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Seismic performance of a multi-span bridge fitted with superelastic SMA based isolator

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ABSTRACT: Although seismic isolation is a mature technique of protecting bridges against potential earthquake damage, new and innovative research efforts have been extended to find out the most effective base isolation devices. Conventional lead–rubber bearings (LRB) and High Damping Rubber Bearing (HDRB) are widely used for mitigating earthquake induced damage. But these bearings may have a problem of instability and unrecovered deformation with a strong ground motion. The superelastic behavior of shape memory alloys (SMAs) provides a stress-strain relation, which is characterized by large hysteresis, superelastic effect, large ductility and variation of the material properties at different level of strain and all these properties make SMA a potential candidate to be used in isolation system. Superelastic SMAs are unique alloys that have the ability to undergo large deformations, but can return to their undeformed shape by removal of stresses. This study illustrated the behavior of shape memory alloy used as an isolation device in a two-span continuous RC bridge. The results showed that SMA devices were able to limit the relative motion between the base and the superstructure and could regain its original position after the earthquake. The results were also compared to the performance of lead–rubber bearings and high damping rubber bearing.

1 INTRODUCTION

Smart base isolation techniques (Skinner *et al*., 1993; Soong and Dargush, 1997; Nagarajaiah, 2007) have been studied for years throughout the world to protect structures against devastating earthquakes due to their affordability in terms of production and maintenance. Lack of structural redundancy and adaptive structural characteristics make simple span highway bridges susceptible to earthquake induced damage. Seismic isolation, a contemporary trend in earthquake resistant design has been developed to extenuate the effect of earthquake on buildings, bridges and other structures. Seismic isolation strategy imposes period shift of structures and cutting of load transmission paths. Most of the simple span bridges have their fundamental period of vibration in the range of 0.2 to 1 s which is in the vicinity of the predominant periods of earthquake-induced ground motions (Kobe earthquake, Kobe, 1995 etc.). Seismic isolation can quash the seismic forces on the bridges by prolonging the fundamental period of the bridge. Isolation literary means separation and practically seismic isolators uncouple the bridge deck (which is responsible for the development of base shear in the supporting abutments and piers) from bridge substructure during hazardous ground motion, accordingly abridging the forces imparted to abutments and piers. Thus, seismic isolation protects the bridge against damage from the earthquake by limiting the earthquake attack rather than resisting it.

Innovative techniques for controlling structural response are searching for smart materials which can introduce new possibilities in earthquake protection methods. One class of such materials known as shape memory alloys (SMAs). Superelastic (SE) SMAs are unique alloys that have the ability to undergo large deformations and return to its original shape upon stress removal. This is a distinct property that makes SMAa smart material and a strong contender for use as smart material in seismic regions (Alam et.al 2007).

Worldwide applications of seismic isolation and research projects signify the efficacy of this technology against seismic events. Numerous research works have been carried out on seismic isolation of bridges and have been well evaluated and reviewed. The potency of lead-rubber bearings in reducing the seismic response of bridges have been reviewed by (Ghobarah and Ali 1988) and (Turkington et al. 1989). Analytical and experimental studies utilizing Friction Pendulum System (FPS) conducted by (Constantinou et al. 1992) and (Tsopelas et al. 1996a) resulted that the inclusion of the FPS can considerably subdued the imparted inertia forces and displacements. Eftekhari and Zadeh (1996) discussed the effects of isolators and their locations on the dynamic behaviour of isolated bridges. Sugiyama (2000) investigated that during a strong ground motion the response of a sliding type base isolation system is better than a LRB system although the relative displacement between the superstructure and the substructure is considerably large. Abe et al. (2000) evaluated the seismic performance of bridges isolated with lead-rubber bearings, high damping rubber bearings and natural rubber bearings and compared their stiffness and damping values. A study on simple span bridges supported on two column piers conducted by Saidi et al. (1999) showed that proper design of isolators can result in relatively small displacement while reducing dynamic forces.

