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Performance deterioration of corroded RC beams and reinforcing bars under repeated loading

Junzu Sun *, Qiao Huang, Yuan Ren

School of Transportation, Southeast University, Nanjing 210096, China

HIGHLIGHTS

- Failure mode of corroded RC beams under repeated loading was investigated.
- Flexural stiffness change of corroded RC beams under repeated loading has two obvious features of stages.
- Characteristics of stress–strain curves for reinforcing bars after corrosion fatigue changed significantly.
- Modified calculation formula for flexural stiffness of corroded RC beam under repeated loading was presented.
- Constitutive relation model for the reinforcing bar after corrosion fatigue was presented.

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ABSTRACT

Based on the accelerated corrosion test and fatigue loading test of RC beam specimens and the static tensile test of reinforcement specimens that were removed from the beam specimens after fatigue loading test, failure mode and flexural stiffness of corroded RC beams under repeated loading and mechanical behavior of reinforcing bars after corrosion fatigue were studied. We find that flexural stiffness change of corroded RC beams under repeated loading has two obvious features of stages, namely, slowly decreasing stage and stable stage. Considering the effects of corrosion and fatigue respectively, stiffness correction coefficients were introduced to quantitatively present the modified calculation formula for flexural stiffness of corroded RC beam under repeated loading. After corrosion fatigue, characteristics of stress–strain curves for reinforcing bars changed obviously: the yield strength decreased, percentage of elongation shortened, features of yield plateau changed. Mild steel changed into hard steel to varying degrees. Combined with the experimentally obtained stress–strain curves, constitutive relation model for the reinforcing bar after corrosion fatigue was quantitatively presented. The results of this study can provide reference for calculation and assessment of corroded RC bridge structures under long-term live load.

1. Introduction

The widespread occurrence of steel reinforcement corrosion in existing reinforced concrete (RC) bridge structures is a common problem with great damage. Steel reinforcement corrosion will cause decrease in load-carrying capacity and degradation in durability of bridge structures. Especially, the coastal environment with high content of chlorine ion as well as the extensive use of chloride salt snow-melting agent in winter aggravates the corrosion of steel reinforcing bars in bridge structures. The existing highway and railway bridge structures in operation are mostly subjected to repeated action of live vehicle load in addition to dead weight load. When damage of repeated loading accumulates to a certain extent, it will lead to brittle fatigue failure without any warning. Particularly, the rapid growth of traffic and widespread overload of freight make the repeated fatigue effect of vehicle load more and more significant. Without a doubt, when RC bridge structures are under dual adverse effects of chloride ion corrosive environment and repeated vehicle load, namely the steel reinforcement is under coupling effects of corrosion and fatigue, performance of RC bridge structures will deteriorate rapidly. Especially, the flexural behavior of RC beams and mechanical properties of steel reinforcing bars will change significantly, which are important assessment indexes for structural serviceability and safety of RC bridge structures. Therefore, it has important theoretical value and practical significance to carry out research on performance deterioration of corroded RC beams and reinforcing bars under repeated loading.

* Corresponding author.
E-mail addresses: sunjunzu@163.com (J. Sun), qhuanghit@126.com (Q. Huang), magren@126.com (Y. Ren).

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A large amount of studies have investigated load-carrying capacity [1], residual flexural capacity [2], flexural stiffness [3] and load–deflection curve [4] of corroded RC beams taking into account the effects of stirrup corrosion [5], different types of reinforcing bars [6], size-effect of tensile reinforcement [7] and bond strength degradation [8]. Flexural behavior of RC beams which were corroded under constant sustained service loads was analyzed [9]. Corroded RC beam was simulated through two-dimensional [10] and three-dimensional [11] finite element modeling approaches considering material and geometrical non-linearity [12], material properties change in steel and concrete, bond-slip deterioration and cracking [13]. Based on numerical analysis and simplified methodology, crack width prediction [14], performance assessment [15], assessment of structural safety level [16] and residual life evaluation [17] of corroded RC beams were discussed. In addition to static behavior, fatigue performance of RC beams has caused wide concern. Fatigue life [18], flexural stiffness [19], crack width [20] and crack growth [21] of RC beams under repeated loading have been investigated by various researchers. Non-linear behavior of cracked RC beams under variable stress amplitude was numerically simulated [22]. All of the investigations mentioned above are behavior of RC beams under the influence of pure corrosion or pure fatigue. There has been little concern about combined effects of corrosion and fatigue historically [23]. Fang et al. [24] experimentally investigated flexural behavior of corroded RC beams under repeated loading regarding corrosion influence on bond strength as the most important factor and indicated that a low corrosion level increased the bond strength between concrete and reinforcing bar. Oyado et al. [25] conducted fatigue loading test of corroded RC beams and found that the reduction of fatigue strength was proportionate to the weight loss of reinforcing bar. Yi et al. [26] found out that corrosion caused brittle fatigue failure and an increase in degree of corrosion caused a corresponding reduction of fatigue life. Masoud et al. [27] experimentally compared the fatigue performance of corroded RC beams strengthened by FRP wrapping and CFRP wrapping. Above existing investigations mainly discussed bond strength and flexural fatigue life of corroded RC beams under repeated loading. However, for the study of flexural stiffness for corroded RC beams under repeated loading in serviceability limit state, the research progress mainly focused on qualitative variation law, few researches have been carried out in the aspect of quantitative calculation formula currently, and there is no unified understanding.

