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Effects of sustained loading and corrosion on the performance of reinforced concrete beams

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HIGHLIGHTS

- Performance of RC beams under simultaneous loading and corrosion is studied.
- Flexural behaviour of beams with different levels of corrosion is examined.
- Corrosion of reinforcements increases with the corrosion period and loading level.
- Increasing loading extends the longitudinal cracks but not the crack width.
- Load and deformation capacities of beams decrease with increasing corrosion level.

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ABSTRACT

This paper presents an experimental investigation on the behaviour of reinforced concrete (RC) beams under simultaneous loading and reinforcement corrosion. Corrosion of reinforcements within beams were created by an accelerated method using a 5% NaCl solution combined with a constant impressed current. Three different corrosion durations at 5, 10 and 20 days and four levels of sustained loading at 0, 15%, 30% and 60% of ultimate loading capacity were applied to the beams. Totally 13 RC beams were tested to examine the corrosion of reinforcements, cracking of beams, and structural behaviour of the corroded beams. Test results indicate that corrosion of reinforcements increases with the sustained loading but undergoes an initially increasing rate followed by a decreasing rate. Higher loading level and longer corrosion period are prone to cause the brittle failure of RC beams. Increasing the sustained loading extends the longitudinal crack but not the crack width. The joint effects of sustained loading and corrosion duration, compared to the single effect of either one factor, are more significant on the performance of RC beams in terms of corrosion of reinforcements, failure mode, ultimate loading capacity, and deformation ability. At a higher sustained loading level, beams' ultimate loading capacity and deformation ability decrease more significantly with the corrosion periods. It is also found that a lower loading increases the flexural stiffness of RC beams, but a higher loading level instead decreases it.

1. Introduction

Corrosion of reinforcements has been recognized as one major cause of structural degradation in reinforced concrete (RC) structures [1–3], especially for those exposed to the marine environment. This is mainly attributed to the reduction of reinforcement section area as well as cracking and/or spalling of concrete induced by the expanded corrosion products [4]. Probabilistic modes considering corrosion of reinforcements have also been proposed to predict the service life of RC structures [5–7]. Corrosion variability of reinforcements was properly considered in their modes, leading to a more accurate prediction for RC structures. Wang et al. [8] reported that the width, density and tortuosity of cracks are the main parameters affecting the chloride diffusion of concrete. Moreover, corrosion of reinforcements causes the bonding deterioration between the reinforcements and the concrete, which significantly

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affects the safety and service life of the infrastructures [9]. Therefore, it is necessary to estimate the performance of RC structural members subject to different levels of corrosion.

A large number of studies have been focusing on investigating the behaviour of RC beams in the presence of corrosion and loading [10–12]. Longitudinal tensile strains on the tensile surface of corroded beams under the service loadings would increase monotonically with the corrosion periods at a decreasing rate [10]. It has been known that the joint action of corrosion and loading would increase the deflection of corroded RC beams [11]. Nevertheless, the joint effect of corrosion and loading on the performance of RC beams could be further studied, such as flexural stiffness. It was previously found that a low-level corrosion could enhance the bond between reinforcements and concrete [13] as well as increase the flexural stiffness of the beam [14]. As corrosion further increases, the flexural stiffness of corroded beams under a constant loading was found to be constant. This is mainly attributed to the secondary longitudinal strains of reinforcement from the expansive corrosion products, which supersede the increase of bond between reinforcement and concrete [15]. However, it remains unclear how would the flexural stiffness of RC beams be affected when the loading is further increased.

Corrosion rate of reinforcements within the RC beams would significantly affect the service life of RC structural members. Currently, there are controversial findings regarding the corrosion rate of beam reinforcements subject to various levels of sustained loading. Yoon et al. [16] stated that the corrosion of RC beams would increase at an increasing rate under high levels of sustained loads. While other researchers (e.g., Liu and Weyers [17]; Weyers [18]) found that the corrosion rate of reinforcements would decrease as the corrosion level increased. Differently, Zhe et al. [19] reported that the corrosion of reinforcements within RC beams developed in a stochastic manner. Therefore, the effect of sustained loading on the corrosion rate of reinforcements within RC beams needs further study.

Existing studies demonstrated that crack width on corroded beams under sustained loading was wider than that without loading. However, most studies (e.g., Zhu et al., [12]; Du et al., [20]; Yin et al., [21]) focused on studying the cracking behaviour of RC beams after corrosion process. Cracks would propagate on the corroded beams subject to a constant loading as the corrosion period increased. There has been limited research investigating the development of cracks for the RC beams with different corrosion levels. The effect of sustained loading on the cracking behaviour of corroded RC beams remains unclear.

