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Monitoring and Testing of Steel Corrosion based on Fiber Optic Sensing Technology

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Corrosion of reinforcing bar (Rebar) is the most important factor of reducing the durability of reinforced concrete structures and causing heavy losses. Optical fibre is an ideal sensing element for long-term monitoring. It has the advantages such as high durability, high stability, anti-electromagnetic interference, multiple parameters and distribution measurement. In this paper, based on optical fibre sensing technology, the rebar corrosion expansion in concrete was monitored and tested, and the numerical simulation of corrosion-induced cracking on concrete cover was performed. By simulating the corrosion-induced microcrack propagation in the concrete cover, the radial displacement at the time of cover cracking was used as an indicator to numerically analyse the effects of the three variables: concrete cover thickness, concrete strength and rebar diameter on the uniform corrosion of reinforcing bar. The radial displacement increases linearly with the tensile strength of the concrete. When the rebar diameter and the concrete strength are constant, the radial displacement at the time of cover cracking increases as the concrete cover thickness increases.

1. Introduction

Rebar corrosion worldwide is considered to be one of the most important factors causing premature failure of concrete structures. It will reduce the ductility and load carrying capacity of concrete structures, directly affecting its safety and durability. And more severe corrosion can also directly cause structural damage, resulting in high maintenance costs. This is because with the rebar corrosion, the volume of the generated corrosion product expands 2-4 times and it is a loose sheet structure, which on one hand makes the cross-sectional area of the rebar reduced, decreasing the strength and ductility; on the other hand, causes the concrete cover to crack and fall off, thus reducing the effective cross-sectional area of concrete, and degrading or losing the bond performance between rebar and concrete. In order to ensure structural safety, reduce economic losses and casualties, efforts should be made to improve the corrosion resistance of rebar and prolong the service life of the structure. At the same time, it is more and more important to grasp the corrosion and safety of rebars in major projects of reinforced concrete in real time (Li and Ge, 2003; Lu et al., 2012; Ožbolt et al., 2014; Richard et al., 2016). In this paper, based on optical fibre sensing technology, the rebar corrosion expansion in concrete was monitored and tested, and the numerical simulation of corrosion-induced cracking on concrete cover was performed. By simulating the corrosion-induced microcrack propagation in the concrete cover, the radial displacement at the time of cover cracking was used as an indicator to numerically analyse the effects of the three variables: concrete cover thickness, concrete strength and rebar diameter on the uniform corrosion of reinforcing bar. The radial displacement increases linearly with the tensile strength of the concrete. When the rebar diameter and the concrete strength are constant, the radial displacement at the time of cover cracking increases as the concrete cover thickness increases.

2. Corrosion of Reinforced Concrete Structures

2.1 Mechanism and conditions of rebar corrosion

The corrosion of rebar in concrete is electrochemical corrosion. According to the principle of electrochemical corrosion, the corrosion of rebar in concrete requires the following three conditions:
There is dissolved oxygen and water required for the corrosion reaction on the surface of the rebar.

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There is potential difference on the surface of the rebar, which constitutes the corroded battery.
The passivation film on the surface of the rebar is destroyed and the rebar is in an activated state. The rebar corrosion process in concrete has the characteristics of general electrochemical corrosion, that is, there are at least two electrode reactions on the outer surface of the rebar (Zivica and Palou, 2014). One is the anodic dissolution reaction of the metal, i.e., after the metal is oxidized, it is ionized into the solution, and its chemical reaction equation is:

$$Fe \rightarrow Fe^{2+} + 2e^{-} \tag{1}$$

In the vicinity of the anode, it combines with OH- to be Fe(OH)2, which is oxidized to Fe(OH)2 under the action of O2, that is:

$$Fe^{2+} + 2OH^{-} \rightarrow Fe(OH)_2 \tag{2}$$

$$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3 \tag{3}$$

In the vicinity of the cathode region, oxygen is released to the surface of the rebar, which dissolves in the water film on th

