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APPLICATIONS OF SHAPE MEMORY ALLOYS IN EARTHQUAKE ENGINEERING

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ABSTRACT

Shape Memory Alloys (SMAs) are unique materials with the ability to undergo large deformations, and return to their undeformed shape through stress removal (superelasticity) or heating (shape memory effect). This makes them potential candidates for use in seismic resisting elements in the form of reinforcing bars, bracings, and/or connectors. Because of their high damping, they have been used as the kernel components of various damping devices, isolators and actuators for passive, semi-active and active seismic control of structures. Moreover SMAs have been efficiently used for rapid and convenient repair and strengthening of seismically damaged or deficient structures. This paper presents state-of-the-art of numerous seismic applications of SMAs and their devices in various structures. The paper also reviews the fundamental characteristics of SMAs emphasizing on the factors influencing their properties.

Introduction

The past and recent earthquakes demonstrated that bridges and buildings in seismic regions are susceptible to collapse and severe damage due to excessive lateral deformations. These civil engineering infrastructures constitute a large portion of national wealth of any country and thus, their safety and serviceability are of great concerns. Earthquake resistant structures need to be sufficiently ductile so that they can behave elastically for moderate earthquakes. For strong ground motions, it is not feasible to build structures, which will perform elastically. Steel and Reinforced Concrete (RC) structures designed according to current seismic code are expected to behave nonlinearly to dissipate the energy of a ground motion while encountering permanent deformations and damage. It is advantageous to have structures that can survive major earthquakes with minor damage and remain operational.

The Shape Memory Effect (SME) and Super-Elasticity (SE) are two distinct properties that make SMA a smart material. SMAs have the potential to be used as reinforcement at the critical locations of RC structures (Sakai et al. 2003, Wang 2004). Joints are known to be the weakest links during earthquakes as they were responsible for a number of failures during the 1994 Northridge earthquake (Mahin 1998). SMA material can be effectively employed in the joints in order to reduce the vulnerability of structures by dissipating greater energy and reducing plastic deformation in the beam-column and column-foundation joints (Ocel et al. 2004, Tamai et al. 2003). SMA materials also have the potential to be used in the kernel

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component of dampers and various energy dissipation devices (Dolce et al. 2000).

Over the past 15 years a substantial amount of research has been done on the material science and possible uses of SMAs in structural applications. It is being realized that SMAs possess a substantial potential to replace conventional materials while achieving great gains in performance under seismic action. This paper presents a summary of the basic characteristics of SMAs and a review of the state-of-art of their possible applications in earthquake engineering.

Fundamentals of SMA

SMAs are smart materials that exhibit variable stiffness and strength associated with their different polycrystalline phases. SME is the unique phenomenon by which SMA can recover its predetermined shape by heating even after large deformations. A Superelastic SMA can restore its initial shape spontaneously even from its inelastic range upon unloading. Various compositions of SMAs such as Ni-Ti, Cu-Zn, Cu-Zn-Al, Cu-Al-Ni, Fe-Mn, Mn-Cu, Fe-Pd, and Ti-Ni-Cu have been developed and their properties have been investigated (Otsuka and Wayman 1999). Among these, Ni-Ti has been found to be the most appropriate SMA for structural applications because of its large recoverable strain, superelasticity and exceptionally good resistance to corrosion (Janke et al. 2005). In this paper, unless otherwise stated, SMAs are mainly referred to Ni-Ti SMA (commonly known as Nitinol).

