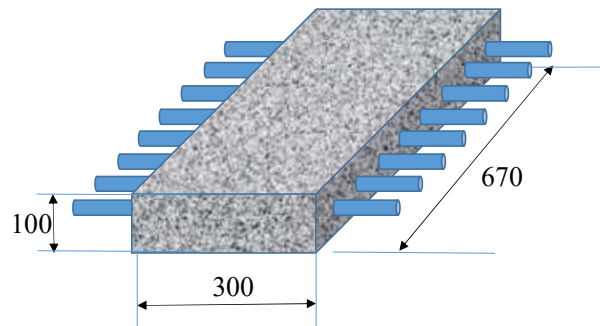


Figure 1: Dimensions of the concrete slab specimen (unit: mm).

The concrete used in this study was a mixture of Portland cement, coarse aggregates, fine aggregates, and tap water with a ratio of 1:3.48:2.63:0.62 by weight. Limestone with a maximum diameter of 10 mm was used as coarse aggregates. The 28-day average compressive strength of 150×150×150 mm concrete cubes was tested to be 21.8 MPa.

Deployment of Optical Fiber and Measurement Points of Half-Cell Potential

After air curing for 28 days, the top surface of the slab was polished with a sand wheel, and then one polyimide coated single-mode optical fiber was attached onto the surface with an epoxy resin. The direction of the fiber was perpendicular to the direction of the steel bars as shown in Figure 2. The fiber was attached back and forth four times so that there are four intersections between the fiber and every steel bar. The spacing of the fiber on the top of the steel bar is 7.5 cm. The open circuit potential (OCP) was measured with a saturated calomel electrode (SCE), and a total of 45 measurement points were selected and uniformly distributed on the surface of the concrete slab as shown in Figure 2.

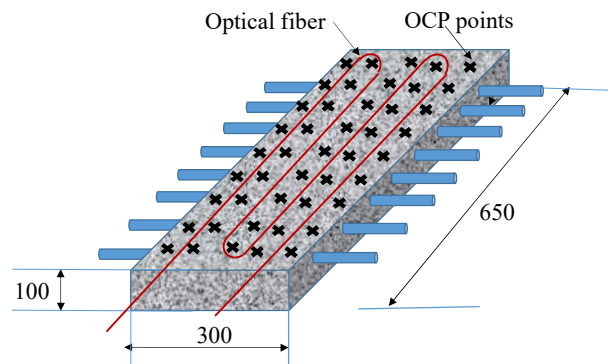


Figure 2: Deployment of optical fiber and OCP measurement points on the top surface of concrete.

Accelerated Corrosion Test

After deployment of the optical fiber, the concrete slab was moved into a wood container filled with wet sand, as schematically illustrated in Figure 3. A wood levee was also made around the four sides of the top concrete surface to limit the top wet sand. In order to establish a corrosive environment, 3.5 wt.% NaCl water was sprayed periodically onto the sand to provide moisture and chloride ions. To accelerate the corrosion of steel bars, an electrical current ~ 400 mA was applied on the steel bars using an external power supply. The steel bars were successively connected in series with the positive end of the power supply after different times to reach different corrosion levels. To establish an electrical circuit, a graphite rod with a diameter of 6.35 mm was connected to the negative end and inserted in the river sand. The test was carried out at room temperature around 20 °C.

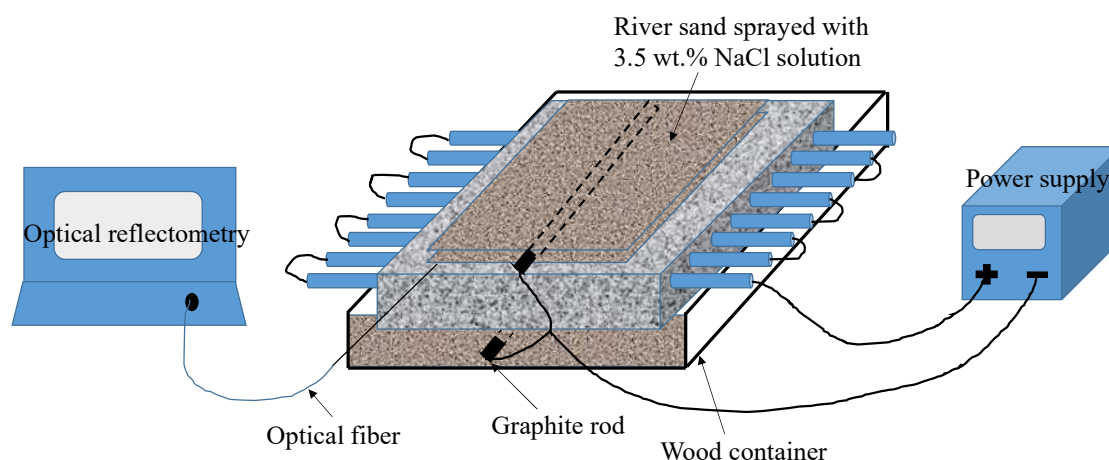


Figure 3: Accelerated corrosion test setup.

The amount of corrosion in terms of mass loss is related to the electrical energy consumed, which was estimated according to the following equation: ²⁹

$$\Delta m = \frac{MIt}{zF} \quad (1)$$

where Δm is the mass of steel consumed (g), M is the atomic weight of the metal (56 g for iron), I is the electrical current flowing through the steel bar, t is the time in seconds, z is the ionic charge (2 for iron), and F is the Faraday constant (96,500 C mol⁻¹).

Measurement of Crack Width and Cross-Sectional Area Loss of Corroded Steel Bars

After corrosion testing, photos were taken on the top of the slab specimen with a crack width meter as the scale as shown in Figure 4. The crack width along the length of steel bars was determined with image processing at every 10 mm. After measurement of cracks, the corroded steel bars were taken out of the slab with a hammer. The residual cross-sectional area of the corroded steel bars was determined with a caliper.

Half-Cell Potential

Figure 5 shows the distribution contour of open circuit potential (OCP) on the surface of the concrete slab before corrosion testing (Figure 5a), and after the first (Figure 5b), the second (Figure 5c) and the third (Figure 5d) steel bars were successively connected in series for accelerated corrosion test. It is