Seismic assessment of bridge structures isolated by a shape memory alloy/rubber-based isolation system

Osman E. Ozbulut and Stefan Hurlebaus

Zachry Department of Civil Engineering, Texas A&M University, 3136 TAMU College Station, TX 77843

Abstract: This paper explores the effectiveness of shape memory alloy (SMA)/rubber-based isolation systems for seismic protection of bridges against near-field earthquakes by performing a sensitivity analysis. The isolation system considered in this study consists of a laminated rubber bearing, which provides lateral flexibility while supplying high vertical load-carrying capacity and an auxiliary device made of multiple loops of SMA wires. The SMA device offers additional energy dissipating and re-centering capability. A three-span continuous bridge is modeled with the SMA/rubber-based (SRB) isolation system. Numerical simulations of the bridge are conducted for various near-field ground motions that are spectrally matched to a target design spectrum. The normalized forward transformation strength, forward transformation displacement and pre-strain level of the SMA device, ambient temperature and the lateral stiffness of the rubber bearings are selected as parameters of the sensitivity study. The variation of seismic response of the bridge with considered parameters is assessed. Also, the performance of the SRB isolation system with optimal design parameters is compared with an SMA-based sliding isolation system. The results indicate that the SRB isolation system can successfully reduce the seismic response of highway bridges; however, a smart isolation system that combines sliding bearings together with an SMA device is more efficient than the SRB isolation system.

1. Introduction

The concept of seismic isolation has been considered an attractive strategy over the past decades to mitigate the damaging effects of earthquakes on civil structures such as multi-story buildings, bridges and nuclear power plants. Seismic isolation aims to shift the fundamental frequency of a structure away from the frequency band of most common earthquakes in order to reduce seismic loads applied to the structure and to provide additional damping capacity to the structure. Among various isolation systems that have been proposed, rubber isolation systems have been widely studied and used throughout the world [1]. Laminated-rubber bearings have considerable lateral flexibility, vertical load-carrying capacity and restoring force capability. The commonly used rubber isolation systems combine laminated-rubber bearings and some mechanical dampers such as hydraulic dampers, viscous dampers, steel bars or lead-plugs within the bearing itself. Laminated-rubber bearing with lead core, known as lead-rubber bearing, is the most popular rubber isolation

1 shurlebaus@civil.tamu.edu; phone 1 979 845-9570, fax: 1 979 845 6554
Another widespread rubber isolator is high-damping rubber bearings which increases the damping of the isolation system by incorporating damping in the elastomer itself [2].

Although seismic isolation has become one of the most popular solutions for seismic protection of bridge structures, the performance of the isolated bridges against near-field earthquakes has been questioned by several researchers in recent years [3-5]. Near-field earthquakes are characterized with long period and large velocity pulses in the velocity time history. Since the period of these pulses usually coincides with the period of isolated structures, ground motions with near-field characteristics amplify seismic response of the isolation system [6]. In particular, the isolation devices experience very large displacements under near-field ground motions which may cause critical problems such as instability in the isolator, pounding as well as unseating of the deck. For example, a post-earthquake bridge performance investigation after 2008 Wenchuan earthquake revealed that many bridges were heavily damaged in the earthquake affected region. It was concluded that the rubber bearings can successfully reduce the seismic hazards to bridges in the area; yet, further research is recommended to limit the excessive bearing deformations [7].

In recent years, several attempts have been made to combine smart materials with rubber bearings [8, 9]. One such material is shape memory alloy (SMA) that is a class of metallic alloys. SMAs can recover their original shape after experiencing large strains. SMAs owe this unique characteristic to solid-solid phase transformations. These phase transformations can be mechanically induced, known as superelastic effect, or thermally induced, named as shape memory effect. Due to its re-centering and energy dissipating capabilities, the superelastic behavior of the SMAs has attracted attention for vibration control of structures over the past decades [10-13]. Superelastic SMAs are initially in their austenitic phase, and transform to martensite phase when a stress is applied beyond a critical level. Upon removal of loading, the material experiences a reverse transformation from martensite back to austenite, resulting in a unique stress-strain curve. By exploiting the complete shape recovery ability and hysteretic behavior of the superelastic SMAs, several researchers have proposed a smart isolation system [14-17].

