International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
SJIF (2019): 7.583

Using Smart Materials in Enhancing the Seismic Behavior of Structures State-of-the-Art Report

Mohamed Omar

King Abdul-Aziz University, Faculty of Engineering at Rabigh, Rabigh 21911, Saudi Arabia.
Aswan University, Faculty of Engineering, Aswan 81542, Egypt
E-mail: *moh_omat77[at]yahoo.com*

Abstract: ***Recently, with the improvement of materials and innovation, numerous new materials discover their applications in structural designing to manage the infrastructure deteriorating. One example of these materials is smart material that needs a deep attention, from study to application. Shape Memory Alloys (SMAs) are increasingly becoming a topic of research in the area of 'smart materials'. SMAs are novel functional materials, which can exhibit large strains under loading–unloading process without residual deformation. They have the ability to remember a predetermined shape even after severe deformation. Under various temperatures, the two phases of shape memory alloy, Austenite and Martensite, the smart material shows two uncommon properties not quite the same as other metallic materials. One is shape memory, and the other is superelasticity. Both of these two properties can suit different applications in structural engineering, for example, prestress bars, self-restoration, and two-way actuators, and so on. The aim of this article is to investigate the using smart materials in enhancing the seismic behavior of structures by focusing on the literature review, basic information collection, and basic mechanical properties of smart materials. This article first presents an overview of the characteristics of SMAs associated with the temperature-induced and stress-induced reversible hysteretic phase transformation between austenite and martensite. The recent experimental studies and numerical simulations, which have been led to demonstrate the powerful role played by SMAs, are also presented in this article. Currently, research efforts have been extended to using SMAs as sensors, actuators, passive energy dissipaters and dampers for shape control and vibration control of civil structures. This article then presents a review of applications of the SMAs materials for controls of different structures. This article shows a broad survey of seismic uses of SMAs. Initial, an essential portrayal of two special effects of SMAs, shape memory and superelastic effect, is given. Next, the material models genius presented to catch the reaction of SMAs in seismic applications are quickly presented. Finally, utilizations of SMAs to structures and extensions to improve seismic behavior are completely assessed.***

Keywords: Smart Materials, Seismic Behavior, Shape Memory Alloys, Shape Memory Effect, Pseudoelasticity

1. Introduction

The smart materials refer to the materials that have unique properties that can be utilized in structural elements to enhance the behavior of the structure. A large number of innovative systems and devices have been developed to either reduce the earthquake forces acting on a structure or to absorb a part of the seismic energy [1]. All the time, various earthquakes occur all over the world, affecting a huge number of lives. Structures are affected severely, urban communities lose their capacity to work as extensions and significant structures, for example, medical clinics, are demolished; costing the city billions of dollars in harm. Presently, seismic design takes into consideration structures to encounter plastic deformation to dissipate the large energy. Though, numerous structures may even now be seriously harmed, destroyed, and should be wrecked. Advancement of seismic designing methods is always showing signs of change, and it will never dispense with the repercussions of earthquake occasion. However, it is conceivable to limit the harm so next to zero harm is done on the primary structural members.

Recently, seismic design approaches have transformed from a strength-based to deal with a behavior-based structure. As far as seismic design, safety and breakdown counteractive action was the main need. Park and Paulay understood that a structure would perform better if the quality was conveyed all through the structure instead of designing dependent on the base shear [2]. Moreover, it was realized that if plastic hinges were formed in beams instead of columns, the structure would perform much better. The performance-based design can be identified by these parameters [3]. The known performance-based design approach is called the direct displacement based design (DDBD) method. DDBD allows for a structure to experience a stable and reliable hysteresis response with high levels of energy dissipation, whilst having a lower stiffness. It has been found that damage of a structure is better correlated to the displacements rather than the forces it experiences, hence why engineers have moved away from a strength-based approach [4, 5]. The structures should little affected after earthquake shock, this is more important factor has to be taken into consideration. This could be happened in structures which can be re-center itself after earthquake. To overcome this deficiency, there have been intensive research efforts in the field of structural engineering over the past decades to employ smart materials technologies in seismic response control of structures. A particularly appealing and interesting class of smart materials is known as shape memory alloys (SMAs). SMAs have the ability to regain their original shape after being deformed well beyond 6—8% strain [6]. Oudah [7] found that utilizing SMAs in plastic hinge regions of structures may lead to re-centering of the structure joints. As a results, to eliminate members damages. Nowadays, SMAs have been widely investigated for their possible application in civil engineering structures. This article presents an in-depth review on recent development for applications of smart materials in enhancing the seismic behavior of structures. SMA, NiTi has been presented as an example of these smart materials. SMAs applications in seismic engineering along with an overview of essential mechanical characteristics and modeling techniques of SMAs is presented.

2. Smart Materials and Smart Structures

Smart Materials are materials that respond to changes in their environment and then undergo a material property change. These property changes can be leveraged to create an actuator or a sensor from the materials without any additional control or electronics required. A smart structure is a system containing multifunctional parts that can perform sensing, control, and actuation; it is a primitive analogue of a biological body. Smart materials are used to construct these smart structures, which can perform both sensing and actuation functions.

