Use of Shape Memory Alloys with Laminated Rubber Bearings in Seismic Isolation of Multi-Span Continuous Moderate to Strong Seismic Zones

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SUMMARY:
This study is devoted towards evaluating seismic performance of a three-span continuous highway bridge subjected to moderate to strong earthquake ground motions in its longitudinal direction. In this regard, nonlinear dynamic analysis of the bridge based on the direct time integration approach using the 4th order Runge-Kutta method is conducted. Two types of isolation bearings are used in the analysis: high damping rubber bearing (HDRB) and SMA-rubber bearing (SRB) consisting of Ni-Ti SMA wires and natural rubber bearing. The hysteretic behavior of HDRB is evaluated using the strain-rate dependent rheology model (i.e. visco-elasto-plastic model), while for the SRBs the hysteretic behavior is modeled by the nonlinear elasto-plastic model. The nonlinear force-displacement relation for the bridge pier as characterized by the bilinear model is employed in the analytical model of the bridge. Finally, the variation in seismic responses of the bridge due to the use of HDRB and SRBs is investigated. The bridge response quantities evaluated in the investigation include peak values of deck displacement, pier top displacements, and deck acceleration. The comparison shows that the seismic responses of the bridge are affected by the use of different isolation systems; more specifically the displacements of the bridge pier are noticeably reduced in the case of SRBs compared to those in the case of HDRBs.

Keywords: Shape memory alloy; high damping rubber bearing; rate dependent rheology model

1. INTRODUCTION

Seismic isolation has been considered to be an efficient technology for providing mitigation to seismic damages for highway bridges and has proven to be reliable and cost effective. In order to improve the seismic performance for both new and retrofitting applications, different forms of seismic isolation devices have been widely employed for the last few decades (Naeim and Kelly, 1996). Laminated rubber bearings are widely used for seismic isolation of highway bridges. Three types of laminated rubber bearings are used as seismic isolation devices: natural rubber bearing (NRB), lead rubber bearing (LRB), and high damping rubber bearing (HDRB). Laminated rubber bearings experience some consequence-problems when subjected to strong earthquake excitations, especially the near field earthquake ground accelerations (Ozbulut and Hurlebaus, 2011). The unfortunate coincidence of the natural period of the seismically isolated bridge with that of the near field earthquakes amplifies the seismic responses of isolation system. Consequently, laminated rubber bearings experience large horizontal deformation under near field earthquakes which cause detrimental problems such as instability of the bearings, pounding and unseating problems of the bridge deck (Choi et al., 2005). In recent years, a number of attempts have been reported, by combining natural rubber bearing (NRB) and shape memory alloy (SMA) in seismic isolation of highway bridges, to partially solve the above mentioned limitations of the laminated rubber bearings (Wilde et al, 2000 and Choi et al., 2005). The super-elasticity accompanied by hysteresis property of the SMA allows it to fabricate with laminated rubber bearings to reduce the residual deformation of the bridge system. Considering the restoration and energy dissipation capacity of SMAs, its use is gaining wide interest in seismic protection of highway bridges (Ozbulut and Hurlebaus, 2011, DesRoches and Delemont, 2002). Recently, Billah et al. (2010) has carried out the performance evaluation of two span continuous highway bridge isolated

by an isolation bearing consisting of high damping rubber bearing and Ni-Ti SMA restrainer, and subsequently demonstrated the effectiveness of the bearing in reducing the residual displacement of bridge deck. In all these attempts discussed above, natural/lead rubber bearings (NRBs/LRBs) were mostly employed in constructing the SMA based isolation bearings. Moreover, either the equivalent linear model or the bilinear model as specified in American Association of State Highways and Transportation Officials (AASHTO, 2000) and Japanese Road Association (JRA, 2002) was adopted as analytical models for NRBs/LRBs in the previous studies. However, it has been experimentally evident from the previous works (Bhuiyan, 2009 and Hwang et al, 2002) that the mechanical behavior of the laminated rubber bearings cannot be rationally replicated by using such simple models, since the compounding and vulcanizing of the rubber at its manufacturing stage significantly affect the mechanical behavior of the bearings. In addition, very few or no studies were reported to consider the nonlinear force-displacement relation for the bridge pier to include the inelastic responses under strong earthquake excitations.

