SEISMIC PERFORMANCE ASSESSMENT OF AN NOVEL HIGHWAY BRIDGE USING SMA RC PIERS AND SUPERELASTIC RESTRAINERS

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Abstract

This study aims at numerically studying the effectiveness of a novel bridge system with shape memory alloy (SMA) reinforced piers as well as retrofitted with SMA cable restrainers in mitigating the residual drift of bridge pier and preventing the bridge spans from unseating problems. In the bridge, conventional steel reinforcements in the plastic hinge regions of bridge piers are replaced with SMA rebar, which provides self-centering capacity of the bridge pier. Simultaneously, SMA restrainers are designed to suppress the displacement response for seismic protection of bridges against over displacement. A typical three-span continuous highway bridge is modeled with SMA reinforced piers and SMA restrainers. Numerical simulations of the bridge are conducted under destructive near fault ground motions. The seismic fragility curves of the novel bridge are assessed and compared with the prototype bridge and the bridge with only SMA reinforced piers. The results revealed that the proposed novel bridge using SMA reinforced piers as well as retrofitted with SMA restrainers is more efficient than the bridge with only SMA reinforced piers in mitigating the seismic damage.

Keywords: Seismic fragility, Shape memory alloy, Self-centering pier, SMA cable restrainer, Multi-span continuous bridge

1. Introduction

Recent large earthquakes have demonstrated that highway bridges in the regions of high seismicity have a high possibility to experience severe damages [1]. Large residual drift of bridge piers is one of the major causes of failure during earthquakes such as the Northridge 1994, Kobe 1995, Chi-Chi 1999, Wen-Chuan 2008 and other events. Following the 1995 Kobe earthquake in Japan, more than 100 reinforced concrete (RC) bridge piers were demolished due to a high residual drift ratio (over 1.75%) [2]. It can be attributed to the residual strains in steel reinforcement bars after an earthquake resulting in a large permanent deformation of bridge piers. The inevitable residual deformation could make bridge structures unserviceable or unsafe. Unseating of bridge spans is another cause of bridge collapse due to large relative displacement between the deck and pier [3]. After such failure, the bridges need to be demolished and reconstructed. More than 30 highway bridges experienced span unseating during the Northridge 1994, Chi-Chi 1999, Wen-Chuan 2008, and Chile 2010 earthquakes. In such a situation, it highlights the necessity of enhancing the self-centering behavior of bridge piers and implementing effective unseating prevention measures in bridges simultaneously.

During the last few decades, large efforts have been made to improve the seismic performance and post-earthquake functionality of bridge piers using innovative structural systems with re-centering properties [4]. One of such innovative systems is using shape memory alloy (SMA) as reinforcements at plastic hinge regions of bridge piers. Many researchers investigated the seismic performance of SMA reinforced bridge piers through numerical and experimental analysis [5,6]. Most of previous studies focused on the seismic behavior or fragility of bridge piers at component level. However, limited studies have investigated the effect of SMA RC piers on performance of other structural critical components (such as bearings) and bridge system. Shrestha et al. [7] performed numerical analysis and shake table tests to study the seismic responses of a four-span bridge incorporating innovative materials. Ge and Saiidi [8] numerically investigated the seismic behavior of the SR99 bridge with innovative materials considering fault-rupture effect. However, since lack of studies focused on the performance-based damage states of SMA reinforced piers, the seismic vulnerability of such innovative bridge system is still not well understood under earthquakes.

Although the effect of SMA as reinforcement in bridge piers is well-documented, SMA reinforced pier has negligible influence in reducing large displacement response and residual displacement of bridge spans and bearings. As per seismic code [9, 10], additional restrainers (e.g. steel cables or rods) have been recommended to retrofit the bridges and prevent the unseating problems due to their low cost and ease of installation. However, the conventional restrainers have some limitations, such as limited ductility, poor energy dissipation capability, and small elastic strain range [11]. To address the problems of conventional restrainers, SMA cable restrainers have been proposed in numerous experimental and numerical studies [12-14]. The researchers have found that SMA restrainers can effectively limit the deck drift with small residual displacement and also can partially dissipate the energy as supplementary passive dampers. In the latest studies, the authors [15,16] have proposed a design guideline of SMA restrainers and evaluated the seismic performance of highway bridges retrofitted with SMA restrainers.

