Civil Engineering Infrastructures Journal, 47(2): 153 – 171, December 2014
ISSN: 2322 – 2093

Application of Shape Memory Alloys in Seismic Isolation: A Review

Alvandi, S.[1] and Ghassemieh, M.[2*]

[1] M.Sc., Student, School of Civil Engineering, College of Engineering, University of Tehran, P.O. Box: 11155-4563, Tehran, Iran.
[2] Associate Professor, School of Civil Engineering, College of Engineering, University of Tehran, P.O. Box: 11155-4563, Tehran, Iran.

Received: 11 May 2013; Revised: 08 Dec. 2013; Accepted: 28 Dec. 2013

ABSTRACT: In the last two decades, there has been an increasing interest in structural engineering control methods. Shape memory alloys and seismic isolation systems are examples of passive control systems that use of any one alone, effectively improve the seismic performance of the structure. Characteristics such as large strain range without any residual deformation, high damping capacity, excellent re-centering, high resistance to fatigue and corrosion and durability have made shape memory alloy an effective damping device or part of base isolators. A unique characteristic of shape memory alloys is in recovering residual deformations even after strong ground excitations. Seismic isolation is a device to lessen earthquake damage prospects. In the latest research studies, shape memory alloy is utilized in combination with seismic isolation system and their results indicate the effectiveness of the application of them to control the response of the structures. This paper reviews the findings of research studies on base isolation system implemented in the building and/or bridge structures by including the unique behavior of shape memory alloys. This study includes the primary information about the characteristic of the isolation system as well as the shape memory material. The efficiency and feasibility of the two mechanisms are also presented by few cases in point.

Keywords: Passive Control, Re-Centering, Seismic Isolation Systems, Shape Memory Alloys (SMA), Structural Control.

INTRODUCTION

It is progressively being recognized that using various methods of structural control effectively protect structures from earthquake forces. They are not only effective for mitigating earthquake forces, but also are efficient in controlling undesirable vibrations of structures caused due to wind or seismic excitations. In recent years, many factors have appeared to show the need for the control of the structural response. These factors include increasing the flexibility of the structural systems, increasing safety levels, stringent performance level, and economic considerations.

Nowadays, for buildings and bridges, significant attention has been focused in research and development of structural control devices, with intention of reducing wind and seismic response. In the last two

* Corresponding author E-mail: mghassem@ut.ac.ir

decades, appreciable efforts have been made in developing the structural control concept into a workable technology. These control systems develop controllable force to add or dissipate energy in a structure, or even both. They can operate due to the specific devices incorporated with sensors, controllers, and real-time processes. Theses control systems are divided into four types: passive, active, hybrid and semi-active; which are described in what follows.

In passive control systems, one or more devices attached or embedded to a structure, designed to improve the stiffness or the structural damping and develop the control forces opposite to the motion of the structure. These devices do not require any external power source to operate and they are economical and simple in application (Marazzi, 2003). In active control systems, a large external power source controls actuators that apply forces to the structure. In an active feedback control system, the signals sent to the control actuators are a function of the response of the system measured by physical sensors (Marazzi, 2003; Pastia et al., 2005). Hybrid control systems employ a combination of passive and active devices with the goal of achieving improved performance and increasing the overall reliability and efficiency of the controlled structure (Faravelli and Spencer, 2003). The passive device can decrease the amount of required energy power if it is installed in the structure. It should be noted that the fundamental difference between an active and hybrid control system is in the amount of external required power to be implemented (Housner et al., 1997; Pastia et al., 2005). Semi-active controlled systems are a group of control systems that need energy to change the mechanical properties of the devices and to develop the control forces opposite to the motion of structure. In semi-active control systems the external energy requirements are smaller than those of typical active control. Therefore, in contrast to active control devices, semi-active control devices do not have the potential to destabilize the structural system (Marazzi, 2003; Spencer and Nagarajaiah, 2003).

Seismic isolation system, as a passive control system is one of the most well accepted way of protecting a structure against earthquake forces. The seismic isolation system effectively improves the seismic performance and seismic sustainability of the structure. In this system, the whole or part of a structure is separated from ground or other structural part to reduce the seismic response during an earthquake.

Despite the efficiency of base isolation system, demanding performance requirements have encouraged the development of new devices and using the unique characteristics of new advanced materials. This system has some limitations and drawbacks such as difficulties related to ageing, durability, complexity of the installation, maintenance and placing permanent displacements after strong earthquakes. This type of passive system needs to be replaced and change in the geometry of the structure after the earthquake (Dolce et al., 2000).

This paper investigates and reviews the latest applications of new materials such as Shape Memory Alloys (SMAs) in base isolation systems in order to overcome the above limitations. The important features of SMAs are: extraordinary fatigue resistance under large strain cycles, great durability, remarkable corrosion resistance, and no degradation due to ageing. Therefore, by implementing the SMAs in seismic base isolations, the following advantages are gained: lifetime limits (without having maintenance or replacement problems, even after several strong earthquakes), good control of forces and self-centering capability. Considering the widespread use of Shape Memory Alloy (SMA) in the context of civil engineering, this paper exclusively deals with the application of SMA Nitinol alloy in base isolation systems. Although most new SMA alloys have great damping capabilities, Nitinol has less damping efficiency in comparison with other isolation systems types such as high damping bearings and lead rubber bearing. This type of SMA alloy functions more as a restorer and controller. Ferrous shape memory alloys with greater damping capability than Nitinol are good choices to be used in base isolation systems; however, evaluation of Ferrous-SMA's performance and the effect of pre-straining need further study. Furthermore, applying this innovative system to structures is a new topic for future studies.

In what follows, primary characteristics of these new technologies in which contributed very much in the base isolation system will be presented.

BASE ISOLATION SYSTEM

Base isolation system is a new technology on seismic control of structure that is based on the concept of reducing the seismic demand rather than increasing the earthquake resistant capacity of the structure. Proper application of this technology leads to better performance of the structures during large earthquakes (Naeim and Kelly, 1999). It is a passive control device that is installed between the foundation and the base of the building structure. For bridges, the base isolators are installed between the deck and the pier. In buildings, the base isolator protects the structure from earthquake forces by reducing the seismic energy input into the structure and making the base of the building flexible in lateral directions. This results in increasing the fundamental period of the structure. Thus seismic isolation system can significantly reduce both floor accelerations and inter-story drift and therefore provide a proper economic solution to reduce the nonstructural damages due to earthquakes. As a result, two important features can be observed from the response of the structural system utilizing the base isolation system (Figures 1 and 2). The first feature is the period shift effect; which noticeably elongates the period of the structure and therefore results in significant reduction in the base shear of a structure or the pseudo-acceleration, as shown in Figure 1. The amount of reduction depends on the nature of the ground motion and the period of the fixed-base structure. The further flexibility lengthens the period of the structure and relative displacements across the isolators will increase. The second feature is the energy dissipating effect which provides extra damping in the system. With addition of structural damping in the system, the deformation of the structure can significantly be reduced (Figure 2). Also, a smaller base shear force will be induced on a structure with larger damping (Figure 1), and it is obvious that with higher damping levels the response of structure is less sensitive to variations in ground motion characteristics, as indicated by the smoother response curves for structures in both figures. It should be noted that for devices that extend the period of the structure, it is important to make sure that the structure is not located on soft soils region. For structures that are situated on soft soils which have long periods, the response of the structure expands and for such structures the devices with energy dissipation mechanisms should be used (Yang et al., 2003).

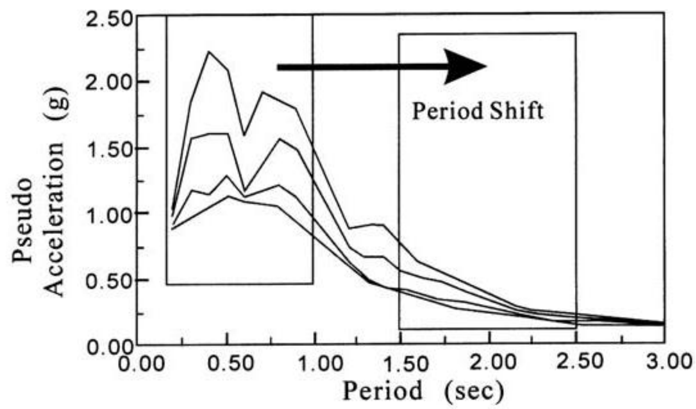


Fig. 1. Schematic of pseudo-acceleration spectra (Yang et al., 2003).