The objective of this work is to carry out seismic performance analysis of a three-span continuous highway bridge subjected to moderate to strong earthquake ground accelerations in longitudinal direction, considering nonlinear force-displacement relations in laminated rubber bearings and bridge pier. In this regard, two types of isolation bearings are used in the analysis: high damping rubber bearing (HDRB) and combined isolation bearing consisting of Ni-Ti based SMA wires and natural rubber bearing, entitled as SRB hereafter. The nonlinear force-displacement relation for the bridge pier governed by the bilinear hysteresis model is employed in the analytical model of the bridge. Nonlinear dynamic analysis of the bridge, based on the direct time integration approach using the 4th order Runge-Kutta method, is conducted. Finally, the variations in seismic responses of the bridge system due to the use of HDRB and SRB are explored.

2. ANALYTICAL MODELING OF THE BRIDGE

A three-span continuous highway bridge isolated by isolation bearings is considered in the analysis as shown in Fig. 1. The isolation bearings consist of HDRB, SRB. The bridge comprises continuous reinforced concrete (RC) deck-steel girder isolated by isolation bearings installed below the steel girder supported on RC piers. The superstructure consists of 250 mm RC slab covered by 75 mm of asphalt layer. The height of the continuous steel girder is 2000 mm. The mass of a single span bridge deck is 600×10^3 kg and that of a pier is 240×10^3 kg. For simplicity, the bridge model is idealized as a two-degree of freedom (2-DOF) system. This simplification holds true only when the bridge superstructure is particularly assumed to be rigid in its own plane. The mass proportional damping of the bridge pier is considered in the analysis. The geometry and material properties of the bridge pier, bearings and SMA wires are given in Table 1.

For simplicity, only a single pier is considered and modeled by two degrees of freedom (2-DOF) as shown in Fig. 1. Equations that govern the dynamic responses of the bridge can be derived by considering the equilibrium of all forces acting on it using the d'Alermbert's principle. In this case, the internal forces are the inertia forces, the damping forces, and the restoring forces, while the external forces are the earthquake induced forces. Equations of motion are given as

$$m_p \ddot{u}_p(t) + F_p(u_p, t) - F_{is}(t) = -m_p \ddot{u}_g(t) \tag{1a}$$

$$m_d \ddot{u}_d(t) + F_{is}(t) = -m_d \ddot{u}_g(t) \tag{1b}$$

where m_p, m_d, u_p and u_d are the masses and displacements of pier and deck, respectively. $\ddot{u}_p$ and $\ddot{u}_d$ are the accelerations of pier and deck, respectively. $\ddot{u}_g$ is the ground acceleration. F_p is the internal restoring force of the pier to be evaluated by bilinear model. F_{is} is the restoring force of the isolation bearings.
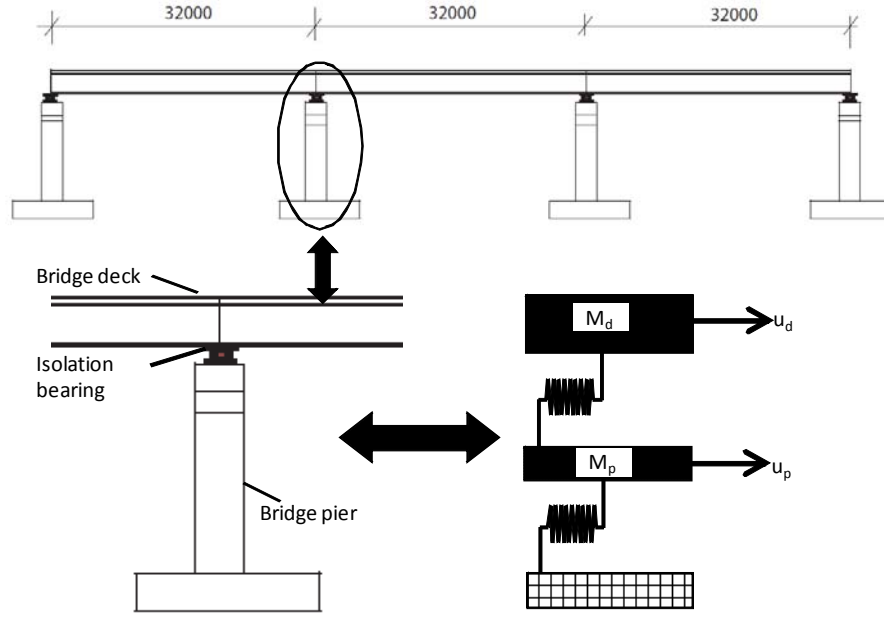
Figure 1. Analytical modeling of the bridge pier