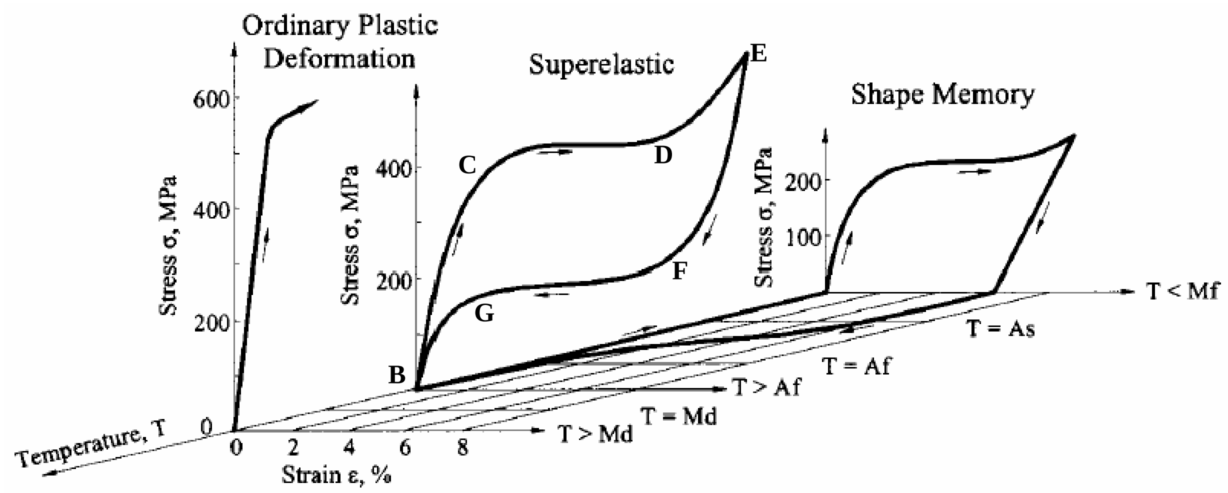


Figure 1. 3D stress-strain-temperature diagram of SMA showing SME in martensite phase, SE in austenite/martensite phase transformation, and elastic-plastic behaviour of austenite at high temperatures (DesRoches et al. 2004).

At relatively low temperature SMA exists in the martensite phase, which is soft and ductile. When heated, its stiffness and strength increase with temperature as it experiences a transformation to the austenite phase (crystalline change). In the stress (σ) free state, SMA is characterized by distinct transformation temperatures: martensite start (M_s), martensite finish (M_f), austenite start (A_s), and austenite finish (A_f). SMA exists in a fully martensite state when $T<M_f$ and in a fully austenite state when $T>A_f$. During the phase change from martensite to austenite and vice versa, both martensite and austenite phases coexist with temperatures between A_s and A_f, and M_s and M_f, respectively. In the martensite state ($T<A_s$), some residual strain will remain upon unloading as shown in the rightmost curve of Fig. 1. Upon heating, the material regains its original shape by following the curve on the T-ε plane in Fig. 1. In the austenite state ($A_f <T< M_d$), six distinctive features can be recognized in the middle stress-strain curve of Fig. 1 (DesRoches et al. 2004): (a) elastic response of austenite material at low strains (ε <1%) as denoted by BC; (b) stress-induced transformation from austenite to martensite with a long and constant stress plateau at intermediate strains (ε = 1-6%), indicated by CD; (c) elastic response in the stress-induced martensite state at large strain (ε >8%) represented by DE; (d) elastic recovery of strain upon stress removal as shown by EF; (e) instinctive recovery of strain at an almost constant stress path because of the reverse transformation to austenite due to instability of martensite at $T > A_f$ as depicted by FG; and finally (f) elastic recovery in the austenite phase as indicated by GB. This exceptional property of SMA with the ability of recovering substantial inelastic deformation upon unloading yields a characteristic hysteresis loop, which is known as superelasticity (SE). If the temperature in the austenite phase exceeds a temperature M_d, then SE of SMA is completely lost and it behaves like an elastic-plastic material as shown in the leftmost curve of Fig. 1.