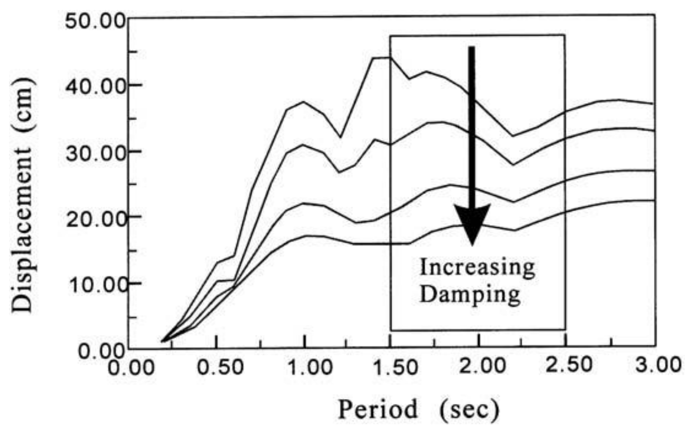


Fig. 2. Schematic of deformation spectra (Yang et al., 2003).

During the last 2 decades, different types of isolation devices including elastomeric bearings (with and without lead core), frictional/sliding bearings and roller bearings have been used practically for a seismic design of buildings in many new buildings. In choosing an isolation system, different parameters and issues would be considered in addition to shift the vibration period and add damping to the structure. Those factors are: (i) initial stiffness, (ii) yielding force and displacement, (iii) capacity of re-centering after deformation and (iv) vertical stiffness. There are two basic types of isolation systems: elastomeric bearings and sliding bearings. The elastomeric bearings with assigning low horizontal stiffness shift fundamental period of the structure to avoid resonance and the sliding isolation system is based on the concept of sliding friction. Most important characteristics of those systems will be presented; as follows:

Elastomeric Bearings

Natural Rubber Bearing (NRB) as the first introduced elastomeric bearing is composed of large rubber blocks without the steel reinforcing plates. It has a vertical stiffness several times more than the horizontal stiffness and with rubbers which are comparatively undamped. In this type of elastomer, the horizontal motion is connected to a rocking motion; thus resulting in vertical acceleration due to the rocking mode. In recent years, natural rubber bearings with internal steel reinforcing plates are introduced in order to reduce the lateral bulging of the bearings and also to increase the vertical stiffness (Naeim and Kelly, 1999). The natural laminated rubber bearings are included steel and rubber plates in the alternate layers as shown in Figure 3 and provide horizontal flexibility and high vertical stiffness (Datta, 2002).

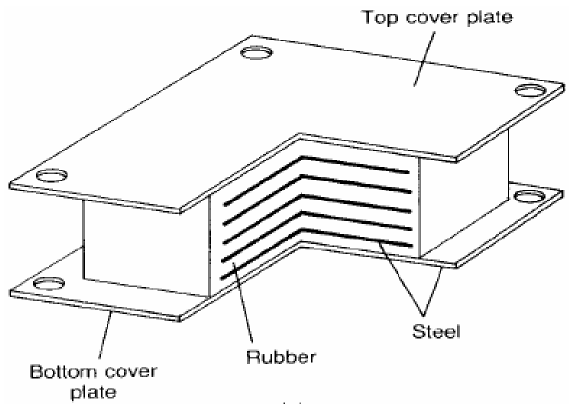


Fig. 3. Natural laminated rubber bearings (Datta, 2002).

Lead-Rubber Bearing (LRB) is now the most frequently used isolation system; as illustrated in Figure 4. This type of bearing is similar to the Natural laminated rubber bearing with additional central lead metal core which provides extra energy dissipation and less lateral displacement of the isolator (Mayes, 2000).

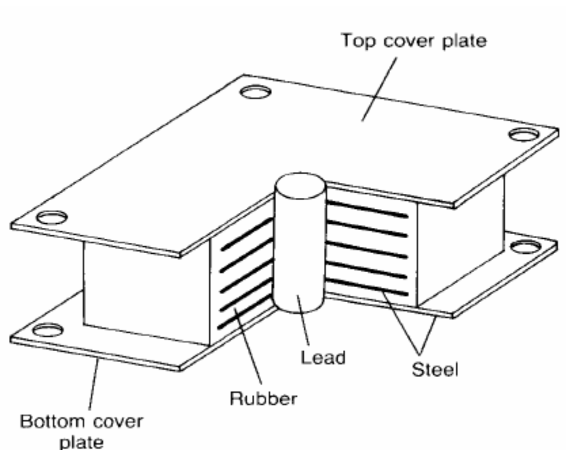


Fig. 4. Lead-rubber bearing (Datta, 2002).

High Damping Rubber Bearing isolator (HDR) as one type of elastomeric bearing is similar in shape to the Natural elastomeric bearing shown in Figure 3, except that it is made of specially compounded rubber that exhibits effective damping range between 0.1 and 0.2 of critical. One common feature of these systems is that they all share the desired feature of high damping capacity (Naeim and Kelly, 1999; Kelly, 2001).

Sliding Isolation Bearings

Utilizing the sliding isolation devices in the structures is the most effective technique in the seismic isolation which reduces the high levels of the superstructure's acceleration. In comparison with other isolator systems, these isolators are insensitive to the frequency content of earthquake excitation. The advantages of sliding isolation systems as compared with other conventional rubber bearings are: (i) being effective for a wide range of frequency input, and (ii) reducing torsional effects caused by the asymmetric building (Mayes, 2000).

The simplest sliding isolation system is the pure friction (P-F) system which is based on the mechanism of sliding friction which provides resistance to motion and dissipates energy. When this system is subjected to small earthquakes, it performs like a fixed base system due to the static frictional force. However, when it is subjected to large earthquake excitations, the static value of frictional force is conquered and sliding reduces the level of acceleration.

Mostaghel and Khodaverdian (1987) presented another type of sliding bearing named as Resilient Friction Base Isolation (R-FBI); which is shown in Figure 5. This base isolator is comprised of a central core of rubber and concentric layers of Teflon plates that are in friction contact with each other. The system provides damping and restoring force through the parallel action of friction.

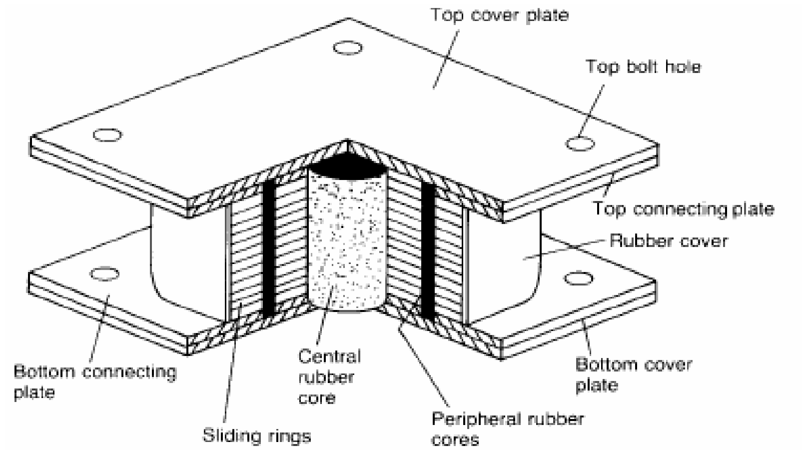


Fig. 5. Resilient friction base isolation (R-FBI) system (Mostaghel and Khodaverdian, 1987).