Wilde et al. [18] compared the performance of two isolation systems that couple laminated rubber bearing with either a lead-plug or an SMA device for seismic protection of elevated highway bridges. Cacciati et al. [19] developed an isolation device that consists of a sliding system and inclined CuAlBe SMA bars, and carried out extensive experimental tests on a prototype of the device. In another study by Cacciati et al. [20], the performance of the developed SMA isolation device was investigated for a seismically-excited highway bridge benchmark problem. Choi et al. [21] proposed an SMA-rubber bearing composed of a laminated-rubber bearing and pre-stressed superelastic NiTi wires wrapping the bearing in the longitudinal direction. Numerical simulations were conducted on a multi-span continuous bridge in order to evaluate the effectiveness of the
proposed smart bearing. Note that the effect of temperature on the behavior of superelastic SMAs has not been considered in the above studies.

In this study, a sensitivity analysis is conducted in order to investigate the effectiveness of an SMA/rubber-based (SRB) isolation system for protecting highway bridges against near-field earthquakes. The smart isolation system consists of a laminated rubber bearing that decouples the superstructure from the bridge piers and an SMA device that provides additional energy dissipation and re-centering capacity. First, a neuro-fuzzy model that is capable of simulating superelastic behavior of SMAs at various temperatures and loading rates is briefly introduced. Then, a three-span continuous bridge is modeled together with laminated-rubber bearings and an auxiliary SMA device. Nonlinear time-history analyses of the isolated bridge are performed for a total of six excitation cases. A time-domain method, which spectrally adjusts time histories of historical ground motions to match a target spectrum at multiple damping levels, is employed to generate artificial earthquakes that are used for dynamic analyses. The variation of seismic response of the isolated bridge with the normalized forward transformation strength of the SMA device $F_o$, the forward transformation displacement of the SMA device $u_o$, the pre-strain level of the SMA wires, the lateral stiffness of the laminated rubber bearings $k_b$ and environmental temperature changes is investigated. The bridge response quantities evaluated in the sensitivity analysis include peak values of deck drift, deck acceleration, and normalized base shear.

2. A temperature- and rate-dependent model of superelastic SMAs

In order to conduct numerical simulations of bridges isolated by the SRB isolation systems, an effective model that characterizes hysteretic behavior of superelastic SMAs is needed. The mechanical response of SMAs is highly dependent on temperature and loading-rate [22, 23]. When SMAs are used as an isolation system component for seismic protection of bridges, they will experience both temperature changes and dynamic loads. Therefore, it is essential to consider the degree to which behavior of SMAs is affected by variations of loading-rate and temperature.

Figure 1 presents the results of the uniaxial tensile tests conducted on NiTi shape memory alloy wires using an MTS (Material Testing System) servo-hydraulic load frame. The SMA wire has a diameter of 1.5 mm and is obtained from SAES Smart Materials. The alloy chemical composition is 55.8% nickel by weight and the balance titanium. The austenite start and finish temperatures are specified by manufacturer as $A_s = -10^\circ C$ and $A_f = 5^\circ C$, respectively. The tests conditions covered a loading frequency range of 0.05-2 Hz and a temperature range of 0-40$^\circ C$. The results of the tests that are conducted at different strain amplitudes, different temperature and different loading frequencies are given in each subplot of figure 1. It can be seen that the loading frequency and temperature considerably affect the behavior of superelastic SMAs. In particular, an increase in either temperature or loading frequency shifts the hysteresis loop upward. Also, the area of the hysteresis
loop, which indicates the energy dissipation of superelastic SMAs, narrows with increasing temperature or loading frequency. Note that the effect of the temperature is more pronounced as compared to the influence of loading frequency.

![Figure 1. Experimental stress-strain curves at various loading conditions](image1)

This study employs a neuro-fuzzy model to capture the temperature- and rate- dependent behavior of NiTi shape memory alloys. A fuzzy inference system (FIS) is a simple scheme that maps an input space to an output space using fuzzy logic. Here, a FIS which employs strain, strain rate and temperature as input variables and predicts the stress as single output is created. Adaptive neuro-fuzzy inference system (ANFIS) which employs neural network strategies to develop a fuzzy model whose parameters cannot be predetermined by user’s knowledge is used to tune the parameters of the initial FIS. A thorough description of the model can be found in the work by Ozbulut and Hurlebaus [24]. Figure 2 illustrates the stress-strain curves for experimental results and the prediction of fuzzy model for different loading conditions. It can be seen that the developed fuzzy model satisfactorily reproduces the hysteresis loops of superelastic SMAs at different temperatures and loading frequencies.

