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COMPARISON OF PERFORMANCE OF SHAPE MEMORY ALLOY REINFORCED BRIDGE PIERS WITH CONVENTIONAL BRIDGE PIERS USING INCREMENTAL DYNAMIC ANALYSIS

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ABSTRACT

Bridge piers built in active seismic regions can sustain large residual displacements following a strong earthquake. In many recent major earthquakes residual displacement enforced demolition of bridge piers due to the serviceability and/or safety concerns. Consequently, in order to reduce residual displacement after major earthquakes many innovative methods were explored in the last decade. One of such innovative method is to replace the conventional longitudinal steel reinforcement in the plastic hinge regions of bridge piers with super-elastic Shape Memory Alloy (SMA). This study numerically investigates efficacy of SMA reinforced concrete bridge piers on mitigating the residual displacement after major seismic events. In this study, firstly numerical model and the computational platform used for the analysis are validated using data from shake table experiment of scaled SMA reinforced pier. Then numerical study on three prototype bridge bents with single and multiple piers are conducted to compare the effectiveness of using the SMA bars in plastic hinge regions to reduce the residual displacement of the bridge piers. The seismic performance of the three bridge bents with steel and SMA reinforced piers are evaluated using incremental dynamic analysis. The numerical results demonstrate the effectiveness of using SMA reinforcement on reducing the permanent displacement of bridge piers after severe earthquake shakings.

KEYWORDS

SMA, seismic design, residual displacement, bridge piers, incremental dynamic analysis.

INTRODUCTION

Reinforced concrete bridges designed to current seismic design codes in the regions of the high seismicity are susceptible to severe damage during large earthquakes, leading to the possibility of large residual displacements. The present design philosophy for reinforced concrete structures allows the structures to dissipate the energy by yielding of the steel. During major earthquake such as the Northridge 1994, Kobe 1995, Duzce 1999 and other events, it was found that structure based on the design philosophy received severe damages and lost the serviceability after an earthquake. Consequently, post disaster rescue and relief operation were severely affected. The main reason for the loss of serviceability was the residual strain in steel after the earthquake resulting in residual inclination of bridge piers. During the 1995 Kobe earthquake 88 bridge piers along the Hanshin expressway were demolished because of the large residual inclination even though some those piers had received only light damage (Fujino et al. 2005). As a result, there is a consensus among the engineering practitioners that the residual displacement has a greater significance in the overall structural performance of the infrastructure under earthquake loading.

To address the problem of the residual displacement innovative design methods capable of re-centering after an earthquake event were explored in the last decade. One of such innovative methods is using a relatively new material to civil infrastructure super-elastic SMA, in plastic hinge regions of the structures. SMAs are able to undergo large strains and still recover their shape through either heating (shape memory effect) or stress removal (super-elastic effect).Shape recovery would be beneficial in many ways, especially in reducing permanent deformation of structural components. In general, SMAs exhibit two distinct crystal structures or phases. These phases are Martensite, with the ability to completely recover residual strains by heating, and Austenite, with nominally zero residual strain when unloaded after up to 10% strain under arbitrary mechanical loading without the application of heat. Few experimental studies were conducted on super-elastic SMA reinforced column in the last decade to identify its potential as a reinforcement of concrete structures (Saiidi and Wang 2006, Saiidi et al. 2009, Youssef et al. 2008). Recently, Billah and Alam (2012, 2014) studied the seismic performance of concrete columns with hybrid SMA and FRP bars analytically and developed analytical fragility curves for concrete bridge piers with SMA reinforcements. These studies confirm the unique ability of super-elastic SMA to experience large deformation and retrieve its original shape upon load removal. This unique ability of super-elastic SMA makes it a strong contender for use as reinforcement in RC structures at plastic hinge regions, which are prone to experience significant damages during the seismic events resulting in larger residual deformations. However, previous experimental and analytical studies considered only a particular type of column. To give a more generalized conclusion specific studies on realistic bridge bents with different geometries and numbers of piers are required.

