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INFLUENCE OF CHLORIDE ION CORROSION ON THE PERFORMANCE OF REINFORCED CONCRETE BEAM BRIDGE IN OFFSHORE ENVIRONMENT

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Chloride ion erosion in offshore environment may damage the mechanical properties of beam bridges. In this study, the reinforced concrete specimen was designed, accelerated erosion experiments were carried out to simulate the coastal corrosion environment, and the corrosion rate, nominal strength and equivalent strength of steel bars, concrete cracks and reliability of beam bridges were calculated to understand the time-varying mechanical properties of beam bridges. The results showed that the nominal and equivalent strength of reinforcing bars decreased with the increase of corrosion rate of reinforcing bars. The change of yield strength was greater than that of equivalent strength. The change of crack width of concrete showed a slow-fast-slow trend, and the reliability of beam bridges decreased significantly in about 50 years. The experimental results show that chloride ion corrosion can significantly damage the mechanical properties of the beam bridge and affect the time-varying reliability of the beam bridge. Therefore, it is necessary to carry out timely maintenance and inspection and take effective methods to control steel corrosion to ensure the safety of the use of the beam bridge.

Keywords: Time-varying properties, reinforced concrete structure, chloride ion erosion, time-varying reliability, mechanical properties

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1. INTRODUCTION

Reinforced concrete structure has been widely used in buildings [1, 2]. Similarly, in beam bridges, concrete beam bridges account for more than 90% of the total. In offshore environment, reinforced concrete beam bridges are subject to both load and environment, and structural changes such as shrinkage and creep may occur. Under chloride ion erosion, steel corrosion is very serious [3]. The expansion of the volume of steel bar after corrosion will lead to the cracking of concrete protective layer; as a result, chloride ions contact steel bar directly, which further accelerates the corrosion of steel bar and deterioration of the performance of concrete [4]; finally the durability of the whole structure is severely affected [5]. Guo et al. [6] mainly studied the change of seismic performance of coastal piers under corrosion effect. Cyclic experiments were carried out on coastal piers. The results showed that the seismic performance of structures decreased significantly with the increase of corrosion degree. Xi et al. [7] studied the overall structural change of concrete coating by numerical simulation, analyzed the influence of thickness of coating and spacing of reinforcement on crack width, and pointed out that the prediction of concrete crack was beneficial to prolong the service life of the structure. To study the influence of steel corrosion on structural deterioration, Nepal et al. [8] designed a method of calculating structural life reliability by deterioration model and found by experiments that the method could correctly evaluate the damage caused by steel corrosion and predict structural reliability. Lee et al. [9] proposed an arc thermal spraying method to protect the reinforced concrete structure and prevent the penetration of acidic solution and found through experiments that the technology exhibited high impedance values in three acidic PH solutions. Li et al. [10] studied the corrosion of steel bars after cracking of reinforced concrete with the percentage concentration of chloride ion and crack width as variables and found that the corrosion rate of specimens increased with the increase of chloride content and crack width. Chen et al. [11] simulated the permeability process of chloride in the reinforced concrete structure using the finite element method and established the reinforcement corrosion and corrosion expansion model based on Faradaypsilas law to evaluate the deterioration process of the reinforced concrete structure.

Yang et al. [12] designed a cohesive crack model to predict the crack width of concrete caused by corrosion and verified its effectiveness through an example analysis. Tomasz Jaśniok et al. [13] studied the corrosion rate of steel bars, designed six reinforced concrete specimens, set the environmental temperature changes between 7 °C and 35 °C, the humidity changes between 30% and 90%, monitored the temperature and moisture content of the concrete surface in real time, established the corrosion rate model of steel bars. In this paper, the time-varying and mechanical properties of beam bridges were studied by accelerated corrosion experiment, and some reliable results are obtained. It was found that the coastal corrosion is a great threat to the safety of beam bridges. It indicated that the beam bridges must be strengthened or rebuilt in time to meet the needs of the use of beam bridges, which makes some contributions to ensure the safe use of offshore beam bridges.