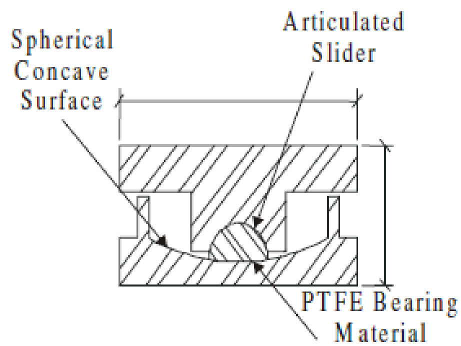


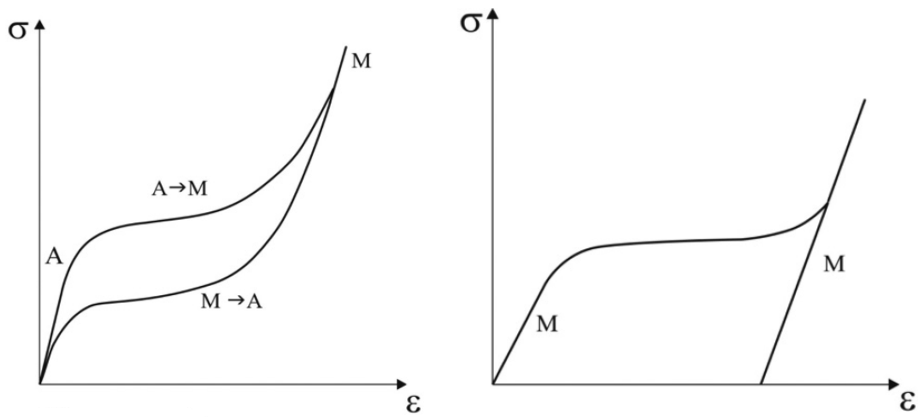
Fig. 6. Friction pendulum system (FPS) (Zayas et al., 1990).

Zayas et al. (1990) expressed the concept of sliding bearings compounded with the concept of a pendulum type response known as a friction pendulum system (FPS); as illustrated in Figure 6. In FPS, the isolation is acted by an articulated slider on spherical concave chrome surface. The slider is faced with a bearing material in which when it is in contact with the polished chrome surface, it results in a maximum sliding friction coefficient (Kunde and Jangid, 2003).

SHAPE MEMORY ALLOY MATERIAL

The major advance in construction technology is the development of advanced materials and its integration in innovative structural systems to provide better performance. An example of the advanced and smart materials is the shape memory alloy. SMAs were discovered in the 1930s but gained attention first in the late 1960s and later in the 1980s when smart materials were started to be introduced in the building industries. SMAs are materials to withstand large strains (up to 10%) without exhibiting plasticity (Brocca et al., 2002). Large elastic strain range, high damping capacity, re-centering, high fatigue resistance, no need of maintenance, durability and the recovery of strains by heat are unique characteristics which have made SMAs an effective damping device (DesRoches and Delemont, 2002; Motahari et al., 2007). Lately the maximum superelastic strain in such material reach up to 13.5% in different types of SMAs such as Ferrous shape memory alloys (Tanaka et al., 2010).

Shape memory alloys are materials that have the ability to recover their shape after undergoing large deformations through either heating or removal of load. The special property is made possible by a Martensitic phase transformation between a crystallographic high-symmetry (cubic crystal structure) Austenitic phases to a low-symmetry (monoclinic crystal structure) Martensitic phase. Austenite is stable at higher temperatures and lower stresses and Martensite is stable at lower temperatures and higher stresses. This will cause the phases to transform into each other at the presence of stress and/or temperature changes. A reorientation process known as twinning and de-twinning can also take place between Martensite variants at low temperatures. Because of this, two different behavioral phases can take place. The first one is the Pseudo-elasticity (PE) behavior, in which by applying stress to a material initially austenite with temperature above austenite start temperature, it will cause the material to transform inelastically into Martensite. This deformation will be fully recovered (on a different path) by removing the applied load; thereby resulting in the super-elastic behavior (Figure 7(a)). The second type of behavior is the reorientation of Martensite variants (De-twinning); in which at temperature lower than Martensite finish temperature, the SMA exhibits the shape memory effect. Deformations due to an applied stress are recovered by heating the material above the Austenite finish temperature. So a large hysteresis loop due to reorientation is revealed by applying tension–compression cyclic loading (Figure 7(b)) (DesRoches et al., 2004; Brocca et al., 2002).



(a) Pseudoelasticity (b) Shape memory effect

Fig. 7. Different behaviors of SMA material.

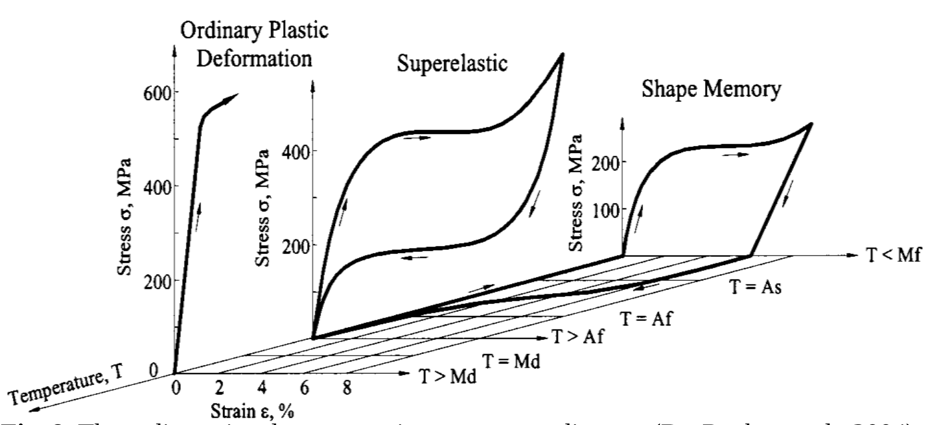


Fig. 8. Three-dimensional stress–strain temperature diagram (DesRoches et al., 2004).

Figure 8 illustrates the thermomechanical relation of stress-strain behavior with temperature of the NiTi shape memory alloy (DesRoches et al., 2004). Because of the thermomechanical nature of the phase transformation, the SMA behavior is rate dependent. In low rate type loadings the process can release heat and the temperature of the material remains constant which is known as an isothermal process. But in high rate loadings like earthquake excitations, the material does not have sufficient time to exchange heat with the environment and the latent heat of the material causes the temperature to change. This process is also known as an adiabatic process.

SMA IN COMBINATION WITH BASE ISOLATION TECHNOLOGY

The unique properties of SMA have led to use it in many control system. The most important characteristic is SMA's damping property to reduce the response and plastic deformation of the structures subjected to severe loadings. SMAs can be used effectively for this purpose via ground isolation mechanisms. SMA made isolators, which are installed between a super-structure and the ground, filter the seismic energy transferred from the ground motion to the super-structure so that the damage on the super-structure is lessened. In addition to energy dissipation and restoration after unloading, other advantage of this alloy as isolator is to provide variable stiffness to the structure in accordance with the excitation levels (Song et al., 2006).

Some experimental and numerical studies have been carried out in recent years in order to utilize SMAs in seismic devices. In the following, the findings of research studies carried on the base isolation system implemented in the building and bridge structures by including the unique behavior of shape memory alloys will be discussed. First, the review on the numerical studies conducted on such system are presented, followed by the assessment of the experimental studies on such system.

Numerical Studies on the SMA Base Isolators

Wilde et al. (2000) proposed a smart isolation system consisted of a laminated rubber bearing with a device made of shape memory alloy (SMA) to evaluate bridge response subjected to earthquake hazards. The model of bridge is illustrated in Figure 9. They considered two system of isolation in the superstructure from the pier. The laminated rubber bearing with an additional SMA bars, referred to as an SMA system, and a laminated rubber bearing with a lead core and displacement restrainer, referred to as an NZ system.

