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# Experimental investigation on seismic performance of corroded reinforced concrete moment-resisting frames

Xiaojuan Liu[a,b], Huanjun Jiang[c,d,*], Liusheng He[c,d]

[a] College of Civil Engineering, Huaqiao University, Xiamen 361021, China
[b] Key Laboratory of Structural Engineering and Disaster Prevention of Fujian Province, Xiamen 361021, China
[c] State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
[d] International Joint Research Laboratory of Earthquake Engineering, Tongji University, Shanghai 200092, China

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ABSTRACT

For reinforced concrete (RC) structures located in seismic zones, reinforcement corrosion over time may have adverse effects on their seismic performance. Therefore, it is necessary to evaluate the effect of reinforcement corrosion on the seismic behavior of RC structures. In this study, an experimental study on corroded RC moment-resisting frames was carried out to investigate the effect of longitudinal reinforcement corrosion on the seismic behavior of RC frames. Six frame specimens, including five corroded frames and one frame without corrosion, were tested under quasi-static cyclic loading. The corrosion ratio of longitudinal reinforcement and the axial compression ratio were the main variable parameters. It was found that with the increase of corrosion ratio, the lateral load carrying capacity as well as the deformation capacity of RC frames decreased roughly linearly, and the energy dissipation capacity reduced approximately exponentially. For corroded frames with low axial compressive load level, the lateral strength and energy dissipation capacity were enhanced with the increase of the axial compression ratio, and the effect of axial compression ratio on the deformation capacity was insignificant. For frames with larger corrosion ratio or higher axial compression ratio, damages at beam ends developed more significantly during the loading process. In comparison with the beam, the damage evolution of columns was less affected by the corrosion ratio and axial compression ratio.

## 1. Introduction

During the lifetime of RC structures the corrosion of steel reinforcement occurs commonly, leading to the deterioration of structural behavior. The corrosion of RC structures is usually caused by carbon dioxide ($CO_2$) or chlorides penetration, which generally results in uniform or localized attacks [1]. Uniform corrosion reduces the loading-resistance of the steel bar, while pitting corrosion induces localized yielding and fracture of the steel bar, and decreases both its loading-resistance and ductility. The volumetric expansion of corrosion by-product, such as rust, induces external cracking and ultimately leads to spalling of concrete cover. In addition, the expansion of rust and spalling of concrete cover potentially reduce the bonding strength between the reinforcement and surrounding concrete. Corrosion of steel reinforcement is a long-term process that may gradually induce internal damage to RC members, and ultimately lead to impaired behavior of RC structures. In seismic zones reinforcement corrosion over time may weaken RC structures and damage their seismic capacity [2].

To clarify the effect of reinforcement corrosion, quite a number of experimental investigations on the mechanical behavior of corroded RC members have been carried out over the past few decades [3–8]. According to the previous research results, when the corrosion ratio of the steel bar in RC members was less than a limit value, both the strength and the failure mode of corroded members were similar to those without corrosion. Once the corrosion ratio exceeded the limit value, however, the failure mode and loading-resistance were altered. The influence of reinforcement corrosion on the loading-resistance and failure mode of RC members is a complex issue, which depends on many factors, i.e., the relative corrosion level of longitudinal and transverse reinforcement, the original reinforcement ratio, the corrosion distribution of reinforcement, etc. The experimental study on corroded RC beams carried out by Du et al. showed that reinforcement corrosion caused the failure mode of over-reinforced beams exhibiting a less brittle manner, but made under-reinforced beams fail in a more brittle manner [5]. The research conducted by Torres-Acosta et al. indicated that when the corrosion of steel bars occurred locally, the effect of corrosion on the strength of RC beams was less significant [8].

There are also a number of studies on the seismic performance of

* Corresponding author at: State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China.
*E-mail address:* jhj73@tongji.edu.cn (H. Jiang).

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corroded RC members. Test results indicated that the strength, energy dissipation capacity and ductility of RC members decreased as the corrosion ratio increased [9–16]. The failure mode of some corroded members under cyclic loading switched from flexural failure to flexural-shear failure [10–12], and both the failure mode and seismic performance of corroded RC members were significantly affected by the corrosion location [12]. In addition, the hysteretic loop became less stable as the corrosion level increased [13]. Based on the cyclic loading test results of corroded RC columns, the relationship between corrosion level and deformation capacity of flexural critical RC columns was established by Goksu and Ilki [14]. It was shown that with the increase of the corrosion ratio, the deformation capacity of RC columns degraded due to the premature failure at the significant pit zones of corroded reinforcement.

In reality in RC structures the corrosion usually occurs not only in the longitudinal reinforcement but also in the transverse reinforcement. However, the effect of longitudinal reinforcement corrosion on the seismic performance of the structure is different from that of transverse reinforcement. In order to easily and clearly understand the seismic performance of real corroded RC structures with the complicated combination effect of the corrosion of longitudinal and transverse reinforcement, the knowledge on the individual effect of the longitudinal and transverse reinforcement corrosion should be acquired at first. Therefore, the corrosion of longitudinal and transverse reinforcement should be simulated separately clearly in the laboratory in a controlled manner to quantify the individual effect on the structural behavior [4]. Nevertheless, most of the previous experimental studies were carried out on RC members with both the longitudinal and transverse reinforcement corroding, making it hard to distinguish the effect of longitudinal reinforcement corrosion from transverse reinforcement corrosion. In addition, the previous studies mainly focused on corroded beams and columns in the member level, while very limited information was available in the structural level.

