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Structural behavior of corroded reinforced concrete beams under sustained loading

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HIGHLIGHTS

- An experimental study on combined effects of reinforcement corrosion and sustained loads on flexural behavior of reinforced concrete beams was carried out.
- Reinforcement corrosion had a slight effect on the development of transverse crack width.
- A higher load level and a lower current density leads to more obvious deflection development of RC beams.
- The effect of reinforcement corrosion on the beam's deflection cannot be ignored.

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ABSTRACT

This paper presents the results of an experimental study designed to investigate the combined effects of corrosion and sustained loads on the structural performance of reinforced concrete beams. A total of eight RC beams, including both uncorroded beams and corroded ones accelerated by the impressed current method, were tested. All the beams were subjected to a four-point sustained bending load which was equivalent to 17%, 33% or 50% of the designed ultimate load, respectively. Corrosion degree, crack patterns, crack width and mid-span deflection of the beams were monitored during the test. The results showed that reinforcement corrosion had no obvious effect on the transverse crack spacing and a slight effect on the development of transverse crack width for the beams under simultaneous loading and corrosion. A higher load level and a lower current density allow for more sufficient oxidation of corrosion products with a larger volume expansion rate, leading to premature initiation and rapid propagation of corrosion cracking, and more obvious deflection development of RC beams. For a beam under simultaneous loading and reinforcement corrosion, the effect of reinforcement corrosion on its deflection cannot be ignored, because it may exceed creep effect at a relatively low corrosion degree.

1. Introduction

Reinforced concrete (RC) is one of the most widely used construction materials in the world. RC structures are usually regarded as permanent structures that can be free of severe degradation problems for a long period time owing to their good service performance. Although steel bars embedded in concrete are normally protected against corrosion during the service life of a structure, the concrete cover can deteriorate under the effects of some aggressive agents, leading to corrosion of the steel bars in concrete. For RC structures, corrosion of steel bars is one of the most important factors causing durability problems [1]. On the one hand, corrosion can lead to the cross-sectional loss of steel bars and degradation of their mechanical properties thereby reducing the bearing capacity of a structural member. On the other hand, steel bars corrosion can also degrade the bonding behavior between the concrete and steel, thereby inducing stiffness reduction, which can increase the deflection during the service life.

Much research has been done on behavior of corroded RC beams. However, the most previous work has focused on the short-term behavior of corroded RC beams where the beam specimens were pre-corroded before loading to failure. Cabrera [2], Mangat et al. [3] and Torres-Acosta et al. [4] found that transverse crack width and crack spacing increased with the corrosion degree, but the quantity of cracks decreased. Actually, corrosion of steel bars normally takes place while a structure is subjected to a sustained load. The sustained load may lead to an accelerating effect

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List of notations

A	atomic weight of iron
F	Faraday's constant
D_1, D_2, D_3 and D_4	deflection value of the test beam
D_{down}	the mid-deflection value of the bottom beam
D_{up}	the mid-deflection value of the top beam
i	current density
r	the original radius of the steel bar
t	time elapsed
Z	valency of the reacting electrode
η_s	the mass loss ratio or the corrosion degree of a corroded steel bar
ρ	the steel density

on the corrosion process [5,6]. Furthermore, beam behavior under the combined effects of loading and corrosion is time-dependent. To predict the service life of corroded RC structures, it is important to clarify the time-dependent behavior of the corroded beam.

Combined action of loading and corrosion was considered in the experiments by many researchers, and different current densities have been applied in the accelerated corrosion process. Experimental study by Ballim et al. [5] showed that the sustained load effect on the deflection of a RC beam could not be ignored during the corrosion process. The current density applied in the experiment carried out by Ballim et al. was 400 μA/cm^2, which could get an ideal corrosion degree in a short period of time. However, the common current density that governs the corrosion rate of actual in-service corroding concrete structures normally ranges between 0.1 and 100 μA/cm^2 [7,8]. Additionally, the nominal current density applied in the accelerated corrosion testing should be less than 200 μA/cm^2 [9]. The experiment carried out by El Maaddawy et al. [10] and Malumbela et al. [11,12] used a relatively low current density. EI Maaddawy et al. monitored the corrosion crack development and the deflection of the testing beams under the current density of approximately 150 μA/cm^2 during the testing process; moreover, results showed that the sustained load significantly reduced the initiation time of corrosion-induced cracking and slightly increased the corrosion crack's width. The results also indicated that the flexural crack induced by the sustained load could initially increase the corrosion rate of the steel bars. Malumbela et al. did a series of experiments on the beams under the current density of 189 μA/cm^2 and recorded the deflection, corrosion crack width, crack pattern, and so on. The results also suggested that effects of the sustained load could not be ignored.