Graesser and Cozzarelli (1991) explored the possibility of using SMAs as new materials for seismic isolation. Experimental and theoretical studies have recently been carried out on exploiting SMA-based devices for structural control implementation (e.g. Witting and Cozzarelli, 1992, Aiken et al., 1993; Hodgson and Krumme, 1994; Dolce et al., 2000; Duval et al., 2000). Dolce et al. (2000) gave a state-of-the-art review of the development of passive control devices based on SMAs up to 1999.

In this paper the effectiveness of SMA isolation systems in reducing structural seismic responses has been assessed through a finite element analysis on a two span continuous reinforced concrete (R/C) bridge. In order to get a comprehensive evaluation, the structural response of the models equipped with SMA isolation systems was compared to that of models equipped with more common isolation devices such as high damping rubber bearing (HDRB) and lead rubber bearing (LRB).

2 SHAPE MEMORY ALLOY

Shape memory means the ability of recovering large strains induced in certain alloys (Ni–Ti, Cu–Al, etc.) spontaneously or by heating, without any residual deformation. The particular characteristic of shape memory alloys is strongly related to a reversible solid–solid phase transformation, which can be thermal or stress-induced. An SMA remains in the austenite state at relatively high temperatures, while it changes to the martensite state with cooling. In the stress-free state an SMA has four states according to temperature variation: M_s and M_f during cooling and A_s and A_f during heating. The temperatures at which the transformation starts and finishes are represented by M_s and M_f, respectively, and A_s and A_f indicate the temperature that at which the inverse transformation starts and finishes, respectively as shown in fig.1 (a).

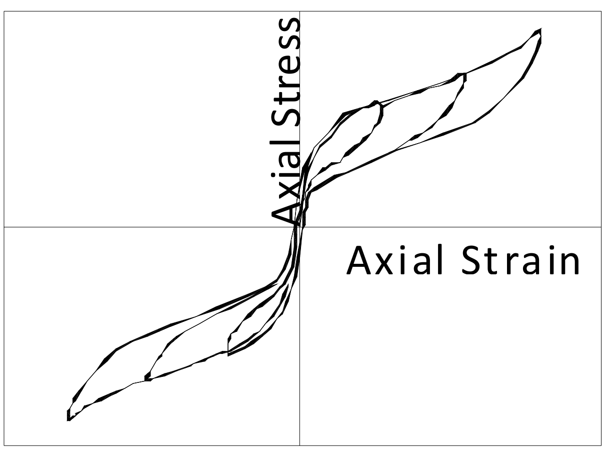

Figure.1(a) Stress–strain relationship of the SMA

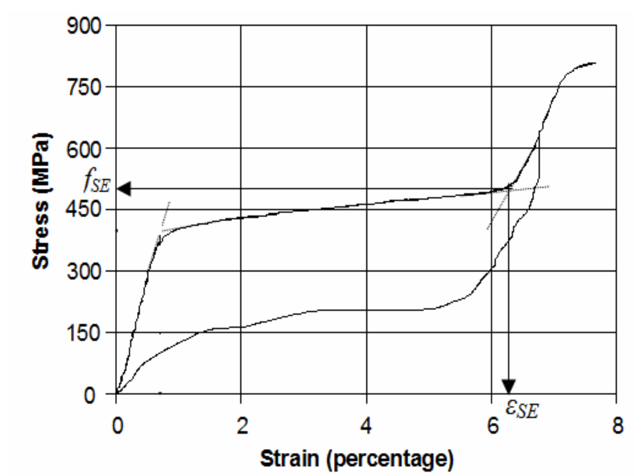

Figure.1 (b) Superelastic effect of the SMA

For some SMAs, such as Nitinol (Ni–Ti SMA), the phase transformation can be induced by stress at room temperature if the alloys have the appropriate formulation and treatment. When an SMA in austenite state is stressed, a phase change from austenite to martensite occurs at a critical stress level because the martensite state becomes stable over the critical stress value. In reverse unloading process, as unstressed martensite is unstable, the austenite state again becomes stable and the original undeformed shape is recovered. Nitinol shape memory alloys (Ni-Ti SMAs) hold several desirable properties for their use 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 at strains above 6%, (*v*) excellent fatigue resistance, and (*vi*) excellent corrosion resistance. Looking at the stress–strain relationship of SMAs in Fig. 1 (b), their primary features of the superelastic effects can be understood. At first, Ni–Ti

SMAs show elastic range, then a long horizontal plateau, followed by a significant stiffness hardening, and in an unloading process a large hysteretic area is developed without any residual strain. This feature possesses a high level of energy dissipation and the stress induced martensite state, occurring approximately at 6–8% strain, is very useful as for restrainer action.