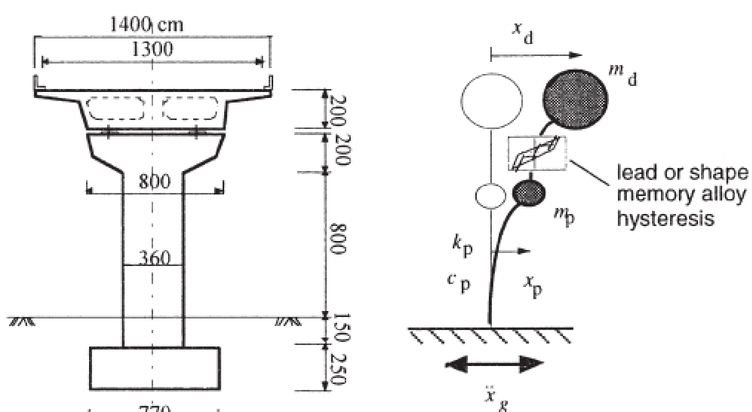


Fig. 9. Model of the elevated highway bridge (Wilde et al., 2000).

The smart base isolation utilizes the different responses of the SMA at different levels of strain to control the displacements of the rubber bearing at various excitation levels. It can be seen that hysteretic responses of the SMA system are large and provide considerable amount of damping and it is used intentionally in order to increase the energy dissipation. However, the force in the SMA isolation system is about three times larger than in the NZ system. The SMA isolation system provides stiff connection between the pier and the deck for small external loading. Relative displacement between deck and pier with these systems were compared under incremental excitation amplitude. For a medium size earthquake, the SMA bars increase the damping capacity of the isolation due to stress induced Martensitic transformation of the alloy. For the largest considered earthquake, the SMA bars provide hysteretic damping. Also, the SMA isolation system revealed its re-centering ability due to the super-elastic response of the alloy.

Dolce et al. (2001) and Dolce and Cardone (2003) presented a parametric study on reinforced concrete base isolated building structures with different types of nonlinear devices which included high dissipation capacity or re-centering capacity utilizing shape memory alloys. By conducting the nonlinear dynamic analyses, they compared the performance of the structure through response parameters such as maximum and residual displacement and ductility demands in the isolation system and maximum stresses and drifts in the structure. In elasto-plastic devices, the threshold force must be limited to avoid excessive residual displacement and fatigue whereas the re-centering SMA-based devices have high fatigue resistance and allow lower threshold values. So it was concluded that SMA-based isolation systems have shown better performance than elasto-plastic based isolation systems.

Khan and Lagoudas (2002) analytically simulated the application of SMA springs to isolate a single-degree-of-freedom system from a ground excitation in a shake table. The results show that seismic isolation is greatly dependent on the relative displacement of SMA spring; as this directly affects the extent of phase transformation attained. Moreover, the SMA springs achieved the best isolation effect only when the system vibrated at a frequency near its resonance frequency and under higher loading levels (Figure 10).

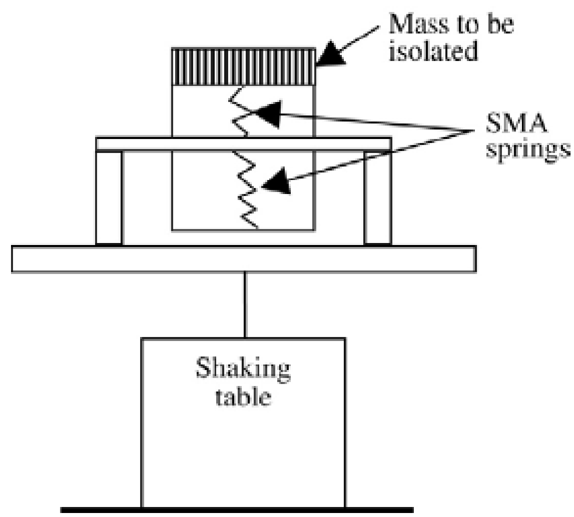


Fig. 10. Schematic of the SMA spring isolation device (Khan and Lagoudas, 2002).

Corbi (2003) proposed a system using the SMA tendon placed at low level part of a multi-story shear frame (Figure 11) to isolate the ground excitation. Most of the dynamic excitation energy is dissipated by the isolator which prevents the superstructure from entering the plastic region. The numerical investigation showed that the SMA tendon isolation device decisively improves the dynamic response capacity of the structures either in terms of response reduction or re-centering capacity.

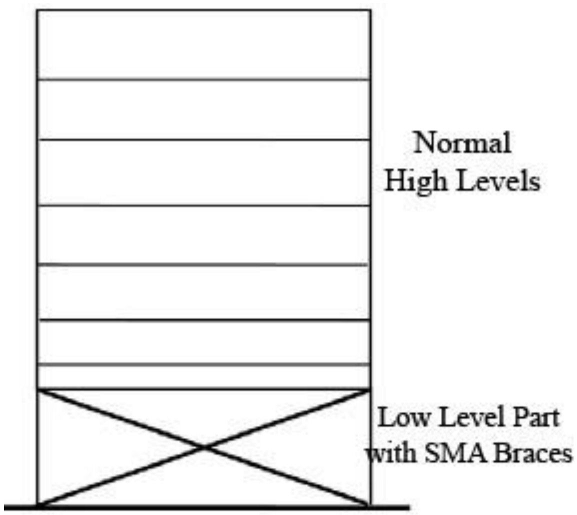


Fig. 11. Schematic of the SMA tendon isolation system for a MDOF structure (Corbi, 2003).

Yamashita et al. (2004) investigated restoring force and durability of softening spring using SMA wires. The SMA spring shows great softening characteristic and after unloading it recovers to its original form as illustrated in Figure 12. Furthermore, they introduced the SMA springs in addition to base isolated systems and evaluated acceleration transmissibility index of system. With increasing input acceleration they conclude reduction in highest acceleration transmissibility in the system.

Xue et al. (2005) investigated the seismic isolation performance of single-layer spherical lattice shell by a new type of SMA-rubber bearings. They concluded greater performance of SMA-rubber bearing compared with ordinary rubber bearing. They also indicated that the proposed SMA-rubber bearing is a suitable energy absorbing isolation device for vibration control of the spatial lattice structures.

Choi et al. (2006) proposed a new concept of an isolation device in which shape memory alloy wires are incorporated in an elastomeric bearing to control the instability and unrecovered deformation in the conventional lead-rubber bearings (Figure 13). A three-span continuous steel bridge was used for seismic analyses in order to compare the performance of lead-rubber and the proposed bearings. They reported that the SMA-rubber bearings restrained the deck displacement and the relative displacement between deck and pier and they showed no residual deformation even after strong ground motions. However, conventional lead-rubber bearings exposed to strong earthquakes showed large permanent deformations and they need be replaced.

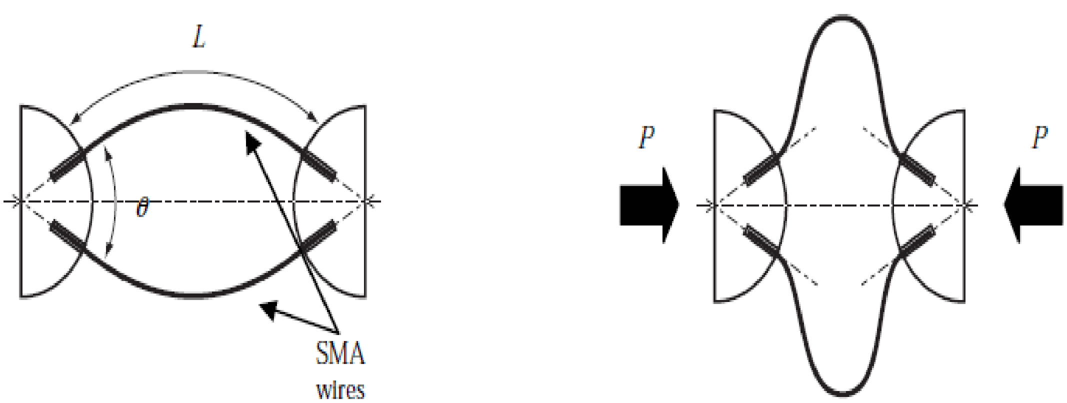


Fig. 12. SMA spring (Yamashita et al., 2004).