Cyclic Behaviour of SMA within the Superelastic Range

Typical stress-strain curves of austenite SMA under cyclic axial, shear and torsion forces are presented in Fig. 2. When an SMA specimen is subjected to a cycle of axial deformation within its superelastic strain range, it dissipates a certain amount of energy without permanent deformation. This results from the phase transformation from austenite to martensite during loading and the reverse transformation during unloading ensuing a net release of energy. SMA with SE has an advantage over other common metals/alloys in the sense that besides dissipating a considerable amount of energy under repeated load cycles, it has a negligible residual strain.

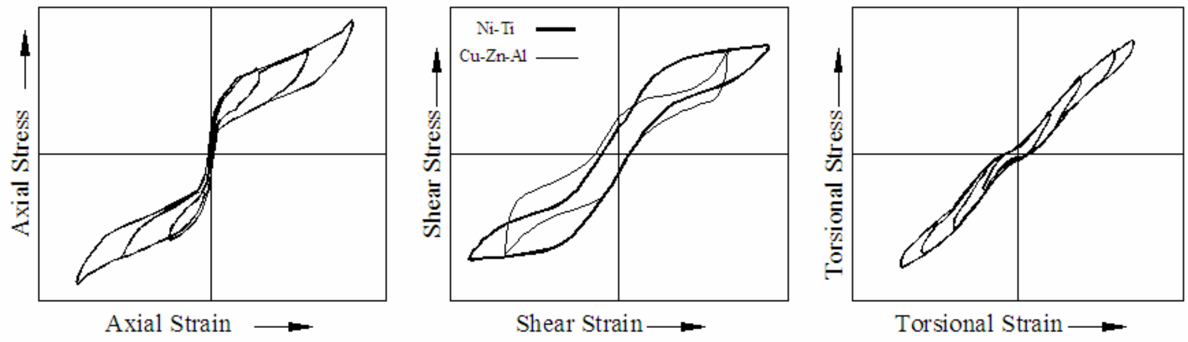


Figure 2. Typical stress-strain curve of superelastic SMA under cyclic axial (Dolce and Cardone 2001b), shear (Vivet et al. 2001) and torsion stresses (Dolce and Cardone 2001a).

Under shear and torsion stresses, superelastic SMA has some residual strain after unloading, which may be due to the presence of some partially stabilized martensite (Orgeas et al. 1997). SMA with SE exhibits stable and repeatable hysteresis under torsion (Dolce and Cardone 2001a). Generally, the loading plateau and the hysteretic loop gradually decrease and the residual strain increases for successive loading cycles of a superelastic SMA due to localized slip, which facilitates the formation of stress induced martensite. However, this behaviour has been proven to decrease and stabilize at a large number of cycles (Miyazaki et al. 1986).

The strain rate has also an important effect on the mechanical properties of SMA. Increased strain rate causes an increase in both the loading and unloading stresses with a narrow resultant hysteretic loop, thus resulting in an overall decrease in the energy dissipation capacity (DesRoches et al. 2004). This is mainly due to self-heating of the specimen during cycling, requiring larger stress to induce martensite state.

Cyclic Behaviour of SMA outside the Superelastic Range

When SMA is loaded in the martensite phase, it yields at a nearly constant stress after initial elastic deformation and displays strain hardening at larger strains. When unloaded there remains some residual strain at zero stress. This martensitic composition of SMA generates a full hysteresis loop around the origin (Fig. 3). Thus, martensite SMA dissipates a much higher amount of energy compared to that of the austenite phase due to its larger hysteresis loop. In the martensite phase under tension-compression cycles, the maximum stress attained in compression has been found to be approximately twice that in tension (Fig. 3). This may be due to the cyclic hardening and softening process that takes place at maximum and zero strain, respectively (Liu et al. 1999).