This paper investigates the effectiveness of the SMA reinforcement at plastic hinge regions of bridge piers on mitigating the serviceability losses after the major earthquakes owing to the residual displacement of the bridge piers. The accuracy of the numerical models is validated using the experimental shake table study conducted by Saiidi and Wang (2006).

EXPERIMENTAL STUDY

Test Specimen Details

The numerical model of the bridge piers is constructed on Seismostruct (Seismostruct 2012). Numerical model as well as the computation platform is validated using the experimental results conducted by Saiidi and Wang (2006). A quarter scaled reinforced concrete pier with SMA reinforcements in the plastic hinge region was tested on a shake table at the structural laboratory of University of Nevada, Reno. The most commonly used NiTi rods of 356 mm long were used in the experimental as the longitudinal reinforcement in the plastic hinge area. Details of the experimental column (SMAC-1) are presented in Figure 1. The mechanical properties of the SMA bars along with the reinforcement are presented in Table 1. The compressive strength of the concrete is 43.8 Mpa. An axial load of 624 kN was applied corresponding to an Axial Load Index (ALI), defined as the ratio of the axial load and the product of the gross column section and the specified concrete compressive strength, of 0.25. The column was subjected to a synthetic ground motion compatible to the Applied Technology Council 32 document (Applied technology Council 1996) for medium soil (ATC-32-D) with Peak Ground Acceleration (PGA) of 0.44g. The specimen was subjected to 11 run of the ground motion excitation, with amplitude normalized to 15% for the first run to 300% for the last run of the ATC-32-D record amplitude.

Finite Element Model

Displacement based nonlinear beam column elements discretized into 12 finite elements is used. The fiber section used for the column is discretized into core fiber, cover fiber and steel/SMA fiber. SMA are modeled using the uni-axial model for super-elastic SMA, programmed by Fugazza(2003). For the prototype bridge the yield strength of the reinforcement is limited to 414 Mpa and the compressive strength of the concrete is 35 MPa. The bond slip at the pier footing is considered using modified Wehbe model (Wehbe et al. 1999) that uses a tri-linear curve composed of the bilinear idealized curve followed by an extension branch with zero stiffness. In order to model slippage of SMA rebars inside the coupler, a bond slip model is incorporated in the analytical model of SMA reinforced bridge piers. The bond slip relation for SMA rebar was obtained from the experimental study of Alam et al. (2010) and was validated numerically in the study of Billah and Alam (2012). The bond slip element was modelled using modified Takeda hysteretic curve (Otani 1974) as done in the latter study.

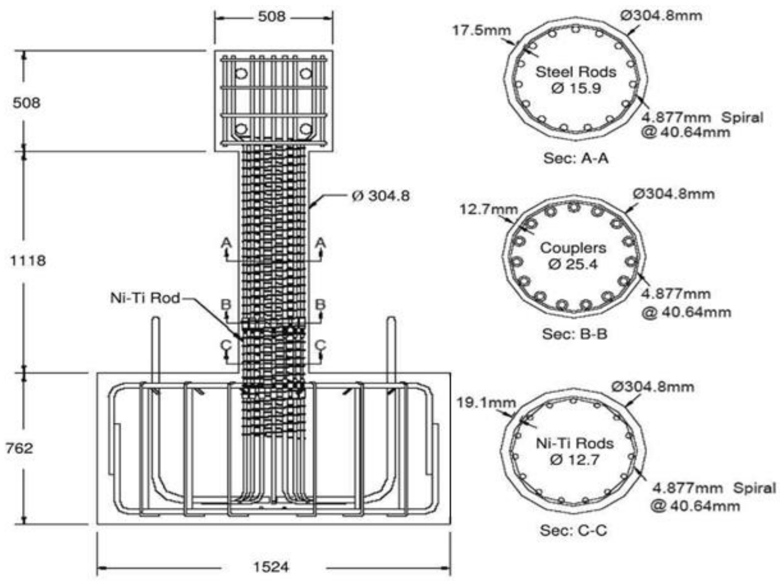


Figure 1. Details of SMA RC column (Saiidi and Wang, 2006)