The objectives of this research lie in that: (1) to investigate the effect of sustained loading on the corrosion rate of reinforcements within RC beams; (2) to characterize the cracking behaviour of corroded RC beams under multiple sustained loadings and corrosion periods; and (3) to analyse the joint effects of sustained loading and corrosion on the flexural behaviour of RC beams, specifically, to study the flexural loading capacities and load-displacement response of the corroded beams. The research findings would provide insights on the joint effects of sustained loading and corrosion levels on corroded RC beam's behaviour, especially at high loading levels (i.e., 30% to 60% of ultimate loading capacity).

2. Experimental programme

2.1. Specimens

Totally 13 RC beams with the same reinforcement details and concrete strength were prepared for experimental tests. Each beam had the cross-section of 120 mm × 200 mm and the length of 1700 mm. The beam section was reinforced with two T12 in the tension zone and two R8 in the compression zone. T12 is the HRB335 high strength steel bars with the nominal diameter of 12 mm while R8 is the HPB235 round steel bars with the diameter of 8 mm. The longitudinal reinforcements in the tension zone extended beyond both ends of the RC beam, and the extended portion of reinforcements were polished, bonded with copper wires, and sealed by epoxy resin. Stirrups R6.5 were provided along the beam at spacing of 80 mm except the constant moment zone in the middle of beam. R6.5 is the HPB235 round steel bars with the diameter of 6.5 mm. The clear span of each beam was 1500 mm. The dimension and reinforcement details of the beam are shown in Fig. 1.

The C30 concrete was used to cast the RC beams. In the concrete mix, the ordinary Portland cement 42.5 was used. The natural gravel with the maximum size at 20 mm was adopted as the coarse aggregate and the river sand with the fineness modulus at 2.6 was used as the fine aggregate. To guarantee the concrete strength, all beams were cast by one batch of ready-mix concrete and were cured under the same condition. The measured 28-day cubic strength of concrete was 34.2 MPa. The HRB335 high strength steel bars were used as the longitudinal reinforcements while mild steel bars were adopted as the stirrups.

The specimens are exposed to different sustained loadings and corrosion conditions. Four levels of sustained loadings at 0, 15%, 30% and 60% of ultimate loading capacity of the beam were adopted. Under each loading level, three levels of corrosion durations at 5, 10 and 20 days were applied to the beams. In addition, one RC beam without sustained loading and corrosion exposure was included as the control specimen. Further detailed experimental programme can be found in Table 1.

2.2. Corrosion setup

The test setup for the beam consists of a sustained loading system and an accelerated corrosion system as illustrated in Fig. 2. The load was applied through a mechanical jack installed between the specimen and the reaction frame. A load cell was installed to monitor the loading level for each beam. After reaching the loading level for each beam, the sustained loading level was maintained through adjusting the jack during the corrosion process.

The accelerated corrosion system comprises of a direct current (DC) source and a salt water spray cycling. The DC source supplied the maximum voltage and current of 30 V and 3.0 A, respectively. The current applied on each RC beam was controlled by a separate DC source. The bottom reinforcements were connected to the positive electrode of the DC supply. A stainless steel plate with the length of 1450 mm was set at the bottom of the RC beam and connected to the negative electrode. The corrosion current was controlled by the steady flow. According to the Faraday's law, the corrosion level of reinforcement can be controlled by the applied current density and the corrosion duration as expressed in the equation $m_l = W \cdot I \cdot t / F$ [9]. Here, m_l is the mass loss of reinforcement per unit of surface area; I is the applied current density; t is the corrosion duration; W and F are the equivalent weight of steel and the Faraday's constant, respectively. To achieve a mass loss of reinforcement around 10% for 10 days' corrosion, the current density of the RC beam reinforcements was calculated at 1.0 mA/cm^2. The 5% NaCl solution was sprayed to the RC beam to simulate wet-dry cycling, which was designed to provide the RC beams with corrosion environment. Two PVC pipes were installed at both sides of the beam along the longitudinal direction. Sprinklers were placed at 100 mm spacing along the PVC pipes, which were connected to the pump through hoses. As shown in Fig. 2(b), the accelerated corrosion system could form the water circulation to provide controllable spraying. The wet-dry alternate condition was set in the 24-h wetting followed by 24-h drying cycle.