Construction and Building Materials 173 (2018) 160–171

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Shaking table tests of coastal bridge piers with different levels of corrosion damage caused by chloride penetration

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HIGHLIGHTS

- A shaking table test for coastal bridge piers with non-uniform corrosion is conducted.
- Structural displacement, acceleration and average curvature distribution are analyzed.
- Different seismic failure mode of corroded pier is investigated.

ARTICLE INFO

Article history:
Received 6 December 2017
Received in revised form 5 April 2018
Accepted 6 April 2018
Available online 24 April 2018

Keywords:
Shaking table test
Coastal bridge pier
Non-uniform corrosion
Seismic performance
Accelerated corrosion
Failure mode

ABSTRACT

Coastal bridges in a marine environment are vulnerable to corrosion damage, which reduces the seismic capacity of the structures during a long-term service period. This paper presents the results of shaking table tests conducted for coastal bridge piers by considering the effect of a non-uniform corrosion. Four structural specimens with different degrees of corrosion at the designed splash and tidal zone are first fabricated by the electrochemical accelerated corrosion method. After subjecting the specimens to a series of gradually increasing ground motions, the natural period, damping ratio, displacement and acceleration responses, and average curvature distribution of the structures are analyzed. Based on the time-dependent constitutive models of the reinforcements, the finite element models of the aging columns are constructed. Four possible seismic failure modes are identified for the bridge piers through the evolution of the curvature distribution form during the entire service period. The results indicate that the structural seismic performance degrades continuously with the increase in the corrosion level. The significant performance difference between the atmospheric, splash and tidal, and submerged zones will probably result in the plastic hinge transfer phenomenon.

1. Introduction

Owing to humidity and sea salt, coastal bridges in a marine environment usually suffer from continuous corrosion during their entire service life. Chloride-induced corrosion can cause cracking and spalling of the concrete cover [1], a reduction in the area and strength of the reinforcement [2,3], and a decrease in the steel–concrete interface bond capacity [4]. Consequently, the performances of the structural members are effectively weakened, and the vulnerability of the bridges to a seismic hazard is increased [5–9]. To ensure that the corroded bridges remain safe when subjected to earthquake motions as well as provide appropriate guidance for their maintenance and repair, it is important to understand the seismic behavior of the aging structures [9,10].

Corrosion of coastal structures is a slow long-term process and closely related to chloride penetration. Previously, the corrosion status was generally modelled by using chloride diffusion models [11,12] and material deterioration models [13–15]. In experiments, corrosion of the specimen was usually achieved by exposure to the natural environment [16,17], a salt spray [18], or artificial control [19]. Considering reinforcement corrosion is the major cause of the deterioration of reinforced concrete (RC) members, rapid and efficient electrochemical acceleration corrosion, corresponding to the third method, was commonly used in laboratory tests [13,20].

Researchers and engineers have devoted numerous efforts for performing the seismic performance analysis and cost estimation of aging structures. Choe et al. [21] conducted a fragility analysis of corroded columns based on the proposed probabilistic drift and shear force capacity models. Akiyama et al. [22] investigated the time-dependent reliability of RC structures by taking into account the hazard associated with airborne chlorides. By incorpo-

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https://doi.org/10.1016/j.conbuildmat.2018.04.048
0950-0618/

rating the age and environmental exposure into the fragility functions, Rao et al. [23] developed a framework for the seismic risk assessment of RC bridge piers. In addition, Kumar et al. [24] presented a probabilistic approach to compute the life-cycle cost of aging bridges by considering the combined effect of the cumulative seismic damage and chloride-induced material deterioration. Zanini et al. [25] performed an extensive cost analysis of the structural maintenance and retrofitting based on the condition and seismic vulnerabilities of existing bridges.

In recent decades, the behavior of a corroded RC structure has been experimental studied by some researchers. Ma et al. [26] investigated the seismic performance of thirteen corroded circular columns by conducting cyclic loading tests. The results indicated that a higher corrosion level could cause a more obvious deterioration of the structural strength, stiffness, ductility, and energy dissipation capacity. Furthermore, a brittle failure was observed for some specimens, owing to the severe damage of stirrups and a high axial load. Lin et al. [27] evaluated the dynamic properties of a corroded RC frame via the shaking table test. The results demonstrated the significant effect of rebar corrosion on the response of the displacement, acceleration, and spectral curve of the structures. Lee et al. [28] conducted a cyclic horizontal loading test on six damaged columns strengthened by carbon fiber sheets. It was found that the dominant reasons for the structural performance degradation were the detachment of the concrete cover and reduction in the mechanical properties of the corroded reinforcements.