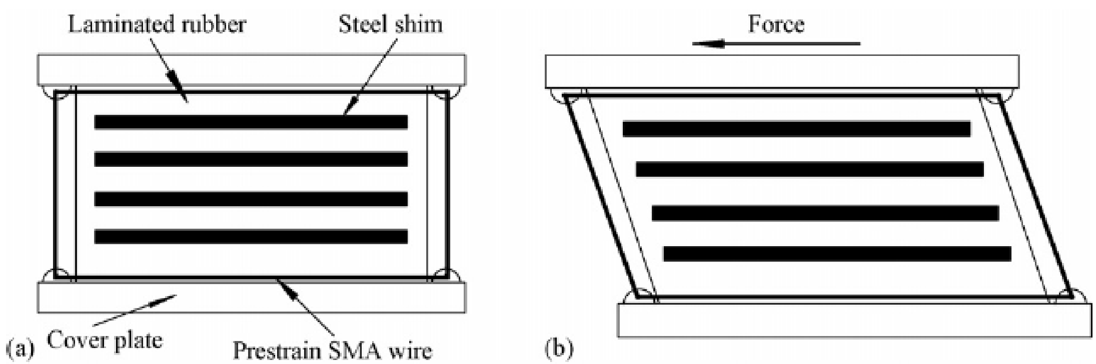


Fig. 13. SMA-rubber bearing and its deformation (Choi et al., 2006).

Shook et al. (2008) proposed a hybrid base isolation system composed of linear elastomeric bearings (EB), friction-pendulum bearings (FPB), shape memory alloy (SMA) wires, and magnetorheological (MR) dampers (Figure 14).

They used each component for a unique task in managing superstructure response. SMA wires obtain recoverable hysteretic behavior and were used as an additional restoring force. They also utilized MR dampers to provide variable viscous damping for smart enhancement of superstructure response. They modeled and designed SMA and MR elements by Neuro-fuzzy techniques. A fuzzy logic controller (FLC) is produced using a multi-objective genetic algorithm for optimal modulation of MR damper resistance levels. Results show that the proposed superelastic semi-active base isolation system can reduce base drifts by 18% and keep desirable superstructure response.

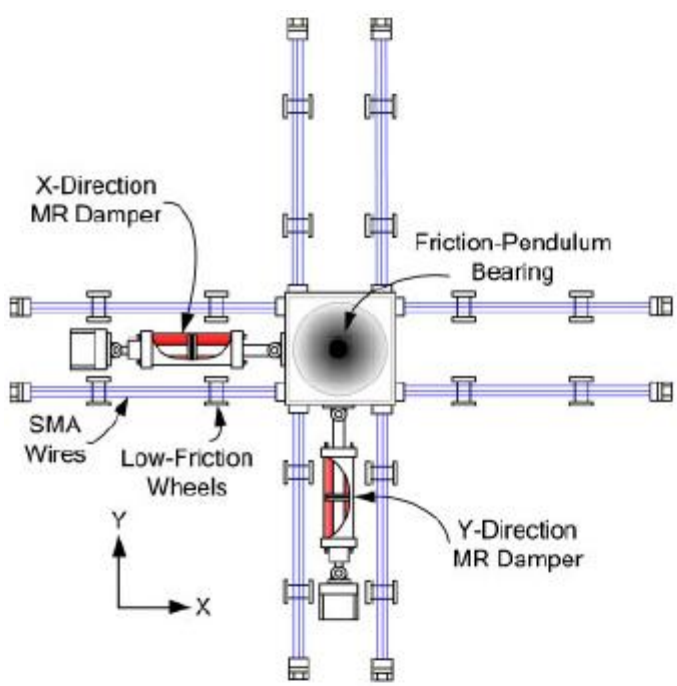


Fig. 14. Configuration of MR, SMA, and FPB devices (Shook et al., 2008).

Attanasi et al. (2009) investigated the feasibility of a new seismic isolation device concept based on the super-elastic effect given by shape memory alloys and compared it with equivalent traditional bearing response through dynamic time history analyses. Results show that force and displacement demands in the two systems are quite similar for medium to high flag shaped dissipation capability range. They conclude that the application of SMA in seismic isolation has several advantages. A SMA device used as a lateral restrain element for a bearing system would provide re-centering properties together with good energy dissipation capability.

Ozbulut and Hurlebaus (2010a) studied the seismic performance of a sliding-type base isolation system considering environmental temperature changes for a multi-span continuous bridge. The smart sliding base isolation system dissipates energy as a result of its frictional behavior and provides re-centering force and additional damping because of shape memory alloy (SMA) device. A neuro-fuzzy model is applied to predict the force at superelastic NiTi shape memory alloy wires at different temperatures and loading frequencies. The length and cross-sectional area of NiTi wires are optimized through a multi-objective genetic algorithm process. Nonlinear time history analyses of the isolated bridge are conducted for outside temperatures of 0°C, 20°C and 40°C. The results show that the temperature has low effect on the performance of this base isolation system. They concluded that the SMA-based sliding isolators recover almost all deformations; which eliminates the need of bearing replacement after a strong earthquake.

Ozbulut and Hurlebaus (2010b) explored sensitivity of seismic response of a multi-span continuous bridge isolated by an SMA/rubber-based isolation system. The SMA device provides additional energy dissipating and re-centering capability. They assessed the normalized yield strength, yield displacement and pre-stress level of the SMA device and environmental temperature changes as parameters of the sensitivity study. They observed pre-stressed SMA/rubber-based isolation system to be more effective. The results indicated that ambient temperature affects the performance of the bridge isolated by SMA/rubber-based isolators considerably.

Jalali et al. (2011) proposed the Smart Restorable Sliding Base Isolation System (SRSBIS) as a new base isolation system to protect structures against earthquakes. They used the SMA materials as simply connected wires, coupled with flat sliding bearings, to provide the necessary horizontal stiffness and restoring capability. The schematic configurations of SRSBIS differing in the arrangement of SMA wires are depicted in Figure 15; in which (v) stands for vertical, (b) stands for bracing and (h) stands for horizontal.

They assessed the seismic performances of SRSBIS by nonlinear time-history analyses. The results showed that SRSBIS reduce the maximum base shear more than FPS. Also due to the thermo-mechanical behavior of superelastic SMA wires, the residual displacement can be fully restored as soon as temperature increases; where as for the FPS, an external force is required to fully restore the system.

Ozbulut and Hurlebaus (2011) expressed the effectiveness of SMA/rubber-based (SRB) isolation systems for protection of bridges against near-field earthquake; as shown in Figure 16.

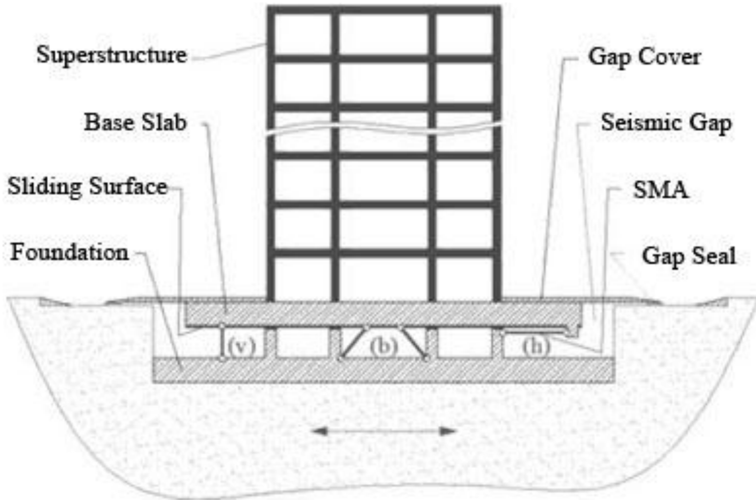


Fig. 15. Configurations of SRSBIS differing in the arrangement of SMA wires: vertical (v), bracing (b) and horizontal (h) (Jalali et al., 2011).