2.1 Types of smart materials

Piezoelectrics: Piezoelectric materials convert electrical energy to mechanical energy, and vice versa. They offer a wide range of utility and can be used as actuators (provide a voltage to create motion), sensors, such as many accelerometers, and energy harvesters since the charge generated from motion can be harvested and stored. Common applications for piezo materials are BBQ igniters and actuators for inkjet printer heads.

Shape Memory Alloys: The most commonly available Shape Memory Alloy is Nitinol, which was originally developed by the Naval Ordinance Laboratory. SMA's have the ability to change phase as a function of temperature, and in that process generate a force or motion. They are capable of relatively high energy but move slowly. Typically applications include morphing structures, thermal triggers, and some high strain energy absorbing applications. Advanced materials still under development include magnetically activated shape memory alloys.

Magnetostrictive: Similar to piezoelectric materials that respond to changes in electrical fields, this class of materials responds to changes in magnetic fields and can perform as an actuator, or sensor if deformed. While they can work well, they exhibit a large hysteresis which must be compensated when using the material in sensor applications.

Shape Memory Polymers: Shape Memory Polymers (SMP) are similar to Shape Memory Alloys except the obvious fact they are made from a polymer matrix. They possess much greater recoverable strains than the alloys, but typically under lower forces. Morphing structures has been the area of greatest use to date for SMP's.

Hydrogels: Hydrogels can be tailored to absorb and hold water, or other liquids, under certain environmental conditions. Hydrogels have been around for a long time, specifically in disposable diapers. A key feature however is the gels can be tailored chemically to respond to different stimuli.

Electroactive Polymers: There are many forms of electroactive polymers and many are still being refined. They have great potential as the flexibility of how they can be used provide advantages over some of the metals and ceramics mentioned above. Most typically applications include energy harvesting and sensing (see Stretchsense development kit) however some researchers are looking at high voltage, low current actuators.

Bi-Component Fibers: Adaptive thermal insulation can enable smart clothing that can change its thermal properties based on the environment.

3. Shape Memory Alloy (SMA)

A SMA is a developing material with unique properties appropriate for enhancing the performance of structures in seismic regions. To understand how SMA can be utilized to limit damages of structures when a structure affected by earthquake, it is important to know all information about SMA.

3.1 SMA History

Shape memory effect in different alloys has been reported since the mid 1930s, prompting various business items in the mechanical and aerospace ventures. Ni-Ti is the most commonly utilized SMA. In 1965, shape memory alloys (Nitinol) as a smart material derived from Nickel and Titanium were first patented by Buehler and Wiley [8] in Naval Ordnance Laboratory. Since then, tremendous effort has been infused to the utilization and study of this smart material.

In recent years, the properties of SMAs have attracted the attention of many researches for application to smart structural systems. Although SMAs have been known for decades, they have not been used in structures until rather recently.

3.2 SMA Properties

SMAs are found in two main phases: the high temperature phase, which is called austenite, and the low temperature phase, which is called martensite. SMAs could be transformed from austenite to martensite either by reducing the temperature or by applying a mechanical stress. On the other hand, martensite transforms into austenite by either increasing the alloy's temperature or removing the applied stress. SMAs have four transformation temperatures: (a) the austenite start temperature (TAs), where the austenite starts to develop in the alloy; (b) the austenite finish temperature (TAf), where the development of austenite in the alloy is 100% complete; (c) the martensite start temperature (TMs), where the development of martensite starts; and (d) the martensite finish temperature (TMf), where the development of martensite is 100% complete.

There are three groups of shape memory effects [9]. All of them have one common speciality, namely at least one shape (macroscopic state) of the material is recoverable. In the case of one-way effect the material gets a permanent deformation by applying mechanical load in a relative cool temperature (T < TAf). However, this deformation can disappear by heating above TAf and it remains unchanged during the cooling to the start temperature, Fig. 1.a.

When the start temperature is above TAf, mechanical load can cause deformation, but it disappears during unload. It seems like an elastic behavior, but the deformation can be unusually great. This effect is the PE, which does not concern only shape memory properties, Fig. 1.b.

The third effect is the two-way effect that requires only thermal load to change between two stable shapes. One of the shapes is stable above T_{Af} and the other one is stable below a different temperature $T_{Mf} < T_{Af}$. This effect can be produced only after a special treatment, Fig. 1.c.

