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Corrosion performance of reinforcing steel in concrete under simultaneous flexural load and chlorides attack

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HIGHLIGHTS

- The corrosion rate of steels is increased gradually with increasing stress ratio.
- The probability of pitting corrosion with 0.5 stress ratio is higher than 0.3 stress ratio.
- Steel corrosion behavior in tidal zone is very sensitive to stress ratio.
- The tensile stress is the dominating factor affecting steel corrosion.

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ABSTRACT

In this study, the corrosion behavior of reinforcing steels in concrete under simultaneous flexural load and chlorides attack was studied by means of linear polarization resistance (LPR), electrochemical impedance spectroscopy (EIS) and cyclic potentiodynamic polarization (CPP) measurements. The influence of different stress ratios and exposure zones in marine environments on uniform corrosion resistance and pitting corrosion resistance of steels was analyzed. Moreover, different corrosion patterns were observed for the top part and bottom part of steels according to the casting direction. It was proposed that the tensile stress effect and the possible steel-concrete interfacial defects are mainly responsible for this difference.

1. Introduction

Chloride-induced steel corrosion in reinforced concrete structures (RCSs) is of major concern in marine environments [1,2]. In general, the high alkalinity of concrete pore solutions leads to protective passive film on steel surface which delays the time to corrosion initiation. However, when the content of chloride ions at the steel-concrete interface reach the chloride threshold level (CTL), steel starts to corrode, and corrosion products generates gradually on steel surface, ultimately leading to premature cracking and spalling of RCSs [1,3]. To date, many studies have been performed to investigate the corrosion behavior of steel in simulated concrete pore solutions [4–6] and RCSs [7,8] in aggressive environments. However, little attention has been given to the influence of external load on the corrosion behavior of steels in concrete. In effect, it is a well-known fact that RCSs are usually subjected to various types of external loads (compression, tension and flexure, etc.) during the long-term service process [9–14]. Among them, the flexural load is the most common and important load type.

Generally, the flexural load exerts influence on three typical processes in the service life of RCSs in marine environments: passivation stage of steel (the formation of protective passive film), corrosion initiation stage (the penetration of chlorides and the degradation of passive film) and corrosion propagation stage (the evolution of corrosion rate and the formation of corrosion products) [11–25].

Feng et al. reported that the passivation ability of steels decreased as the tensile stress increased in simulated concrete pore solutions [15]. Under higher stress, irreversible damages occurred in the passive film. However, if the load magnitude was low enough, the micro-cracks in passive film can be completely recovered after unloading [15]. Recently, Feng et al. investigated the different failure modes for steel passive film under tensile and compressive stresses in concrete pore solutions [16]. The results confirmed that compressive stress contributed to more

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severe degradation of the passive film than the tensile stress due to the de-bonding effect of the interface between the passive film and the steel substrate under compressive stress [16].

So far, many researchers have studied the effects of loads on the penetration of chloride ions in concrete [14,17,18,26]. It was found that the effects of load on the corrosion initiation of steel were significantly connected with the width of load-induced cracks and the self-healing effects of cracks [14]. Li et al. [17] reported that the content of chloride ions was higher in tensioned concrete than in unstressed concrete. However, for concrete stressed in compression, the content of chloride ions in concrete primarily depended on the stress ratio.

There are also many studies with respect to the steel corrosion behavior in concrete under simultaneous chloride ions and service loads [11–13,19–25]. Different loading conditions (static loading and dynamic loading) were compared for their influence on steel corrosion rate and the distribution of corrosion products in concrete [20,21]. Moreover, compressive and tensile stresses have been focused for their effect on corrosion performance of steels [23,25]. It was found that the degradation pattern of rebar in the compressed mortars is very different from that subjected to tensile stresses, which was mainly attributed to the degradation of the rebar-mortar interface [23]. The different behavior of concrete cracking and section loss of compressed and tensed reinforcements was also compared for reinforced concrete beams [25].

However, limited studies concerning the impact of stress ratio of flexural load on the corrosion behavior of steels in concrete are available in previous studies [11,12,19]. It was found that [11], stress ratio of 0.25 may be the critical load limit to affect the steel corrosion behavior in concrete. Under this loading condition, some microcracks started to be interconnected, facilitating the transport of chloride ions and initiating steel corrosion. Moreover, Wang et al. [19] indicated that the depassivation time of steels in concrete subjected to 0.4 stress ratio was more than 50 cycles earlier than those with stress ratio of 0.3.

Despite this interest, few researchers as far as we know, have studied the corrosion resistance of steels exposed to different exposure zones under simultaneous flexural load and chlorides attack. Accordingly, the main purpose of this study is to investigate the influence of different flexural stress ratios on the corrosion behavior of steels in concrete, using various electrochemical techniques and corrosion morphology observations. Moreover, three typical exposure zones (submerged zone, tidal zone and atmospheric zone) in marine environments were also compared for their effect on steel corrosion performance.