2. REINFORCED CONCRETE STRUCTURE ERODED BY CHLORIDE IONS

The failure process of concrete structure under chloride ion corrosion can be divided into four stages, as shown in Fig. 1.

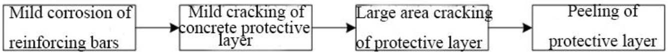

Fig. 1 Failure process of eroded concrete structure

In the first stage, slight corrosion of reinforcing bars under the action of chloride ions may cause local pitting corrosion of reinforcing bars; in the second stage, the amount of corrosion of reinforcing bars increases, and the volume of corroded objects expands, resulting in tensile stress in concrete and leading to cracking of protective coatings [14]; in the third stage, after cracking of protective coatings, the contact of external water, oxygen, chloride ions with reinforcing bars intensifies [15], resulting in further corrosion of reinforcing bars and extensive cracking of the protective coatings. In the fourth stage, the steel bar is deeply eroded and the protective layer is continuously cracked, and finally the protective layer peels off.

In this process, the section area of reinforcing bar decreases, the performance of binding between reinforcing bar and concrete decreases, and concrete cracks and peels, so that the overall performance of the structure begins to change. In this study, the time-varying mechanical properties of structures were studied by experiments.

3. EXPERIMENTAL METHODS

3.1. SPECIMEN DESIGN

The specimens used in the experiment were typical reinforced concrete beams with cross-section size of 100 mm × 150 mm. The cross section is shwon in Figure 2. Main reinforcement was HRB500 steel bar, with a diameter of 20 mm and a length of 300 mm. Stirrups and erecting reinforcement was HRB400 steel bar, with a diameter of 10 mm, a length of 300 mm and a spacing of 100 mm. The thickness of the concrete coatings was 15 mm. C30 concrete was used, and the ratio of cement, water, fine aggregate and coarse aggregate was 1 : 0.58 : 2.14 : 3.65. The cement was Huaxin Baolei brand P·C 32.5 loaded Portland cement. Fine aggregate was natural river sand. Coarse aggregate was continuous graded macadam. The measured yield strength of steel bar was 579.68 N/mm^2, and the ultimate strength was 756.58 N/mm^2. The compressive strength of concrete cube was 38.6 MPa after 28 days of curing. Two groups of specimens were casted and cured for 28 days. One group of specimens was used for studying the mechanical properties of steel bar, numbered A, B, C, D, E. The other group was used for studying the time-varying properties of concrete cracks, numbered F, G, H, I and J.

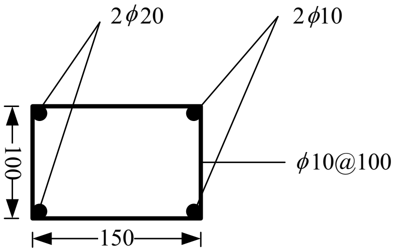

Fig. 2 The cross section of the test specimen

3.2 STEEL BAR CORROSION EXPERIMENT

In order to simulate the erosion of specimens in offshore environment, the specimens were placed in wet salt sand, the steel bars to be eroded were connected by direct current anode, and the copper sheets in the wet salt sand were connected by cathode. The corrosion amount of steel bars was controlled by the time of electrification and current intensity. In order to ensure that the current passes only in the main bars, insulation measures were adopted for stirrups and erecting bars.

After the corrosion was completed, specimens in group A were crushed, steel bars were taken out, pickled, dried and weighed, and the corrosion rate was calculated:

$$\gamma = \frac{g_0 / l_0 - r_1 / l_1}{g_0 / l_0} \times 100\% \tag{1.1}$$

where:

g_0 –the initial mass of reinforcing bars, l_0 – the length of reinforcing bars, g_1 – the mass of the corroded steel bar, and l_1 – the length of the corroded steel bar

3.3 CORROSION MODEL OF REINFORCEMENT BARS

According to Fick's second diffusion theorem, the time when the j-th reinforcing bar begins to be corroded can be expressed as:

$$t_j = \frac{X^2}{4D_c}\left[erf^{-1}\left(\frac{cl_s - cl_{cr}}{cl_s - cl_0}\right)\right]^{-2}, \tag{1.2}$$

where:

X – the thickness of the protective layer, D_c – the rate of diffusion of chloride ion, $erf(\ )$ – error function, cl_s – the surface chloride ion concentration, cl_{cr} – the critical chloride ion concentration, and cl_0 – the initial chloride concentration.