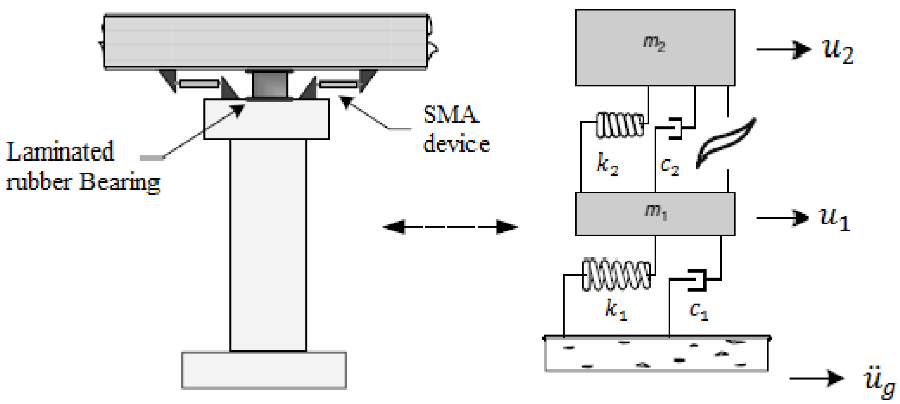


Fig. 16. Isolated bridge model with an SMA/rubber isolation system (Ozbulut and Hurlebaus, 2011).

They investigated the sensitivity of the seismic response of the bridge with parameters such as transformation strength, transformation displacement, pre-strain level of the SMA device, ambient temperature and the lateral stiffness of the rubber bearings. They also compared the results obtained from their proposed system with the result obtained from SMA- friction base isolator (S-FBI). The peak deck drift response for two systems is similar; but the peak deck acceleration and peak base shear values in the S-FBI were smaller. The energy dissipation in the S-FBI system is through friction and SMA device acts as a re-centering device. Since the energy dissipations in the SRB isolation system proceed from the hysteric behavior of SMAs, so a larger amount of SMA material is required. At last they concluded that the S-FBI has more desirable properties with respect to SRB isolation system.

Alam et al. (2012) analytically determined the seismic fragility of a three-span continuous highway bridge fitted with laminated rubber bearings and SMA restrainers. Two types of laminated rubber bearings were used in the bridge system in addition to the SMA restrainers: high damping rubber bearings and lead rubber bearings. They evaluated the fragility curves for the entire bridge system at different damage states. The numerical results showed that the failure probability of the bridge system is dominated by the bridge piers over the isolation bearings. Moreover, the inclusion of SMA restrainers in the bridge system exhibits high probability of failure, especially when the system is isolated with lead rubber bearings.

Bhuiyan and Alam (2013) investigated seismic performance of bridge equipped with different isolators such as high damping rubber bearing (HDRB), combined natural rubber bearing (NRB) and SMA-based rubber bearing (SRB). They introduced analytical models for those isolators. In assessment of seismic responses of the bridge, six standard response parameters were obtained for each earthquake ground acceleration record. They were bearing displacement, deck displacement, pier displacement, deck acceleration, residual displacement of the bridge deck after earthquake and dissipated energy of the isolation bearings. They showed lower residual displacement of the deck in the case of SRB compared to HDRB for moderate and strong earthquakes. Pier displacements were smaller in the cases of SRBs for moderate earthquakes and higher for strong earthquakes. Also deck displacement, bearing displacement and deck acceleration, were significantly larger in the cases of SRBs compared to those of HDRB.

Dezfuli and Alam (2013) proposed two different configurations of smart elastomeric bearings using shape memory alloy wires. In their proposed system, their rubber bearings are composed of natural rubber layers equipped with straight and cross SMA wires as shown in Figure 17. They used SMA wires as a supplementary element to improve the performance of steel-based natural rubber bearings in terms of energy dissipation capacity and the residual deformation at large shear strain amplitudes.

They investigated the effect of several factors on the performance of SMA-NRBs such as the shear strain amplitude, the type of SMA, the aspect ratio of the base isolator, the thickness of wire, the configuration of SMA wire and the level of pre-strain in SMA wires. Six varius types of SMA wire were used namely NiTi, NiTi45, TiNi40Cu10, CuAlBe, FeMnAlNi, and FeNiCuAlTaB (FeNCATB). Their results showed that when the SMA-NRB isolator system is subjected to high shear strain amplitudes, FeNiCuAlTaB introduced as ferrous SMA wire, with 13.5% super-elastic strain and a very low austenite finish temperature (-62 °C), is the best selection. Also Cross and straight configuration of SMA wire were compared in terms of the lateral flexibility and wire strain level and results indicated that the smart rubber bearing with a cross configuration of SMA wires is more efficient. They concluded using SMA wires with 2% pre-strain in a smart NRB increases the dissipated energy by 74% and reduces the residual deformation by 15%.

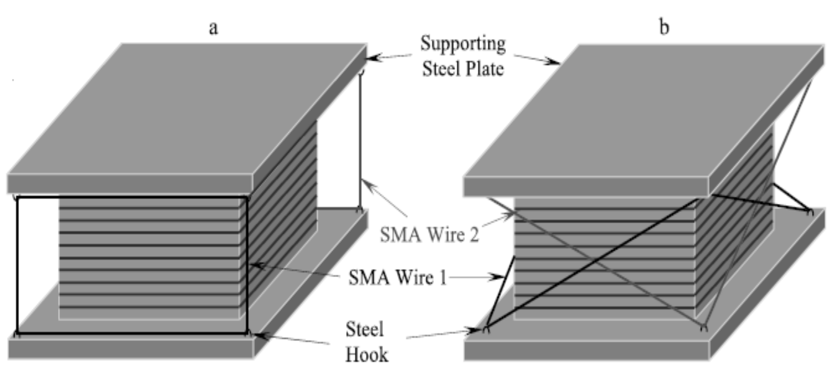


Fig. 17. Smart natural rubber bearing; (a) straight SMA wires, (b) Cross SMA wires (Dezfuli and Alam, 2013).

Experimental Studies on the SMA Base Isolators

Dolce et al. (2000) implemented and tested special braces for framed structures and isolation devices for buildings and bridges based on shape memory alloy (Figure 18). They verified basic features of the SMA devices such as: re-centering capability, high stiffness for small displacements, and good energy dissipation capability. They also indicated re-centering seismic isolation devices with SMA aquire the most efficient mechanical characteristics and recover the initial position of the structure with a good control of displacements. Indeed SMA-based devices provide supplemental forces to well controlling forces and recover the undeformed shape of the structure at the end of the action, resulting in the elimination of any residual displacement, while allowing yielding in the structural elements.

Casciati et al. (2007) introduced a new and innovative base isolation device. It consists of two disks, one vertical cylinder with an upper enlargement sustained by three horizontal cantilevers, and three inclined shape memory alloy (SMA) bars. A prototype of the device was built and experimentally tested on the shaking table and the device is shown in Figure 19. These bars have four functions: (i) to provide stiffness against low intensity excitations; (ii) to distinguish very large displacements; (iii) to re-center the device; and (iv) to dissipate energy. It is observed that when the system is subjected to cyclic loading, the super-elastic behavior of the alloy caused wide load displacement loops, where a great amount of energy is dissipated. These loops become smaller as the excitation intensity decays, resulting in the re-centering of the device.