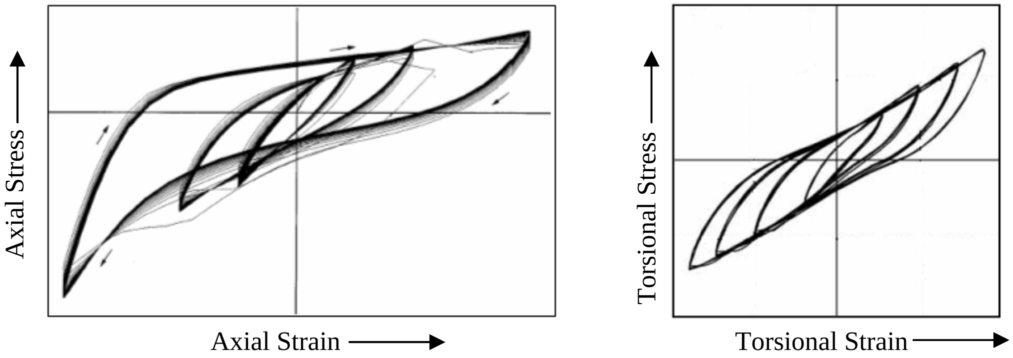


Figure 3. Typical stress-strain curve of martensite SMA under cyclic axial (Liu et al. 1999) and torsion (Dolce and Cardone 2001a).

It has been found that SMA in the martensite phase exhibits highly stable and repeatable hysteresis under torsion (Dolce and Cardone 2001a). SMAs exhibit high damping capacities owing to their hysteretic stress-strain relationships (Ma and Song 2005). Generally, martensite has a larger damping capacity compared to that of the austenite phase (Liu et al. 1998). Ma and Song (2005) measured the damping capacity of SMA wires in the martensite, austenite and martensite-austenite co-existence (MAC) phases. Their experimental results showed that the damping capacity of SMA depends on the strain level. SMAs in the MAC phases are generally less sensitive to temperature changes, while SMAs in the austenite phase have been found to be the most sensitive. SMAs in the MAC phase generally perform better in suppressing repeated vibration compared to other phases.

SMAs in Earthquake Engineering

The unique properties of SMA under cyclic load have made it attractive for various earthquake-engineering applications. These applications are presented in this section.

Utilizing Superelastic SMAs in Earthquake Engineering

SE is the property that makes the use of SMA in earthquake-engineering applications attractive. The recentering capability of superelastic SMAs has created new ideas that will minimize the retrofitting required for seismically damaged structures. These ideas include:

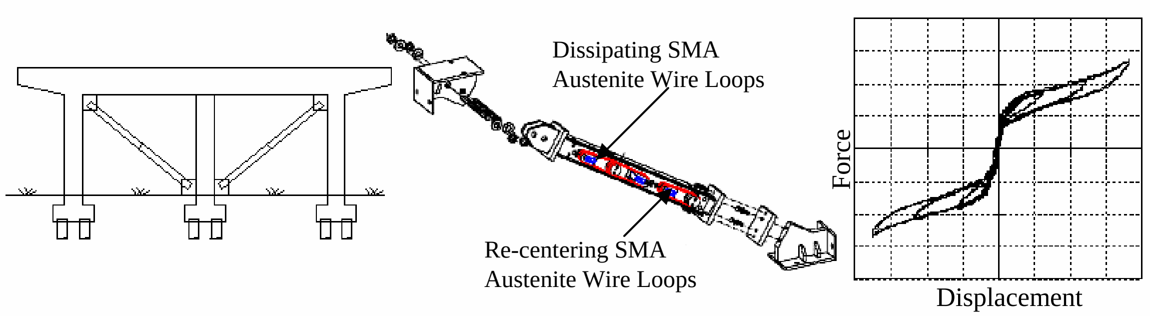
Reinforcements in RC Members

The seismic performance of RC columns with SMA longitudinal reinforcement in plastic hinge area was investigated by Wang (2004). Two quarter-scale spiral RC columns with SMA longitudinal reinforcement in the plastic hinge area were designed and constructed for shake table testing at University of Nevada, Reno. It was observed that the SMA RC columns were superior to the conventional steel RC columns in limiting relative column top displacement and residual displacements. SMA reinforced columns withstood stronger earthquakes. The shake table data showed that SMA-RC columns were able to recover nearly all of post-yield deformation, and thus exhibiting the potential of such columns to require minimal repair even after strong earthquakes.

