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Experimental investigation on the cyclic performance of reinforced concrete piers with chloride-induced corrosion in marine environment

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ABSTRACT

Coastal bridges in marine environments suffer from serious corrosion, resulting in the degradation of the seismic capacity of the structures during the long-term service period. This paper presents a cyclic experiment of coastal bridge piers considering the corrosion effects. Four test specimens, among which one is a sound structure and the others are structures with different levels of corrosion damage from accelerated corrosion, were used for the cyclic tests in this study. Using the measured force–displacement hysteretic responses, the effects of the corrosion damage on the seismic behavior of the specimens were investigated. The test results indicated that the seismic performance of the structure showed obvious degradation with the increase in the level of corrosion.

1. Introduction

Chloride penetration is one important reason induced the damage and deterioration of concrete structures [1,2]. In marine environments, high levels of humidity and chloride concentration in the seawater and air cause more serious corrosion to coastal engineering than inland areas. The corrosion leads to mass loss of reinforcement [3,4], cracking of concrete cover [5,6] and degradation of the bond capacity on the interface of concrete and reinforcement [7–9]. For the structural components, the strength [10,11], stiffness, ductility [12] and energy dissipation capacity [13] would be reduced due to the continuous aging and deterioration in the corrosion environment during the long-term service period. Moreover, many coastal regions are also located in earthquake-prone areas. The coupled actions of corrosion and earthquake hazard will increase the economic and human losses from earthquake events and present severe challenges to the engineering community [14].

Coastal bridges are an important component of the transportation system in coastal areas. Improving the understanding of the seismic capacity deterioration of aging bridges will enhance life-cycle analysis and the design and maintenance of civil infrastructure [15–18]. Columns, beams and slabs are three types of main components of bridge structures. Thus far, the capacity reduction of aging reinforced concrete (RC) beams and slabs has been investigated by some researchers [19–21]. The analysis and experimental results indicated that the flexural strength of beams was not obviously affected by the corrosion of longitudinal reinforced bars at the initial stage, whereas the stiffness and flexural strength were significantly decreased due to the loss of the cross-sectional area of the longitudinal reinforcement with extensive corrosion of the reinforcements [19,20]. The failure of the RC slab with corroded reinforcement showed a closed relationship with the corrosion of the reinforcement with mass loss of more than 13% [22]. The failure mode of the corroded RC beam has the potential of switching from flexural failure to flexural-shear failure under the cyclic loads due to the fracture of the transverse reinforcement [23]. Under cyclic loads, the energy dissipation capacity of the beam and beam-column joint also showed a continuous decrease with the increase in the level of corrosion [13].

For columns, Ma et al. [24] experimentally investigated the seismic behavior of 13 circular RC columns with corrosion damage under cyclic loading. The experimental results demonstrated that the loading capacity, stiffness, ductility and energy dissipation capacity decreased with increasing corrosion. However, it was also found that the corroded specimens have almost the same energy dissipation capacity at the same displacement excursions when the mass loss was less than 14%. Li et al. [12] experimentally investigated the behavior of a corroded RC column strengthened with a carbon fiber-reinforced polymer and steel jacket. The test results of 14 RC columns indicated that the corrosion degree significantly affected the behavior of the columns, and the ductility of the

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column was effectively improved by using the retrofit methods. Additionally, some researchers focused on the analysis and evaluation method for the corroded piers. Tapan and Aboutaha [10] developed a strength evaluation method to estimate the load-carrying capacity of bridge piers. The analysis results indicated that the corrosion of reinforcement reduces the ultimate load-carrying capacity of deteriorated RC piers. Ou et al. [25] developed a seismic evaluation methodology for RC bridges undergoing chloride attack based on a nonlinear static pushover analysis approach. Pillai et al. [26] investigated the service reliability of post-tensioned bridges with damaged tendons induced by chlorides, voids and moisture.

Cyclic experiments are a major method to provide insight into the seismic performance of the structural component. However, although it is recognized that the corrosion-induced damage on coastal bridge piers significantly affects the safety of the structures during the long-term service period, the damage mechanism and the mechanical behavior are still seldomly understood. This paper presents an experimental investigation on the cyclic performance of the bridge piers under chloride attack in a marine environment. The aim of this study is to provide new insight into the potential effects of corrosion-induced structural degradation on the seismic performance of coastal bridges. To achieve this purpose, four specimens with different levels of corrosion damage were used for the pseudo-static cyclic tests. Considering the more serious corrosion of the bridge piers in the splash and tidal zone in marine environments, a specific case of corrosion occurring in the plastic hinge region of the pier was investigated in this study. With the test data, the seismic performance of the specimens, including the strength, deformation, ductility and energy dissipation capacity, were investigated for the specimens with different levels of corrosion. The test results indicated that the seismic capacity of the piers is strongly dependent on the chloride-induced corrosion damage and that the seismic performance of the coastal bridges in marine environments should be carefully considered for evaluating the long-term behavior in the whole life cycle.