Table 1. Material properties for SMA RC column

Material	Property	Value
Longitudinal Steel	Yield Strength (MPa)	469
	Young's Modulus (MPa)	199000
	Fracture Strain (%)	15
Super elastic SMA	Modulus of Elasticity (MPa)	48300
	Austenite to martensite starting stress (MPa)	379
	Austenite to martensite finishing stress (MPa)	405
	Martensite to austenite starting stress (MPa)	180
	Martensite to austenite finishing stress (MPa)	100
	Superelastic plateau strain (%)	5.5

Comparison of Experimental and Numerical Results

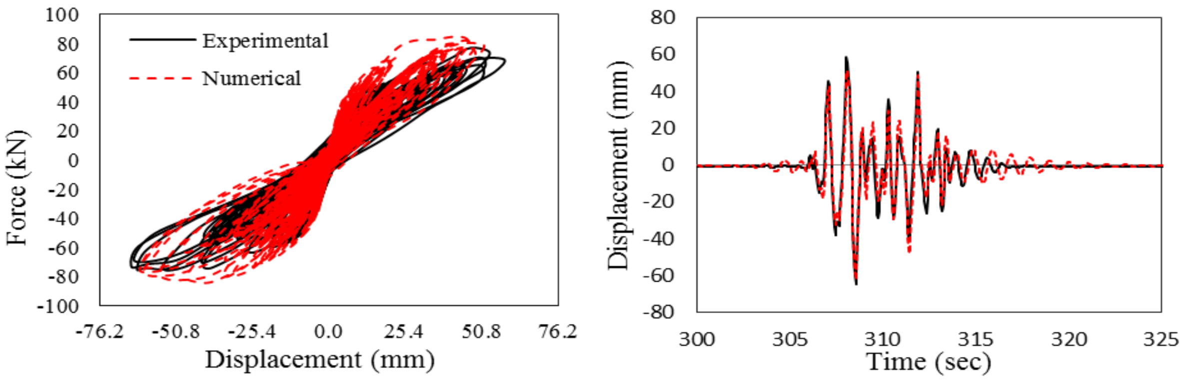
Figure 2(a) compares the measured and the calculated cumulative hysteretic curve of the specimen. The maximum base shear and the tip displacement measured were 77.2 kN and 65.6 mm compared to the calculated value of 84 and 62.8 mm, that represents variation of 8.8% and 4.3% for base shear and tip displacement respectively. The total energy dissipation obtained from the numerical study was 4.4% higher than the energy dissipation from the experimental study. Displacement histories of experimental and numerical results for run11 are presented in Figure 2(b). The presented result shows very close match between experimental and numerical results.

Prototype Bridge Bents

To evaluate the performance enhancement resulting from the application of SMA reinforcement at the plastic hinge region of the bridge piers, three typical prototype bridge bents with single and three piers are selected for the study. Structural details of the prototype bridge piers are presented in Figure 3. It could be noticed in the Figure 3 that at plastic hinge area the replacement NiTi bars with lower cross-sectional area compared to steel reinforcement is placed. This reduction in bar area ensures the NiTi yielding before the yielding of steel and confines most of the inelastic behavior within the NiTi bars. The plastic hinge length, L_p is calculated according to the relation given by Paulay and Preistley (1992):