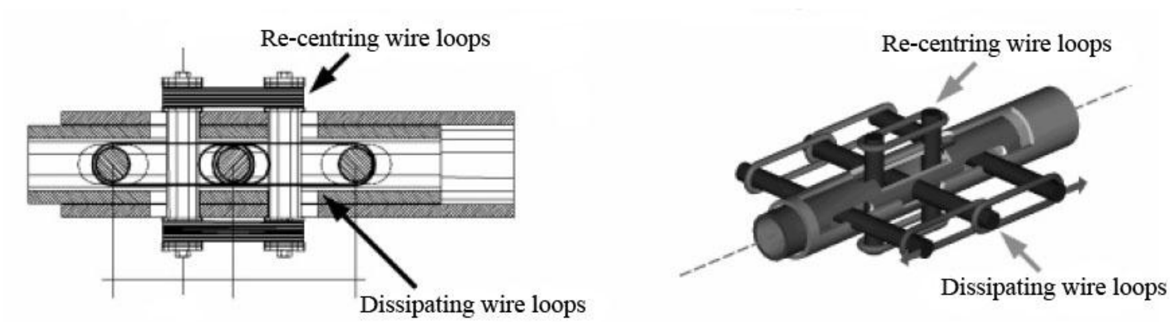


Fig. 18. Seismic device including both functional groups of SMA-wires (Dolce et al., 2000).

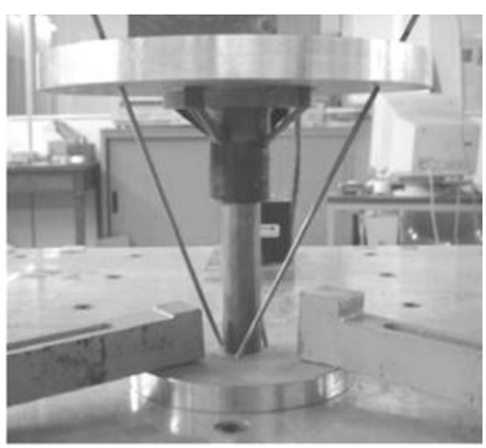


Fig. 19. Prototype of base isolator (Casciati et al., 2007).

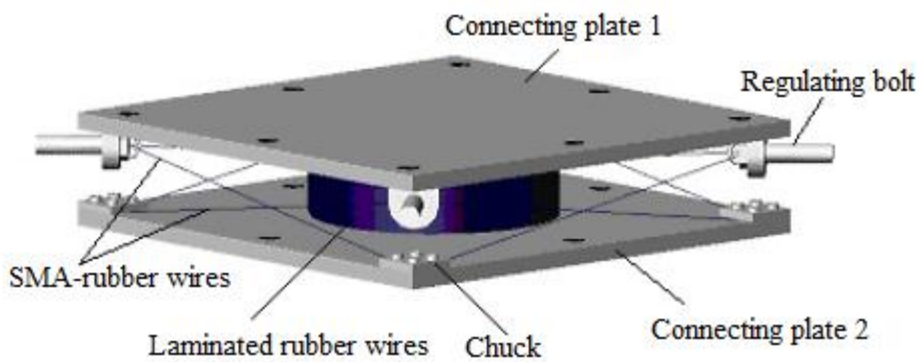


Fig. 20. Detail of the SMA-rubber bearing (Xue and Li, 2007).

Xue and Li (2007) proposed three types of dampers (SMA damper, SMA-MR damper and SMA-friction damper) and an isolation bearing (SMA-rubber bearing). They presented mechanical models of these devices and their experimental verifications. They investigated the performance of SMA-MR damper and SMA-rubber bearing. The detail of SMA-rubber bearing is shown in Figure 20 in which cross lines showing the SMA wires installed around a cylinder rubber pad. SMA wires went through the ring of the regulating bolt along the diagonal line of the connection plate 1, and chucks along diagonal line of connection plate 2. They screwed the regulating bolts to stretch SMA wires to get a pre-strain position after fixing them with the chucks.

The control devices offer some advantages such as stable performance, long service life, good durability, good energy dissipation capability, excellent fatigue and corrosion resistance property, etc. So, they are suitable for vibration control of structures.

Riegler (2009) analyzed, designed, and fabricated a two-story structure (Figure 21) and he subjected the frame to vibration on the shake table. He suppressed the vibration of system in two steps. First, he implemented base isolation technology to uncouple the substructure from the superstructure. In this way, the acceleration of system became limited and consequently it was prevented from structural failure along the foundation during the simulated excitation of earthquake. Secondly, he implemented and associated the super-elastic SMA springs with the isolation system. He equipped the base isolation system in three different configurations, namely, an isolation system with four super-elastic springs, an isolation system with two super-elastic springs and an isolation system with two regular pre-tension springs. He compared the performance of those three systems with the conventional non-base isolated system. The displacement of the base was the smallest when four super-elastic springs were used and largest when two steel springs were used. The accelerations of the base and floors were much smaller with the inclusion of the manual slider. The acceleration was largest when the manual slider was fixed and acted as a non-base isolated system. Also test results revealed that the displacements using SMA springs are much smaller than that of the steel springs even with the extra stiffness. The outcome proved that SMA springs were the better choice to dampen vibration than regular steel springs. Finally, he tried to balance the acceleration and displacement as important factors to control damage in order to have a safe structure within and subsequent seismic excitations.

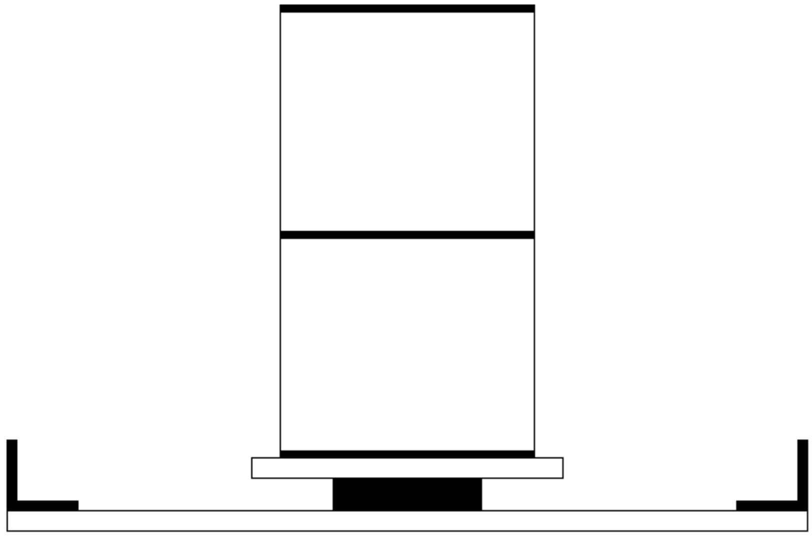


Fig. 21. Front view of model (Riegler, 2009).

CONCLUSIONS

This paper presents the review on the performance of base isolation technology as passive control of civil structures. Also it points the application of advanced materials such as SMA and its integration in innovative structural systems in order to provide enhanced performance. The unique properties of shape memory alloys as an example of smart material are discussed. Special characteristics such as high damping capacity, high fatigue resistance, re-centering, exhibiting no plasticity in large strains, recovery of strains by heat caused SMA to be an effective damping device or component of base isolators. This study reviews latest articles and research studies in which the base isolation system with the SMA to obtain the best performance of structures when subjected to seismic excitations. SMA-based devices provide supplemental forces to well control applied load, recover the undeformed shape of the structure at the end of the action and eliminate any residual displacement. The SMA device used as a lateral restrain element for a bearing system would provide re-centering properties together with good energy dissipation capability. Finally most studies reveal the feasibility and effectiveness of a new seismic isolation device utilizing the super-elastic effect of the shape memory alloys.

ACKNOWLEDGEMENT

The authors of this paper thank two anonymous peer reviewers for their insightful and constructive comments which contributed very much to the technical value and merit of this article.

REFERENCES

Alam, M.S., Bhuiyan, A.R. and Billah, A.H.M. (2012), "Seismic assessment of SMA-bar restrained multi-span continuous highway bridge isolated by different laminated rubber bearings in medium to strong seismic risk zones", *Bulletin of Earthquake Engineering*, 10(6), 1885–1909.

Attanasi, G., Auricchio, F. and Fenves, G. (2009), "Feasibility assessment of innovative isolation bearing system with shape memory alloys", *Journal of Earthquake Engineering*, 13(1), 18–39.