3 HIGH DAMPING RUBBER BEARING

Among several methods of seismic isolation, the application of High Damping Rubber Bearings (HDRBs) is considered as one of the most promising isolation devices. Rubber bearings for base isolation devices are usually made with alternating thin horizontal layers of rubbers bonded to steel plates. In the concept of base isolation, the steel plates provide large stiffness under vertical load, while the rubber layers provide low horizontal stiffness, when the structure is subjected to lateral loads (e.g., earthquake, wind, etc.). The devices are usually subjected either to compression or to a combination of compression and shear (Amin et al. 2006).

Different models are used to simulate the behaviour of HDRB in its horizontal direction. For reasons of simplicity, a viscoelastic linear model is usually applied for the purposes of design of isolated structures (Kelly, 1990). However, when the analysis of the response of an isolated structure is conducted, an accurate structural response during the whole time of the earthquake is required. In this case, an accurate nonlinear strain rate dependent model of HDRB is essential. In some specifications (e.g. .AASHTO, 2000; JRA, 1996, 2002) the nonlinear characteristics of HDRBs are expressed in terms of a bilinear model for seismic design of bridges with HDRB. However, the past investigation conducted by some authors (Hwang et al.2002, Dall'Asta and Ragni, 2006, Bhuiyan et al. 2009) have indicated that the mechanical behaviour of HDRBs is characterized by strain-rate-dependent hysteresis property. For this purpose, an accurate nonlinear model of HDRB is considered in this paper. The bearing's parameters that describe the lateral force– displacement bilinear law are the initial elastic stiffness K_u, the post yield stiffness K_d, the characteristic strength Q_d. Values for these parameters are acquired from (Bhuiyan, 2009).

4 LEAD RUBBER BEARING

The lead-rubber bearing was developed in response to the inadequate damping characteristics of the natural rubber bearing (Park and Otsuka 1999). The bearing is essentially identical to the natural rubber bearing except for the addition of a cylindrical lead "plug" located at the center of the bearing. The lead plug induces a bilinear response to high levels of lateral excitation, where the stiffness of the system decreases after the plug deforms inelastically in shear.

LRB can be considered to consist of two elements: (a) a linear viscoelastic element representing the rubber component, and (b) a linear elastic–perfectly plastic element simulating the lead plug. This model assumes that the response relationship is bilinear, as indicated in Fig.2

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Following AASHTO Guide Specifications for Seismic Isolation Design (AASHTO, 1999), LRB is modeled by a bilinear model based on the parameters as shown in Fig. 2. Here, K_u is the elastic stiffness, which is effective in resisting service loads such as wind, K_d is the post-yield stiffness that is important in resisting activated when the lateral force exceeds F_y , Q_d is characteristic strength, F_y is the yield force where the initial stiffness changes to post yield stiffness, K_{eff} is the effective stiffness; d_y is the yield displacement; d_{max} is the maximum displacement; F_{max} is the maximum design force of the isolator and EDC is the energy dissipated in one fully reversed cycle to the maximum displacement shown by the area within the force–displacement loop. The equivalent viscous damping, β can be approximated as:

$$\beta = \frac{EDC}{2\pi k_{eff} d_{\max}^2} \tag{1}$$

where, EDC is the total area under the hysteresis loops, K_{eff} is the effective stiffness, and d_{max} is the maximum displacement.

One of the most important parameters is F_y/W (the ratio of the yield force of the isolator to the total weight of structure), which is largely related to structural responses and the absorbing energy of isolators under earthquake loadings [15]. The yield strength of the isolator is associated with the characteristic strength by the relation, $F_y = Q_d/(1-K_d/K_u)$. The elastic stiffness K_u is usually taken as 10 times the post yield stiffness (Naeim and Kelly 1999). Based on these assumptions the values of various parameter for this study are selected (Table 1).