Superelastic SMA rebars could be effectively employed in bridge decks and girders for its self-restoration capacity. To investigate this idea, Sakai et al. (2003) tested mortar beams reinforced with superelastic SMA wires. Static one-point loading tests were carried out up to the inelastic range on three mortar beams, two of which were reinforced with SMA wires and the third reinforced with steel wires. It was observed that beams with SMA could return to about one-tenth of their maximum deflection. The range of deflection of the beams reinforced with SMA was more than seven times that of the beam with steel, proving to be more ductile. A wide single crack occurred at the midspan of the mortar beam with SMA due to relatively weaker bond strength between the SMA and mortar during loading. However, the crack nearly closed after unloading. The results show that SMA reinforcements have the ability to be used in RC structures, where structural members can recover from residual deformations induced by earthquakes.

Connectors

Joints are the weakest links of a structure during earthquake type loading. Superelastic SMA material can be effectively employed in the joints in order to reduce the vulnerability of structures by dissipating greater energy and reducing plastic deformation. Tamai et al. (2003) tested the possibility of using SMA rods for anchoring steel columns of a building structure. A column was welded to a base plate, which was fastened to the base with anchor bolts. Each anchor bolt consisted of an SMA rod connected to an ordinary steel bolt via a coupler. The seismic resisting mechanism of the column base with SMA anchorage was investigated under reversed cyclic loading on cantilevers. The test results revealed that SMA anchorage has the ability to improve the restoring force characteristics of a column base and to prevent plastic deformation and damage in the column. It was found that it is possible to design a column base with SMA anchorage that does not require repair after earthquakes.



(a) (b) (c)

Figure 4. a) Retrofitting of frame structures with SMA-based supplemental recentering bracing, b) arrangement of SMA wires inside the device, and c) typical cyclic force-displacement behaviour (Cardone et al. 2004).

Bracing Members

Deficient frame structures that are vulnerable against lateral loading can be effectively retrofitted with SMA bracings (Fig. 4a). Salichs et al. (2001) conducted a feasibility study on using SMA diagonal bracing wires as passive devices for vibration suppression of a one-storey building model. SMA superelastic hysteresis lowered the peak lateral drift compared with that for steel bracing having similar stiffness. McCormick and DesRoches (2003) made an analytical evaluation of the effectiveness of using large diameter superelastic SMA bars as bracing members. The reduction in the inter-storey drift and column rotation of an RC frame achieved by using SMA bracing members was more than that achieved by using steel bracing. Dolce et al. (2004) retrofitted an RC frame structure by using braces made of superelastic SMAs (Fig. 4b). The expected typical force-displacement relationship is shown in Fig. 4c. The test results demonstrated that the passive protection system based on the use of SMA wires provided the tested RC frame structure with a strong recentering capability, increased safety at the Ultimate Limit State, and enhanced displacement control at the Damage Limit State. SMA-based bracings in frame structures have a great potential and practical feasibility owing to greater initial stiffness and lower weight, and more importantly a recentering capability, compared to steel braces (Cardone et al. 2004).

Prestressing Tendons

An early practice of utilizing SMAs in rehabilitation of real structure has been found in the work of Indirli et al. (2001). Trignano S. Giorgio Church built in 1302 in Italy is an ancient structure, which was seriously damaged by a 4.8 Richter magnitude earthquake on October 15, 1996. The masonry column supporting bell tower within the church was critically damaged and needed to be retrofitted. In order to increase the flexural resistance of the tower, four vertical prestressing steel tie bars anchored at the top and bottom were used at the corners of the column. Four post-tensioned SMA devices were put in series in each tie bar, with the aim of maintaining the force applied to masonry constant and below 20 kN. Each SMA device included sixty superelastic SMA wires of 1 mm diameter and 300 mm length. The performance of the rehabilitation scheme was positively verified after the tower was shaken by another 4.5 Richter magnitude earthquake on June 18, 2000. No forms of distress or damage were noticed after the shock.