The effect of corrosion on mechanical properties of reinforcing bars has been extensively studied through static tensile test. It was observed that local or pitting corrosion lead to moderate loss of strength [28] and significant reduction of ductility [29]. High degree of corrosion caused a brittle failure [30]. Pitting corrosion was more critical in the case of low corrosion degree and more likely to increase the chance of brittle fracture failure from ductile yielding [31]. It was strongly suggested that the spatial variability of pitting corrosion be considered [32], which lead to a considerable reduction in structural reliability [33]. The mechanism of pit development, the pit depth, the pit area and the effect of pits on the mechanical properties of embedded steel bar due to chloride induced corrosion were studied [34]. In addition, results of axial tensile fatigue test for reinforcing bars were presented in terms of failure mode, *S*–*N* curve [35] and stress concentration [36]. However, relatively little research has dealt with the fatigue performance of corroded reinforcing bars. Apostolopoulos et al. [37] carried out experimental studies on low cycle fatigue properties of corroded reinforcing bars to simulate seismic loading condition and found that load-carrying capacity, available energy and fatigue life were gradually reduced. Similar conclusions were also reached by Hawileh et al. [38]. Low cycle fatigue test [39] and finite element modeling [40] of nonlinear cyclic response and inelastic buckling for corroded reinforcing bars were carried out. Zhang et al. [41] investigated fatigue behavior of natural corrosion and accelerated corrosion induced reinforcing bars and the axial tensile fatigue test results showed that fatigue life of corroded reinforcing bars decreased significantly with the increase of corrosion degree and stress amplitude. The existing related researches mostly focused on mechanical properties of corroded reinforcing bars in the case of no fatigue, low cycle fatigue performance of corroded reinforcing bars and the corrosion influence on axial tensile fatigue life of reinforcing bars. However, for the research on mechanical properties of reinforcing bars in concrete after corrosion fatigue, few studies have been reported so far, and there is no consensus.

In this paper, combined with previous research work, on the basis of the actual stress level of tensile reinforcement in existing RC bridge structures, further efforts were made through accelerated corrosion test and fatigue loading test of corroded RC beams and static tensile test of reinforcing bars after corrosion fatigue. Change law for flexural stiffness of corroded RC beams under repeated loading was analyzed, and calculation formula for flexural stiffness of corroded RC beams under repeated loading was quantitatively presented. Degradation law for mechanical properties of reinforcing bars in concrete after corrosion fatigue was discussed, and constitutive relation model for reinforcing bars in concrete after corrosion fatigue was quantitatively presented. Our findings are expected to provide reliable theoretical supports and practical technique methods for the research on fatigue performance of corroded RC in-service bridge structures.

2. Experimental procedure

2.1. Details and materials of test specimen

13 RC beam specimens were designed, among which, 1 specimen was subjected to monotonic static loading without corrosion, 1 specimen was subjected to repeated fatigue loading without corrosion, the other 11 specimens were subjected to repeated fatigue loading after accelerated corrosion, as shown in Table 1. Dimension details and reinforcement arrangement of the beam specimen are shown in Fig. 1. Strength grade of the concrete was designed to be C25, and the measured average compressive strength was 31.3 MPa. The tensile reinforcement used HRB335 of the same factory batch, whose diameter was 16 mm. And the measured yield strength and tensile strength were 478 MPa and 608 MPa respectively. The tensile reinforcing bars extended the beam end by 150 mm, which was used for connecting wires. Before assembling the reinforcements, initial mass of each one of the tensile reinforcing bars was weighed.

2.2. Accelerated corrosion test

The beam specimens have been maintained for 28 days after casting. Then direct current was produced and flowed through the tensile reinforcement to conduct electrochemical accelerated corrosion test, as shown in Fig. 2. According to Faraday's law, by controlling the applied current intensity and conduction time, different degree of corrosion was achieved. As soon as the electrochemical accelerated corrosion test was completed, namely the expected degree of corrosion was reached, fatigue loading test was conducted.

2.3. Fatigue loading test

The beam specimens were subjected to four-point bending fatigue loading. Calculated span is 1500 mm, the length of pure bending section between the loading points is 500 mm, the length of bending shear section between the load point and the fulcrum is 500 mm. Measuring points of deflection were shown in Fig. 3.

Table 1
Grouping of the beam specimens.

Group	Number of the beam specimens	Name of the beam specimen	Accelerated corrosion or not	Fatigue loading or not
I	1	J7	No	No
II	1	J13	No	Yes
III	11	J1–J6, J8–J12	Yes	Yes