Bhuiyan, A.R. and Alam, M.S. (2013), "Seismic performance assessment of highway bridges equipped with super-elastic shape memory alloy-based laminated rubber isolation bearing", *Journal of Engineering Structures*, 49, 396–407.

Brocca, M., Brinson, L.C. and Bazant, Z.P. (2002). "Three-dimensional constitutive model for shape memory alloys based on microplane model", *Journal of the Mechanics and Physics of Solids*, 50(5), 1051–1077.

Casciati, F., Faravelli, L. and Hamdaoui, K. (2007). "Performance of a base isolator with shape memory alloy bars", *Journal of Earthquake Engineering and Engineering Vibration*, 6(4), 401–408.

Choi, E., Nam, T.H., Oh, J.T. and Cho, B.S. (2006). "An isolation bearing for highway bridges using shape memory alloys", *Journal of Materials science and Engineering*, 438-440(25), 1081–1084.

Corbi, O. (2003). "Shape memory alloys and their application in structural oscillations attenuation", *Simulation Modeling Practice and Theory*, 11(5-6), 387–402.

Datta, T.K. (2002). *Seismic analysis of structures*, John Wiley and Sons (Asia) Pte Ltd, Singapore.

DesRoches, R. and Delemont, M. (2002). "Seismic retrofit of simply supported bridges using shape memory alloys", *Engineering Structures*, 24(3), 325–332.

DesRoches, R., McCormick, J. and Delemont, M. (2004). "Cyclical properties of super-elastic shape memory alloys", *ASCE Journal of Structural Engineering*, 130(1), 38–46.

Dezfuli, F.H. and Alam, M.S. (2013). "Shape memory alloy wire-based smart natural rubber bearing", *Journal of Smart Materials and Structures*, 22(4), 1–17.

Dolce, M. and Cardone, D. (2003). "Seismic protection of light secondary systems through different base isolation systems", *Journal of Earthquake Engineering*, 7(2), 223–250.

Dolce, M., Cardone, D. and Marnetto, R. (2000). "Implementation and testing of passive control devices based on shape memory alloys", *Journal of Earthquake Engineering and Structural Dynamics*, 29(7), 945-968.

Dolce, M., Masi, A. and Telesca, F.R. (2001). "The design of R/C framed buildings with non-linear isolation systems", *Proceedings of 7th International Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibration of Structures*, Assisi, Italy.

Faravelli, L. and Spencer, B.F.J. (2003). *Proceedings of the US Europe (ESF-NSF) Workshop on Sensors and Smart Structures Technology*, Como and Somma Lombardo, Italy, 2002, Wiley, NY.

Housner, G.W., Bergam, L.A., Cauchy, T.K., Spencer, B.F. and Yau, J.P.T. (1997). "Structural control: Past, Present and Future control", *Journal of Engineering Mechanics*, 123(9), 897–971.

Jalali, A., Cardone, D. and Narjabadifam, P. (2011). "Smart restorable sliding base isolation system", *Bulletin of Earthquake Engineering*, 9(2), 657-653.

Kelly, T.E. (2001). "Base isolation of structures: design guidelines", Holmes Consulting Group Ltd, Wellington, New Zealand, Retrieved August 08, 2013 from http://www.holmesgroup.com/assets/Uploads/online-library/design-guidelines/base-isolation-of-structures.pdf

Khan, M.M. and Lagoudas, D.C. (2002). "Modeling of shape memory alloy pseudoelastic spring elements using preisach model for passive vibration isolation", *Proceedings of Smart Structures and Materials 2002: Modeling, Signal Processing, and Control*, San Diego, CA.

Kunde, M.C. and Jangid, R.S. (2003). "Seismic behavior of isolated bridges: A-state-of-the-art review", *Electronic Journal of Structural Engineering*, 3, 140–170.

Marazzi, F. (2003). Semi-active control of civil structures: Implementation aspects. PhD thesis, Department of Structural Mechanics, University of Pavia, Pavia, Italy.

Mayes, R.L. (2000) "Design of structures with seismic isolation", In Naeim, F. (Ed.), *The Seismic Design Handbook*, Springer.

Mostaghel, N. and Khodaverdian, M. (1987). "Dynamics of resilient-friction base isolator (R-FBI)", *Earthquake Engineering and Structural Dynamics*, 15, 379–390.

Motahari, S.A., Ghassemieh, M. and Abolmaali, S.A. (2007). "Implementation of shape memory alloy dampers for passive control of structures subjected to seismic excitations", *Journal of Constructional Steel Research*, 63(12), 1570–1579.

Naeim, F. and Kelly, J. (1999). *Design of isolated structures: from theory to practice*, John Wiley and Sons Inc.

Ozbulut, O.E. and Hurlebaus, S. (2010a). "Evaluation of the performance of a sliding-type base isolation system with a NiTi shape memory alloy device considering temperature effects", *Engineering Structures*, 32(1), 238-249.

Ozbulut, O.E. and Hurlebaus, S. (2010b). "Performance evaluation of shape memory alloy/rubber-based isolation systems for seismic response mitigation of bridges", *Proceedings of Sensors and Smart Structures Technologies for*

Civil, Mechanical, and Aerospace Systems Conference, San Diego, CA.

Ozbulut, O.E. and Hurlebaus, S. (2011). "Seismic assessment of bridge structures isolated by a shape memory alloy/rubber-based isolation system", *Journal of Smart Materials and Structures*, 20, 1-12.

Pastia, C., Luca, S.G., Chira, F. and Roşca, V.O. (2005). "Structural control systems implemented in civil engineering", *Bulletin of the Polytechnic Institute of Jassy, Construction. Architecture Section*, 76-80(1-2), 41–50.

Riegler, J. (2009). "Vibration suppression of a two-story structure using smart memory alloy springs via base isolation technology", Retrieved May 08, 2013 from http://rsmsl-1.me.uh.edu/reu_civil/REU08/Jason Riegler/REU Report Vibration Suppression of a Twostory Structure using Smart Memory Alloy Springs via Base Isolation Technology.pdf.

Shook, D.A., Roschke, P.N. and Ozbulut, O.E. (2008). "Superelastic semi-active damping of a base-isolated structure", *Structural Control and Health Monitoring*, 15(5), 746-768.

Song, G., Ma, N. and Li, H.N. (2006). "Applications of shape memory alloys in civil structures", *Engineering structures*, 28(9), 1266–1274.

Spencer, B.F.J. and Nagarajaiah, S. (2003). "State of the art of structural control", *Journal of Structural Engineering*, 129(7), 845-856.

Tanaka, Y., Himuro, Y., Kainuma, R., Sutou, Y., Omori, T. and Ishida, K. (2010). "Ferrous polycrystalline shape-memory alloy showing huge superelasticity", Science, 327(5972), 1488–1490.

Wilde, K., Gardoni, P. and Fujino, Y. (2000). "Base isolation system with shape memory alloy device for elevated highway bridges", *Journal of Engineering Structures*, 22(3), 222–229.

Xue, S. D., Zhuang, P. and Li, B.S. (2005). "Seismic isolation of lattice shells using a new type of SMA-rubber bearings", *Proceedings of IASS Symposium*, Bucharest, Romania.

Xue, S.D. and Li, X. (2007). "Control devices incorporated with shape memory alloy", *Earthquake Engineering and Engineering Vibration*, 6(2), 156-169.

Yamashita, Y., Masuda, A. and Sone, A. (2004). "Base isolation system using shape memory alloy wires", *Proceedings of Smart Structures and Materials 2004: Damping and Isolation*, San Diego, CA.

Yang, Y., Chang, Kuo. and Yau, J. (2003). "Base isolation", In Scawthorn, C. and Chen, W.F. (Eds), *Earthquake Engineering Handbook*, CRC Press, Washington DC.

Zayas, V.A., Low, S.S. and Mahin, S.A. (1990). "A simple pendulum technique for achieving seismic isolation", *Earthquake Spectra*, 6(2), 317–334.