SMA-based Dampers and Isolators

Clark et al. (1995) conducted experimental and analytical research on energy dissipation devices using SMAs. Two different types of reduced-scale dampers using SMAs were tested over a range of strain amplitudes, loading frequencies, and temperatures. The basic model of the device was composed of 0.508 mm thick Nitinol wire wrapped around two cylindrical posts. There were 210 loops of wire in the preliminary device design. The device was initially prestressed at 2.75% strain and tested under in-plane cyclic loading. The test showed good hysteresis with a little reduction in the yield stress. The function of this SMA device was analytically studied by fitting it in a six storey, steel frame where the results showed good performance in reducing displacement response of the structure under earthquake excitation.

Adachi and Unjoh (1999) proposed an energy dissipation device made of SMA plate to reduce seismic force through pseudo yield effect. The study mainly focused on the increase in damping provided by the device in bridge structures. By conducting a series of shake table tests, it was found that SMA plates significantly reduced the seismic response of the bridge structure. Han et al. (2003) developed a damper device based on SMA wires and conducted a vibration control experiment of a two-storey steel frame fitted with eight devices. The top of the frame was pushed along its longer direction and released suddenly. It took about 45 seconds for the uncontrolled frame to decay its vibration to half of its initial displacement, whereas the frame with SMA dampers took less than 1 sec. The result shows that SMA is quite suitable for making damper devices for vibration control.

Pre-strained SE SMA wires wrapped in the longitudinal direction of a conventional elastomeric bearing can be used as an isolator in RC bridges. An analytical study was conducted by Choi et al. (2005) to determine the effectiveness of SMA-Rubber Bearings (SRBs) compared to that of conventional Lead-Rubber Bearings (LRBs). A three span continuous bridge fitted with SRBs and LRBs were subjected to scaled-ground motions of El Centro and Loma Prieta earthquakes (PGA of 0.2g, 0.4g, 0.6g, 0.8g and 1.0g). The results showed that LRBs retain residual deformation even with the weakest ground motion whereas SRBs recover all the deformation even after the strongest motion.

Bridge Restrainers

One of the major problems of bridges during earthquakes is their unseating due to excessive relative hinge opening and displacement (Schiff 1998). Limitations of existing unseating prevention devices include small elastic strain range, limited ductility, and no recentering capability. These limitations can be overcome by introducing SMA restrainers. For instance, DesRoches and Delemont (2002) evaluated the effectiveness of SMA restrainers through an analytical study of a multi-span simply supported bridge subjected to a set of ground motion records. The performance of SMA restrainers was compared to that of conventional steel restrainers. The results demonstrated that SMA restrainers were capable of reducing relative hinge displacements much more effectively than conventional restrainers. Moreover, Andrawes and DesRoches (2005) conducted nonlinear time history analyses on a typical multiple frame RC Box-girder Bridge to assess the performance of superelastic restrainers and conventional steel cable restrainers. High damping and elastic strains of superelastic elements significantly reduced the relative hinge displacement compared to that of steel restrainers.

Utilizing Shape Memory Effect in Earthquake Engineering

This section describes the earthquake engineering applications of SMA utilizing its SME. SMA in the martensite state has greater damping and large hysteresis compared to SMA in the austenite state.