Table 1. Geometric and material properties of the bridge, bearing and SMA wire

Properties	Specifications
Cross-section area of the pier cap (mm^2)	2000x12000
Cross-section area of the pier body (mm^2)	2000x9000
Height of the pier (mm)	15000
Young's modulus of elasticity of concrete (N/mm^2)	25000
Young's modulus of elasticity of steel (N/mm^2)	200000
Cross-section of the bearing (mm^2)	1000X1000
Thickness of rubber layers (mm)	300
Nominal shear Modulus of rubber (MPa)	1.2
Modulus of elasticity of SMA wire (N/mm^2)	72000
Yield strength of SMA wire (N/mm^2)	270
Length of SMA wire(mm)	2500

3.   ANALYTICAL MODELING OF ISOLATION BEARINGS

The experimental investigations conducted by several authors (Bhuiyan, 2009 and Hwang et al., 2002, etc.) have revealed four different fundamental properties, which together characterize the typical overall response of HDRBs: (i) a dominating elastic ground stress response, which is characterized by large elastic strains (ii) a finite elasto-plastic response associated with relaxed equilibrium states (iii) a finite strain-rate dependent viscosity induced overstress, which is portrayed by relaxation tests, and finally (iv) a damage response within the first cycles, which induces considerable stress softening in the subsequent cycles. Considering the first three properties, a strain-rate dependent constitutive model for the HDRBs is developed by Bhuiyan (2009) which is verified for sinusoidal excitations and subsequently implemented in professional structural engineering software (RESP-T, 2006) for conducting seismic performance analysis of multi-span continuous highway bridge. Eqs. 2 (a) to (e) provide the explicit expressions for the average shear stress τ and shear strain γ of HDRB. The readers can refer to the earlier publications by Bhuiyan (2009) and Bhuiyan et al. (2009) for details of the model, parameter identification procedure and underlying motivations for generating the framework.

$$\tau = \tau_{ep}(\gamma_a) + \tau_{ee}(\gamma) + \tau_{oe}(\gamma_c) \tag{2a}$$

$$\tau_{ep} = C_1\gamma_a \quad \text{with} \begin{cases} \dot{\gamma}_s \neq 0 & \text{for} \quad |\tau_{ep}| = \tau_{cr} \\ \dot{\gamma}_s = 0 & \text{for} \quad |\tau_{ep}| < \tau_{cr} \end{cases} \tag{2b}$$

$$\tau_{ee} = C_2\gamma + C_3|\gamma|^m \operatorname{sgn}(\gamma) \tag{2c}$$

$$\tau_{oe} = C_4\gamma_c \quad \text{with} \ \tau_{oe} = A\left|\frac{\dot{\gamma}_d}{\dot{\gamma}_o}\right|^n \operatorname{sgn}(\dot{\gamma}_d) \tag{2d}$$

and

$$A = \frac{1}{2}\left(A_l \exp(q|\gamma|) + A_u\right) + \frac{1}{2}\left(A_l \exp(q|\gamma|) - A_u\right)\tanh(\xi\tau_{oe}\gamma_d) \tag{2e}$$

where C_i ($i = 1$ to 4), τ_{cr}, m, A_l, A_u, q, n, and ξ are the model parameters determined from experiments (Bhuiyan 2009). The values of model parameters are as follows: C_1(MPa) = 2.501, C_2(MPa) = 0.653, C_3(MPa) = 0.006, C_4(MPa) = 3.25, τ_{cr}(MPa)= 0.25, $m = 6.62$, A_l(MPa) = 0.354, A_u(MPa) = 0.241, $n = 0.22$, $q = 0.43$, $\xi = 1.22$.

A rigorous experimental investigation of different types of NRBs, carried out by Bhuiyan (2009)has revealed that NRB exhibit comparatively less strain-rate dependent viscosity induced overstress compared to that of HDRB; however, the elastic ground stress response characterized stain hardening feature of NRB at large strains becomes more dominant than that of HDRB. In order to take this fact into account, a simplified version of the rheology model suitable for NRB is employed using the first three equations for HDRB. Eqs. 3(a) to (c) constitute the rheology model for NRB. C_1(MPa) = 1.95, C_2(MPa) = 0.798, C_3(MPa) = 0.005, τ_{cr}(MPa)= 0.15, $m = 7.62$.

