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Chloride diffusivity and service life prediction of fatigue damaged RC beams under seawater wet-dry environment

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HIGHLIGHTS

- Synthetic actions of low fatigue load level and chloride corrosion are simulated.
- Chloride diffusivity of concrete in compression and tension zone are compared.
- Service life is predicted considering fatigue damage based on Monte-Carlo Method.

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ABSTRACT

The effects of low fatigue load level with lower limit of 0.1 Pu and upper limit of 0.2 Pu or 0.3 Pu on chloride diffusivity of RC beams were experimentally studied after 100 times of seawater wet-dry cycles, where Pu is the static ultimate strength of the RC beams and the cycles of fatigue loading was 200,000. Based on the test results, residual service life was also discussed here. Results show that, chloride diffusivity was accelerated as fatigue load level increased. When the load level was 0.2, based on Fick's 2nd law, chloride diffusion coefficient of tensile concrete was higher than that of compressive concrete, but the result was reverse for the load level of 0.3. Furthermore, based on the Monte-Carlo Method, the predicted residual service life in one-dimensional state of chloride diffusion would be shortened by 85 percent when the fatigue load level was 0.2, and by 95 percent when fatigue load level was 0.3, compared with that of no fatigue damaged RC beam. The predicted service life in two-dimensional state was about half of that in one-dimensional state. It was concluded that fatigue damage has a more considerable effect on shortening service life of RC structures in chloride environment.

1. Introduction

Reinforced concrete bridge structures are usually subjected to the combined actions of cyclic load and chloride corrosion in coastal areas. The micro-cracks in concrete were generated and developed (damage accumulation) by the cyclic load, then the chloride penetrated easily through these cracks into concrete and caused the steel corrosion, which greatly affect the durability of RC structures. The study of Xiang [1] have illustrated that the accumulation of fatigue damage had obvious effect on the time-dependent reliability of chloride concentration on the pre-stress tendon position that affected the durability of concrete structures.

Existing studies have proved that the cyclic load has more adverse effects than static load on chloride diffusivity of concrete [2–7]. Jaffer [2] imposed static and dynamic load on beams and these beams were then exposed to chloride solution wet-dry cycles for 18 months. Results showed that corrosion occurred only at intersections of the rebar with cracks in the concrete. Ahn and Reddy [3] applied static and fatigue load on RC specimens, and the corrosion of the steel bars was accelerated by a galvanostatic corrosion technique. It was found that fatigue load led to more corrosion of RC beams than static load. In the study of Sheng [4], RC beams were immersed in 5% NaCl solution under sustained loads with 0, 20%, 40% and 60% of ultimate strength, respectively. After 6 months of wet-dry cycles, bending fatigue test was applied on these beams. It was found that the combined actions of chloride corrosion and sustained load greatly weakened the fatigue life of the specimens and the specimens with the sustained load of 40% of ultimate strength showed the longest fatigue life, which indicated that a certain range of initial deformation increased the fatigue life of beams under chloride corrosion. Saito [5] experimentally studied the effect of repeated compression load on chloride diffusion. Results showed that the static load up to 90% of the ultimate

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strength had little effect on chloride permeability while when the repeated compression load was 60% of the ultimate strength or more, chloride permeability increased significantly. The study of Nakhi [6] obtained similar conclusion and the results of ultrasound measurements concluded that chloride penetrated into deeper part of concrete at higher load level and higher level of mechanical load on concrete created higher degree of internal damage. Ren [7] applied fatigue load and static load on concrete specimens under chloride environment. Results illustrated that the chloride diffusion coefficient was higher under the bending fatigue load than that under the static load at the same load level, and the service life of concrete structures would be greatly shortened under the combined actions of bending fatigue load and chloride environment.

Many studies predicted the service life of concrete members under chloride environment [8–10]. Kwon [8] predicted the service life of cracked RC structures exposed to chloride environment based on the relationship between chloride diffusion coefficients and crack widths. The results showed that the service life calculated from probabilistic framework of Monte Carlo Simulation was shorter than those obtained from deterministic method. RC column specimens were corroded by chloride environment in the study of Alkam and Alqam [9], and through a transient, two-dimensional simulation of chloride diffusion into concrete column, service life of this column was predicted. It was indicated that regions closed to the corners of the column cross section were more vulnerable to chloride ion penetration than regions far from the corners. The effect of sustained load on chloride diffusivity were experimental studied and the service life of RC columns with different level of sustained load were predicted by Wu and Faye [10]. But the effect of fatigue load on chloride diffusivity and service life were not studied until now.