Table 1: Properties of Isolation Devices Used for Bilinear Modeling: (Bhuiyan, 2009).

Isolator	Type	Initial Stiffness (kN/m)	Post yield Stiffness (kN/m)	Yield Strength (kN)	Characteristic Strength (kN)	Effective Stiffness (kN/m)	Effective Damping
HDRB	Bilinear	69665	11533	1153.7	962.7	16347	17%
LRB	Bilinear	124900	11800	900	800	15900	15%

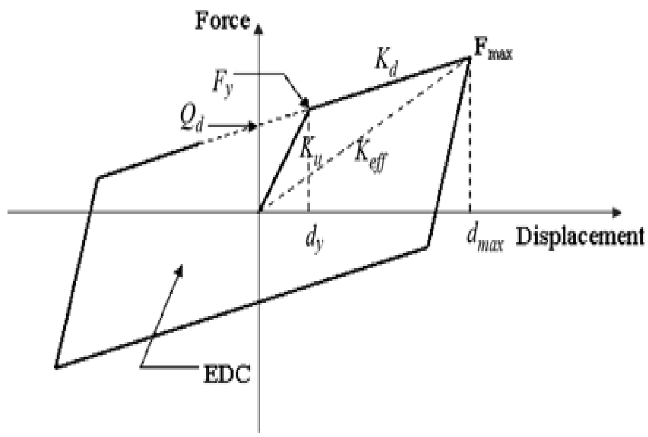

Figure 2. Bilinear Force-Displacement Characterization of LRB.

4 SMA BAR BASE ISOLATOR

The SMA bar base isolator used in this study is similar to that of (Wilde et al. 2000). This model revealed that the SMA isolation system provides variable responses to excitation as well as a notable damping. The SMA bar base isolation system is illustrated in the following figure. The SMA was modeled following the model of (Auricchio *et al*., 2001). A superelastic SMA bar having a diameter of 34 mm is used to connect the pier with the deck. The bar is supported by cushion materials around; however, its contribution to the response has been neglected. Table-2 illustrates the properties of the SMA used in this model.

Table 2: Properties of SMA Device Used for Modeling: (Alam et al. 2008).

Isolator	Type	Modulus of Elasticity (kPa)	Austenite to Martentise starting stress (kPa)	Austenite to Martentise finishing stress (kPa)	Martentise to Austenite starting stress (kPa)	Martentise to Austenite Finishing stress (kPa)	Superelastic plateau strain length (%)
SMA	Superelastic	5.42 E+07	414000	530000	380000	130000	6.2

The selected parameters of SMA correspond to an alloy with perfect superelastic behavior. The length and the cross-sectional area of the SMA bars are optimized such that the stress in the SMA bars reaches the elastic response of pure martensite during the strongest considered ground motion.

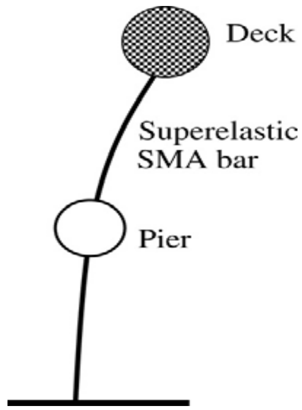

Figure 3. Schematic of the SMA isolation device for bridge [Wilde et al.2000]

5 BRIDGE MODEL

A simple two span bridge located in the western part of Canada was used as the basis of the model analyzed in this study. Figure 3 represents the schematic diagram of the bridge considered. The superstructure is a continuous girder element supported on isolators at the top of the piers. The superstructure is of steel and concrete composite type, having two spans each having a length of 31500 mm supported on three piers. The substructure of the bridge consists of reinforced concrete piers having a length of 17000 mm as shown in Fig. 4.

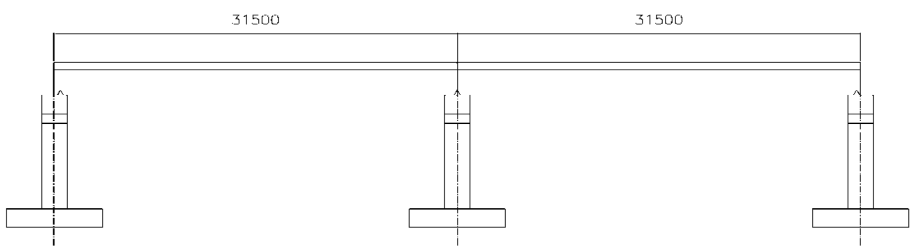

Figure 4. Conceptual Geometry of The Analyzed Model.