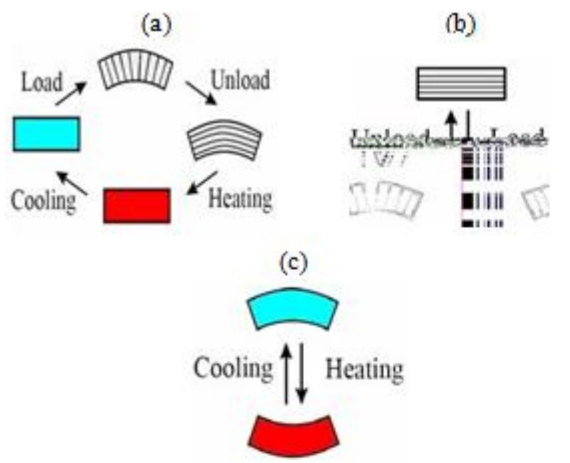
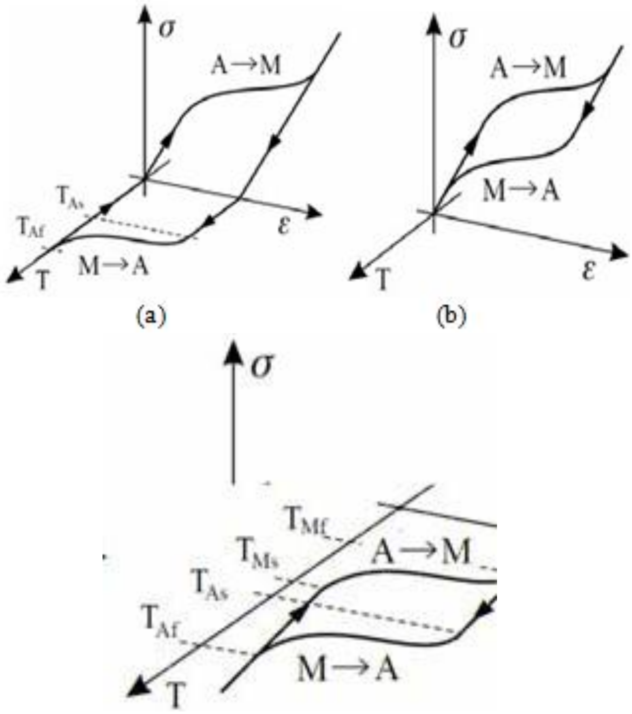


Figure 1: Shape memory phenomena: one-way effect (a), pseudoelasticity (PE) (b), and two-way effect (c) [10]



(c)

Figure 2: Shape memory phenomena in stress-strain-temperature space: one-way effect (a), pseudoelasticity (PE) (b), and two-way effect (c) [10]

Behind these effects, there is a crystallographic transformation, namely the martensitic phase transition. As it can be seen from the phenomena, the phase transitions can be induced by mechanical and thermal load. Figure 2 shows the effects in a stress-strain-temperature space. The forward (austenite to martensite, A→M) and backward (martensite to austenite, M→A) transitions and their temperatures are also illustrated.

Nitinol shape memory alloy (NiTi SMA) characteristics can be shown comparing to steel, as shown in Table 1

Table 1: Comparison of NiTi and steel properties

Property	NiTi	Steel
Recoverable elongation	8%	0.2%
Young's modulus	1.4-2.8E4 MPa	2.07E5 MPa
Yield strength	70-140 MPa	248-517 MPa
Ultimate strength	2000 MPa	448-827 MPa
Elongation at failure	5–10%	20%
Corrosion performance	Excellent	Fair

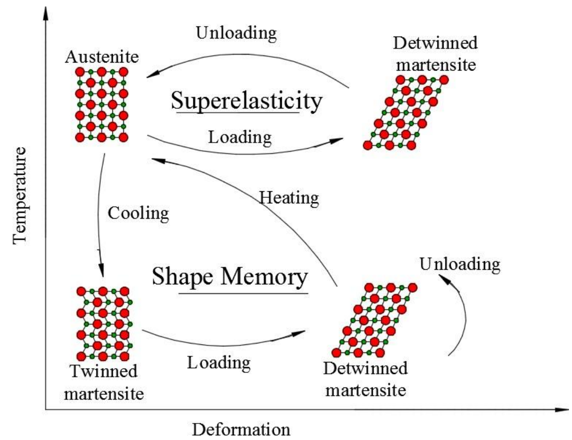


Figure 3 Temperature and deformation relationship of SMA microstructure for shape memory effect and superelasticity