In the corrosion experiment, the corrosion current density was i_{corr}, and the average erosion rate can be expressed as: $\lambda_{c0} = 0.01174 i_{corr}$, the pitting erosion rate can be expressed as: $\lambda_c = 0.01174 C_R i_{corr}$, where C_R represents the pitting influence coefficient. The calculation formula of i_{corr} can be expressed as:

$$\ln 1.08 i_{corr} = 10.69 + 0.618 \ln 1.69 cl - \frac{3034}{T} - 0.000105 R_c, \tag{1.3}$$

where:

cl –concentration of chloride ion around reinforcing bar, T –temperature, and R_c –the resistance of concrete protective layer.

The formula for calculating the corrosion rate of reinforcing bars can be expressed as follows:

(1.4)
$$\eta(t)=1-\sum_{i=1}^{n}\frac{D_i^2(t)}{D_0^2},$$

where:

n–number of reinforcing bars, $D_i(t)$ –the diameter of the i-th reinforcing bear at t , and D_0 –the initial diameter of reinforcing bars.

3.4 LOADING SCHEME OF SPECIMENS

Tensile tests were carried out with WAW-Y1000C electro-hydraulic servo universal testing machine. The tensile rate was 25 MPa/s. Nominal strength f and equivalent strength f' of reinforcing bars were mainly measured. The calculation formula is:

(1.5)
$$f=\frac{P}{A},\quad f'=\frac{P}{A'},$$

where:

P –actual load, A –the nominal area of reinforcing bar, and A' –the average weighing area of reinforcing bar.

3.5 MEASUREMENT OF CONCRETE CRACK

For specimens in group B, with the progress of the corrosion experiment, concrete cracks were measured at intervals, and 50 mm × 50 mm squares were drawn on transparent soft glass and covered on the specimens. The most significant cracks on the specimens were taken to measure the change of crack width.

3.6 CALCULATION OF TIME-VARYING RELIABILITY OF BEAM BRIDGES

The beam bridge is composed of reinforced concrete beams. The time-varying reliability of the i -th beam at $[0, T]$ [16] can be expressed as:

(1.6)

$$R_s(T) = \exp\left\{ -\lambda T \left[1 - \frac{1}{T} \int_{\infty}^{\infty} P_{S_D} P(T, S_D) dS_D \right] \right\},$$

where:

λ –the Poisson arrival rate of live load, T –time, P_{S_D} –the constant load probability density function, and d –diameter of reinforcing bar.

The overall reliability of beam bridges can be expressed as:

(1.7)

$$R(T) = \prod_{i=1}^{n} R_s(T).$$

4. EXPERIMENTAL RESULTS

4.1 MECHANICAL PROPERTIES OF REINFORCING BARS UNDER CORROSION

The theoretical corrosion rate of steel bars was calculated according to the reinforcement corrosion model in section 2.3, and the comparison with the actual results are shown in Table 1.

Table 1. The theoretical and actual calculation results of corrosion rate of reinforcing bars

Specimen number	Theoretical corrosion rate/%	Actual corrosion rate/%
A	1	2.1
B	2	1.8
C	4	5.4
D	6	6.7
E	7	7.6

It can be found from Table 1 that there was little difference between the theoretical results and actual results, indicating that the reinforcement corrosion model used in this study had good reliability and could accurately calculate the corrosion rate of reinforcing bars. Basically, the actual corrosion rate of reinforcing bars was slightly higher than the theoretical corrosion rate.