In a marine environment, coastal structures undergo complex performance deterioration because of the different corrosive surroundings along their elevation. It is widely accepted that materials in the splash and tidal zone suffer from a more serious corrosion-induced damage than in the atmospheric and submerged zones [29–31]. In conventional bridges piers, the seismic-induced damage is typically concentrated in the bottom region owing to the large bending moment. However, in bridge piers with a non-uniform corrosion, the final structural failure mode has the possibility of changing when the load-resisting capacity of the splash and tidal zone is significantly lower than the other two zones. This phenomenon should be carefully addressed as it deviates from the initial design objective and affects the seismic behavior of the structures.

Focusing on this issue, in this study, a shaking table test was conducted to investigate the seismic performance and failure mode of non-uniformly corroded bridge piers. The main contents of this paper are organized as follows: First, we describe the fabrication of columns with different chloride-induced damage levels at the designed splash and tidal zone by the electrochemical accelerated corrosion method. Then, the test setup and loading protocol are presented. Next, the experimental observations on the crack pattern and failure mode are provided. Following this, analysis of the natural period, damping ratio, displacement and acceleration responses, and average curvature distribution of the different specimens is discussed. Subsequently, the finite element models of the aging structures are presented along with their analysis by the OpenSees software, and the numerical modeling approach is validated by the test data. The four possible seismic failure modes of the coastal bridge piers during the entire service life are discussed. Finally, the main research findings are summarized in the conclusions.

2. Experimental setup

2.1. Specimen design

For the experiments in this study, a simple RC-supported bridge was selected as the prototype structure. Owing to the limitations on the size and bearing capacity of the shaking table, only one bent of the bridge with a single column was adopted for the test with a geometrical scaling of 1:6. The detailed scaling factors of the structural, geometric, material, and dynamic parameters used in model design are summarized in Table 1 based on the consistent similitude law [32]. To investigate the effect of non-uniform corrosion on the seismic performance of the bridge piers, four specimens with identical geometric sizes and material properties were constructed for the shaking table tests in this study.

Fig. 1 shows the schematic of a test specimen. As depicted in the figure, a 2.1 × 2.1 × 0.6-m RC mass block is set at the top of the column to represent the weight and inertial mass of the superstructure. To facilitate construction, a reusable steel member that was welded by four steel beams and one steel trough is used to realize the fixed connection between the substructure and mass block. At the bottom, a rigid foundation of size 1.2 × 1.1 × 0.3 m is set to attach the shaking table to the pier.

The diameter of the cylindrical column is 200 mm with a cover thickness of 15 mm. From the column bottom to the center of the mass block, the effective structural height is measured to be 1600 mm. 6 reinforced rebars with 10 mm diameter are used as longitudinal bars with a reinforcement ratio of 1.5%. 6 mm diameter circular stirrups with a pitch of 80 mm are set at both ends of the column within a range of 250 mm, while a pitch of 100 mm is adopted for the remaining part. To connect the additional weight, 8 steel bars with 22 mm diameter are pre-embedded in the concrete of the column cap. The yield and ultimate strength of the longitudinal bars were tested to be 421.55 MPa and 661.97 MPa, respectively. For the stirrups, the corresponding strength was 412.04 MPa and 678.75 MPa, respectively. For the concrete material, the water cement ratio is 0.38. Moreover, the medium sand and the gravel with the largest size of 12 mm are used. Six concrete cylinders with the diameter of 150 mm and the height of 300 mm were cast along with the bridge columns. The 28-day average compressive strength and modulus of elasticity were tested to be 36.27 MPa and 19.5 GPa, respectively. When the additional weight of 7.86 tons applied to the column, the axial compression ratio of the column was calculated to be 0.07.

2.2. Accelerated corrosion

Owing to the abundant oxygen and wetting–drying cycles, the splash and tidal zone of a coastal bridge is optimal for chloride penetration and corrosion propagation. In this experiment, the range of [300,550] mm above the footing was designed to represent the splash and tidal zone, where electrochemical-accelerated corrosion was induced. Because an extremely rapid corrosion reaction would lead to an impractical damage extent of the surface morphology of reinforced bars and an inadequate oxidation of the corrosion products [33], a corrosion current density of 300 $\mu A/cm^2$ was adopted for the accelerated corrosion of the tested specimens [34]. Furthermore, to investigate the effects of the corrosion level on the seismic performance of the structures, four specimens (D0, D30, D60, and D105) were designed for the shaking table test. Among them, D0 was the sound structure, and D30, D60, and D105 were the corroding specimens sustaining corrosion duration times of 30, 60, and 105 days, respectively, with the specified corrosion current density.

The schematic of the corrosion circuit and photograph of the final corrosion state of Specimen D105 are shown in Fig. 2. As seen from Fig. 2(a) and (b), the reinforced bars with height of [300, 550] mm above the footing and copper mesh act as the anode and cathode of the resulting circuit, respectively, while 4.0% NaCl solution serves as the electrolyte. A direct current (DC) power supply is used to supply the corrosion current during the accelerated corro-