Soil Dynamics and Earthquake Engineering 93 (2017) 135–146

Contents lists available at ScienceDirect

Soil Dynamics and Earthquake Engineering

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

Seismic failure mode of coastal bridge piers considering the effects of corrosion-induced damage

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, the 2nd Campus, Harbin 150090, China

ARTICLE INFO

Keywords:
Coastal bridge pier
Marine environment
Corrosion
Seismic failure mode
Hysteretic response
Equivalent plastic hinge length

ABSTRACT

Coastal bridges exposed to an aggressive environment are vulnerable to corrosion damage, which reduces the seismic resisting capacity of the structures. Focusing on the corrosion varying along the column height of the coastal bridge piers, this paper investigates the time-dependent failure mode and equivalent plastic hinge length of the aging bridge piers under seismic excitation in the whole life cycle. First, the possible seismic failure modes and the method to estimate the equivalent plastic hinge length are analyzed and discussed. Then, the corrosion initiation time and performance deterioration of the reinforcement are presented. After that, the finite element models of the sound and aging bridge piers are introduced based on the OpenSees software package and the time-dependent constitutive models of the reinforcement. According to the proposed flowchart of the computational procedure, a numerical simulation is conducted to investigate the plastic hinge evolution process of the coastal bridge pier. The analysis results indicate that the seismic failure mode of the continuously corroded bridge pier varies with the service time, and the plastic hinge has the possibility of transferring from the column end to the bottom of the splash and tidal zone.

1. Introduction

Coastal bridges exposed to a marine environment always suffer significant chloride-induced corrosion. During the whole service life of the bridge, the continuous penetration of chloride ions induces cracking and spalling of the concrete cover [1], degradation of the bond capacity [2] and decrease of the material strength [3,4]. In seismic-prone regions, the corrosion damage of the bridges would significantly reduce the lateral load-resisting capacity of the structure in a seismic event. Understanding the seismic performance of the corroded coastal bridges is an important issue for researchers and engineers to assure the safety of the aging structures when sustaining earthquake excitations.

In a marine environment, chloride penetration directly induces material deterioration. To investigate the time-dependent performance of the structures, many researchers have investigated the corrosion penetration model and material deterioration model. Based on Fick's law, the chloride diffusion models in saturated [5,6] and non-saturated [7,8] concrete have been developed and employed for determining the corrosion initiation time of the reinforcement. For the reinforced concrete (RC) structures, the corrosion-induced performance degradation of reinforced steel is recognized to be the dominant cause of premature failure of the structures [9,10]. Focusing on this issue, some researchers have conducted experiments to investigate the time-dependent corrosion damage of the reinforced bars, including the mass loss of the steel and the reduction of strength, diameter and ductility [11,12]. During the experiments, the corrosion of the specimens was always achieved by exposure in the natural environment [13] or through an accelerated corrosion method [14]. In addition, limited efforts have been made to investigate the corrosion-induced cracking [15], degradation of stiffness [16] and delamination [17] of the concrete cover.

In the last decade, some researchers and engineers also devoted to establish appropriate methods for the fragility analysis, life-cycle reliability assessment and cost estimation of corroded bridges [18]. Based on currently available probabilistic models for pristine bridges, Choe et al. [19,20] proposed novel probabilistic models for the seismic demand and capacity (deformation and shear force) of corroded RC bridges. Seismic fragility increment functions were also developed to determine the fragility of corroded RC bridge columns in various environment and material conditions [21,22]. Considering the reduction in cross-sectional area of the reinforcement and in stiffness due to concrete cover spalling, Simon et al. [23] and Zhong et al. [24] investigated the seismic responses and fragility of deteriorated RC

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

http://dx.doi.org/10.1016/j.soildyn.2016.12.002
Received 17 August 2016; Received in revised form 16 November 2016; Accepted 2 December 2016

bridges. The simulation results indicated that the losses in strength and stiffness only marginally influenced the seismic fragility of the analyzed bridge. Akiyama et al. [25] proposed a novel computational procedure to evaluate the life-cycle seismic reliability of corroded RC bridges due to the airborne chloride hazard in marine environment. In addition, Kumar et al. [26] proposed a probabilistic approach to compute the life-cycle cost (LCC) of corroded RC bridges considering the uncertainties of the ground motions and the cumulative damage associated with low-cycle fatigue and chloride- induced corrosion of reinforcement. Ghosh and Padgett [27] developed a probabilistic approach to explicitly incorporate time-dependent seismic vulnerability of aging bridges in the seismic loss estimation via a framework based on a non-homogeneous Poisson process. Incorporating the visual inspection and the seismic vulnerability analysis, Zanini et al. [28] established an integrated procedure for assessing the maintenance state and related costs of existing road bridges.

In the marine environment, the coastal bridge piers would suffer corrosion varying along the column height in the submerged zone, splash and tidal zone and atmospheric zone due to different types of exposure. Many research efforts had been devoted to investigate the time-dependent performance of the materials in one of the three zones [4,29]. It is widely accepted that the materials in splash and tidal zone has the highest risks of corrosion [30,31]. For conventional bridge piers, the seismic-induced damage always occurs in the column bottom due to large bending moment. However, if the load-resisting capacity at specific region, such as the splash and tidal zone of the coastal bridge, is more significantly reduced than the other regions due to corrosion, the failure of the aging structures would deviate from the expected failure status, and consequently affects the seismic performance of the structures.