Connectors

Ocel et al. (2004) investigated the effectiveness of partially restrained steel beam-column connections using SMA elements. In the martensite state, SMAs have the ability to recover large residual deformations by heating the alloy above its transformation temperature. The connection consisted of four large diameter SMA bars connecting the beam flange to the column flange serving as the primary moment transfer mechanism. Two full-scale connections were tested. The SMA connections exhibited a high level of energy dissipation, large ductility capacity, and no strength degradation after being subjected to cycles up to 4% drift. Following the test, the tendons were heated, which initiated the shape memory effect within the tendons and allowed recovering the residual beam tip displacement. The connections were retested, displaying repeatable and stable hysteretic behaviour. An additional test was performed under dynamic loading to examine the strain rate effects on the performance of the connection. The dynamic tests showed similar behaviour, except for a decrease in energy dissipation capacity when compared to the quasi-static tests. The results of this proof-of-concept test show promise for the use of SMAs in seismic resistant design and retrofit.

Bracing Members

An analytical investigation was carried out by Shahin et al. (1997) where SMA tendons were used as active bracing members of building models. Active control was achieved by heating the SMA tendons electrically to the austenitic phase to oppose the motion of the structure. Numerical simulation illustrated that the use of these tendons reduces the relative displacement between the base and the floor of the model.

Ma et al. (2004) employed SMA braces to reduce the vibration of a frame structure. Constant electrical current and periodically applied pulse current were used to ensure the shape recovery of the martensite SMA braces. Shake table test simulating 1995 Northridge earthquake was performed on a single frame structure to study the effectiveness of using active SMA braces utilizing SME over soft iron braces and superelastic braces. Experimental results show that increased damping was obtained in martensite phase than austenite phase using SMA braces and they prove to be more effective in reducing vibration as compared to soft iron braces and superelastic braces.

Dampers and Isolators

Casciati et al. (1998) investigated the possibility of utilizing large diameter SMA bars in martensite phase to dissipate energy through elastoplastic flexural during strong dynamic excitation. The static and dynamic experimental results confirmed martensite SMA to exhibit large hysteretic cycles with suitable ductility and high dissipation of energy. An energy dissipation device was designed using martensite SMA as a structural component, and finite element modelling illustrated the performance of the device in dissipating significant amount of energy.

Cost and Economy

Although there is a substantial potential of utilizing SMA in engineering structures, the cost of this material is a primary restraining factor to a larger implementation of SMA-based elements in structural applications. The feasibility of using SMA materials and devices in full-scale construction projects has been studied by Bruno and Valente (2002). They considered various costs in their study including direct (structural, non-structural) and indirect (injuries and deaths). The cost of SMA-based dampers, isolation devices or bracings turned out to be of the same order as that of conventional steel devices. SMA devices have been found much preferable in the sense that they do not require additional costs such as for maintenance or replacement. The efficiency of these devices is unique in reducing economic losses and minimizing human risk associated with natural disaster events.

Conclusions

This paper presents several applications of SMAs in earthquake engineering. In seismic design, if SMA material can be used at the critical regions, it can yield under strains caused by seismic loads but potentially recover deformations at the end of earthquakes. SMAs have great potential to be used in both RC and steel structures as connectors, bracings, and bridge restrainers. They will be able to dissipate significant amount of energy. Post-tensioning with SMA wires and tendons also proves to be a better option over conventional steel tendons in retrofitting works. The main advantage of this repair scheme is that the corrective forces to the structural system can be reapplied in case of any slip or elastic deformation. SE and SME are unique properties of SMAs that make them an ideal contender to be used as kernel components in seismic protection devices. A number of experimental and analytical studies of SMA devices (dampers and base isolators) prove them to be effective ways in improving the response of buildings and bridges to earthquake loadings. The recentering capability of SMA can be very efficient in reducing the cost of repairing and retrofitting of various structures even after a severe earthquake.

Applications of SMA are numerous, while new ideas of using them in various fields and new applications are still emerging. Suitable memory alloys need to be developed to suit the production for industrial and building application. The high cost of SMA is limiting its wider use in the construction industry. To enhance its uses and applications, the cost of the alloy needs to be considerably lowered. Fe-based SMA alloys may prove to be less costly and well suited for application in cement-based mortar, concrete and steel. If lower price can be ensured, SMAs have a great possibility of becoming an essential material for earthquake engineering in the near future.

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