It's well-known that time-dependent flexural behaviors of RC beams subjected to sustained loading or reinforcement corrosion have a direct relation to loading level or corrosion rate. However, the current densities and loading levels recorded in tests are always different from that of actual in-service structures, and the current density in the actual RC structures is always less than that applied in tests. Thus, in this paper, an experimental investigation was carried out on the structural behavior of RC beams subjected to simultaneous loading with different levels and reinforcement corrosion with different rates. Particular attention was paid to the combined effects on initiation and propagation of corrosion crack, deflection of RC beams.

2. Experimental program

2.1. Specimen preparation

Eight RC beams with the same dimensions of 150 × 200 × 2200 mm were designed and casted, as shown in Fig. 1. The flexural reinforcement consisted of two 14 mm-diameter deformed steel bars in the tension zone and two 10 mm-diameter deformed bars in the compression zone. The thickness of concrete cover was 25 mm. The shear reinforcement consisted of 6 mm diameter plain stirrups spaced at 150 mm intervals along the beam. Eight beams were divided into two groups. Three of these beams were uncorroded, which belonged to Group A, and the other five were corroded, which belonged to Group B. The tensile steel bars in Group B were extended to protrude approximately 50 mm out of the end of the specimen to allow them to be connected to the power supplies during the accelerated corrosion process. Stirrups in Group B were coated with epoxy resin to protect them from corrosion. As a further precaution, plastic wires were used to fasten the longitudinal steel bars to the stirrups. Tensile testing was carried out on the tensile bars used in the experiment. The average tested yield strength and ultimate strength of three 14 mm deformed bars were 353 MPa and 533 MPa, and the modulus was 201 GPa.

The concrete mixture proportions are given in Table 1, and the 28-day compressive strength was acquired by conducting uniaxial compressive tests on the concrete cube specimens with a length of 150 mm. Ordinary Portland cement and tap water were used in this research. Crushed gravel with continuous grading ranging from 5 mm to 20 mm was used as the coarse aggregate, and natural sand with a fineness modulus of 2.64 was used as the fine aggregate.

2.2. Sustained loading system

The three specimens in Group A were subjected to sustained loading at three different load levels. The specimens in Group B were under three different load levels and three different current densities were applied to the corroded specimens, as shown in Table 2. In order to decrease the effect of concrete creep, all the beams were loaded after 150 days of casting.

A sustained loading system was designed to study the performance of flexural members, as shown schematically in Fig. 2. The beams in the sustained loading system were tested with a four-point bending over a span of 1800 mm with a constant moment region of 600 mm. The load was applied on specimens by hanging weights on a lever beam. Two lever arms were used to amplify the hung weight to the load at the midpoint of the distributed beam. Lever arm I was used to magnify a hung weight G from point A to point B. Load N at point B equals $l_1 \cdot G$. Point A could be one of the three different holes. When the weight hung at the different holes, the value of l_1 could be 8, 9 or 10. Load F at point C was 9 times greater at point B after magnified by lever arm II, i.e. $F = 9N$. Therefore, after magnification of two lever arms' action, the load at point C to the distributed beam could be up to 72, 81 or 90 times of the hung weight G at point A. The distribution beam distributed the load equally to two loading points placed at the ends of the middle third position marked on the top beam, and F_{py} at each loading point was equal to 0.5 F.

One or two pairs of two beams were loaded back-to-back simultaneously in the loading system, where the bottom beams were loaded with tensile face up and the top beams were loaded with