Soil Dynamics and Earthquake Engineering 102 (2017) 112–123

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Experimental investigation on the cyclic behaviors of corroded coastal bridge piers with transfer of plastic hinge due to non-uniform corrosion

Wei Yuan, Anxin Guo*, Hui Li

Ministry-of-Education Key Laboratory of Structural Dynamic Behavior and Control, School of Civil Engineering, Harbin Institute of Technology, Harbin 150090, China

ARTICLE INFO

Keywords:
Cyclic experiment
Coastal bridge pier
Non-uniform corrosion
Plastic hinge
Accelerated corrosion
Hysteretic response

ABSTRACT

Coastal bridge piers exposed to marine environments always suffer from non-uniform corrosion along the elevation. Severe degradation in the splash and tidal zone would significantly affect the seismic performance of the structure with a specific phenomenon of the plastic hinge transferring from the column end to the splash and tidal zone. In a companion paper of the authors [1], a theoretical method to identify the time-dependent failure mode and equivalent plastic hinge length of the aging bridge piers under seismic excitation in the whole life cycle was conducted. In this study, cyclic loading tests of six reinforced concrete circular bridge piers with different levels of corrosion are carried out to investigate the seismic performance of such types of structures and validate the proposed method. The test specimens and the experimental setup are first introduced. Based on the measured hysteretic curves, the experimental results of the curvature distributions, hysteretic characteristics, loading-resistance capacity, ductility, energy dissipation, equivalent viscous damping ratio and equivalent plastic hinge length are analyzed and discussed. The test results demonstrate the accuracy of the analysis results for the seismic failure modes presented in the companion paper. It is also indicated that the seismic performance of the non-uniformly corroded columns exhibited a small variation before the transfer of the plastic hinge location, while an obvious reduction was observed for moderately and severely corroded structures.

1. Introduction

Coastal bridges located in the marine environment are exposed to aggressive environmental conditions and are easily susceptible to chloride-induced corrosion. The continuous penetration of chloride ions in the long-term service period may reduce the concrete and the steel area [2,3], decrease the bond strength between the concrete and reinforcements [4–6], and weaken the material strength [7,8]. In earthquake-prone zones, the seismic-resistance capacity of the coastal bridges may be strongly affected by the corrosion-induced deterioration as well [9]. To ensure the safety of coastal bridges, it is essential and necessary to understand the time-dependent seismic performance of corroded coastal bridges and to provide appropriate guidance for the maintenance, rehabilitation, and repair of such types of civil infrastructures [10,11].

In recent decades, several research efforts have been devoted to the influence of corrosion on structural capacity. For corroded reinforced concrete (RC) beams, many analytical models [12–14] and finite element models [15,16] have been proposed to predict and evaluate the residual flexural strength [12,14,15], shear behavior, and stiffness of the structures [13,16]. It has been identified that the capacity deterioration of beams becomes more obvious with the increase in the degree of corrosion [12,13,15]. At high corrosion degrees, the decrease in the capacity of the beams is mainly due to the decrease in both the cross-section and the strength of the steel reinforcements, whereas the major cause for strength reduction of the beams subjected to low corrosion degrees is the loss of bond capacity between the steel and surrounding concrete [15]. For corroded RC slabs, limited efforts have been made in terms of investigating structural safety and serviceability [17], deformation behavior [18], ductility, and failure mode [19].

For corroded columns, the relevant studies were mainly focused on the time-dependent capacity of the corroded columns and the resulting influence on the structural seismic performance. Choe et al. [20] established probabilistic drift and shear force capacity models for corroded RC columns. A fragility estimation method considering the model uncertainties and the environmental condition uncertainties was presented. Akiyama et al. [21] proposed an evaluation method of structural displacement ductility capacity based on the buckling model of corroded longitudinal bars. In addition, a novel computational procedure was developed to assess the life-cycle seismic reliability of bridge piers, considering both the probabilistic seismic hazard and the airborne chloride effects. Rao et al. [22,23] investigated the time-

* Corresponding author.
E-mail address: guoanxin@hit.edu.cn (A. Guo).

http://dx.doi.org/10.1016/j.soildyn.2017.08.019
Received 3 May 2017; Received in revised form 28 July 2017; Accepted 27 August 2017

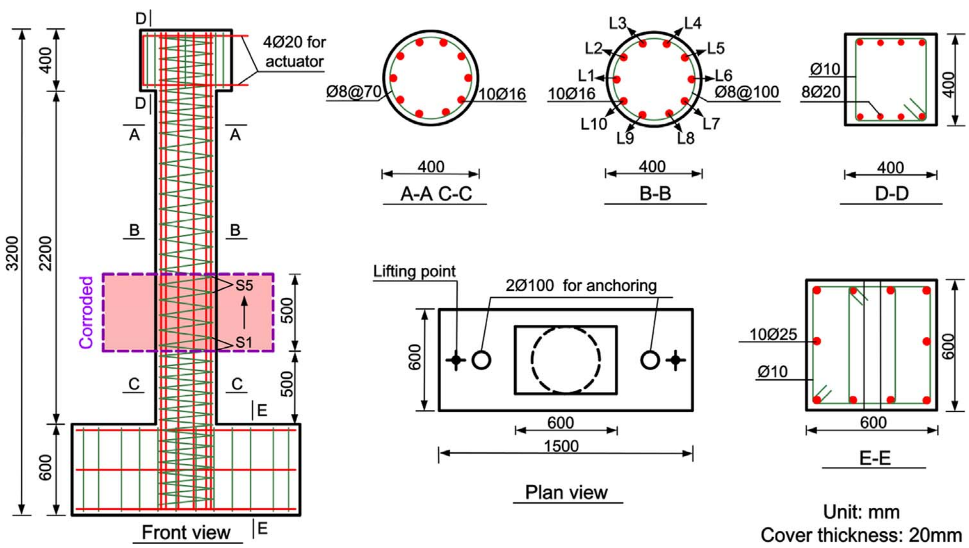

Fig. 1. Schematic diagram of the specimens.