The main motivation of this study is to get proper understanding of the corrosion effect of longitudinal reinforcement on the seismic performance of RC moment-resisting frames. For this purpose, an experimental study on the seismic performance of RC frames with corrosion induced only in the longitudinal reinforcement was carried out. Six RC frames, including five corroded frames and one frame without rebar corrosion, were tested under combined constant vertical load and cyclic lateral load. The main research variables were the corrosion ratio of longitudinal reinforcement and the axial compression ratio. The failure mode, strength, hysteretic behavior, deformation capacity, and energy dissipation capacity were investigated and discussed.

## 2. Experimental program

### 2.1. Specimen information

A typical three-bay and three-story RC moment-resisting frame was selected as the prototype structure and designed according to the current Chinese structural design codes [17,18]. The prototype structure is located in the earthquake prone region with the seismic fortification intensity 7, site soil class III, and design group 1. Based on the seismic fortification intensity, site characteristic period and fundamental vibration period, the seismic effect coefficient of the prototype structure was determined. Strong-shear and weak-flexure principle was adopted in the structural design to insure that the non-corroded RC frame would fail in the flexural mode under combined lateral and axial compression load. The central bay and side bay of the first story of the frame were selected as the prototype substructure.

In this study the test frame was a 1/2-length-scaled model of the prototype substructure. A total of six specimens were designed and constructed accordingly. Electrochemically accelerated corrosion was imposed to five frames, and the other one was non-corroded. The corrosion ratio of the longitudinal steel bar and the axial compression ratio were the main variable parameters. The design parameters are summarized in Table 1. In this study the corrosion ratio refers to the average weight loss ratio of the corroded steel bar. Five corrosion ratios of longitudinal reinforcement, i.e., 0%, 5%, 7.5%, 10% and 15%, were considered, and the accelerated corrosion period were determined according to the designed corrosion level. Geometrical dimensions and reinforcement details were identical for all specimens. Fig. 1 illustrates the dimensions and reinforcement details of the specimens. All specimens were cast with the same batch of concrete and steel reinforcements at the same time. According to the results of concrete sampling tests, little variation was found for the concrete mechanical properties of different specimens. The average cubic compressive strength, prism compressive strength and elastic modulus of the concrete were 46.0 MPa, 38.9 MPa and $3.32 \times 10^4$ MPa, respectively. The actual yield and ultimate strengths of the longitudinal reinforcement with a diameter of 12 mm were 405 MPa and 591 MPa, respectively, while those strengths of the longitudinal reinforcement with a diameter of 14 mm were 426 MPa and 590 MPa, respectively. The actual yield and ultimate strength of the transverse reinforcement with a diameter of 6 mm were 335 MPa and 511 MPa, respectively. For five specimens, the axial compression load applied on the top of the column was 135 kN, which corresponded approximately to 10% of the designed axial loading capacity of the column determined based on the concrete design compressive strength, without consideration of the contribution of longitudinal reinforcement. The compressive load of these frames was determined according to the compression level of the side column in the first floor of the prototype structure. For Specimen F10-2, the axial compression load was 270 kN, which was double of the axial compression load applied on the other specimens. The compression load of Specimen F10-2 was considered according to the compression level of the central column in the first floor of the prototype structure.

**Table 1**
Design parameters of specimens.

| Specimen No. | $\eta_d$ (%) | $n_d$ | $N$ (kN) |
|---|---|---|---|
| F0-1 | 0 | 0.1 | 135 |
| F5-1 | 5.0 | 0.1 | 135 |
| F7.5-1 | 7.5 | 0.1 | 135 |
| F10-1 | 10.0 | 0.1 | 135 |
| F10-2 | 10.0 | 0.2 | 270 |
| F15-1 | 15.0 | 0.1 | 135 |

Notes: $\eta_d$ is the designed corrosion ratio of the longitudinal reinforcement; $n_d$ is the designed axial compressive load ratio; and $N$ is the actual compressive load applied on the top of the RC column.

### 2.2. Electrochemically accelerated corrosion in reinforcement

After a standard curing period of 28 days after casting, the corroded specimens were subjected to an accelerated corrosion process. Corrosion was expected to occur only in the longitudinal reinforcement in beams and columns, and thus only the longitudinal reinforcement was imposed with a constant current. Insulating sleeves were placed at the intersection between the longitudinal reinforcement and the transverse reinforcement to prevent the latter one from being corroded. Similar insulation method was taken to prevent the reinforcement in the base beam from being corroded. The whole frame was immersed in a water tank filled with NaCl solution with the concentration of 5%. Copper bars were placed in the tank and connected to the cathode of the D.C. power supply. Longitudinal reinforcements in each frame member were connected in parallel by electric wires and used as the anode. A total of three D.C. power supplies were used for each specimen. The accelerated corrosion method is shown in Fig. 2. The electric current density was 0.2 mA/cm$^2$ determined according to the surface area of the longitudinal reinforcement. Since longitudinal reinforcements in each frame member were connected in parallel, the