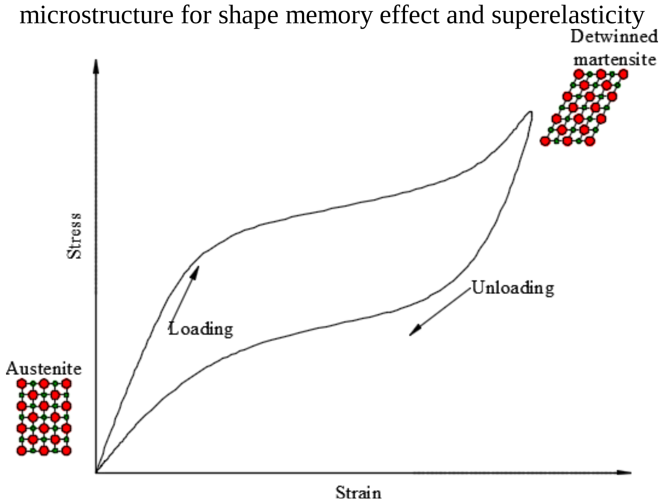


Figure 4: Stress-strain relationship for shape memory effect in SMAs

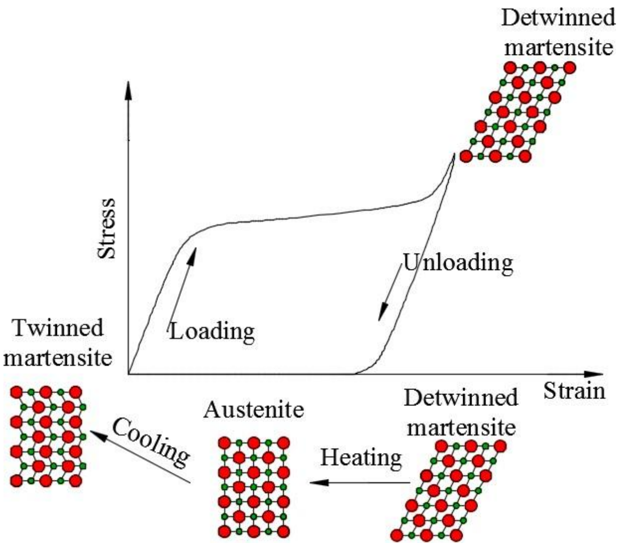


Figure 5: Stress-strain relationship for superelastic SMAs

Today, a wide range of SMA compositions has been developed and investigated to improve the characteristics of SMAs and the performance of structures in various engineering applications. The NiTi alloys have been the most commonly used and commercially available SMAs due to their superior thermo-mechanical properties, reliability, biocompatibility, and excellent strain recovery. In order to reduce the cost of SMA materials, researchers have developed different compositions of SMAs. The three major types of SMA systems that have been most explored over the last two decades are NiTi, copper (Cu), and iron (Fe) SMAs.

Table 2: Comparative advantages of three shape memory alloy compositions

Property	NiTi SMA	Cu SMA	Fe SMA
Modulus of Elasticity	Moderate	Low	High
Shape memory effect	High	Moderate	Low
Maximum recoverable strain	8%	5%	<5%
Production cost	High	Low	Low
Fabrication	Low	Good	Moderate
Workability	Moderate	Low	Good
Processing	Demanding	Easy	Easy

4. Using SMA in Enhancing Seismic Behavior of Structures

SAM has been researched in wide range to be used in seismic control. SMAs shape memory effect have been investigated for vibration control techniques [11,12]. SMAs are considered in many structural applications where exhibit the superelastic effect. The SMAs properties enable them to be used in structural applications. These properties like re-centering ability, energy dissipating capacity, SMAs superelastic and the ability to undergo large deformations, in addition to good fatigue resistance, and excellent corrosion resistance. The limitations of existing technologies for passive protection devices can be summarized as follows:
1) Problems related to ageing and durability (e.g., rubber components).
2) Difficulty in maintenance (those based on fluid viscosity)
3) Installation complexity or replacement and geometry restoration after strong events (those based on steel yielding or lead extrusion)
4) Variable performances depending on temperature (polymer based devices)

Properties, which enable SMA for civil engineering application are:
1) Repeated absorption of large amounts of strain energy under loading without permanent deformation
2) Possibility to obtain a wide range of cyclic behaviour from supplemental and fully recentering to highly dissipating by simply varying the characteristics of SMA components.
3) Strain range of 2 to 10%
4) Extraordinary fatigue resistance under large strain cycles.
5) Their greater durability and reliability in the long run.

4.1 SMA as beam-column connection

There are several studies that investigated the use of SMAs as beam-column connection elements, Fig. 6. Ocel et al. [13] experimentally evaluated the performance of partially restrained steel beam-column connections using martensitic SMAs. Four large diameter NiTi bars were used to connect the beam flange to the column flange and serve as the primary moment transfer mechanism. Two SMA-based full-scale connections were tested under static and dynamic cyclic loading. The SMA bars were heated above the transformation temperature to initiate shape memory effect after the initial test. It was observed that the SMA connections were able to recover 76% of the beam tip displacement.

Ma et al. [14] studied a self-centering beam-column connection using superelastic SMAs. The connection consists of an extended end-plate, long beam SMA bolts, continuity plates, beam flange ribs, and web stiffeners. The steel I-beam and column were connected by the extended end-plate and eight long beam superelastic NiTi bolts. The SMA connection was modeled in the finite element program ANSYS and numerical simulations were performed to predict the behavior of the connection. The connection was found to have good energy dissipating characteristics and ability to recover 94% of its total deformation. No local buckling of the connecting beam, typically observed in traditional connections, occurred during the whole loading history, Fig. 7.

Youssef et al. [15] explored the feasibility of using superelastic SMAs as reinforcement in beam-column joints of RC structures. They tested two large-scale beam-column joint specimens. One specimen was reinforced with regular steel rebars, while the other was reinforced with NiTi longitudinal rebars in conjunction with steel rebars. The results demonstrated that SMA reinforced beam-column joints had lower energy dissipation capacity and lower bond strength to concrete compared to those of steel joints; yet, they recovered most of its post-yield deformation whereas steel joint experienced large residual drifts. This indicates that an SMA joint can remain functional even after a strong earthquake. The same researchers also developed a numerical model that can simulate the behavior of SMA-RC beam-column joints in another study [16].

International Journal of Science and Research (IJSR)
ISSN (Online): 2319-7064
SJIF (2019): 7.583

DesRoches et al. [17] also studied the seismic performance of steel frames with beam-column connections that incorporate SMA bars. They considered a superelastic SMA connection with re-centering capability and a martensitic SMA connection with energy dissipation capacity. Numerical models of both connections were developed in a finite element analysis and validated using full scale experimental test results. Then, the models were implemented to carry out nonlinear time history analyses of three and nine story moment-resisting frames. SMA connections were found to be most effective in controlling structural response under high levels of seismic intensity. In a companion paper, the researchers carried out a probabilistic seismic demand analysis to assess statistically the efficacy of utilizing SMA connections in steel moment-resisting frames [18].