Both superstructure and substructure are modeled as a lumped mass system divided into a number of small discrete segments; each adjacent segment is connected by a node and at each node two degrees of freedom is considered. Masses of each segment are assumed to be distributed between two adjacent nodes in the form of point masses. Piers and decks consist of 400 fiber elements for unconfined and confined concrete and reinforcements. The footings were assumed to provide full fixity at the base of the column to maximize the demand on bridge element.

6 RESPONSE ANALYSIS

A non-linear time-history analysis is conducted in this study on a base-isolated bridge, isolated with three different isolators (i.e. SMA, HDRB and LRB) idealized as a rigid deck, ignoring flexibility in bridge deck to find out the bridge response under earthquake excitation. This simplified mathematical model of base-isolated simple- span bridge is considered excited under unidirectional horizontal component of Vancouver BC earthquake ground motion. The time histories (acceleration and displacement) of the considered ground motion are presented in Fig. 5.

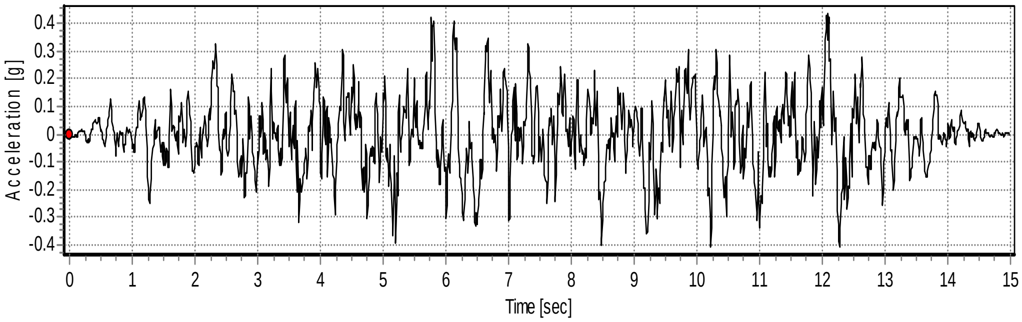

Fig.5 Time History of the Ground Motion Considered

The time histories of the Deck displacement of the bridge with the SMA, HDRB and LRB systems are plotted in Fig.6.

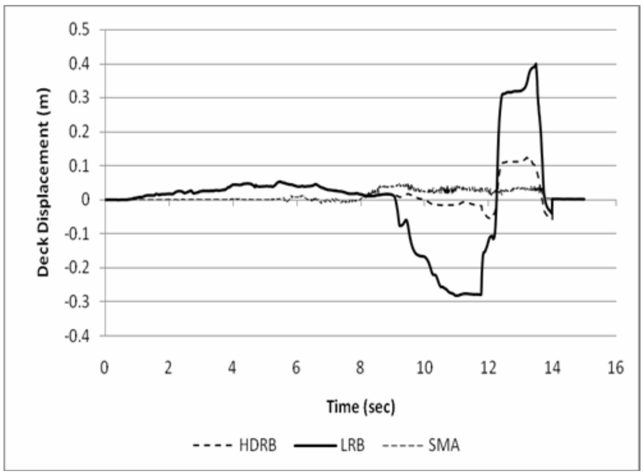

Fig.6 Comparison of Time variation of deck displacement in the Bridge isolated by HDRB, LRB and SMA Isolation Device

For this excitation amplitude, the SMA device works like a fixed connection between deck and pier, while with the LRB system, even for this excitation amplitude, the relative displacement reaches 0.4 m and that for HDRB is 0.123m. Looking at the result for deck displacement the SMA is most effective in reducing the deck displacement whereas the effectiveness of LRB is less than that of HDRB. The effective restriction of the deck displacement is desirable to prevent unseating of the deck and instability of the bearings.