$$\tau = \tau_{ep}(\gamma_a) + \tau_{ee}(\gamma) \tag{3a}$$

$$\tau_{ep} = C_1\gamma_a \quad \text{with} \begin{cases} \dot{\gamma}_s \neq 0 & \text{for} \quad |\tau_{ep}| = \tau_{cr} \\ \dot{\gamma}_s = 0 & \text{for} \quad |\tau_{ep}| < \tau_{cr} \end{cases} \tag{3b}$$

$$\tau_{ee} = C_2\gamma + C_3|\gamma|^m \operatorname{sgn}(\gamma) \tag{3c}$$

Smart materials such as shape memory alloys (SMAs) have great potentials in seismic hazard mitigation applications (Wilde et al., 2000). Various types of SMAs (for instance, Ni-Ti, Ni-Ti-Cu, Cu-Zn-Al, Cu-Al-Be etc) in the form of wires and bars with different diameters have been experimentally investigated by a number of researchers under tensile, compressive, torsional, and shear forces where the details can be found in Alam et al. (2007). SMAs possess several desirable properties to be used as dampers and restrainers in bridges. These properties are (*i*) large elastic strain range, (*ii*) hysteretic damping, (*iii*) highly reliable energy dissipation due to repeatable solid state phase transformation, (*iv*) strain hardening, (*v*) excellent fatigue resistance, and (*vi*) excellent corrosion resistance. Considering the restoration and energy dissipation capacity of SMAs, use of superelastic Nitinol (Ni-Ti) is increasingly recognized in seismic protection of highway bridges (Billah et al., 2010, DesRoches and Delemont, 2002, Ozbulut and Hurlebaus, 2011 and Wilde et al., 2000, etc.).

In general, the constitutive model of SMA is very complicated in a sense that it depends upon many factors such as strain rates, strain magnitude and strain history. Three categories of constitutive models are used for characterizing the superelasticity and damping properties of SMA, such as parametric, nonparametric and differential equation-based models. The differential equation-based constitutive models comprise two versions of models, such as phenomenological models (Auricchio et al., 1997) and thermodynamics based models. In realization, the complexity of replicating the mechanical behavior of SMAs by the use of phenomenological models, three versions of the models are used in seismic applications (Andrawes and DesRoches, 2008). The models include a simplified model, which is constructed based on experimentally obtained data; a thermomechanical model, which considers the stress-strain-temperature relationship in SMAs; and a thermomechanical model, which also takes into account the cyclic loading effects in SMAs. In recognizing the intricacy of the phenomenological models considering the thermomechanical behavior of SMAs, the simplest version of the models, i.e., the simplified model is used in the current study to model the SMAs. The simplified model comprises nonlinear elastic ground force along with visco-elastic damping force of the SMAs. These two branches of the force are idealized from the experimental characterizations of SMA wires.

The simplified model of the SMA wire can be written as

$$\tau_s = \tau_{es}(\gamma_s) \quad + \quad \tau_{vs}(\dot{\gamma}_s) \tag{4a}$$

$$\tau_{es}(\gamma_s) = E_s\gamma_s \qquad 0 < \gamma_s < \gamma_{sy} \tag{4b}$$

$$\tau_{es}(\gamma_s) = \tau_{sy} + E_s(\gamma_s - \gamma_{sy}) \qquad \gamma_{sy} < \gamma_s < \gamma_{st} \tag{4c}$$

$$\tau_{es}(\gamma_s) = \tau_{sh} + E_{sh}(\gamma_s - \gamma_{st}) \qquad \gamma_{st} < \gamma_s \tag{4d}$$

$$\tau_{vs}(\dot{\gamma}_s) = c_s\dot{\gamma}_s \tag{4e}$$

where τ_s is SMA stress as a function of strain γ_s and strain rate $\dot{\gamma}_s$; τ_{es} and τ_{vs} are nonlinear elasticground and viscoelastic stresses of SMA, resptectively; τ_{sy} and τ_{sh} are SMA stresses at beginning and end, respectively, of martensitic transformation; γ_{sy} and γ_{st} are SMA strain at beginning and end of martensitic transformation; E_s is the modulus of elasticity of SMA and c_s is damping constant of SMA, which can be realized from experimental data.