Speicher et al. [19] created a simple ductile re-centering system so they tested a steel beam-column connection with steel tendons and NiTi tendons embedded at the connection point. They found that the NiTi SMA tendons were able to recover 85% of their strain when cycled to 5% drift; whereas the steel tendons lost their re-centering abilities at a 1.5% drift. The SMA system proved to be very effective as the connection was able to reach a 5% drift with little residual deformations. SMA connections are not only for beam-column joints but they have been applied to shear walls. Wang and Zhu [20], placed SMA bars at the base and at the top of the wall, where the plastic hinge would typically develop. When the wall was subjected to the loading, it was able to reach a peak drift of 2.5% and a maximum strain of 3.3% in the SMA bar with almost zero residual deformation. In 2010, Roh and Reinhorn [21] studied the hysteretic behaviour of rocking segmental bridge piers reinforced with SMA bars. A rocking column is a type of double hinged column where it is only connected through compression at the contact surfaces, it has been shown to reduce the maximum acceleration and thus the associated forces of the earthquake. Twelve unbonded Nickel Titanium (NiTi) SMA bars were placed around the square precast concrete column and anchored to the footing of the column to prevent premature failure. The SMA bars removed the plastic hinge that would form when the column rocked. A bonded post-tensioned (PT) cable was placed down the center of the segmental pieces to hold the segments together as well as it provided additional re-centering abilities. By providing the SMA, they found that not only was complete damage to the column avoided, but the self-centering ability allowed for the structure to undergo subsequent shocks. Oudah [22] studied the seismic performance of single-slotted and double slotted self-centering concrete beam-column connections that were strengthened using PE NiTi SMA bars. By doing so, he suggested that it would relocate the location of the plastic hinge away from the face of the column. At the connections, he placed the SMA bars to re-center the structure as well as to dissipate some of the seismic energy. He found that using PE SMA bars significantly improved the seismic response of the proposed system by achieving a self-centering behaviour and thus minimizing permanent damage done on the structure. However, he found that the use of SMA bars led to a reduction in the damping capabilities. Another drawback of the system is providing proper anchorage for the SMA bar so that failure does not occur before the full capacity of the material is met.

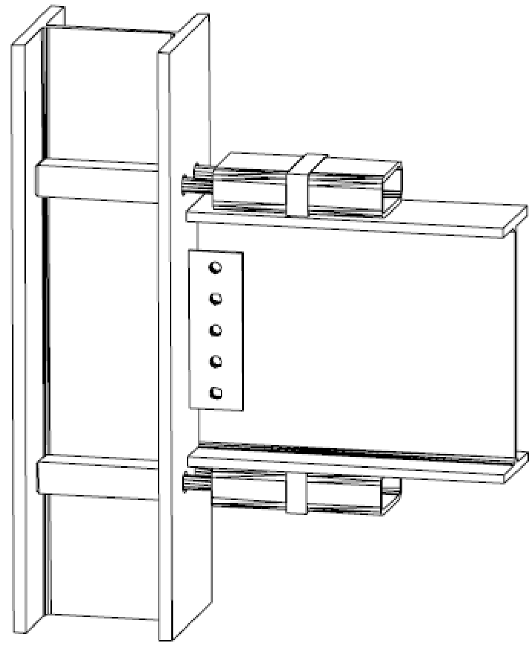


Figure 6: Innovative Steel Beam-Column Connection Using Shape Memory Alloys Tendons

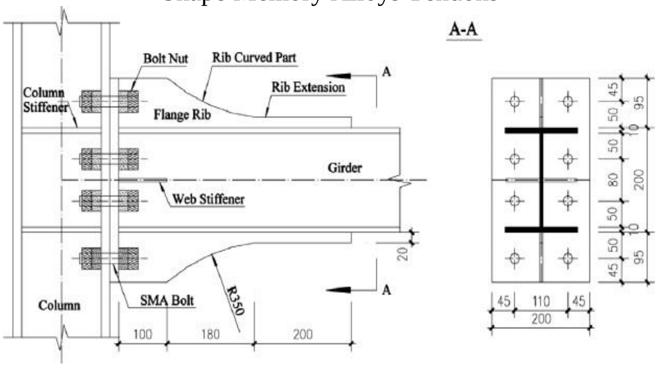


Figure 7: The SMA connection diagram

4.2 SMA as base connectors

The anchor bolts are used for column bases in steel structures. Column base and anchor bolts behavior have a strong effect on the overall behavior of the steel frames, hence improvement of the anchor bolts behavior in the column base connections is most important, and so a more attention should be paid to the proper modeling and the right construction. Mohamed Omar et al. [23] presented a numerical parametric study of the steel tower cable-stayed bridge which has been conducted to investigate the efficiency of the shape memory alloy anchor bolts in order to enhance the seismic behavior of cable stayed bridge. The proposed anchorage system of the bridge tower was presented with a numerical modeling of the new shape memory alloy. It is found that the shape memory alloy is more effectively reduced maximum displacement at the tower top and it provides a large elastic deformation range in comparison with ordinary steel anchor bolts. Also, SMA anchor bolts have the ability to return to its original shape after cyclic loadings and therefore their resisting performance remains the same to prevent plastic deformation and damage in the structural columns. SMA anchors are very effective in dissipating energy and reducing the total input energy of the whole towers under severe seismic ground motion. Using of the SMA anchor bolts is more effectively in controlling the reaction force at the base tower and stresses, Fig. 8.