2. Experimental

2.1. Materials and specimens

The chemical composition of Portland cement (P·I 52.5) and the mixture proportions of concrete specimen are given in Table 1 and Table 2, respectively. River sand with the fineness modulus of 2.40 and gravel with the maximum size of 10 mm were used as fine aggregate and coarse aggregate, respectively.

Prismatic concrete specimens with the size of 50 mm × 100 mm × 400 mm were prepared (Fig. 1a). Two deformed low-carbon reinforcing steels (HRB335) with the diameter of 10 mm were embedded in the center of the concrete specimen. The steels were used in as-received condition without any modification of the surface and the chemical composition (wt%) of steel was 0.20 C, 0.55 Si, 1.42 Mn, 0.026 P, 0.028 S and balance Fe. The middle exposed length was 10 cm and the exposed area was approximately 31.4 cm^2, leaving the two ends coated with epoxy coating (Fig. 1a).

Table 2
Mix proportion of concrete specimen (mass ratio).

Cement	Water	River sand	Gravel
1.00	0.53	2.00	3.00

After casting, all concrete specimens were cured in standard curing room for 90 days. The aim of such long curing time is to fully passivate the steels, so that intact passive film can be fully formed [27]. After curing, the concrete specimens were placed in room for 24 h, and then the two end parts of concrete specimens were masked with epoxy resin coating in order to prevent the access of chloride ions. Afterwards, the concrete specimens were stored for loading and exposure tests.

2.2. Loading apparatus

A four-point bending loading apparatus with springs was adopted for sustaining flexural loading test (Fig. 1b). Three features are highlighted for this loading apparatus:

(i) The stress ratio can easily be controlled by the four springs with the same constant elastic coefficient during the experiment. Prior to the loading procedure, six reinforced concrete specimens (as a calibration) were loaded to obtain the mean threshold flexural loads when the first macroscopic transverse crack was initiated on concrete surface. Therefore, on the basis of the elastic coefficient of the springs and the threshold flexural loads of reinforced concrete specimens, the stress ratio can be operated by compressing these springs to a certain length.
(ii) Three concrete specimens are contained in this loading apparatus, where each one can be subjected to a specific exposure zone (atmospheric zone, tidal zone and submerged zone) during the exposure tests. All reinforced concrete specimens were loaded according to the casting direction.
(iii) Electrochemical measurements can be performed without unloading the specimens, so that the stress ratio can essentially maintain constant during the exposure tests. The springs can return to the normal length after unloading at the end of exposure tests, ensuring the essentially constant elastic coefficient after long-term loading.

It should be noted that, however, all steels were embedded in the neutral axis of concrete, as shown in Fig. 1a. Therefore, only concrete cover rather than the steels was under load before the appearance of visible cracks on concrete surface. The configuration of the reinforced concrete specimen is similar with that of Jaffer and Hansson [20,21].

2.3. Exposure conditions

Fig. 1c is the accelerated steel corrosion set-up with flowing 5% NaCl solutions in water tank. Four water pumps were employed to pump and drain NaCl solutions ceaselessly in order to simulate the change of water line in tidal zone. The dotted wavy line in Fig. 1c was used to define the high water level and low water level in tidal zone. During the exposure, a plastic plate was covered in the water tank in order to mitigate the evaporation of NaCl solutions and to make a salt-spray atmosphere for concrete specimens in atmospheric zone. Several air outlets were contained in the plastic plate for the purpose of strengthening the air circulation and assuring enough oxygen in the water tank.

The labels of concrete specimens subjected to different exposure zones and stress ratios are given in Table 3. In these labels, "SR" stands for stress ratio, and "00, 03 and 05" refer to the stress ratio of 0, 0.3 and 0.5, respectively. "A, T and S" stand for atmospheric zone, tidal zone and submerged zone, respectively, and "L" refers to the loaded specimens. Two parallel concrete specimens with four parallel steel electrodes for each exposure condition and each stress ratio were prepared in this study to ensure the reproducibility of results.

2.4. Electrochemical measurements

The classical three-electrode arrangement was used for electrochemical measurements with PARSTAT 2273 Potentiostat. Saturated calomel electrode (SCE) and stainless steel plate were used as the reference electrode and the counter electrode, respectively. The exposed steel acted as the working electrode. Three types of electrochemical measurements, namely, linear polarization resistance (LPR), elec-

Table 1
Chemical composition of cement (% in mass).

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	$Na_2O + K_2O$	Loss on ignition
62.60	21.35	4.67	3.31	3.08	2.25	0.75	0.95