4. SEISMIC GROUND ACCELERATION HISTORIES

Moderate to strong earthquake ground accelerations are used in the dynamic analysis of the 2-DOF bridge pier system. Moderate earthquake ground accelerations are defined as those ground accelerations, which are characteristically similar to the level-2 type-I earthquake ground acceleration, i.e., the Kanto earthquake (Tokyo, 1923) (JRA, 2002) whereas the strong earthquake is considered to be characteristically similar to the level-2 type-II earthquake ground acceleration, i.e., the Kobe earthquake (Kobe, 1995) (JRA, 2002). A total of four earthquake ground acceleration records are used in the dynamic analysis. The peak ground acceleration (PGA) values of the earthquake ground motions range from 0.65g to 1.07g.The acceleration response spectra of the earthquake ground accelerations are shown in Figs. 2(a) and (b), which show the earthquake ground acceleration-time histories and response spectra, respectively.
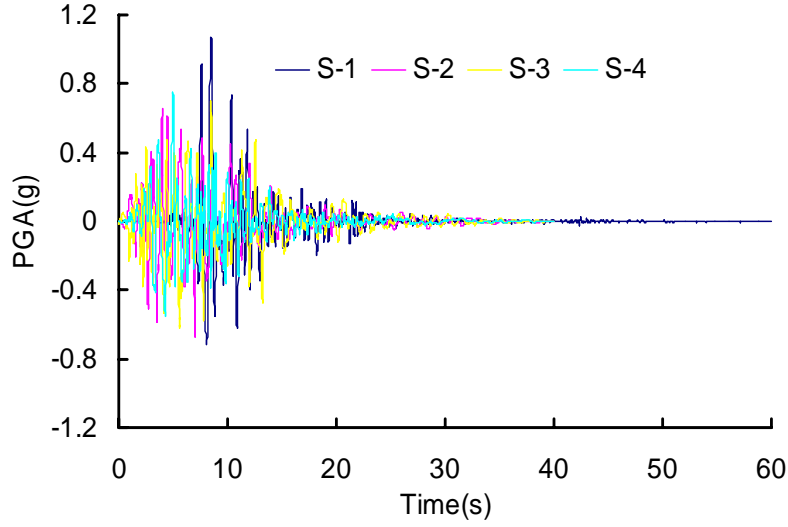
(a)
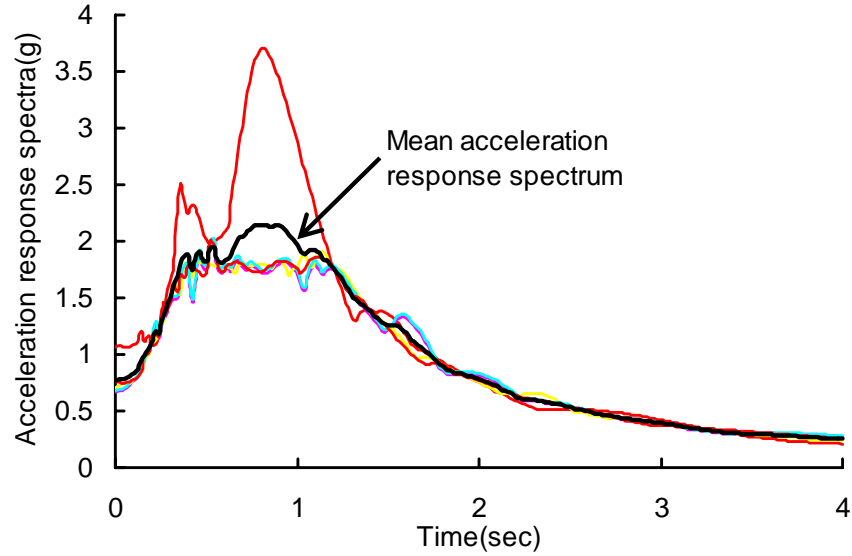
(b)

Figure 2. (a) **A**cceleration-time histories and (b) response spectra of the earthquake ground motions

5. NUMERICAL RESULTS AND DISCUSSION

Seismic responses of the system are evaluated by conducting nonlinear dynamic analysis based on the direct time integration approach using the 4th order Runge-Kutta method. In comparative assessment of seismic responses of the system, three standard response parameters obtained for each earthquake record are addressed in the study such as deck displacement, pier displacements and deck acceleration. Each response parameter of the system equipped with HDRB is compared with that of SRB. The results of the simulation study are summarized in Tables 2.1 and 2.2. Typical responses of the system such as time history responses of deck displacement, pier displacement and bearing displacement are presented in Figs. 3 and 4 for S-1 and S-3 ground motion records and the seismic responses for the remaining earthquake ground motion records are skipped for space limitation.