The failure mode is an important property affecting the seismic performance of the civil infrastructures. For the sound bridge piers, the seismic failure mode can be classified into three categories, i.e., flexure failure, flexure-shear failure and shear failure, depending on the shear span ratio and the shear strength of the components [32]. By testing 13 RC circular columns with different degrees of corrosion and different axial load ratios, Ma et al. [33] experimentally investigated the time-dependent failure phenomena of the uniform corroded components and concluded that the failure pattern could change from flexural failure to flexure-shear failure or shear failure when the stirrups were subjected to serious corrosion.

The plastic hinge length of the columns has a direct correlation with the seismic capacity of the structures. Due to the nonlinearity of the material, the bond-slip behavior between the concrete and the reinforcement, and the shear-bending interactions, the experimental method is a preferred way to estimate its value [34]. Park and Priestley [35] conducted the experiment using four full-size reinforced concrete columns with the application of different axial loads. The conclusion indicated that the plastic hinge length was not sensitive to the axial load level. Considering different grades of reinforced bar, Paulay and Priestley [36] modified the expression proposed by Priestley and Park [37] and demonstrated that the plastic hinge length can be calculated when the column height, the column diameter and the strength of the flexural reinforcement of a column are determined.

This paper presents a methodology to investigate the seismic failure mode of the corroded bridge piers in a marine environment. The main contributions of this study include: (1) the possible time-dependent seismic failure modes of the coastal bridge piers are investigated for the structures with corrosion varying along the height in such specific exposure; (2) a method is proposed for calculating the equivalent plastic hinge length (EPHL) of the corroded bridge piers; (2) a computational procedure is developed for distinguishing the seismic failure mode and determining the EPHL of the corroded bridge piers to obtain insight into the seismic performance of deteriorating bridges piers. The main content of this study is organized as five parts. First, the possible seismic failure modes of corroded bridge piers, the method for estimating the EPHL and the corresponding flowchart for the analysis are studied and discussed. Then, the method to determine the corrosion initiation time and the performance deterioration of the steel reinforcement are introduced, considering the corrosion varying along the column height of the coastal bridge piers. Next, the finite element models of the sound and aging bridge piers are established based on the OpenSees software package and the time-dependent constitutive models of the reinforcement. Using the proposed method, a numerical example is conducted to investigate the time-dependent failure modes of the coastal bridge piers and the corresponding EPHL. The simulation results indicate that the plastic hinge would transfer from the column end to the splash and tidal zone when the difference of the corrosion damage between the submerged zone and the splash and tidal zone reaches a certain degree.

2. Seismic failure mode of the flexural bridge piers with corrosion varying along the column height

2.1. Failure process of the common bridge piers

Due to the water depth, the coastal bridges always have a relatively large height. Therefore, this study is mainly focused on the cantilever piers with a large shear-span ratio. For this type of structure without corrosion damage, flexural failure is always sustained in a seismic event. Under the combined action of constant axial load and monotonically increasing lateral force, the failure process for the flexural bridge piers can be divided into three stages separated by four critical moments, as indicated with circles in the force-displacement curve shown in Fig. 1(a). To explain the damage degree at those critical moments more clearly, Fig. 1(b) depicts the corresponding stress distribution of the reinforcement and the concrete [38]. As shown in the figure, the compression stress of the two types of materials in the

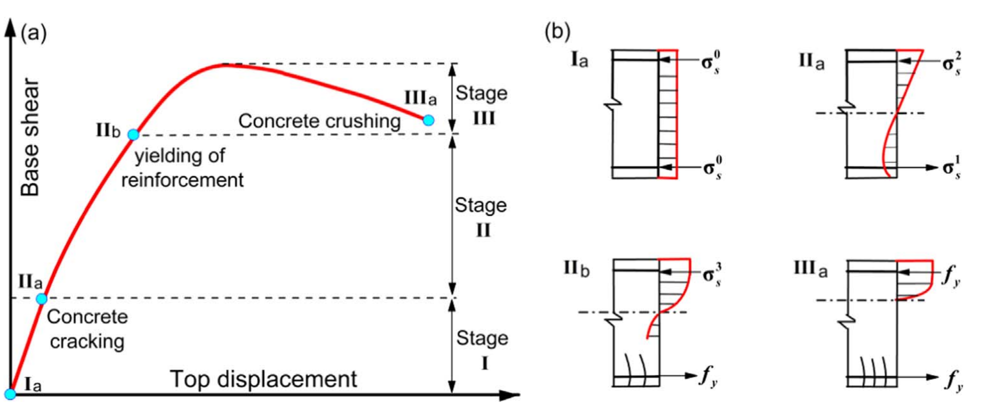

Fig. 1. Flexural failure process of the bridge piers: (a) force-displacement curve, (b) stress distribution.