dependent deterioration model of structures in varying corrosion conditions. Moreover, fragility functions were proposed for sound and deteriorating bridge piers based on the structural age and the surroundings. Huang et al. [24] developed the probabilistic deformation and shear capacity models for RC bridge columns considering the aging and deterioration conditions. Based on those probabilistic models, the fragility analysis of the corroded columns was performed.

Due to the complex environment condition, bridges in the seismic-prone regions are more sensitive to the corrosion damage of the structures. Focusing on this problem, Simon et al. [25] investigated the seismic response of a typical RC bridge considering the corrosion-induced reduction of the cross-sectional area of the reinforcement and the concrete cover spalling. Combined with the developed capacity models for bridge columns [26,27], the fragility of the deteriorated RC bridge were conducted. Choe et al. [28] performed the seismic fragility analysis of the corroded RC bridges based on the novel probabilistic demand model and the existing capacity model for corroding columns [20]. The uncertainties in both the structural properties and the material deterioration processes were included in the analysis. Gardoni and Rosowsky [29] developed the seismic fragility increment functions to assess the time-variant fragility of aging bridges with corrosion of the reinforcements. Jia et al. [30] proposed a method to model the deterioration of the RC bridges due to the corrosion and estimated the instantaneous reliability and resilience of the structures under seismic excitations.

Apart from the aforementioned works, experimental tests have also been conducted by the researchers for the investigation of the seismic performance of the corroded RC columns. Ma et al. [31] conducted cyclic loading tests on 13 circular RC columns with different corrosion damages. The test results demonstrated that the structural strength, stiffness, and ductility were degraded as the corrosion degree increased. Furthermore, the severe corrosion of stirrups could result in the change in the failure pattern, from flexural failure to flexural-shear failure. Lee et al. [32] tested six rectangular RC columns with different corrosion damage of rebar and being strengthened with carbon fiber sheets. The experiment results revealed that spalling of the concrete cover and degradation of the mechanical properties of the corroded reinforcements were the main causes for the deterioration of the structural behavior. Both the shear capacity and the ductility of the columns were improved after confining using the carbon fiber sheets. Cardone et al. [33] conducted a comprehensive cyclic test on eight RC hollow bridge piers, among which half of the specimens were constructed with corroded rebar. The test results indicated that the lateral strength, the secant stiffness, and the energy loss per cycle of the piers had significantly decreased owing to the corrosion of the reinforcements.

The coastal bridges exposed to marine environments experience more complicated performance deterioration than the urban structures. In particular, the corrosion of the structural components is non-uniform along the elevation of the bridge piers, and is typically divided into three regions, namely the atmospheric zone, the splash and tidal zone, and the submerged zone. In the splash and tidal zone near the still water level, the bridge piers are subjected to a more aggressive exposure owing to higher surface chloride concentration, oxygen abundance, and wet-dying cyclic [34,35]. Severe performance deterioration in the splash and tidal zone would weaken the seismic-resistance capacity of the structures. Furthermore, the failure mode and the location of the plastic hinge of the column would change when subjected earthquake excitation. However, previous studies regarding this issue were seldom addressed by the researchers.

To address this problem, a theoretical investigation and numerical simulation on the seismic failure mode and equivalent plastic hinge length of the coastal bridge piers with non-uniform corrosion has been conducted by the present authors, and it has been presented in a companion paper [1]. In this study, cyclic loading tests of six test specimens with different corrosion damage were conducted for the validation of this specific phenomenon. The contents of this study are mainly organized as follows: in Section 2, we will introduce the experimental program, including the specimen details, the accelerated corrosion process of the test models, the test setup, and the loading protocol. Then, in Section 3, we will describe the observation of the crack pattern and the failure status of the specimens during the test process. Next, in Section 4, the experimental results of the curvature distributions, hysteretic characteristics, loading-resistance capacity, ductility, energy dissipation, equivalent viscous damping ratio, and equivalent plastic hinge length will be analyzed and discussed. Finally, the main research findings of this study will be summarized in Section 5.

2. Experimental program

2.1. Specimen details

To investigate the seismic behaviors of the coastal bridge piers with non-uniform corrosion, six test specimens with identical geometric size and material properties were adopted for the cyclic loading experiments in this study. Fig. 1 shows the schematic diagram of the test models, including the dimensions of the bridge piers and layout of the reinforcements. As illustrated in the figure, the test model was a circular bridge pier with a diameter of 400 mm. The total height of the specimen was 3.2 m, and the effective height, which was measured from