![Figure 2. Stress-strain curves at various conditions for experimental results and fuzzy model](image2)
3. Sensitivity analysis

3.1 Modeling of isolated bridge

A three-span continuous bridge is selected for the sensitivity analysis [25]. The deck of the bridge has a mass of $771.1 \times 10^3$ kg, and the mass of each pier is $39.3 \times 10^3$ kg. The bridge has a total length of 90 m, and each pier is 8 m tall. The moment of inertia of piers and Young’s modulus of elasticity are given as 0.64 m$^4$ and $20.67 \times 10^9$ N/m$^2$, respectively. The fundamental period of non-isolated bridge is 0.45 s. As shown in figure 3, the isolated bridge is modeled as a two-degree-of-freedom system with the SRB isolation system which consists of a laminated rubber bearing and an SMA device. Since the isolation systems installed at the abutment and pier have similar characteristics and therefore, the seismic response of the bridge at the abutment and pier have the same trend, only an internal span is modeled. The equations of motion are given as

\[
\begin{align*}
    m_1 \ddot{u}_1(t) &+ c_1 \dot{u}_1(t) + k_1 u_1(t) - F_{IS}(u_1, \dot{u}_1, u_2, \dot{u}_2, t) = -m_1 \ddot{u}_g(t) \\
    m_2 \ddot{u}_2(t) &+ F_{IS}(u_1, \dot{u}_1, u_2, \dot{u}_2, t) = -m_2 \ddot{u}_g(t)
\end{align*}
\]  

where $m_1$, $m_2$ and $u_1$, $u_2$ are the masses and displacements of pier and deck, respectively, $c_1$ and $k_1$ represent the coefficient of damping and stiffness of piers, and $\ddot{u}_g$ is the ground acceleration. $F_{IS}$ denotes the sum of the restoring force of the laminated rubber bearings and SMA device. Laminated rubber bearings are modeled by linear spring and dashpot elements. The coefficient of damping and stiffness of rubber bearings are denoted as $c_2$ and $k_2$, respectively in figure 3. The equivalent damping ratio of bearings is selected to be 2%. The fuzzy model described above is used to compute the instantaneous force from the SMA elements.

![Figure 3. Model of an isolated bridge with SMA/rubber isolation system](image-url)
3.2 Selection of input time histories

A variety of methods have been proposed to modify a historical time history so that its response spectrum is compatible with a given target spectrum [26, 27]. One approach that is commonly used for generating response spectrum compatible ground motions is to adjust Fourier amplitude spectra in frequency domain. Although it is a straight-forward method and provides a close match to the target spectrum, it also has significant potential problems such as distorting the energy characteristics of accelerograms and producing very unrealistic seismic demands [28]. Hancock et al. [29] proposed an alternative approach that performs spectral matching in time domain using wavelets. The method, known as RspMatch2005, can simultaneously match response spectra at multiple damping values, while preserving the non-stationary character of the reference time history. Unlike the spectral matching in frequency domain, RspMatch2005 does not corrupt the velocity and displacement time histories, and avoids creating ground motions with unrealistic energy content.

In this study, the program RspMatch2005 is used to generate spectrum compatible ground motions that are used in dynamic time history analyses of the isolated bridge. A total of six historical near-field earthquake records are selected as seed accelerograms to investigate the effectiveness of the SRB isolation system under near-field ground motions. Table 1 gives the characteristics of the ground motions such as magnitude, the closest distance to the fault plane, peak ground acceleration and velocity, and significant duration. A response spectrum constructed as per the International Building Code [30] for a site in southern California, assuming firm rock conditions, is selected as target spectrum [31]. The left subplot of figure 4 shows the target response spectrum used in the analysis and response spectra of selected ground motions for 5% damping level. The selected seed accelerograms are adjusted using the RspMatch2005 in order to simultaneously match 5%, 10% and 25%-damped response spectra. The right subplot of figure 4 shows the spectrally matched response spectra of the selected records for 5% damping level. It can be seen that the spectral misfit is reduced significantly after the modification of the accelerograms by the RspMatch2005.