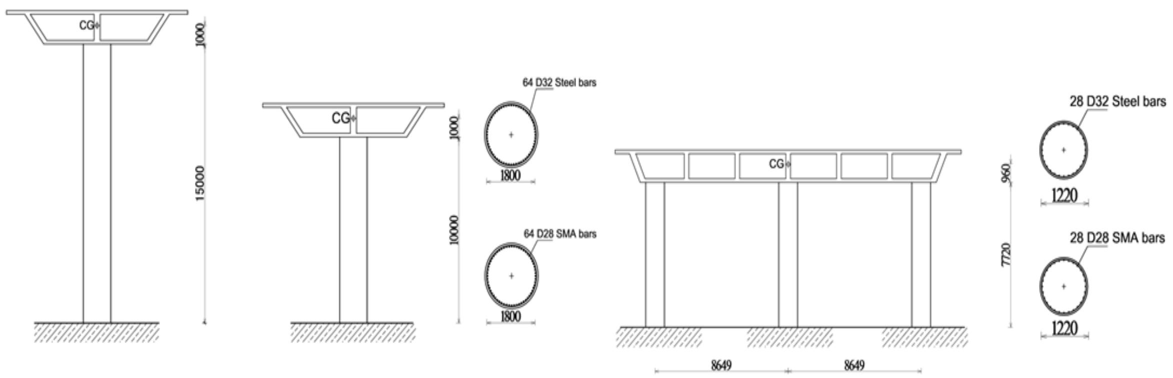
$$L_p = 0.08L + 0.022 d_b f_y \tag{1}$$

where L is the length of the member in mm, d_b represents the bar diameter in mm, f_y is the yield strength of the rebars in MPa. In this study, to conduct the incremental dynamic analysis on three prototype bridges five ground motion records are used. The selected ground motions have wide variation in the frequency contents, as highlight by different spectral shapes presented in Figure 4.



(a) Hysteretic response. (b) Displacement history for run 11.

Figure 2. Response comparison: test result versus numerical result



(a) B1-15 (b) B1-10 (c) B3-7.72

Figure 3. Prototype bridge bents studied

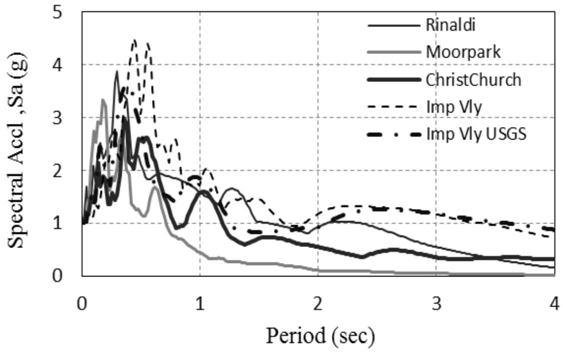
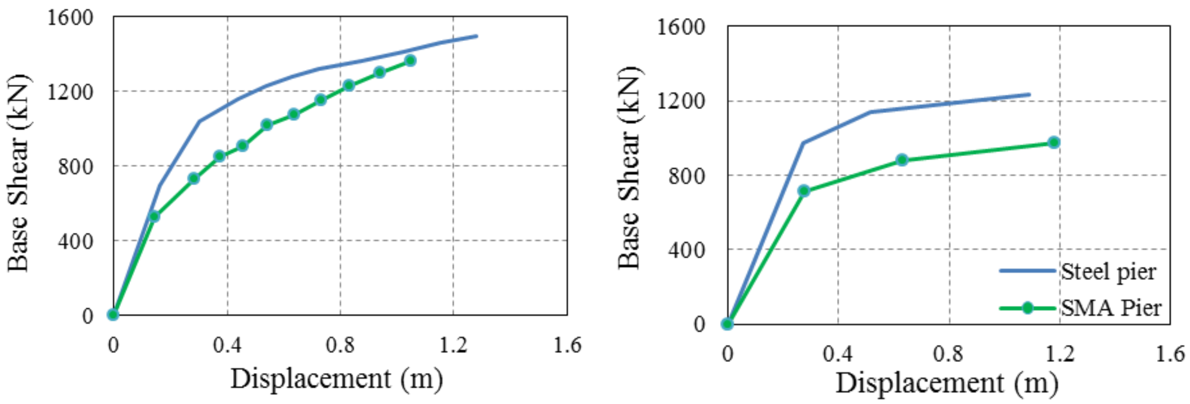