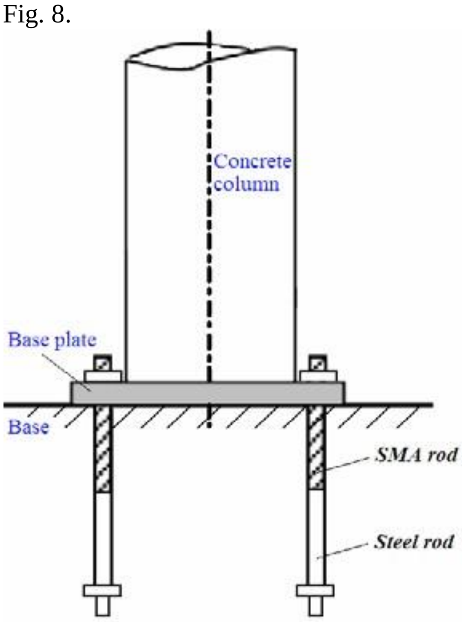


Figure 8: Schematic of SMA bar anchorage for a column

4.3 SMA as dampers

Large number of researchers studied the SMA as damper devices to control the vibration of buildings [24-30]. Dampers are the most commonly used devices in seismic control of structures. The structures include viscous fluid dampers, viscoelastic solid dampers, friction dampers and metallic dampers. These devices are utilized to reduce damages of structures by reducing the inelastic energy demand on the system. The problem in these devices that they give a large amount of deformation of structure elements though enhancing the seismic behavior under strong events resulting in the need for repair or replacement. Ozbulut and Silwal [31], examined the performance of Superelasic-Friction Bearing Isolator (S-FBI) composed of flat steel sliding bearing and superelastic SMA cables. A three-story building was modeled and asset using numerical methods. They determined that when the structure was subjected to seismic loading the control fixed-base model experienced a higher drift and larger floor accelerations when compared to the S-FBI system. In particular, the interstory drift decreased from 3.2% to 1.5% and the peak story acceleration was reduced by 64% relative to the fixed-base model. Similarly, Qian et al. [32], combined SMA wires and friction devices to create a damper that was more efficient in dissipating the energy and recentering the system. The research findings showed the success of the developed SMA friction damper with enhanced structural performance compared to the system without the device, Fig 9.

Han et al. [33] developed an SMA damper that can simultaneously work in tension, compression, and torsion. The damper utilizes superelastic NiTi wires that are subjected to tensile strains for all loading cases. To the verify effectiveness of the damper for tensile, compressive, and torsional motion, analytical and experimental studies were carried out on three reduced scale dampers. Ma and Cho [34] proposed an SMA-based damper consisting of pre-tensioned superelastic SMA wires which provide energy dissipation capacity and two pre-compressed springs which supply restoring force. Numerical studies were conducted to validate the expected behavior of the device. The results revealed that a 1 m long damper can attain an equivalent damping ratio of 12% with a displacement stroke of 30 mm and full re-centering capability. Van de Lindt and Potts [35] proposed an SMA-based device for mitigating seismic response of wood frame structures. The device consists of an inner tube and an outer tube. Two studs are connected to the inner tube and one stud is connected to the outer tube. The SMA wires were installed between these studs and pre-strained.

Li et al. [36] designed two types of SMA-based devices where SMA wires are always subjected to elongation and investigated the performance of the devices by performing shake table tests on a five-story steel frame. Zhang and Zhu [37] investigated an SMA-based device, termed reusable hysteretic damper (RHD). The device comprises two blocks that slide past each other and superelastic NiTi wires attached to the sliding blocks. The hysteretic behavior of the damper can be tuned by adjusting the inclination angle of the wires, the pre-tension level, and the friction coefficient of the sliding surface. In another study, Zhu and Zhang [38] studied the performance of a similar device based on the same concept as the RHD. In this configuration, the energy dissipation capacity of the device was enhanced by adjusting the normal force at the contact surface of sliding blocks with applied bolts, Fig. 10.

Yang et al. [39] proposed a hybrid device which combines re-centering SMA wires with energy absorbing steel struts. The device also utilizes two high strength steel tubes to guide the movement of SMA wires and struts, Fig. 11. Speicher et al. [40] designed a tension/compression device for seismic retrofit of buildings. The device makes use of NiTi helical springs or NiTi Belleville washers in compression. The results of cyclic loading tests suggested that helical springs have good re-centering and damping characteristics while Belleville washers can be used for energy dissipation purposes in an SMA device.

Li et al. [41] directed a hypothetical report on the vibration moderation of a consolidated link SMA damper framework. It was discovered that a SMA damper is prepared to do at the same time stifling the link vibration dominated by the initial couple of modes, yet it was noticed that the presentation of the SMA damper significantly relies upon different plan qualities of the damper. In another investigation, Liu et al. [42] completed test examinations on the consolidated remain link model-SMA damper framework to check the numerical investigation.