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Magnitude (Mw)</th>
<th>Distance (km)</th>
<th>PGA (g)</th>
<th>PGV (cm/s)</th>
<th>Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1979 Imperial Valley</td>
<td>6.5</td>
<td>1.0</td>
<td>0.44</td>
<td>109.8</td>
<td>8.5</td>
</tr>
<tr>
<td>1986 N. Palm Springs</td>
<td>6.0</td>
<td>8.2</td>
<td>0.59</td>
<td>73.3</td>
<td>4.5</td>
</tr>
<tr>
<td>1994 Sylmar</td>
<td>6.7</td>
<td>6.2</td>
<td>0.90</td>
<td>102.8</td>
<td>9.0</td>
</tr>
<tr>
<td>1971 San Fernando</td>
<td>6.6</td>
<td>2.8</td>
<td>1.22</td>
<td>112.5</td>
<td>3.8</td>
</tr>
<tr>
<td>1992 Landers</td>
<td>7.3</td>
<td>1.1</td>
<td>0.72</td>
<td>97.6</td>
<td>13.1</td>
</tr>
<tr>
<td>1989 Loma Prieta</td>
<td>6.9</td>
<td>6.1</td>
<td>0.56</td>
<td>94.8</td>
<td>10.2</td>
</tr>
</tbody>
</table>
3.3 Sensitivity analysis

The cost of SMA material has been one of the impediments to actual implementation even though it considerably decreased in the past decade [32]. However, economically feasible solutions can be achieved with NiTi-based SMAs if they are used in small devices or applied to selected region of structures [33]. The SMA device considered in this study simply consists of multiple loops of superelastic NiTi wires wrapped around two wheels. The simple configuration of the device avoids extra fabrication costs.

Several key design parameters for the SMA device are shown in figure 5 on an idealized force-deformation curve. In the figure, $F_y$ and $u_y$ represent forward transformation force and displacement of the SMA device, respectively; $F_d$ and $u_d$ respectively denote design force and displacement corresponding to the limit of superelastic force-displacement relationship of the SMA device; $k_{SMA}$ and $\alpha k_{SMA}$ denote initial lateral stiffness and post transformation stiffness of the device, respectively. For the NiTi wire considered in this study, $\alpha$, which represents the ratio of post transformation stiffness and initial stiffness of the SMA device, is observed to be 0.1; the forward transformation strain of SMA wire $\varepsilon_y$ is about 1% and the maximum recovery strain of SMA wire is about 6%. Here, $u_y$ is selected as analysis parameter while $u_d$ can be computed directly for the given $u_y$. Another parameter for the sensitivity analysis is selected to be the normalized forward transformation strength of the SMA device $F_o$ which is defined as, $F_o = F_y / W_d$ where $W_d$ is the
weight of the bridge deck. Note that once $u_y$ and $F_y$ are given, the geometric dimensions of the SMA elements can be computed from

$$u_y = e_y \cdot L_{SMA}$$

$$k_{SMA} = \frac{F_y}{u_y} = \frac{A_{SMA} \cdot E_{SMA} \cdot L_{SMA}}{L_{SMA}},$$

where $E_{SMA}$, $A_{SMA}$ and $L_{SMA}$ are the Young’s modulus, cross-sectional area and length of the SMA wires, respectively.

The effects of the environmental temperature changes on the seismic response of the isolated bridge are also evaluated in this study. Lastly, the pre-strain level of the SMA wires and the lateral stiffness of the laminated rubber bearings $k_b$ are considered as other parameters for the sensitivity study. Table 2 tabulates the parameters and the levels of these parameters considered in the sensitivity study.

![Figure 5](image.png)

**Figure 5.** Analysis parameters on an idealized force-deformation curve

<table>
<thead>
<tr>
<th>Normalized forward transformation strength $F_d$</th>
<th>Normalized forward transformation displacement $u_y$ (mm)</th>
<th>Temperature (°C)</th>
<th>Pre-strain level (%)</th>
<th>Lateral stiffness of rubber bearing (kN/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15, 0.17, 0.19</td>
<td>0.21, 0.23, 0.25</td>
<td>20, 30, 40, 50</td>
<td>0, 10, 20, 30, 40</td>
<td>11, 16, 25, 32, 45, 101</td>
</tr>
<tr>
<td>0.27, 0.29, 0.32</td>
<td>0.34, 0.36, 0.38, 0.40</td>
<td>0, 0.5, 1, 1.5, 2, 2.5</td>
<td>11, 16, 25, 32, 45, 101</td>
<td></td>
</tr>
</tbody>
</table>
Numerical simulations of the bridge isolated by the SRB isolation system are conducted in order to assess the influence of above-described parameters on the seismic response of the isolated bridge. The six spectrally-matched historical ground motion records are used as external excitations. The response quantities evaluated here are peak relative displacement of the deck, peak absolute acceleration of the deck, and peak base shear normalized by the weight of the deck.