In order to protect the bridge from severe damage during strong earthquakes, a novel bridge system is considered in the present study. In the bridge, SMA reinforced pier and SMA restrainers are combined and utilized to enhance the performance of bridge pier and suppress the displacement response of bridge spans. This study focuses on exploring the effectiveness of SMA-based novel bridge system in mitigating the seismic failure damage against destructive earthquakes. The fragility functions of the novel bridge are assessed by performing incremental dynamic analyses (IDAs).

2. Design methodology of the novel bridge system

In this study, two SMA-based components mentioned above are provided to enhance the seismic performance of highway bridges under earthquakes. One of them is the piers using SMA bars replace of conventional steel reinforcement at the plastic hinge location and the other one is SMA restrainers connecting the piers with the girders as shown in Figure 1.

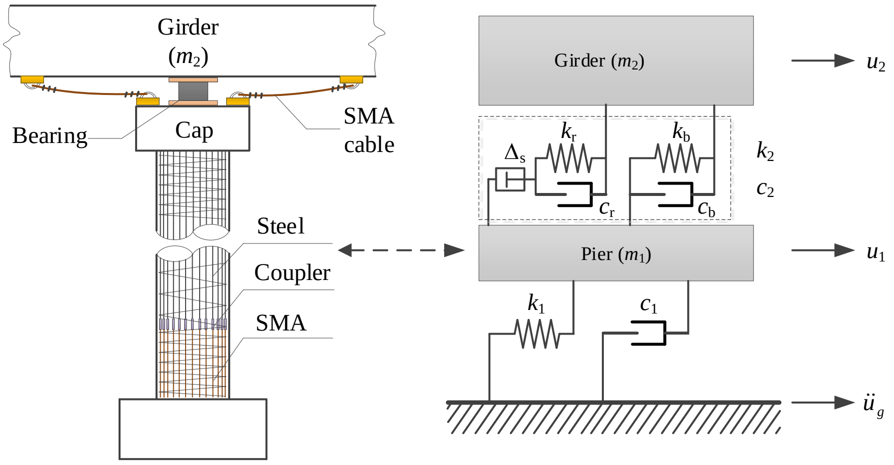


Fig. 1 Configuration and simplified model of the innovative bridge system

The SMA reinforced pier will be first designed following the performance-based design guidelines considering residual drift as the key performance indicator proposed by Billah and Alam [5]. Then, the mechanical properties (e.g. properties of SMA, effective stiffness etc.) of the smart bridge pier will be determined. Finally, a displacement-based design procedure proposed by Li et al [15] will be used to design the restrainers for the bridge with SMA reinforced piers. In the procedure, the bridge system is simplified as two degree of freedom model (see Figure 1). More details of the performance-based design guidelines for SMA piers and the proposed design procedure for SMA restrainers are available in the work of Billah and Alam [5], Li et al. [15] and Wang et al. [16].

3. Case study

In order to investigate the seismic performance of the proposed novel bridge system, a typical three-span continuous highway bridge is considered in this study, as shown in Figure 2. The bridge is supported on two reinforced concrete multi-column bents. The performance of the novel bridge using SMA reinforced piers and SMA restrainers (Bridge III) is compared to the prototype bridge (Bridge I) and the bridge with only SMA reinforced piers (Bridge II). The bridge is assumed to be located in Vancouver, British Columbia (western Canada) with the site soil class-C (stiff soil). The pier has a diameter of 900 mm and is reinforced with 18-M30 steel rebar (reinforcement ratio of 2.0%). Shear reinforcement is provided using 22 mm spirals at 300 mm pitch. Based on the design procedure of SMA reinforced bridge pier, the diameter of the SMA rebar in the plastic hinge length is 30 mm. In this study, NiTi45 SMA [17] will be selected as the SMA rebar and restrainer. The designed SMA reinforced pier has comparable moment capacity with the RC pier.