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-} \tag{4}$$

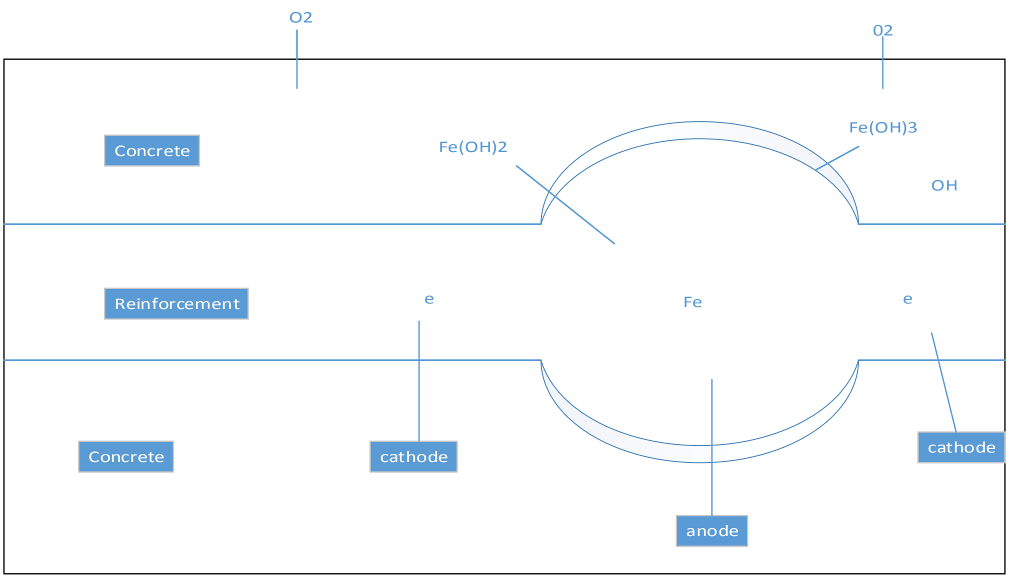

Figure 1: The chemical reaction process of steel corrosion

2.2 Status of rebar corrosion monitoring technology

The hazard of rebar corrosion in reinforced concrete structures and its increasing serious situation have been far more than expected. The rebar corrosion problem of steel-concrete structures has attracted worldwide attention. Therefore, it has very significant economic and social benefits about how to comprehensively and effectively grasp the rebar corrosion state in the steel-concrete structure and give timely warning before the corrosion reaches the unsafe level. In response to this urgent problem, the monitoring of steel reinforced structure corrosion has come into being.
(1) Ordinary optical fibre-based corrosion monitoring technology
Fuhr and Huston designed one corrosion monitoring scheme based on spectral analysis. Its sensing mechanism is to detect the difference of the reflectance spectrum signals in different corrosion states by the spectrum analyser and then determine the degree of corrosion. This method is rarely used in practical applications, because it is difficult to lay fibres in reality, and the monitoring is also discontinuous, so it can determine the corrosion only by relying on the predetermined reagents and chemical reaction with the chloride ion (Bo et al., 2017). This can only make a primary judgment on the corrosion of rebars, but not accurate continuity monitoring, and online monitoring of corrosion.

(2) Fibre Bragg grating-based corrosion monitoring technology

The fibre Bragg grating (FBG) changes the refractive index by deformation or temperature. The principle of the FBG is shown in Figure 2. When the periodic refractive index is disturbed, it will act on some narrow spectrum. This part of light will be reflected back, and the other light will continue to be emitted without being interfered. Therefore, it can be considered that the FBG has the function of recognizing light waves (Sergi et al., 2000; Kubo et al., 2015; Ji and Zhan, 2015).

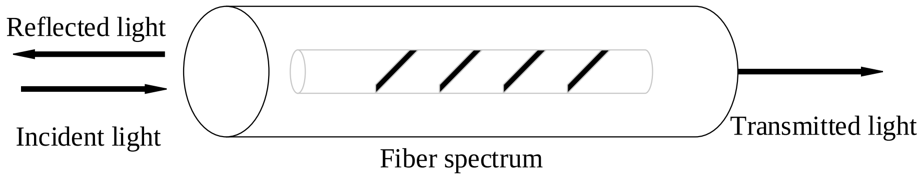

Figure 2: The structure diagram of the sensor

At present, the working principle of various forms of sensing technology based on FBG can be considered as the monitoring of the fibre central wavelength, that is, the drift caused by the interference is influenced by external factors, and the transmission mode of the light in the FBG can be utilized to obtain its reflection wavelength. It's expressed as:

$$\lambda = 2n\Lambda \tag{5}$$

The strain and temperature changes are caused by the external environment to the FBG, and these will also cause some interference to it and produce some changes. The displacement of FBG wavelength with strain and temperature is expressed as:

$$\Delta\lambda = \alpha_\varepsilon \varepsilon + \alpha_t \Delta t \tag{6}$$

where:

$\Delta\lambda$ -the amount of change in the FBG reflection wavelength,

α_ε -strain sensitivity coefficient,

α_t -temperature sensitivity coefficient of FBG,

Δt -changes in temperature.