Figure 6 shows the variation of the peak response quantities with the normalized forward transformation strength of the SMA device. The results are obtained for $u_y = 50$ mm, $T = 20^\circ$C, $k_b = 16$ kN/cm and without any pre-strain in the SMA wires. It can be seen that initially the peak deck drift almost continuously decreases for the increasing values of $F_o$ yet the rate of this decrease becomes smaller or turns even to a slight increase when $F_o$ is over 0.30. The peak deck acceleration and the peak normalized base shear take their minimum values in the vicinity of $F_o = 0.20-0.25$ for most of the excitation cases and then, they start to increase almost constantly for the higher values of $F_o$. It can be concluded from these observations that the optimal value of $F_o$ which effectively reduces the deck drift and simultaneously controls the superstructure acceleration and demands on the substructure is around 0.25.

The variation of the peak deck drift, deck acceleration and normalized base shear with the forward transformation displacement of the SMA device is given in figure 7 for $F_o = 0.25$, $T = 20^\circ$C, and $k_b = 16$ kN/cm. No pre-strain is present on the SMA wires. It is observed that the peak relative displacement of the deck does not change significantly for the different values of $u_y$. Since the smaller values of $u_y$ imply shorter length of the SMA wires, it is preferred to choose a small $u_y$. However, note that the seismic demand on the piers increases with decreasing values of $u_y$. Specifically, there is an average increase of 39% in the peak base shear for the six excitation cases.
when $u_y$ is changed from 50 mm to 20 mm. Also, since the stiffness of the SMA device increases when the length of the SMA wires used for the device shortens, the superstructure acceleration increases. In particular, when $u_y$ is decreased from 50 mm to 20 mm, the deck acceleration amplifies by an average factor of 1.3 for all considered cases. It can be concluded from figures 6 and 7 that the SRB isolation system amplifies the peak deck acceleration and peak normalized base shear for large values of $F_o$ and small values of $u_y$. Therefore, one should make a careful selection for these two parameters in order to mitigate the displacement response of the deck and at the same time limit the deck acceleration and base shear.

In order to investigate the effect of temperature changes on the performance of the SRB isolation system, a set of time-history analyses is conducted for an environmental temperature range of 0-40°C. The simulations are performed for $F_o = 0.25$, $u_y = 40$ mm, and $k_b = 16$ kN/cm. No pre-strain is present on the SMA wires. The variations of peak response quantities with temperature are illustrated in figure 8. The force-displacement relationships of the SRB isolation system for the Imperial Valley, Landers and Loma Prieta earthquakes are also shown in figure 9. It can be seen that there is a reduction in the peak deck drift with the increasing temperature for all excitation cases except the Imperial Valley earthquake. As shown in figure 9, the forward transformation takes places at considerably lower force level at 0°C and the critical force for the forward transformation increases with increasing temperature. The larger hysteretic force generated in the SRB isolation system decreases the displacement response of the deck at higher temperatures. It is also observed that the maximum variation of the peak deck drift as the temperature increases 20°C compared to reference temperature of 20°C is only about 9%. However, there is an increase of 62% in the peak deck drift for the N Palm Springs earthquake when the temperature decreases 20°C compared to the
reference temperature. Furthermore, the average variation of the peak deck drift for the six excitation cases is only 6% when the temperature increases to 40°C, while it is 25% when the temperature decreases to 0°C. This implies deck response is more sensitive to a decrease than an increase in temperature. This can be attributed to the fact that there is a larger change in the forward transformation force when the temperature decreases to 0°C as compared to its increase to 40°C as can be seen in figure 9. In addition, as illustrated in figure 1, the initial stiffness of the SMA wires remains almost constant when the temperature increases 20°C compared to the reference temperature but it somewhat decreases as temperature decreases to 0°C. As a consequence of the larger SMA force at higher temperatures, the peak deck acceleration and peak normalized base shear increase with the increasing temperature. Specifically, the maximum variation of peak deck acceleration and normalized base shear is ±27% when temperature differs ±20°C from the reference temperature of 20°C.