Zuo and Li [43] built up a SMA damper utilizing superelastic SMA wires and numerically and experiment count examined the viability of the damper on the vibration moderation of a link exposed to free and constrained vibrations. A scaled model link stayed scaffold was considered as exploratory test stage. The outcomes demonstrated that SMA dampers can both lessen the vibration rot time and reduction the in-plane acceleration reaction.

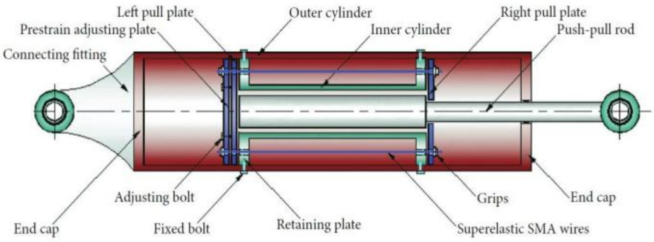


Figure 9: Proposed RSMAD device

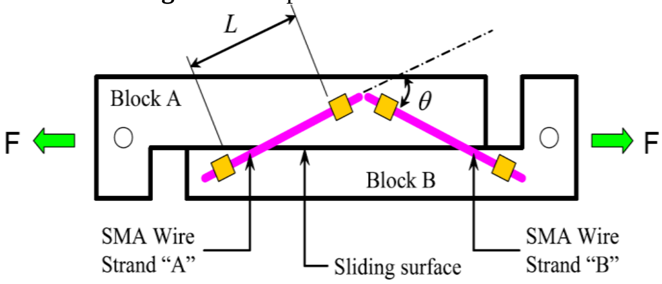
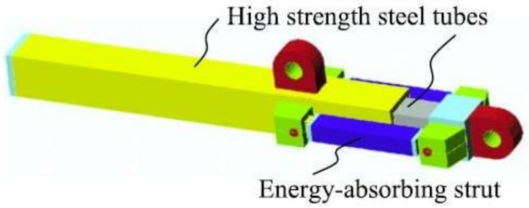
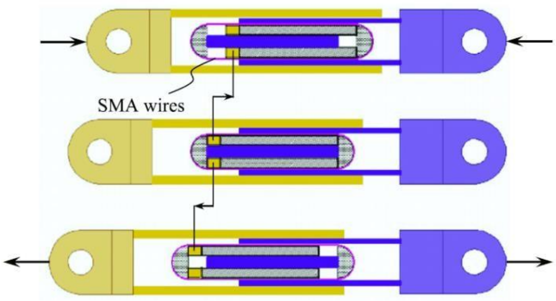


Figure 10: Schematics of the SMA-based reusable hysteretic damper



(a)



(b)

Figure 11: (a) SMA wires inside a hybrid device with clevis pins for chevron bracing; (b) SMA wires inside a hybrid device with clevis pins for diagonal bracing

4.4 SMA as bracing

One of the most popular systems used to enhance the lateral seismic response of frames is the bracing systems. From experimental and numerical studies on SMA as bracing systems, it is found that using the SMA in bracing system can enhance the seismic response by recentering the system as well as dissipating some of the energy, Figs. 12, 13 and 14. Qiu and Zhu [44], investigated the seismic performance of a six-story concentrically braced SMA frame through a numerical analysis. Results showed that the system can successfully mitigate the high-mode effect which results in a uniform distribution of peak inter-story drift ratios, as well as the frames exhibit limited structural and permanent damage even after a very strong earthquake. SMA bracing system have also been applied to concrete frames as a retrofit. Cortes-Puentes and Palermo [45], developed a bracing system composed of tension-only PE NiTi SMA and applied it to a seismically deficient squat RC shear wall. They found that the energy dissipation was substantially increased by the SMA braces and the wall was able to recover over 50% of the imposed lateral displacements

Several studies have considered the use of SMAs as diagonal braces in frame structures [46-49]. Some researchers conducted theoretical studies in order to demonstrate the efficacy of SMA bracing systems. Auricchio et al. [50] investigated the effectiveness of using large diameter NiTi bars as a bracing system for steel structures and compared the SMA braces with buckling-restrained steel braces. The outcome of numerical studies showed that SMA bracing systems can satisfactorily limit the interstory drifts in steel buildings and significantly reduce the residual drifts. Zhu and Zhang [51] compared the performance of an SMA-braced frame system that employs the RHD described above and buckling-restrained brace frames. They carried out non-linear time history analyses of three- and six-story frame buildings and found that the SMA-braced frame can effectively reduce the story drifts while eliminating the residual drift problem. Torra et al. [52] studied the feasibility of using SMA dampers for seismic protection of light buildings, such as single- or double-floor family houses. Numerical analyses on a structure with installed diagonal SMA bracing system made of either NiTi or CuAlBe SMAs were performed.