The variation trend of mechanical properties of reinforcing bars with the corrosion rate is shown in Fig. 3 and 4.

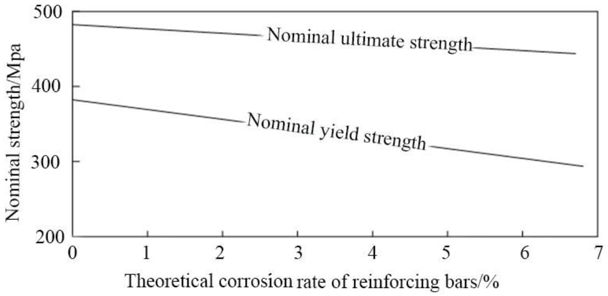

Fig. 3 Changes of nominal strength

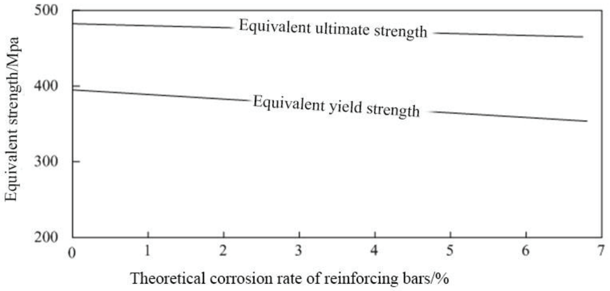

Fig. 4 Changes of equivalent strength

It can be found from Fig. 3 and 4 that the nominal strength and equivalent strength of the reinforcing bars decreased with the increase of corrosion rate of the reinforcing bars. In the nominal strength, the decline rate of the yield strength was larger than that of the ultimate strength, indicating that the nominal yield strength was more sensitive to the change of corrosion of the reinforcing bars. In the equivalent strength, the decline rate of the yield strength was also higher than that of the ultimate strength, indicating that the equivalent yield strength was more sensitive to the corrosion change of the reinforcing bars. Based on Fig. 3 and 4, it can be found that with the increase of the corrosion rate, the strength of the reinforcing bars showed a downward trend, and the mechanical properties of the reinforcing bars decreased.

4.2 TIME-VARYING PROPERTIES OF BEAM BRIDGES UNDER CORROSION

4.2.1 TIME-VARYING PROPERTIES OF CONCRETE CRACKS

With the development of the corrosion experiment, the width changes of the most significant crack of the specimens are shown in Fig. 5.

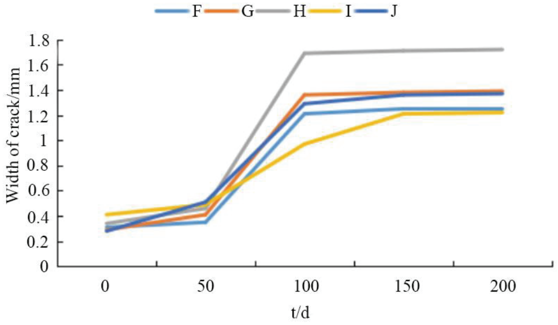

Fig. 5 Changes of crack width

Fig. 5 shows that the width of the initial cracks of different specimens was small, and those cracks were caused by differential settlement and volume shrinkage; the crack width increased slowly within 50 days since the start of corrosion experiment; after 50 days, the crack width increased rapidly, and the maximum crack reached 1.69 mm. After 100 days, the change of crack width became slower and was almost unchanged.

4.2.2 TIME-VARYING RELIABILITY OF BEAM BRIDGES

The variation of time-varying reliability of beam bridges is shown in Fig. 6.