Since the SMA system has larger stiffness than that of LRB and HDRB system the force transmitted to the pier from the deck is larger, resulting in a larger shear force in the pier. The time history of shear force based on the applied ground motion is shown in Fig. 7. The maximum shear force in the pier for the bridge with an SMA system is 4091 kN. The maximum pier shear force for the bridge equipped with an LRB system is 3187 kN and for HDRB system the value is 2717 kN. However shear force exerted on pier isolated by SMA device is 1.3 times larger than that equipped with LRB and almost 1.5 times greater than that of the HDRB system.

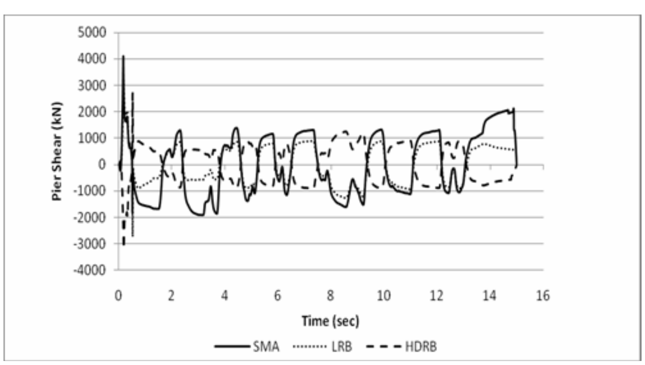

Fig.7: Comparison of Time variation of pier top shear in the Bridge isolated by HDRB, LRB and SMA Isolation Device.

One drawback of the SMA isolation device is an increase in the acceleration response. The nonlinear characteristics of SMAs, particularly during the transition from "plastic" response to the elastic one, result in a sudden jump in acceleration. For all the loading levels, the peak acceleration of the deck with an SMA device is greater than the acceleration response of the LRB and HDRB system. The maximum acceleration induced in bridge isolated with SMA device is 10 m/s^2 and the bridges isolated with LRB and HDRB experienced less than 5 m/s^2. It reveals that SMA causes the deck acceleration to be almost two times than that of other two systems. The difference in the acceleration response under the considered ground excitation is shown in Fig. 8.

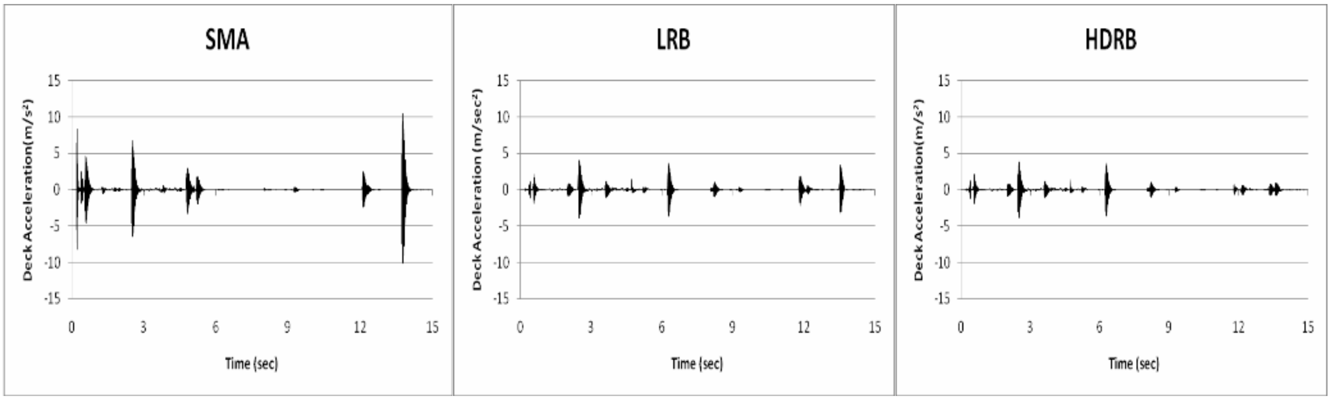

Fig.8: Comparison of Time variation of deck acceleration in the Bridge isolated by SMA, LRB and HDRB Isolation Device.