2. Experimental program

2.1. Specimen details

In this study, four single shaft piers were constructed to investigate the seismic capacity of corroded bridge piers. The four specimens were designed as the identical cantilever columns with the same dimensions. As shown in Fig. 1, the total height of each specimen is 3.2 m. At the bottom, a rigid foundation with dimensions of $1.4 \times 1.4 \times 0.7$ m is set to mount the test model on the ground and to provide the rigid boundary for the columns. The cross section of the columns is 0.25×0.6 m, with a chamfered edge radius of 5.0 cm. For the connection with the actuator, the top of the specimen is slightly enlarged to 0.4 m along a 0.4-m height.

In each column, 12 Ø16-mm steel rebars were adopted as the longitudinal reinforcement, and the corresponding longitudinal reinforcement ratio is calculated to be 1.61%. The Ø8-mm steel bar was selected as the rectangular stirrup. To enhance the shear capacity at the plastic hinge region, the rectangular stirrups were set with the pitch of 60 mm within the height of 0.6 m measured from the bottom. At the upper part, the rectangular stirrup was set along the height with the pitch of 100 mm. The corresponding volume ratios of the steel stirrup were calculated to be 1.42% and 0.58%, respectively. The cover depth of the specimens was 25 mm. The yielding strength of the longitudinal reinforcement and stirrup were 362 MPa and 325 MPa, respectively. The corresponding ultimate strengths were 505 MPa and 448 MPa, respectively. For the concrete, the average concrete compressive strength of the specimens was tested to be 42.9 MPa.

2.2. Accelerated corrosion of the specimens

In the long-term service period, the coastal bridge pier will sustain different levels of corrosion along the elevation of the structure due to the difference in the exposure environments. Generally, the corroded bridge pier can be classified into three different zones according to the degree of corrosion, i.e., the submerged zone, the splash and tidal zone, and the atmospheric zone [27]. The splash and tidal zone is more aggressive than the others due to the higher surface chloride concentration and wetting–drying cycles in the marine environment. Although the bridge pier would also sustain some corrosion-induced damage in the atmospheric zone due to airborne chlorides and carbon dioxide, this experimental study is only focused on the corrosion effects occurring in the splash and tidal zone. Furthermore, it is also recognized that the corrosion damage at the bottom would make the structural deterioration more serious because of the potential plastic hinge in this region. Therefore, the corrosion damage of the specimens was designed to occur in this critical region at a height of 0.5 m above the foundation. During the test, Specimen 1 is set at the pristine status for comparison. Accelerated corrosion was applied to the others for different corrosion levels.

An electrochemistry accelerated corrosion method was adopted to accelerate the corrosion process for the preparation of the corroded specimens. To achieve this purpose, the longitudinal and transverse reinforced bars in the potential plastic hinge region were set as the anode. In the corresponding region, the outside surface of the specimens was surrounded by stainless steel mesh used as the cathode. The bottom of the specimen was enclosed with a brick tank filled with 3.5% NaCl solution. During the accelerated corrosion process, the corrosion current of each specimen was separately supplied by a direct current (DC) power supply. The schematic diagram of the acceleration corrosion circuit and a close-up photo of the specimen after corrosion are shown in Fig. 2.

Before applying the corrosion current on the specimens, the mass loss of the reinforced bars was previously estimated through converting the current flow by Faraday's law to metal loss according to the following formula:

$$\Delta m = \frac{MIt}{ZF} \tag{1}$$

$$\eta = \frac{\Delta m}{M} = \frac{Mi_{cor}t}{Fd\rho} \tag{2}$$

in which Δm is the mass loss (g); η is the corrosion rate (%); M is the molar mass of the iron atom (55.85 g/mol); I is the corrosion current (A); i_{cor} is the corrosion current density (A/m^2); t is the accelerated corrosion time (s); Z is the valence oxidation reaction depending on the oxidation reaction of the final product; F is the Faraday constant (96,485 C/mol); d is the radius of the steel bar (m); ρ is the density of the steel material (7.8×10^3 kg/m^3).

Although the accelerated corrosion was employed for the preparation of the tested specimens, it should be noted that the artificial corrosion is different from natural processes for structures in the field [28]. A too fast corrosion reaction would lead to insufficient oxidation and different chemical compositions in the corrosion products [29]. Furthermore, a constant current density level should be applied for examining the structural member behaviors at different degrees of corrosion [30]. Considering the above reasons, a constant corrosion current of 1.36 A was applied to the specimens during the whole accelerated corrosion process. According to the surface area of the longitudinal and transverse steel bars, the corrosion current density was estimated to be 0.2 mA/cm^2. For the three corroded specimens, the corrosion level was quantified by the mass loss of the reinforcement. To experimentally investigate the seismic capacity of the bridge pier specimens with