Table 2.1 Absolute maximum responses of the system isolated by HDRB

Response/ Seismic ground motion records	Deck Acceleration (m/sec^2)	Pier displacement (mm)	Deck displacement (mm)	Residual displacement (mm)
S-1	11.9	98.3	569.0	25.3
S-2	6.8	87.2	419.2	7.2
S-3	8.2	96.3	423.2	11.4
S-4	6.9	91.4	437.6	29.6

Table 2.2 Absolute maximum responses of the system isolated by SRB

Response/ Seismic ground motion records	Deck Acceleration (m/sec^2)	Pier displacement (mm)	Deck displacement (mm)	Residual displacement (mm)
S-1	14.3	55.8	576.1	13.5
S-2	9.4	75.9	537.2	19.3
S-3	9.8	59.0	530.4	17.1
S-4	9.9	75.8	548.3	28.3

The bridge with SRB experienced larger deck accelerations for each of the earthquake ground motion as compared to that of the bridge with HDRB. The average of the maximum deck accelerations with SRB is 25 % larger than that of HDRB; however, for earthquake ground acceleration (S-4), this value goes to 44% higher than the bridge with HDRB. The increased dissipation energy of high damping rubber bearing (HDRB) is attributed to the results. Tables 2.1 and 2.2 show the maximum deck acceleration isolated by HDRB and SRB, respectively.

For pier displacement, the bridge with SRB has smaller values for earthquake ground accelerations as compared to that of HDRB. The average of the pier displacements with SRB is smaller by 12% to 43% as compared to HDRB. The hardening feature and energy dissipation capacity of SRB in comparison to HDRB are attributed to this phenomenon. Tables 2.1 and 2.2 show the maximum pier displacements isolated by HDRB and SRB, respectively. Figures 3(a) and 4(a) show the time histories of displacements of piers associated with HDRB and SRB for the earthquake ground acceleration records S-1 and S-3, respectively. The similar trend of seismic responses with different magnitudes is observed in Figs. 3(a) and 4(a).

For deck displacement, the bridge with SRB has larger deck displacements for each of the earthquake ground accelerations than the bridge with HDRB. The similar trends of results are also reported in Choi et al. (2005) for strong earthquake ground motion records. The effective restriction of the relative deck displacement is desirable to prevent unseating of the deck and instability of the bearings. Tables 2.1 and 2.2 show the maximum deck displacements of the bridge isolated by HDRB and SRB, respectively. The time histories of the deck displacements associated with HDRB and SRB are shown in Figs. 3(b) and 4(b). Therefore, hardening in SRB obtains a desirable result in restricting the deck displacement caused by strong ground motions.