According to formula 6, the effects of strain and temperature on the wavelength can be superimposed. When receiving the monitoring data by the optical fibre demodulator, the sensor can be set at the monitoring part in the same environment field. Since the FBG has cross sensitivity to the strain and temperature, one fibre temperature compensation sensor and fibre strain sensor should be installed in the same temperature field in the civil engineering monitoring process. The function of the FBG temperature sensor is to remove the interference of the temperature to the strain sensor. At this time, the wavelength changes of strain and temperature sensor are expressed as:

$$\Delta\lambda\varepsilon_1 = \alpha_{\varepsilon 1} \varepsilon + \alpha_{t1} \Delta t \tag{7}$$

$$\lambda_1 = \alpha_{t1} \Delta t \tag{8}$$

Then, according to formula 7, it's given as:

$$\varepsilon = \frac{\Delta\lambda\varepsilon_1 - \frac{\alpha t1}{\alpha t2}\lambda_1}{\alpha_{\varepsilon 1}} \tag{9}$$

It can be seen from formula 9 that when the FBG temperature sensor and the strain sensor are placed in the same environmental field, the strain sensor won't be disturbed by the ambient temperature.

3. Numerical Analysis of Steel Corrosion Damage

3.1 Numerical analysis of factors affecting radial displacement at the time of concrete cover cracking

In order to understand the influence of concrete cover thickness, concrete strength and rebar diameter on the corrosion expansion cracking of concrete cover, this paper makes 36 arbitrary combinations of three types of three concrete cover thickness, four concrete strength grades and three rebar diameters, and then performs numeral analysis for the crack propagation process of the concrete cover. Table 1 lists the values of the thickness, strength and diameter. The radial displacements loaded when the concrete cover is cracked under different conditions are extracted separately. Table 2 gives the numerical simulation results (Otieno et al., 2016; Kashani, et al., 2013).

Table 1: Variable-value in model

Concrete strength grade	Concrete tensile strength (MPa)	Compressive strength (MPa)	Elastic Modulus E(MPa)	Protective layer thickness(mm)	Reinforcement diameter(mm)
C20	1.54	13.4	25500	20	18
C25	1.78	16.7	28000	25	22
C30	2.01	20.1	30000	30	25

Table 2: Radial displacement when concrete cover cracking

		Radial displacement (mm)		
Protective layer thickness	Relative protective layer thickness	C20	C25	C30
20	1.11	2.9	3.3	3.3
25	1.39	4.1	4.3	4.6
30	1.67	5.6	5.9	6.2
20	0.91	2.8	2.9	3.1
25	1.13	3.8	4.1	4.2
30	1.36	4.9	5.2	5.4
20	0.80	2.7	2.8	3
25	1.00	3.6	3.8	4.1
30	1.20	4.7	4.9	5.2

3.2 Analysis of radial displacement with thickness of protective layer at the time of the protective layer is cracked

Figure 3, 4, and 5 show the relationship between the radial displacement and the tensile strength of the concrete at the time of cover cracking with the thickness of 20mm, 25mm, and 30mm, respectively, and the rebar diameters of d=18mm, d=22mm, and d=25 mm. It can be seen from the three figures that when the rebar diameter and the cover thickness are constant, the radial displacement of the concrete cover increases linearly with the increase of the concrete tensile strength. Also, it can be found that when the rebar diameter and the concrete strength are constant, the radial displacement of the concrete cover increases as the cover thickness increases (Otieno et al., 2011).

