Engineering Structures 162 (2018) 97–108

Contents lists available at ScienceDirect

Engineering Structures

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

Probabilistic seismic risk assessment of concrete bridge piers reinforced with different types of shape memory alloys

A.H.M. Muntasir Billah*, M. Shahria Alam

School of Engineering, The University of British Columbia, Kelowna, BC V1V1V7, Canada

ARTICLE INFO

Keywords:
Shape memory alloy
Damage states
Incremental dynamic analysis
Residual drift
Fragility curve

ABSTRACT

Shape memory alloy (SMA) has emerged as an alternative to conventional steel reinforcement for improving the seismic performance of bridges during an extreme earthquake. This paper presents the probabilistic seismic risk assessment of concrete bridge piers reinforced with different types of SMA (e.g. Ni-Ti, Cu-Al-Mn, and Fe-based) rebars. To achieve this objective, the bridge piers are designed following a performance-based approach. Ground motions with different probable earthquake hazard scenarios at the site of the bridge piers are considered. Probabilistic seismic demand models are generated using the response parameters obtained from incremental dynamic analysis. Considering maximum drift and residual drift as demand parameters, fragility curves are developed for five different SMA-RC bridge piers. Finally, seismic hazard curves are generated in order to compare the mean annual rate of exceedance of different damage states of different bridge piers. It is observed that all the bridge piers perform according to the design objective, and the performance of SMA-RC piers is significantly affected by the type of SMA used. The results show that all the SMA-RC piers have very low probability of collapse at maximum considered earthquake level. It is found that the bridge pier reinforced with FeNCATB-SMA (SMA-3) performed better as compared to the other SMA-RC piers.

1. Introduction

Current seismic design guidelines, followed in North America [1,2] and Europe [3], allow bridges other than life line bridges to undergo large inelastic deformation while maintaining the load carrying capacity without being completely collapsed during a design level earthquake. However, past experiences (Kobe 1995, Northridge 1994) have shown that bridges undergoing large lateral drift are prone to large residual deformation which renders the bridges to be unusable and require major rehabilitation or replacement. In order to maintain the structural integrity and functionality of a bridge after an earthquake, it is necessary that the bridge components avoid excessive residual deformation or permanent damage [4]. Bridge pier is one of the most critical components of a bridge since the overall seismic response of a bridge is largely dependent on the response of the piers. The extent of residual or permanent deformation sustained by the bridge piers prescribes the likelihood of allowing traffic over the bridge and dictates the amount of repair works and expected loss. As an example, after the devastating 1995 Kobe earthquake, Japan demolished more than 100 reinforced concrete bridge piers as those piers experienced a residual drift ratio over 1.75 percent [4]. Evidences from recent earthquakes and field reports demonstrated the importance of considering residual deformation as an indicator for defining the overall seismic performance of a structure. Observations from recent earthquakes (Kobe 1995, Northridge 1994) and a desire to develop innovative structural systems with improved post-earthquake functionality have motivated researchers to pioneer and test different novel structural systems. For example, to reduce the residual displacement of bridge piers, researchers have recommended innovative unbonded post-tensioned RC bridge columns [5,6] and Shape Memory Alloy (SMA) reinforced concrete (RC) bridge piers [7,8].

Over the last few years, researchers have experimentally and numerically investigated the potential application of shape memory alloys in civil engineering applications and found promising results [7–9,47,48]. The research outcomes have motivated bridge owners to apply SMA in bridge construction. Washington State DOT has decided to incorporate SMA in bridge pier construction part of the SR 99 Alaskan Way Viaduct Replacement program based on experimental results of Nakashoji and Saiidi [48]. However, the bridge was not designed using a performance-based approach rather following the conventional design method with an aim to increase post-earthquake functionality of the bridge. Cruz and Saiidi [9] tested a four span bridge with Ni-Ti SMA in the plastic hinge region of the bridge pier and found improved performance of the bridge in terms of residual drift and

* Corresponding author at: Bridge Engineer, Parsons, Burnaby, BC V5H4M2, Canada.
E-mail addresses: muntasir.billah@alumni.ubc.ca (A.H.M.M. Billah), shahria.alam@ubc.ca (M.S. Alam).

https://doi.org/10.1016/j.engstruct.2018.02.034
Received 5 June 2017; Received in revised form 29 January 2018; Accepted 8 February 2018
0141-0296/

energy dissipation. Billah and Alam [8] assessed the seismic vulnerability of a SMA reinforced bridge pier and compared with that of conventional bridge pier. However, all the previous studies were focused on the application of Ni-Ti SMA. More recently, Billah and Alam [10,11] developed performance-based damage states and a performance-based seismic design guideline for bridge piers reinforced with different types of superelastic SMA in the plastic hinge region. While the previous studies proved the potential of using this smart material in bridge piers and proposed some design guidelines, adoption of these guidelines and successful implementation require a complete performance-based evaluation of this structural system in light of performance-based earthquake engineering (PBEE). To this end, it is necessary to investigate the ability of such novel structural system in reducing the failure probability as well as the annual rate of exceeding some structural demand parameters given an earthquake scenario.