The bearing displacements are obtained from relative displacements between deck and pier. For SRB, the average of the maximum bearing displacements is 17% higher than HDRB; however, the maximum bearing displacements of SRB vary from 93% to 132%. The increased capacity of dissipation of energy of HDRB may be attributed to this effect. Figs.3 (c) and 4(c) show the time histories of the bearing displacements obtained for HDRB and SRB. Tables 2.1 and 2.2 present the maximum bearing displacements of HDRB and SRB, respectively. The residual displacement of bearing is computed by taking the arithmetic average of the stable absolute values of the last 10 to 15 minutes of the time history of bearing displacements as obtained from the dynamic analysis of the system for each earthquake. The residual displacements of SRB are smaller than HDRB for S-2 and S-3; however, for S-1 and S-4, the residual displacements are seen to be larger than HDRB (Tables 2.1 and 2.2 and Figs. 3 and 4). The characteristics of the earthquakes, energy dissipation and hardening feature of the HDRB and SRB have effect on the results of residual displacements.
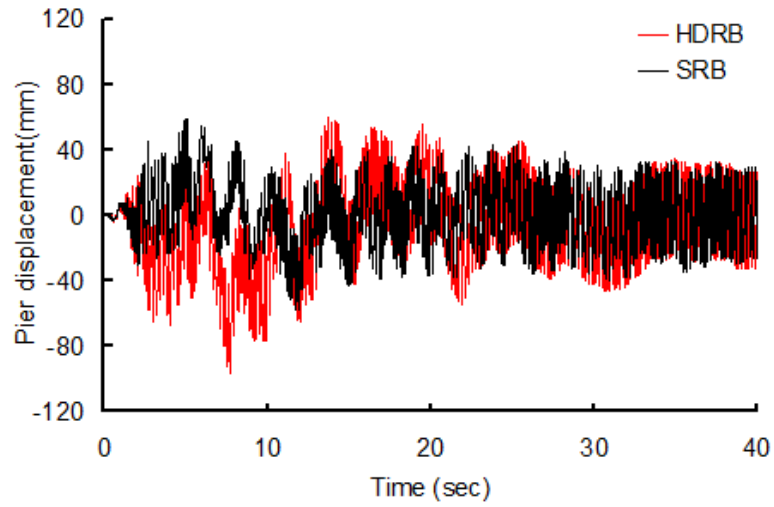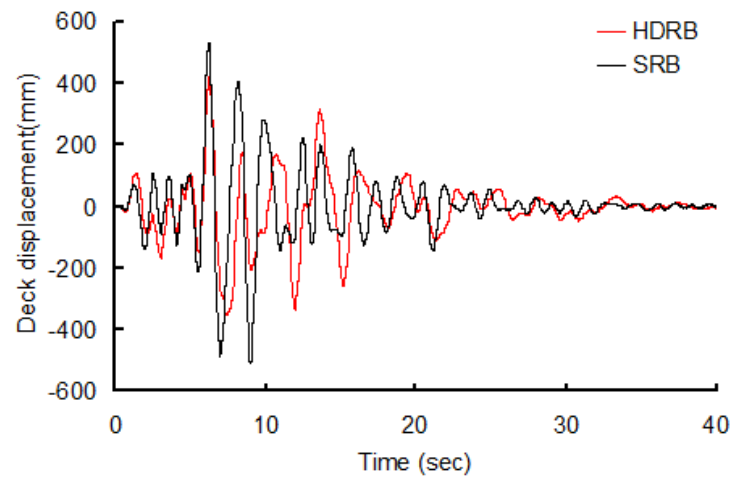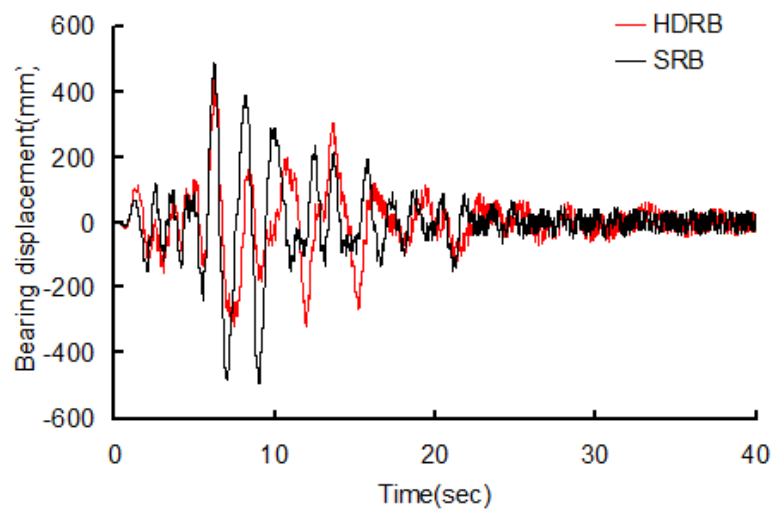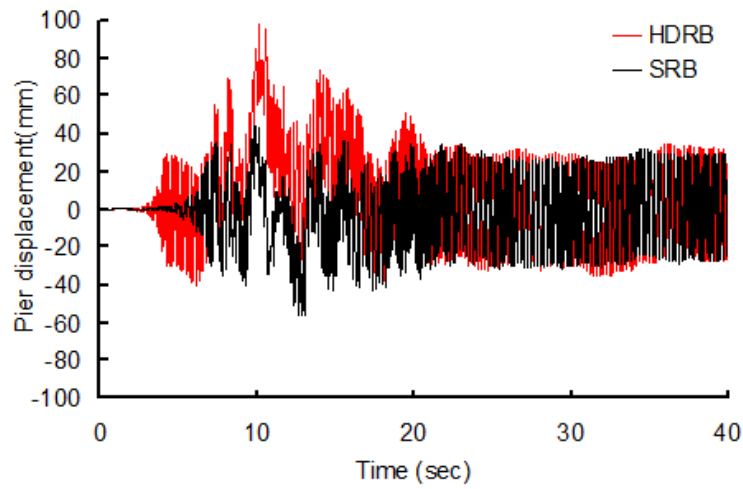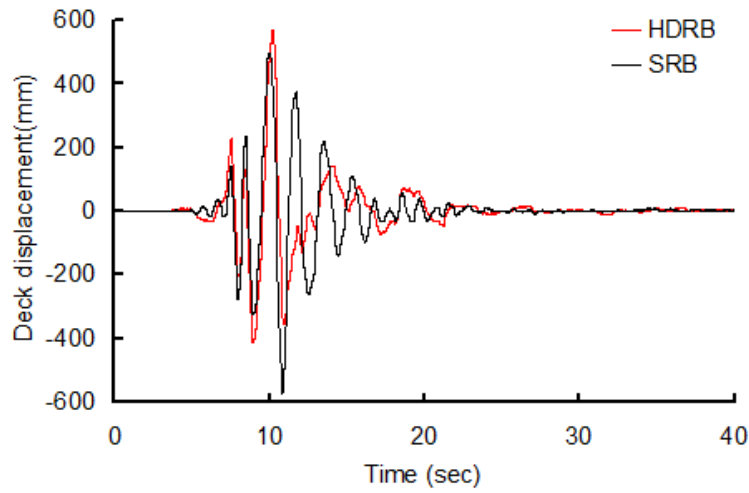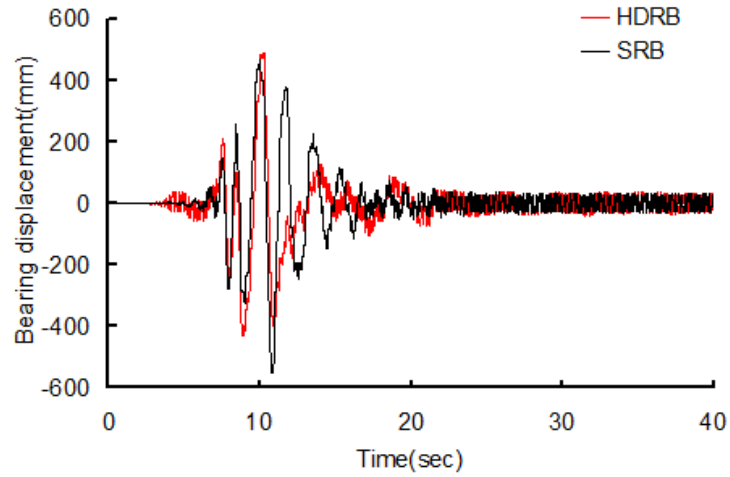
Figure 3. Time history of (a) pier displacement and (b) deck displacement, and (c) bearing displacement of the bridge pier fitted with HDRB and SRB subjected to earthquake ground motion (S-1)