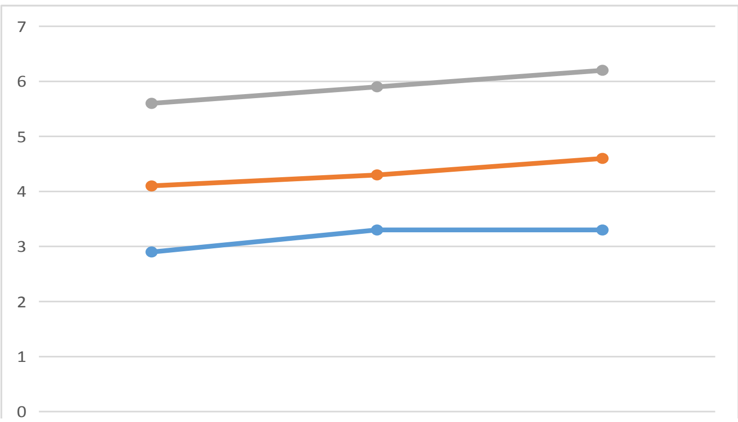

Figure 3: Relationship between radial displacement and concrete tensile strength during cracking of protective layer when d=18mm

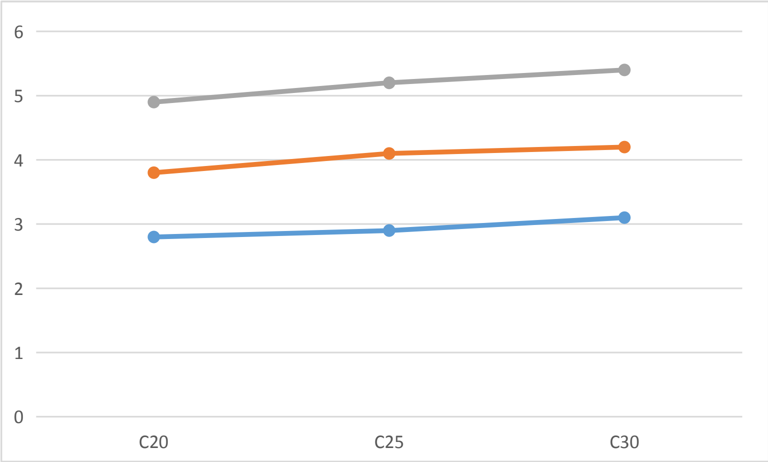

Figure 4: Relationship between radial displacement and concrete tensile strength during cracking of protective layer when d=22mm

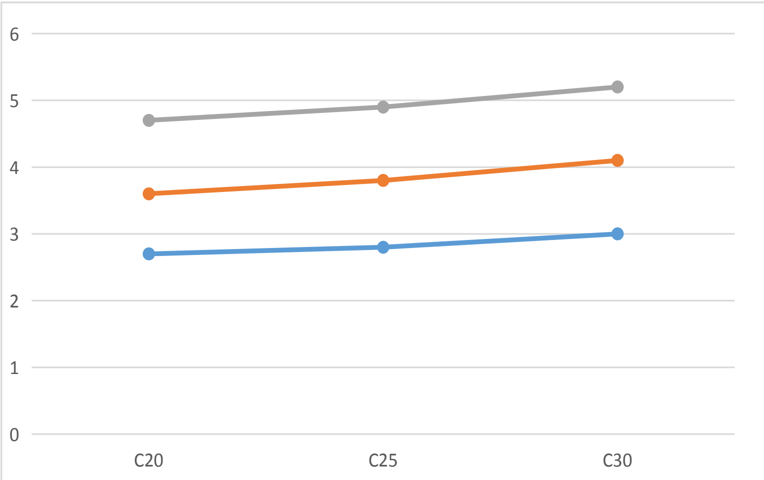

Figure 5: Relationship between radial displacement and concrete tensile strength during cracking of protective layer when d=25mm

4. Conclusion

In this paper, a new type of monitoring device based on fibre optic sensor is proposed according to the rebar corrosion mechanism in concrete structure. The sensor is placed in different positions of the equipment to monitor the changes of the damage value at different parts of the concrete cover. Before the concrete cover is corroded and cracked, its thickness has little effect on the corrosion, and the corrosion expansion propagates slowly; the thicker the protective cover, the longer the cracking time, and the concrete cover can effectively extend the service life of the concrete; after the cover cracking, the propagation speed of concrete cover expansion is increased; it's monitored that the development trend of corrosion expansion and concrete crack width is similar. The numerical analysis of the influencing factors on uniform corrosion of rebars were performed, to find that the concrete cover thickness, the concrete strength and the rebar diameter have an effect on the rebar corrosion at the time of cover cracking. Through the numerical analysis of uniform corrosion, it can be concluded that at the time of concrete cover cracking, the strain increases with the increasing tensile strength of the concrete and concrete cover thickness; it declines with the increasing rebar diameter, and increase with the increasing relative thickness of concrete cover.

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