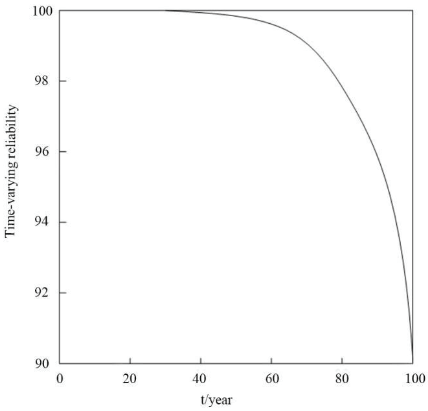

Fig. 6 Time-varying reliability of beam bridges

It can be found from Fig. 6 that the time-varying reliability of reinforced concrete beam bridges decreases with the increase of time under the condition of chloride ion erosion in offshore environment; in 40 years, the time-varying reliability of beam bridges had no changes, and the time-varying reliability was kept at 100; the reliability began to decrease in a very high speed at the 50th year and decreased from 98 to 90 between the 80th year and 100th year. The results reveal that the reliability of the beam bridge will decrease rapidly after serving for several years, and maintenance is needed at that time to keep its working state.

5. DISCUSSION

Beam bridge is an important part of traffic hub. Under the influence of natural and non-natural factors, if damage occurs, it will seriously affect the traffic system. Therefore, the study of its structural reliability and durability has very important research value. The offshore beam bridges are directly scoured by sea waves, and deicing salts are used in some areas of northern China; as a result, the chloride ion corrosion is serious [17]. Reinforcing bar corrosion is the main reason for the deterioration of beam bridges in the offshore environment [18]. The structural performance of beam bridges decreases gradually with the service time [19], which may eventually lead to safety problems. In this study, the time-varying mechanical properties of corroded reinforced concrete beam bridges were analyzed by experiments. The accelerated corrosion of steel bars was realized by direct current. Two groups of specimens were designed, one for observing the change of mechanical properties of steel bars and the other for observing the development of concrete cracks. The theoretical calculation method and practical measurement method of corrosion rate of reinforcing bars and measurement methods of concrete cracks were introduced. Firstly, it can be found from Fig. 2 and 3 that with the progress of the accelerated corrosion experiment, the corrosion rate of the reinforcing bars increased and the strength of reinforcing bars decreases; the decreasing trend of the yield strength was more obvious than that of the ultimate strength, which showed that the yield strength of reinforcing bars was more sensitive to the change of corrosion rate. It can be found from Fig. 4 that concrete cracks developed slowly in the initial stage, fast in the middle stage and slow in the late stage. The contact between chloride ion and reinforcing bars was less as there were few concrete cracks in the initial stage of the experiment. But chloride ion started to fully contact with reinforcing bars after the cracks develop to some extent, leading to the accelerated corrosion and expansion; therefore the crack width developed. In the late stage of the experiment, the rust which appeared on the surface of the reinforcing bars because of corrosion by chloride ion prevent the further contact between chloride ion and reinforcing bars, leading to reduced oxidation reaction, decrease of corrosion and expansion speed, and slowdown of variation of concrete crack width. It was found from Fig. 5 that the reliability of beam bridges started to decrease at the 50th year under the offshore corrosion, which showed that some measures needed to be adopted to maintain beam bridges to prolong the service time.

In the present study, although some achievements have been made in the study of the performance of concrete beam bridge under corrosion, there are still many shortcomings, which need further work to solve:

(1) there is no research on reinforcing bars and concrete with different strength;

(2) the change of bond property between reinforcing bars and concrete is not considered;

(3) the performance change of the beam bridge after maintenance and reinforcement is not considered.

6. CONCLUSION

In this study, the time-varying mechanical properties of reinforced concrete beam bridges in the offshore environment were studied. The mechanical properties of reinforcing bars and the time-varying reliability of beam bridges were calculated by experiments. It was found that with the increase of the corrosion time of reinforcing bars, the strength of reinforcing bars decreased, the cracks of concrete increased, and the overall reliability of beam bridges decreased, suggesting the influence of chloride ion corrosion in the offshore environment on the overall properties of the beam bridges, and it provides some theoretical bases for the timely maintenance of beam bridges.

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LIST OF FIGURES AND TABLES:

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