(a)

(b)

(c)

Figure 4. Time history of (a) pier displacement and (b) deck displacement, and (c) bearing displacement of the bridge pier fitted with HDRB and SRB subjected to earthquake ground motion (S-3)

6. CONCLUDING REMARKS

This study presents seismic performance assessment of highway bridges isolated by high damping rubber and shape memory alloy/natural rubber bearings. This study discusses a simplified analytical /approach for modeling isolation bearings which is comprised natural rubber bearing (NRB) wrapped with shape memory (SMA) wires. The bridge is analyzed for moderate and strong earthquake ground accelerations calibrated with design acceleration response spectra as recommended by JRA (2002). The nonlinearity of the bridge pier is considered by employing the bilinear force-displacement relationship. A complicated strain-rate dependent constitutive model for the HDRB and nonlinear elasto-plastic analytical model for NRB are used in the analysis. A viscoelasticity based analytical model is used for simulating the superelastic and damping properties of SMA wires.

The numerical results have revealed that the high damping rubber bearing satisfactorily restrained deck displacement under the earthquake ground motion records considered in the study. The similar trend of the results is also observed in the case of deck acceleration. However, the SMA-natural rubber bearing can safely protect the bridge pier from large displacement under the given earthquakes.

In the current study, only one interior bridge pier was considered. The ground motion response of such a simplified subassemblage will be different if an exterior pier is considered instead, or the total assembly of the bridge is considered. This is likely to change the dynamics of the response of the entire bridge structure. It should be also noted that the selection of the type and modeling approach of isolation bearings has a remarkable effect on the seismic performance evaluation of highway bridges, which has to be carefully considered in the analysis and design steps of any bridge project.

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