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Damage evaluation of concrete based on Brillouin corrosion expansion sensor

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HIGHLIGHTS

- The sensor of expansion strain of steel corrosion was designed and tested.
- Expansion strain of steel corrosion was monitored by BOTDA.
- Damage factor was proposed to quantitatively evaluate the damage degree of concrete.
- The monitoring method which proposed in this study makes monitoring and evaluation in real-time come true.

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ABSTRACT

To evaluate the damage degree of reinforced concrete due to steel bar corrosion, a damage factor is proposed to quantitatively evaluate the damage degree of concrete before initial cracking and during the development of cracks. Brillouin optical fiber time domain analysis (BOTDA) sensors are fabricated to monitor the expansion strain of steel corrosion. Two concrete specimens embedded with corrosion sensors are cast. An accelerated corrosion experimental program is used to accelerate the process of steel corrosion. The experimental results show that the corrosion sensor can be used to monitor the expansion strain of steel corrosion in real-time. At last, to map the monitoring results with the damage factor, finite element analysis is used to simulate the process of steel corrosion to determine the cracking strain of the interfacial concrete and concrete cover.

1. Introduction

Nowadays, steel corrosion has become a significant concern in many countries. Numerous reinforced concrete structures are repaired, demolished, or collapsed because of steel bar corrosion, which causes incalculable losses [1,2]. Steel corrosion reduces the ultimate yield strength of steel, weakens the bond properties between reinforcement and concrete, and affects the seismic performance and static load capacity of reinforced concrete structures greatly [3–6]. The pH value range of concrete pore solutions is between 12 and 14, the alkaline environment of concrete results in the formation of a passive film of iron oxides at the steel-to-concrete interface that protects the steel from corrosion. However, this film is usually destroyed and activated by the penetration of chloride ions, which subsequently leads to corrosion in the presence of moisture and oxygen. The rust (with Fe_2O_3 as the main component) is produced by steel bar corrosion which causes volume expansion and hoop tensile stress on the concrete, and subsequently leads the concrete to deformation and cracks [7,8].

The use of smart sensors and industrialization of wireless sensor networks have attracted a lot of research attention, structural health monitoring is becoming a key factor in the operational security of major engineering structures [9]. The cutting-edge optical fiber sensing technology has widely adopted in optical communication and structural health monitoring over the recent years, and also successfully applied in civil engineering, hydraulic engineering, and other areas [10–14]. Optical fiber presents many advantages, such as its light weight, anti-interference ability, resistance to corrosion, and facilitation of the real-time and long-distance monitoring in large-scale structures. Therefore, this technology is expected to overcome the defect of traditional steel bar corrosion monitoring method, also, its application needs to be improved urgently in this field [15–17].

To monitor the process of steel corrosion, several types of fiber optic sensors have been developed. Bennett designed a prototype optical fiber sensor to monitor corrosion on large steel structures by pulling a multimode fiber into a tight bend and securing the

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fiber with a “corrosion fuse” [18]. However, a light loss of “corrosion fuse” would fail into the monitoring of the sensor. Greene designed a pre-strained Bragg grating corrosion sensor that maintained the residual strain by bonding a capillary tube to a pre-strained Bragg grating sensor [19]. However, the fiber Bragg grating strain would decrease because of the relaxation pre-stressing even there was no corrosion. Li proposed an optical fiber grating sensor for monitoring corrosion by sticking a Bragg grating on the centre of two bars which were facing against each other [20]. It could be monitored that the wavelength shift of stainless steel sensor increased with time, but the results were not stable. Distributed optical fiber sensing technology is a new sophisticated type of fiber optic sensing technology. Gan applied BOTDR to monitor steel-bar-corrosion-induced concrete expansion and proved the feasibility of applying distributed optical fiber sensing technology to monitor reinforcement steel bar corrosion [21]. Compared to other Broillouin-scattering-based distributed sensing techniques, BOTDA has a higher dynamic range, a simpler signal demodulation, and a higher accuracy [22,23]. Based on BOTDA technology, a new steel bar corrosion sensor, which is applicable to entire lifecycle monitoring was developed and tested in this paper.

The process of steel bar corrosion expansion in concrete can be divided into four phases: reinforcement deactivation, free expansion, appearance of stress and concrete cover cracking [24,25]. With the last two phases causing mainly direct damage to concrete structures, some methods of evaluating the concrete damage degree have been proposed. Yun formulated a relationship among rebar corrosion, longitudinal crack width, cover thickness, rebar diameter, and concrete strength [26]. Alonso found that a linear relationship existed between crack width growth and radius loss of the type during the propagation period of the crack until a certain limit of attack [27]. However, the research could not get a valid assessment when cracks have not reached the concrete surface.