**Figure 8.** Variation of various peak response quantities with environmental temperature changes.
The effect of pre-strain on the SMA wires that are used in the auxiliary SMA device of the isolation system is investigated by changing the pre-strain level of the SMA wires from 0 to 2.5%. The corresponding stress values for 0.5, 1, 1.5, 2 and 2.5 % pre-strain are 150, 247, 288, 310, and 326 MPa. The pre-strain levels are selected such that the maximum strain experienced by the SMA wires is within the 6% recovery strain limit. Figure 10 presents the variation of the mean of the peak response quantities with the pre-strain level of the SMA wires for the isolated bridge subjected to different earthquakes. The simulations are conducted for $F_o = 0.15, 0.20, 0.25$ and $u_y = 40$ mm, $T = 20^\circ$C, and $k_b = 16$ kN/cm. The different values of $F_o$ are considered to evaluate any interaction between the normalized yield strength and the pre-strain level. It is observed that when the SMA wires are pre-strained about to 1%, the relative deck displacement decreases compared to the case without any pre-strain on the wires for all values of $F_o$. Since the initial behavior of the superelastic SMA wires is almost linear elastic and the forward transformation start at over 1% strain, a larger hysteresis loop, i.e. an increase in dissipated energy, is available when the wires are pre-strained. This causes a reduction in the peak deck drift. However, when the pre-strain level is increased more than 1%, the corresponding decrease in deck drift is not significant for most of the cases. It is also observed that applying a pre-strain over 1% tends to increase the peak deck acceleration. Furthermore, the variations in the peak shear force transferred to the piers are small when the pre-strain level is increased from 1% to 2.5%. Overall, these observations imply that applying an initial tensile force to the SMA wires that corresponds to a strain of 1-1.5% increases the effectiveness of the SMA device in reducing the seismic response of the bridges isolated by the SRB isolation system.
Finally, the effect of the rubber stiffness on the performance of the SMA/rubber isolation system is evaluated. Here, the values chosen for the lateral stiffness of the laminated rubber are given in Table 2. These values of the rubber stiffness correspond to isolation periods between 1.0 s and 3.0 s for the bridge isolated by laminated rubber bearings. Figure 11 shows the variation of the mean of the response quantities as a function of $k_b$ for the isolated bridge subjected to different earthquakes. The results are given for $u_y = 40$ mm, $T = 20^\circ$C and $F_o = 0.10, 0.15$ and 0.25. For different design values of $F_o$ for the SMA component of the SMA/rubber isolation system, increasing the stiffness of the rubber bearing decreases the peak deck drift but augments the peak deck acceleration and base shear, which indicates a loss of potential advantages of seismic isolation. Also, since very low values of $k_b$ results in excessive isolator deformations, $k_b = 16$ or 25 kN/cm corresponding to isolation periods of 2.5 and 2.0, respectively, provides the best performance for the considered bridge structure.
3.4 A comparative study

In this section, the performance of the SMA/rubber isolation system is compared with an SMA-based sliding isolation system that is studied by Ozbulut and Hurlebaus [17]. The sliding isolation system, named as superelastic-friction base isolator (S-FBI), combines the superelastic shape memory alloys with a flat steel-Teflon bearing rather than a laminated rubber bearing considered in this study.

Based on the results of the previous section, an optimal SRB isolation system with the design parameters of $u_y = 40$ mm, $F_o = 0.25$, $k_b = 25$ kN/cm and a pre-strain level of 1.5%. The optimum design parameters for the S-FBI system are adopted from [17]. For the S-FBI system, the flat sliding bearings has a friction coefficient of 0.10 and the parameters of the SMA device are $u_y = 30$ mm and $F_o = 0.10$. No pre-strain is applied on the SMA wires. Note that for the above design parameters, the volume of the SMA wires used in the S-FBI system is 71% less than the volume of the SMA material employed in the SRB isolation system. Also, the results from the simulations of the bridge isolated by the laminated rubber bearings (LRB) with a lateral stiffness of $k_b = 25$ kN/cm and 2% viscous damping and pure-friction (P-F) bearings with friction coefficient of 0.10 are given to serve as a benchmark in the performance evaluation of the SMA-based isolation system.