Figure 4. Response of bent B1-15 to Moorpark motion

INCREMENTAL DYNAMIC ANALYSIS

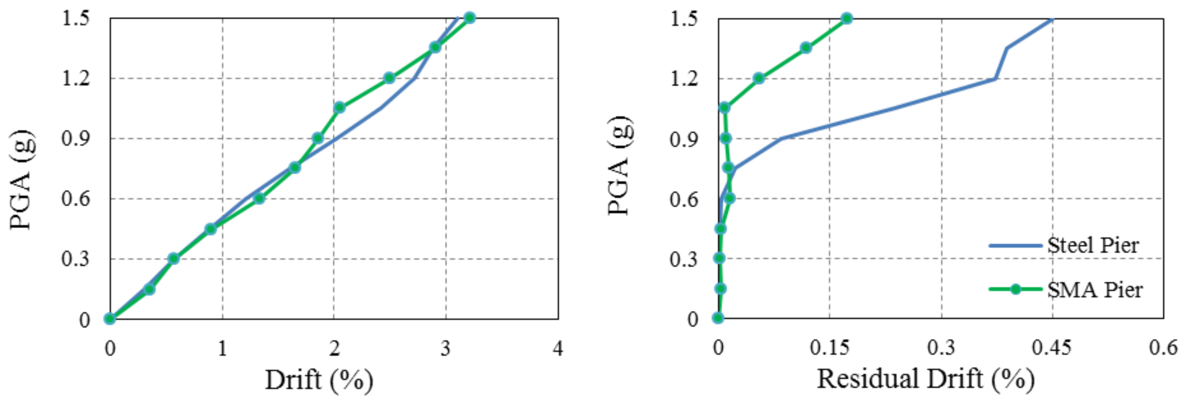
In this study Incremental Dynamic Analysis (IDA) is used to evaluate the performance of six bridge bents with SMA and steel reinforced piers. For brevity only the result for bent B1-15 is presented here. The dynamic pushover curve for SMA and steel reinforced bridge piers are evaluated to compare their performance. For comparison of two kinds of bridge piers; peak drift of the bents, residual drift and hysteretic energy dissipations are observed. The ground motions are scaled from 0.15 g to 1.5 g at an interval of 0.15g. However, the analysis was terminated once the bridge drift exceed 8% drift. The ground motions were applied in transverse direction of the bridge bents.

Figure 5 presents the dynamic pushover curve for bridge bent B1-15 for Rinaldi and Imperial Valley USGS ground motions. The presented result shows that there is only slight difference in the initial stiffness of the bridge piers. The cracked stiffness of SMA reinforced piers are, however, significantly smaller than that of steel reinforced piers as modulus of elasticity of SMA is approximately 1/4 of that of steel. The presented result shows the peak response of the bridge bent is dependent on the ground motions frequency content. The reduction of stiffness resulting from the replacement of steel with SMA bars works similar to that of isolation system by elongating the period and reducing the base shear as well as drift demand for some ground motions, as presented in Figure 5 (a) for Rinaldi motion. However, for other ground motions, particularly with high amplitude in long period range, such shift in period will have no benefit and resulting drift would be higher than that of the steel reinforced piers, as presented in Figure 5 (b).



(a) Rinaldi (b) Imperial valley USGS

Figure 5. Dynamic Pushover curve for B1-15



(a) Peak drift (b) Residual drift

Figure 6. Response of bent B1-15 to Moorpark motion

Comparison between the peak and residual drift responses of the SMA reinforced and steel reinforced bridge pier, B1-15, is shown in Figure 6. As shown, peak drift response for SMA reinforced concrete is nearly similar to the steel reinforced concrete for Moorpark ground motion. Unlike the peak drift response; there is a clear difference in the residual drift response of the two bridge piers. With the increase in intensity of ground motion steel reinforced bridge piers begins to sustain significant residual displacement. Though the SMA reinforced piers also sustained some residual drift, its performance is far superior compared to steel reinforced bridge piers. Performance of both the steel and SMA reinforced bridge piers in terms of peak and residual displacements are nearly similar for lower drift levels. Residual drift increased dramatically for the steel reinforced piers beyond the 2% drift due to the yielding of reinforcements, however, for SMA reinforced bridge piers the increase in the residual drift is gradual.

CONCLUSIONS

The bridge bents with SMA reinforced piers are found to perform well with comparable peak drift response as that of conventional steel reinforcement bridge bents, but with significantly reduced residual drifts. Residual drift increased rapidly for the steel reinforced bridge bents after yielding of the steel rebar, while for SMA reinforced bridge bent the increase is gradual. The results presented in this paper demonstrate the effectiveness of using SMA reinforcement at the critical plastic hinge regions of bridge piers.

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