A total of 12 lead rubber bearings (LRBs), a kind of widely-used elastomeric bearings, are installed at the pier and abutment locations. All the bearings have the same plan area of 350 mm by 350 mm with identical total thicknesses of rubber layers (70 mm). At the same locations, 18 SMA restrainers are installed to connect the pier and girder. The SMA restrainers are designed according to the displacement-based design procedure proposed by the same authors [15]. Considering the optimized configuration of the restrainer [16], the allowable displacement, Δ_a, and the slack in restrainers, Δ_s, are set as 175 mm and 25 mm, respectively. The horizontal angle of the restrainer, θ0, is zero. Here, the allowable displacement of the restrainer is same with the shear deformation of the LRB at collapse damage (i.e. 250% shear strain of LRB). The required length of the restrainers is 2300 mm. The area of each restrainer at abutment and pier locations is 117 and 254 mm^2, respectively. A three-dimensional (3D) finite element model of the bridge is generated in OpenSees [18]. The details of the modeling are available in Wang et al. [16].

The fundamental periods of the prototype bridge (Bridge I) and novel bridges (Bridge II and Bridge III) are 0.598, 0.604 and 0.601 s, respectively. The period of the novel bridge is slightly longer than that of the prototype bridge due to the lower stiffness of SMA rebar.

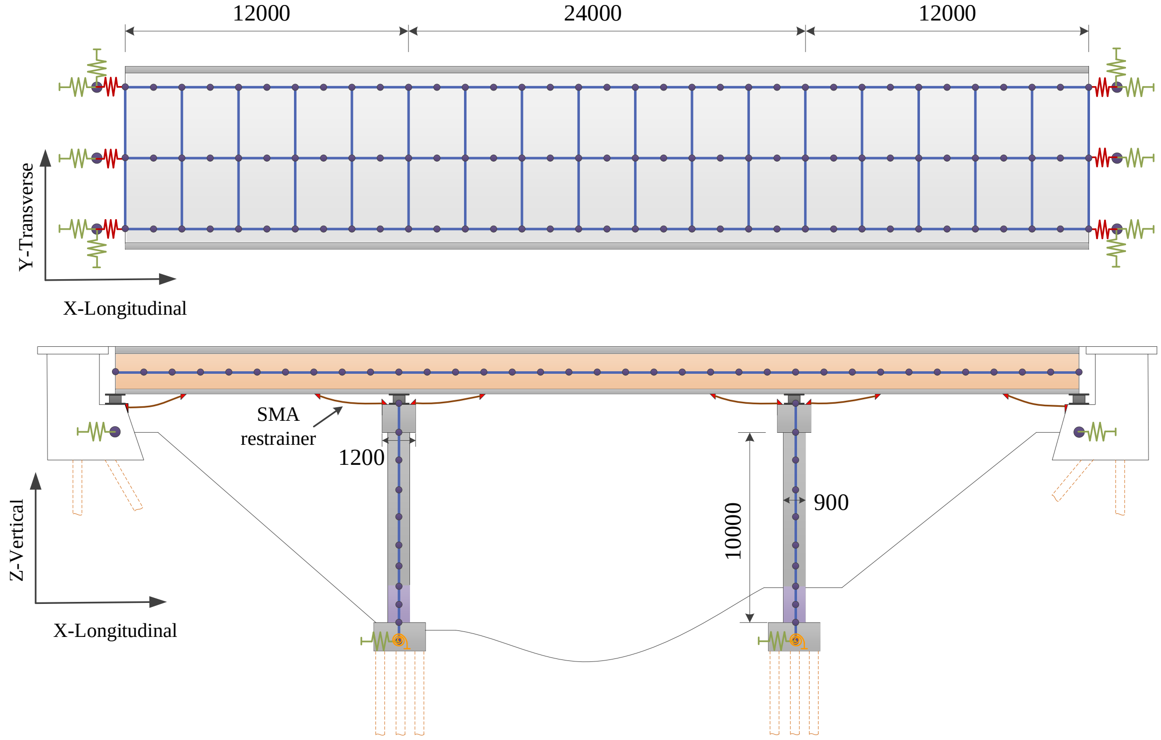


Fig. 2 – Nonlinear numerical model of the continuous concrete-girder bridge (mm)