Plots illustrating the peak response quantities for different isolation systems subjected to the six different earthquakes are given in figure 12 to 14. The mean of the results for these excitations are also presented in the same plots. It is clear that both SMA-based isolation systems successfully reduce the deck drift for all excitation cases. As it can be seen from figure 12, the results for peak deck drift for the SRB isolation system and S-FBI system are very close for the individual earthquake cases and the mean of the results for all excitations are the same. However, the SRB
isolation system produces higher peak deck accelerations and base shears than the S-FBI system. In particular, for the S-FBI system, the mean of the peak deck acceleration for the considered excitations is as low as 53% of that of the SRB isolation system and the mean of the peak normalized base shear is 35% lower than that of the SRB isolation system.

![Figure 12. Peak deck drift for the various isolation systems subjected to near-field earthquakes](image)

![Figure 13. Peak deck acceleration for the various isolation systems subjected to near-field earthquakes](image)
Figure 14. Peak normalized base shear for the various isolation systems subjected to near-field earthquakes

In order to further compare the performance of the two different SMA-based isolation systems, figure 15 displays the time histories of the deck drift, deck acceleration and normalized base shear for the Imperial Valley earthquake. The time history results for the NRB and P-F isolation systems are also provided in the figure.

It can be seen that the use of either the SRB isolation system or the S-FBI system significantly reduces the deck drift. Also, note that there is no residual displacement for both SMA-based isolation systems at the end of the motion. On the other hand, considerable residual deformations are present in the P-F system which lacks re-centering force capability. It can be also seen that the NRB system damp out the vibrations over much longer time.

It can be observed that the SRB isolation system produce higher deck acceleration and base shear response than the S-FBI system. However, the results for the SRB isolation system are still comparable to those of the NRB system. It should be also noted that the P-F system limits the maximum acceleration transmitted to the superstructure to a certain level that is a function of the friction coefficient. As compared to the P-F system, the S-FBI system to some extent increases the deck acceleration and base shear as a result of the increased stiffness due to the SMA device. However, it can be seen that the responses of the S-FBI system are comparable to those of the P-F system.

The increases in the deck acceleration response and pier base shear for the SRB isolation system as compared to the S-FBI system can be better explained by comparing the hysteretic forces generated in both isolation systems. Figure 16 illustrates the force-deformation curves of the SRB isolation system and the S-FBI system for Imperial Valley earthquake. It can be seen that the SRB isolation system has a higher stiffness than the S-FBI system and hysteretic force generated in the SRB isolation system is considerably larger than that of the S-FBI system. This higher isolator force that is transmitted to the piers from deck results in larger base shears for the SRB isolation system.
Figure 15. Time histories of various response quantities of the isolated bridge subjected to Imperial Valley earthquake
Figure 16. Force-deformation curves of the SRB isolation system and the S-FBI system subjected to Imperial Valley earthquake

Figure 17 displays the absolute input energy to the non-isolated bridge and isolated bridge with various isolation systems. It is clear that the input energy decreases when the bridge is isolated. This decrease is more noticeable for the P-F system and the S-FBI system. It should be also noted that the S-FBI system has the minimum energy accumulation at the end of the motion for both absolute and relative energy formulations.

Figure 18 shows the time history of recoverable energy (kinetic energy + strain energy) transmitted to the bridge structure isolated by various isolation systems. It can be seen that there is a substantial reduction in recoverable energy, which is the cause of damage in the structure, for the P-F system and S-FBI system in comparison with that of the NRB system and SRB system. This is due to the fact that the force transmitted to the superstructure by the P-F or the S-FBI system is considerably smaller than that by the NRB or the SRB system. When the SMA-based isolation systems are compared, it can be noticed that the recoverable energy of the bridge structure isolated by the S-FBI system is 60% smaller than that of the SRB system.

Time histories of the absolute input energy and energy absorbed by the subcomponents of SMA-based isolation systems, i.e., the rubber and steel-Teflon bearings and the SMA device are plotted in figure 19 for the S-FBI system and the SRB isolation system subjected to Imperial Valley earthquake. It can be seen that the energy is dissipated mainly by the SMA device for the SRB isolation system whereas the SMA device serves as a re-centering component in the S-FBI system and the energy is dissipated through friction in the sliding surface for the S-FBI system.
Figure 17. Time histories of absolute input energy for the non-isolated and isolated bridge structures subjected to Imperial Valley earthquake.