7 DISCUSSION

Wilde et al. (2000) proposed an isolation system with SMA bar damper added to the laminated rubber bearing. The performance of this isolation system was compared with the performance of a conventional isolation system using lead laminated rubber bearings with an additional stopper device. In this paper a large diameter SMA bar with cushioning around is used as an isolator to connect pier and deck and its performance has been compared to that of conventional HDRB and LRB isolator. Wilde et al. (2000) analyzed the bridge model under various ground excitations and reported that SMA isolation system provides stiff connection between the pier and the deck for small external loading. The displacement time history shows that SMA restricts the relative displacement between deck and pier more effectively than other two systems. Wilde et al. (2000) found that inclusion of SMA increases the induced deck acceleration by almost 3 times whereas the current study shows the increase by 2.75 times, which is close. Moreover, Wilde (2000) reported that the pier shear with SMA device increases by 1.30 times whereas the present analysis shows similar results, which is 1.28 times to be precise.

8 CONCLUSION

In this paper a smart isolation system for highway bridges, consisting of superelastic Shape Memory Alloy (SE-SMA) has been explored and its performance has been compared to that of other two types of isolation devices, which are high damping rubber bearing (HDRB) and lead rubber bearing (LRB). The SMA bearings satisfactorily restrained the deck displacement and the relative displacement between the deck and the pier for strong ground motion. Although the shear demand on the pier increased more than the lead–rubber bearing and high damping rubber bearing, they can safely restrain the deck from falling off the piers during strong earthquakes.

From the present study, the following conclusions may be drawn:

1) The SMA isolation system provides stiff connection between the pier and the deck for small external loading.
2) The SMA isolator satisfactorily restrained the deck displacement and the relative displacement between deck and pier for strong ground motions.
3) The SMA isolation system has inherent centering ability due to the superelastic response of the alloy.
4) The peak acceleration of the deck with an SMA device is greater than the acceleration response of the LRB and HDRB system.

REFERENCES

Abe, M., Fujino, Y. and Yoshida, J. 2000. Dynamic behavior and seismic performance of base-Isolated bridges in observed seismic records. *Proc. of 12th World Conf. on Earthquake Engineering*, Paper No. 0321.

Aiken, I. D., Nims, D. K., and Whittaker, A. S., and Kelly J. M., 1993, "Testing of passive energy dissipation systems," *Earthquake Spectra* 9, 335–369.

Alam, M.S., Youssef, M. A., and Nehdi, M., 2007, Utilizing shape memory alloys to enhance the performance and safety of civil infrastructure: a review, *Canadian Journal of Civil Engineering* 34(9),1075–1086.

Alam, M.S., Youssef, M.A., and Nehdi, M. Analytical prediction of the seismic behaviour of superelastic shape memory alloy reinforced concrete elements. *Engineering Structures* 2008, 30: 3399-3411.

Amin, A.F.M.S., Wiraguna, S.I., Bhuiyan, A.R. and Okui, Y., 2006. Hyperelasticity model for finite element analysis of natural and high damping rubbers in compression and shear. *Journal of Engineering Mechanics*, ASCE .

Auricchio F, Faravelli L, Magonette G and Torra V ,2001, *Shape Memory Alloys: Advances in Modelling and Applications*, Barcelona: CIMNE.

Bhuiyan, A.R., Okui, Y.,Mitamura, H., and Imai, T., 2009. A Rheology model of high damping rubber bearings for seismic analysis: Identification of nonlinear viscosity. *International Journal of Solids and Structures*, 46:1778–1792.

Bhuiyan, A.R. 2009. Rheology modeling of laminated rubber bearings for seismic analysis, *PhD Dissertation. Department of Enviornmental Science and Civil Engineering, Saitama University*.

Constantinou, M.C., Kartoum, A., Reinhorn, A.M. and Bradford, P. 1992. Sliding isolation system for bridges: experimental study. *Earthquake Spectra*, Vol. 8: 321-344.

Ckoi, E., Nam, T. and Cho, B.S., A new concept of isolation bearings for highway steel bridges using shape memory alloys, *Can. J. Civ. Eng*. 32: 957–967 (2005)

Dall'Asta, A., and Ragni, L. 2006. Experimental tests and analytical model of high damping rubber dissipating devices. *Engineering Structures*, 28: 1874–1884.