Most of the existing studies focus on the experimental investigation of the fatigue limit of RC structures with a high level fatigue load. Reinforced concrete bridges in working conditions usually suffered low level fatigue load and the study of fatigue durability of RC structures under low level load is fewer. The service life prediction of RC bridge structures subjected to fatigue load both in one-dimensional and two-dimensional state is lacking.

The synthetic effects of fatigue damage and seawater wet-dry cycles on chloride diffusivity of RC beam specimens were experimentally studied in this paper. The low level fatigue load of 0.2 or 0.3 times of ultimate load was selected to represent the practical working condition of RC bridges and the loading cycle of 200 thousand times was chosen to guarantee the RC beams were in the initial stage of fatigue damage [11–13]. Then seawater wet-dry cycle was adopted to simulate the chloride environment of coastal regions. After 100 times of seawater wet-dry cycle, the chloride content test was conducted and chloride profile of samples were obtained. Apparent chloride diffusion coefficient was determined by the best curve fit of chloride profile based on the Fick's 2nd law. The effects of fatigue load on chloride diffusivity of concrete in compression and tension zone were analyzed. Furthermore, residual service life of fatigue damaged RC beam specimens were predicted in one-dimensional and two-dimensional state, based on Monte-Carlo method.

2. Experimental details

2.1. Specimens

The experimental study here mainly focused on the effect of accumulation of low-level fatigue damage on the chloride diffusivity, the experimental sequence of fatigue load and seawater wet-dry was selected to make the load path and degree of fatigue damage clearer. The testing environments in the current study included seawater wet-dry environment and laboratory natural environment. Four RC beam specimens, named as B1 to B4, with the same sizes and same reinforcements were made, where B2-B4 were fatigue damaged and then exposed in the environment of seawater wet-dry cycles and B1 was static loaded to obtain the ultimate strength(Pu) of the RC beams as reference beam.

The reinforcement arrangements and geometry dimensions of RC beam specimens are showed in Fig. 1. The rectangular cross-section was 100 mm × 150 mm and the length of the beam was 800 mm. The concrete cover was 30 mm and four steel bars with 10 mm diameter were symmetrically placed as longitudinal bars with yield and ultimate strengths of 447 MPa and 624 MPa, respectively. The proportion of concrete mixtures is listed in Table 1. The test method for air content in concrete mixtures and curing method adopted in this study was consistent with that in an earlier experiment of Diao et al. [14]. The compression strength of concrete used for RC beam specimens was 43 MPa at the concrete age of 176 days.

2.2. Testing program

All tests were performed in the Civil Engineering Laboratory at Beihang University in Beijing. At the age of 176 days, static load was applied on B1 to get the ultimate strength (Pu = 47.5 kN). At the age of almost 180 days, two beam specimens of B3 and B4 were subjected to fatigue load in turn as shown in Fig. 2, where the lower limit of the fatigue load was 0.1 Pu and the upper limit of

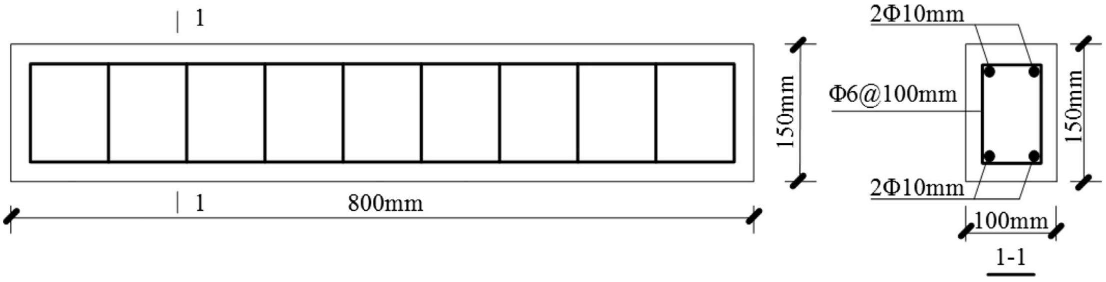

Fig. 1. Reinforcing details and dimension of RC beam specimens.

Table 1
Proportions of concrete mixtures.

Mixtures of concrete	Water (kg/m^3)	Portland cement (P.O. 42.5) (kg/m^3)	River sand (kg/m^3)	Coarse aggregates (kg/m^3)	Fly ash (kg/m^3)	Water-reducing admixtures (kg/m^3)	Air-entraining admixtures (mL/m^3)
	184	460	609	1130	53	4.2	1.5