Figure 18. Time histories of recoverable energy for various isolation system subjected to Imperial Valley earthquake.
4. Conclusions

As an alternative to conventional rubber isolators such as high damping rubber bearing and lead rubber bearing, smart rubber bearing systems with shape memory alloys (SMAs) have been proposed in recent years. As a class of smart materials, shape memory alloys show excellent re-centering and considerable damping capabilities which can be exploited to obtain an efficient seismic isolation system. This study investigates sensitivity of seismic response of a multi-span continuous bridge isolated by an SRB isolation system. The smart isolation system consists of a laminated-rubber bearing and an additional re-centering and energy dissipating device made of NiTi superelastic wires. A temperature- and rate dependent model is used to characterize the behavior of the SMA device. Six historical ground motion records are adjusted using the program RspMatch2005 to match a target design spectrum and employed as the external excitation in simulations. The parameters for the sensitivity analysis are chosen to be the normalized forward transformation strength of the SMA device $F_\alpha$, the forward transformation displacement of the SMA device $u_y$, the pre-strain level of the SMA wires, the lateral stiffness of the laminated rubber bearings $k_b$, and environmental temperature changes. A large number of time-history analyses of the isolated bridge are performed to assess the effects of these parameters on the various response quantities of isolated bridges. In particular, the variation of peak deck drift, deck acceleration, and normalized base shear with analysis parameters are evaluated.

It is found that there is a trade-off between the displacement response of the deck and the deck acceleration, as well as the base shear for the increasing values of $F_\alpha$. The optimum value of $F_\alpha$ is said to be in the vicinity of 0.25. It is also observed that the variation of $u_y$ in the range of 20-50 mm
does not significantly change the peak deck displacement response of the isolated bridge. Yet, since a lower value of $u_y$ implies shorter wire lengths for a fixed 1% forward transformation strain, the stiffness of SMA device increases when $u_y$ decreases and, as a consequence, the deck acceleration and normalized base shear increase about 30% and 39%, respectively. The variation of the seismic response of the isolated bridge with environmental temperature is also evaluated. It is found that the effects of temperature change are more prominent in the case of a decrease in the temperature. Specifically, as temperature decreases 20°C compared to reference temperature of 20°C, peak deck drift experiences an average of 25% increase with a maximum of 62%, and peak deck acceleration and normalized base shear vary to a maximum of 25% and 27%, respectively, for six excitation cases considered here. On the other hand, peak deck drift increases an average of 6% with a maximum of 9%, while there is a maximum increase of 27% in both peak deck acceleration and normalized base shear for all considered cases when temperature increases to 40°C from the reference temperature. Therefore, the effect of temperature change cannot be neglected during design of the isolation system since it affects the seismic response of the isolated bridge considerably. It is also observed that when the NiTi wires are pre-strained so that they will have an initial strain in the range of 1-1.5%, the effectiveness of the SRB isolation system improves. The effect of rubber stiffness on the seismic response of the bridge is also analyzed.

Finally, the performance of the SRB isolation systems is compared with an S-FBI system that combines a flat sliding bearing with an SMA device. It is found that the bridge structure isolated by either the SRB isolation system or the S-FBI system has very similar results for the peak deck drift response for considered excitations. However, it is noted that the peak deck acceleration and peak base shear exhibits higher values in the case of the SRB isolation system.

It is also observed that the S-FBI system attracts smaller quantities of input energy than the S-RBI system. It is shown that the energy is mainly dissipated by the SMA device for the SRB isolation system. On the other hand, the energy dissipation in the S-FBI system is through friction, while the SMA component of the isolation system serves as a re-centering device. Since the energy dissipation in the SRB isolation system almost solely relies on the hysteretic behavior of SMAs, larger amount of SMA material is required for the SRB isolation system. Noting that the high cost of the SMA is mostly cited as one of the main barriers that preclude the use of SMAs in a full-scale seismic application and considering superior structural response of the S-FBI system, it can be concluded that the S-FBI system which combines SMAs with flat sliding bearings has more favorable properties than the SRB isolation system which consists of a laminated rubber bearing and an SMA device.
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