Subramaniam developed an Evans diagram representation of the macrocell corrosion system [28]. The relationship between the current density and the potentials relative to the crack was obtained from the Tafel polarisation responses of active and passive steel in concrete. Chang proposed an empirical model for the polarisation behaviour of steel in concrete [29]. Typical curve-fit results are presented using the proposed model to simulate the polarisation behaviour and evaluate the corrosion rate as well as the Tafel parameters of steel corrosion in seawater. Li studied the damage evolution of the concrete structures and defined the damage degree on the tensile crack stress of concrete edge [30]. This form of evaluation can quantitatively measure the damage before the cracking of concrete surface, but not accurately enough.

In previous studies, there are some argues on the migration of corrosion products. Some studies think that the corrosion products will migrate into the pores and cracks before the concrete surface cracking [31,32]. However, the study of Zhao shows that the corrosion product does not penetrate into the cracks before surface cracking [33]. In addition, the composition of rust is complicated and may expand about 2–6 times the volume of metal removed [34,35]. To eliminate the effect of these uncertainties, a new corrosion sensor which could monitor the corrosion process in macroscopic perspective was designed. This paper also brings forward a new assessment of concrete cracking due to steel corrosion, namely, defining the damage factor of reinforced concrete structures, which can evaluate the damage degree before and during the development of cracks.

2. Basic principle of Brillouin optical fiber time domain system

Fig. 1 shows the schematic of the BOTDA system. If the frequency difference between the pump and the probe waves is tuned to around the Brillouin frequency shift at some location along the test fiber, the probe signal is amplified at that point due to stimulated Brillouin scattering between the pump and the probe lights. Therefore, it is possible to measure the distributed temperature and strain by measuring the time-dependent probe light power for various values, and by obtaining the Brillouin frequency shift distribution along the fiber length [36].

The Brillouin frequency shift is expressed as follows:

$$\nu_B = 2n\nu_a/\lambda \tag{1}$$

where n denotes the refractive index, ν_a denotes the velocity of sound, and λ denotes the wavelength of light.

The relationship of the Brillouin frequency shift at a certain location along the fiber with its corresponding temperature and strain change can be described as follows:

$$\nu_B = k_{ft}\Delta T + k_{f\varepsilon}\Delta\varepsilon + C \tag{2}$$

where k_{ft} denotes the temperature coefficient of Brillouin frequency shift, $k_{f\varepsilon}$ denotes the strain coefficient of Brillouin frequency shift, Δ_T denotes temperature change, Δ_ε denotes strain change, and C is a constant.

Therefore, the local temperature and strain conditions along the fiber can be measured based on the Brillouin frequency shift.

3. Experiments

3.1. Design of the BOTDA steel corrosion sensor

Fig. 2 shows the design of the BOTDA steel corrosion sensor. The fabrication procedures are described as follows: (1) prepares a 500 mm-long and 20 mm in diameter HRB335 rebar. (2) Pour a 5 mm layer of mortar directly on the rebar with one day curing before demould. The mortar was a 190/500/630 mixture of water, cement, and sand, respectively. (3) Three days for curing, then a 3.0 m-long, bend-insensitive optical fiber was winded for several turns on the inner layer of the mortar with pre-stress, ensured that the fiber was tight with the surface of the mortar. Both ends of the fiber were fixed on the mortar with modified acrylate adhesive. The fiber was lead out bilaterally with armoured optical cable along the rebar. (4) A layer of mortar (a 260/500/630 mix of water, cement, and sand, respectively) was cast outside of the fiber. An additional amount of water was mixed to guarantee the fluidity of the mortar, which could prevent the occurrence of damage during the pouring of concrete specimens. The mortar was cured for one day before forming removal and three days more before normal use.

3.2. Design of concrete specimens with embedded sensors

Two steel bar corrosion sensors were embedded in two concrete specimens, respectively. The specimen with stirrups is named B-1 and the one without stirrups is named B-2.The size of concrete specimens was 140 mm × 140 mm × 180 mm and the strength grade was C50. Ordinary Portland cement P.O 42.5 was used in this study. The normal river sand of 0–5 mm was chosen as the fine aggregate, while crushed limestone was used as the coarse aggregate for the sizes from 5 mm to20 mm. Water reducing agent (Polycarboxylic acid type, ASTM C 494 type F, water reducing ration 24.1%) was also used in the experiment. The mix proportions of concrete are shown in Table 1.

Fig. 3 shows the design of B-1. B-2 has two stirrups that were symmetrically arranged 70 mm from the ends of the specimen and were fixed on the template with fine iron wires (Fig. 4). The stirrup type was HPB235 and was 6 mm in diameter. After being vibrated on the vibration table, the concrete specimens were cured