Dolce, M., Cardone, D., and Marnetto, R., 2000, Implementation and testing of passive control devices based on shape memory alloys, *Earthquake Engineering and Structural Dynamics* 29, 945–968.

Duval, L., Noori, M. N., Hou, Z., Davoodi, H., and Seelecke, S., 2000, Random vibration studies of an SDOF system with shape memory restoring force, *Physica B* 275(1–3), 138–141.

Hodgson, D. E. and Krumme, R. C., 1994, Damping in structural application, in *Proceedings of the 1st International Conference on Shape Memory and Superelastic Technologies*, Pacific Grove, CA.

Eftekhari, M. and Zadeh, M.T. 1996. Effect of seismic isolation systems on dynamic behaviour of bridges under earthquake loading , *Proc. of 11th World Conf. on Earthquake Engineering*, Paper No. 1347.

Eugene, E. and Gorton, C. and Hawkins, J. M. 1980. *Oxford American Dictionary*, New York, USA.

Ghobarah, A. and Ali, H.M. 1988. Seismic performance of highway bridges. *Engineering Structures*, Vol. 10: 157-166.

Graesser, E.J., and Cozzarelli, F.A. 1991. Shape memory alloys as new materials for aseismic isolation. ASCE Journal of Engineering Mechanics, 117(11): 2590–608

Hwang, J.S., Wu, J.D.,Pan, T.C. and Yang, G., 2002. A mathematical hysteretic model for elastomeric isolation bearings. *Earthquake Engg Struct. Dyn.* 31:771–789.

Kunde, M.C. and Jangid, R.S. 2003. Seismic behaviour of isolated bridges: A state-of-the-art review. *Electronic Journal of Structural Engineering*, Australia, Vol. 3: 140-170.

Naeim, F. and Kelly, J. M. 1999. *Design of Seismic Isolated Structures: From Theory to Practice*, Wiley, Chichester, England.

Pan, T.C. and Yang, G. 1996. Nonlinear analysis of base-isolated mdof structures. *Eleventh World Conf. on Earthquake Engg.*, Acapulco, Mexico, paper no. 1534.

Park, J. and Otsuka, H. 1999. Optimal yield level of bilinear seismic isolation devices. *Earthquake Engineering and Structural Dynamics*, Vol. 28: 941-955

Saidi, M., Maragakis, E.and Griffin G 1999. Effect of Base Isolation on The seismic response of multi column bridges. *Structural Engineering and Mechanics*, Vol 8: No-4.

Simo, J.C. and Kelly, J.M. 1984. The analysis of multilayer elastomeric bearings. *Journal of Applied Mechanics, ASME*, 51(2), 244-250.

Skinner RI, Robinson WH, McVerry GH (1993), *An introduction to seismic isolation*, Chichester: John Wiley & Sons.

Soong TT, Dargush GF (1997), *Passive Energy Dissipation Systems in Structural Engineering*, Chichester: John Wiley & Sons.

Sugiyama, T. 2000. Comparison of seismic response between bridge with sliding type base isolation system and that with laminated rubber bearing. *Proc. of the Twelfth World Conference*, Paper No. 1221.

Tsopelas, P., Constantinou, M.C., Kim, Y.S. and Okamoto, S. 1996a. Experimental study of fps system in bridge seismic isolation. *Earthquake Engineering and Structural Dynamics*, Vol. 25: 65-78.

Turkington, D.H., Carr, A.J. Cooke, N. and Moss, P.J. 1989. Seismic design of bridges on lead-rubber bearings. *Journal of Structural Engineering, ASCE,* Vol. 115: 3000-3016.

Witting, P. R. and Cozzarelli, F. A., 1992, Shape memory structural dampers: Material properties, design and seismic testing, *NCEER Report*, No. 92/13, *State University of New York, Buffalo, NY.*

Wilde, K., Gardoni, P. and Fuzino, Y.2000, Base isolation system with shape memory alloy device for elevated highway bridges, *Engineering Structures*, 22 (2000) 222–229.