The objective of this paper is to perform fragility based probabilistic seismic risk assessment of concrete bridge piers reinforced with different types of SMA rebars in the plastic hinge region. No baseline comparison is provided with a typical reinforced concrete pier as the focus of this study is to compare the seismic performance of concrete bridge piers reinforced with different types of SMA rebars. Fig. 1 illustrates the methodology adopted in this study. First, the bridge piers are designed following the performance-based design guideline proposed by Billah and Alam [11]. Later, a detailed description of the finite element model is provided to elucidate the details of bridge pier models. Instead of using code-specified design level earthquakes, this study considered three different earthquake scenarios which resembles the regional seismicity of Vancouver, British Columbia (BC), where the bridge is located. The performance and hazard assessment is conducted by considering shallow crustal, mega-thrust interface, and deep in-slab earthquake events [12]. Next, incremental dynamic analysis (IDA) [13] are conducted on each SMA-RC bridge pier model using 30 selected ground motions scaled to the conditional mean spectra of crustal, in-slab and interface earthquakes. The performance parameters of interest, which are maximum and residual drift in this study, are recorded for each motion. Next, the seismic performances of five different SMA-RC bridge piers are evaluated and compared using fragility curves. The fragility curves are developed using the Probabilistic Seismic Demand Model (PSDM). Finally, a probabilistic risk assessment is conducted to evaluate the mean annual frequency of exceeding different damage levels in terms of the selected demand parameters.

Previously, Billah and Alam [11] developed a performance based seismic design guideline for Shape Memory Alloy (SMA) reinforced concrete bridge pier. This current paper focuses on probabilistic seismic risk assessment of different SMA-RC bridge pier designed per the previous paper. The earlier paper [11] proposed the design guideline and the current paper shows how the designed pier performs under different earthquake scenarios. The current paper also focuses on probabilistic risk assessment to evaluate the mean annual frequency of exceeding different damage levels in terms of the selected demand parameters.

2. Probabilistic seismic performance assessment

A commonly used method for probabilistic seismic performance assessment is the Pacific Earthquake Engineering Research (PEER) Centre PBEE methodology [14] which attempts to address structural performance in terms of life safety, capital losses and functional losses [15]. This PBEE methodology is composed of hazard analysis, structural analysis, damage analysis, and loss analysis. However, most of the applications of PBEE have been focused on buildings and few of them focused on bridge structures [5,15]. Moreover, no study has been conducted to date for probabilistic seismic performance assessment of SMA reinforced bridge piers. Previous studies have developed performance-based seismic design guidelines for SMA-RC bridge piers [11] or evaluated seismic performance of SMA-RC piers [9]. This study is intended to elucidate the potential benefit and compare the performance of different SMA-RC bridge piers in light of PBEE. This study conducted three steps of PBEE involving hazard, structural and damage analyses. However, the loss analysis was not performed because of limited information regarding the cost of different types of SMA considered in this study. This study developed fragility curves and seismic hazard curves for different SMA-RC bridge piers considering maximum and residual drift as engineering demand parameters. The developed fragility curves express the probability of reaching or exceeding certain damage states corresponding to a certain intensity of ground motion. The hazard curves relate the mean annual rate of exceeding certain damage states.

Instead of proposing a new methodology for the fragility assessment, this study offers critical insight on the performance-based evaluation of SMA-RC bridge piers using fragility curves. In this assessment different types of SMAs and uncertainties in the seismic hazard of the site are considered. Details of different methods of fragility curve development can be found in [16]. In this study, the fragility curves are developed using a probabilistic seismic demand model (PSDM) and limit state model. The PSDM which relates the median demand to the intensity measure (IM) is developed using the results obtained from IDA and the power law function [17]. The PSDM provides a logarithmic correlation between median demand and the selected IM:

$$EDP = a\,(IM)^b \tag{1}$$

In the log transformed space, Eq. (1) can be expressed as

$$\ln(EDP) = \ln(a) + b\ln(IM) \tag{2}$$

where a and b are unknown coefficients which can be estimated from a regression analysis of the response data collected from IDA. Effectiveness of a demand model is determined by the ability of evaluating Eq. (2) in a closed form. In order to accomplish this task, it is assumed that the *EDPs* follow log-normal distributions. The dispersion ($\beta_{EDP|IM}$) accounting for the uncertainty in the relation which is conditioned upon the IM, is estimated using Eq. (3) [18]:

$$\beta_{EDP/IM} = \sqrt{\frac{\sum_{i=1}^{N}(\ln(EDP)-\ln(aIM^b))^2}{N-2}} \tag{3}$$

where N is the number of simulations. With the probabilistic seismic demand models and the limit states corresponding to various damage states, it is now possible to generate fragilities (i.e. the conditional probability of reaching a certain damage state for a given IM) using Eq. (4) [19].

$$P[LS/IM] = \Phi\left[\frac{\ln(IM)-\ln(IM_n)}{\beta_{comp}}\right] \tag{4}$$

Φ [.] is the standard normal cumulative distribution function and

$$\ln(IM_n) = \frac{\ln(S_c)-\ln(a)}{b} \tag{5}$$

$\ln(IM_n)$ is defined as the median value of the intensity measure for the chosen damage state, a and b are the regression coefficients of the PSDMs, and the dispersion component is presented in Eq. (6) [19].

$$\beta_{comp} = \frac{\sqrt{\beta_{EDP/IM} + \beta_c^2}}{b} \tag{6}$$

where S_c is the median and β_c is the dispersion value for the damage states of different components of a bridge.

By combining the seismic responses obtained from IDA, in terms of maximum and residual drift, with the seismic hazard curve, it is possible to calculate the annual rate of exceeding various levels of demand for each EDP monitored. Using the uniform seismic hazard curve for the site under consideration, and maximum and residual drift responses obtained from IDA, the maximum and residual drift hazard of the SMA-RC piers are calculated based on the convolution integral presented by Deierlein et al. [20]