Table 1–Material properties of concrete and steel reinforcement

Material	Properties	Value	Unit
Concrete	Compressive strength	30	MPa
	Tensile strength	2.5	MPa
	Strain at peak stress	0.2	%
steel	Elastic modulus	210	GPa
	Yield stress	330	MPa
	Ultimate stress	455	MPa
	Ultimate strain	0.14	
SMA	Elastic modulus	62.5	GPa
	Austenite-to-martensite starting stress	403	MPa
	Austenite-to-martensite finishing stress	510	MPa
	Martensite-to-austenite starting stress	370	MPa
	Martensite-to-austenite finishing stress	130	MPa
	Superelastic plateau strain	6.5	%

4. Ground motions

In order to assess the response of the novel bridge under destructive conditions (high level of seismic activity), 21 near-fault earthquake records used in Hedayati Dezfuli et al. [19] are selected in the dynamic time history. These records are selected from the Pacific Earthquake Engineering Research Center Ground Motion Database (PEER). Following the works of Naumoski et al. [20], the ratio of PGA to PGV for these records is between 0.8 and 1.2. The earthquake excitations are applied to the bridge in both the longitudinal and transverse directions.

5. Seismic fragility analysis

Seismic vulnerability assessment has been widely recognized as useful tools for the prioritization of seismic retrofitting, the determination of pre-earthquake planning, and the estimation of post-earthquake loss. A "scaling" approach is used to develop the fragility functions. In this study, two main vulnerable components of highway bridges, i.e. bridge pier and isolation bearing, are considered. Four limit states, i.e. slight, moderate, extensive, and collapse, are defined to describe the damage condition of each bridge component in terms of engineering demand parameter (EDP). The maximum displacement ductility, μ_d, of the piers and the shear deformation, γ, of the bearings are selected as the EDPs for fragility assessment. Based on the available literature, the limit states (LS) of each bridge component (i.e., RC pier, SMA reinforced pier, and bearing) are determined according to the works of Zhang et al. [21] and Hedayati Dezfuli and Alam (2016).

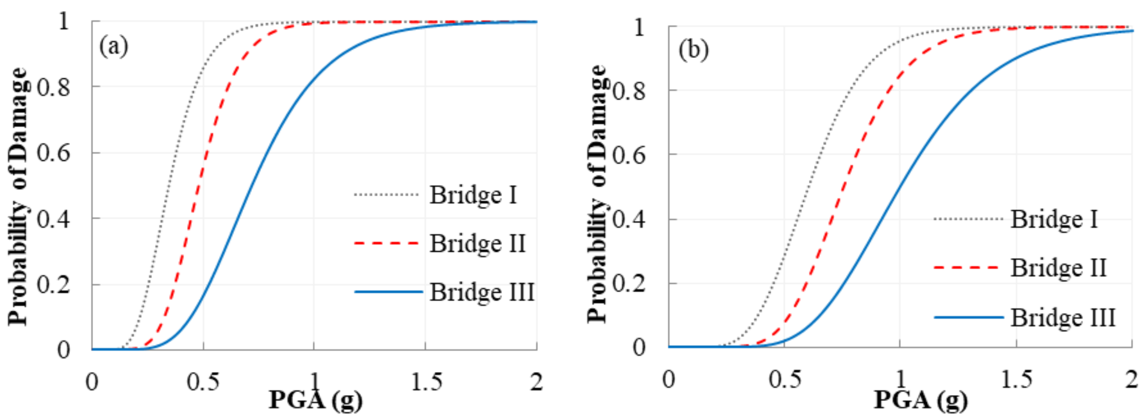
The fragility functions of each bridge component at a limit state can be expresses as follows. In this study, PGA is chosen as the intensity measure (IM).

$$P\left[LS|IM\right] = \Phi\left[\frac{b\ln\left(IM\right)-\left(\ln\left(S_c\right)-\ln a\right)}{\sqrt{\beta_{D|IM}^2+\beta_C^2}}\right] \quad (1)$$

where a and b are the regression coefficients; Φ is the cumulative distribution function of the standard normal distribution; S_c and β_c are the median estimate and the logarithmic standard deviation of the capacity, respectively; $\beta_{D|IM}$ is the standard deviation of the demand. The upper bound of the first order reliability theory is used to conservatively estimate the fragility of the bridge system by combining the fragilities of each bridge component [22].

$$P\left[F_S\right]=1-\left(1-P\left[F_{pier}\right]\right)\left(1-P\left[F_{bearing}\right]\right) \quad (2)$$

The fragility curves of the bridge pier and bearing are developed and combined to assess the damage probability of the bridge system. Figure 3 presents the fragility curves of the bridge systems at each damage state. It can be observed that compared to the prototype bridge, use of SMA reinforced piers and SMA restrainers can noticeably decrease the damage probability of the bridge. Another finding is that the damage possibilities of Bridge II are higher than that of Bridge III.



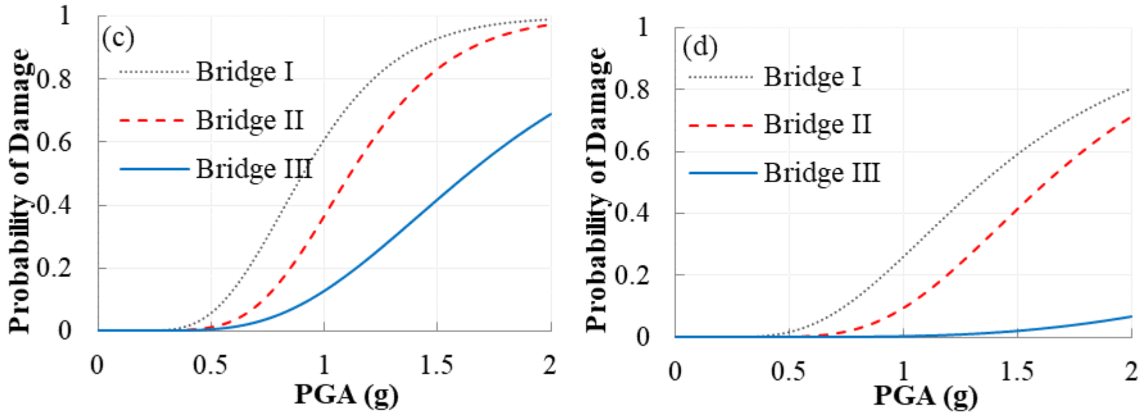


Fig. 3 – Fragility curves for the three bridge systems at (a) slight, (b) moderate, (c) extensive and (d) collapse damage state considering displacement ductility

6. Conclusions

Reconnaissance of structural seismic damages has indicated that the bridges need to be demolished and reconstructed after experiencing large residual drift of bridge pier or unseating of bridge spans. In an attempt to enhance the functionality of bridge system following earthquakes, an innovative self-centering bridge system is proposed in this study. In the bridge, the application of SMA rebars in plastic hinge regions of bridge pier is used to enhance the seismic performance of the bridge pier and SMA restrainers connecting the pier with girder are considered to prevent the bridge spans from over-displacement. The seismic vulnerability of a typical three-span continuous highway bridge located in Vancouver are evaluated under 21 near fault ground motions. Concluding remarks of this study are summarized as follows.

1. The replacement of steel reinforcements with SMA rebars rendered the bridge system less vulnerable at each damage state when compared with the prototype bridge. However, the damage possibility of the bridge with SMA reinforced piers (Bridge II) was higher than the bridge with a combination of SMA reinforced pier and SMA restrainers (Bridge III).

2. Only using SMA reinforced piers in a bridge could not effectively enhance the seismic performance of the bridge. The proposed bridge system (Bridge III) has a considerable advantage for seismic protection of the bridge against extensively large earthquake events.

7. Acknowledgements

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8. Copyrights

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