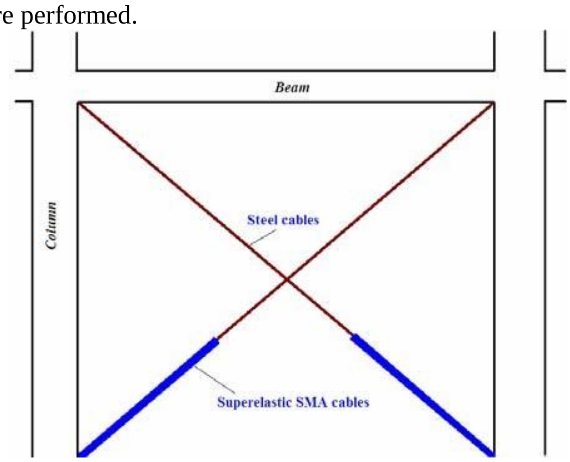


Figure 12: Schematic of the SMA braces for a frame structure

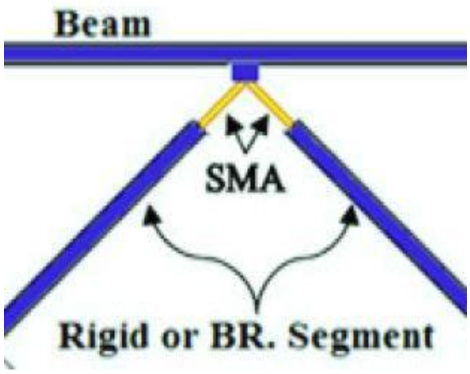


Figure 13: Bracing system with SMA connection in two cases

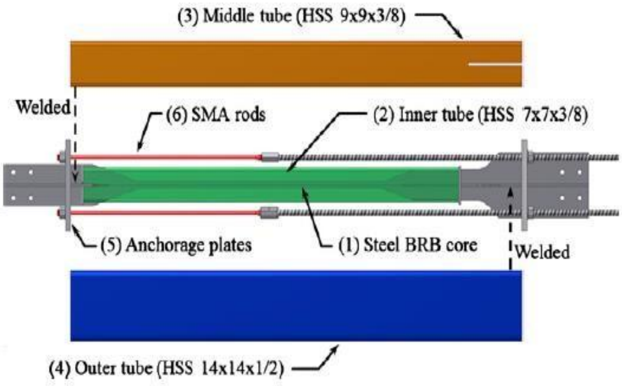


Figure 14: SC-BRB components

4.5 SMA in Masonry walls

SMAs have just been utilized effectively to improve the seismic exhibition of authentic structures. SMA is commonly used to continually apply stress, isolate a structure from loading, or re-center the structure after loading. The restoration of the Basilica of San Francesco in Assisi, Italy after it was severely damaged in an earthquake in 1997 is the world's first application of SMA to improve earthquake resistance. The superelastic of SMA was utilized along the side in both directions to the rooftop. The gravity loads were released from the wall by developing new concrete truss. The tympana of the both directions dividers were then along the side associated with the support utilizing shape memory devices [53-55].

The seismic intervention of the bell tower of the Church of San Giorgio in Trignano, Italy is another ISTECH restoration project using SMA to improve seismic performance completed in 1999 [56]. The system was prestressed such that the SMA reached the stress plateau. The goal for the system was to limit the total applied force from the rods to 80 kN. For more information of the SMA seismic improvement project refer to [57]. The incentive for using SMA was to support the structure and improve the structure's response in future seismic events and consequently the system was proven successful later, in 2000, when the tower experienced another earthquake with a similar magnitude and epicenter yet displayed no damage.

4.6 SMA as retrofitting devices

Some researchers carried out using the SMA as devices to protect the valuable historic buildings. Casciati and Hamdaoui [58] studied the performance of the historic masonry structures retrofitted by pre-stressed SMA wires through experimental and numerical approaches. El-Attar et al. [59] examined the application of SMA wire dampers in rehabilitation of two historic minarets. They conducted experimental tests on a scaled model of a minaret to evaluate the contribution of SMA dampers to the structural damping. El-Borgi et al. [60] carried out monotonic and quasi-static cycling tests on a cantilever masonry wall, representing a part of historical monuments. The wall was retrofitted with an array of SMA wires. One of the few actual implementation of an SMA device is also in the field of rehabilitation of historic structures. A bell tower in Italy was retrofitted using SMA-based dampers that consist of 60 NiTi superelastic wires with a diameter of 1 mm and length of 300 mm [61].

4.7 SMA as Bridge Restrainers

Multiple frame bridges subjected to strong earthquakes can experience large relative hinge displacements that lead to unseating of their superstructure. Several researchers proposed using SMAs as unseating prevention devices to overcome some of the limitations of traditional devices such as steel cable restrainers, steel rods, and shock transmission units, Figs. 15 and 16. Andrawes and DesRoches [62] evaluated the effectiveness of SMA restrainers in preventing the unseating of a typical multiple frame reinforced box girder bridge. SMA restrainers, designed as a tension only device, were represented with the 12.7 mm diameter superelastic NiTi rods. The performance of the SMA restrainers was compared with that of traditional steel cable restrainers. The results of non- linear dynamic analyses showed that SMA restrainers provides significant reduction in relative hinge openings compared to steel restrainers without increasing the ductility demand on the bridge frames. The effect of ambient temperature on the performance of SMA restrainers was assessed in another study by the same researchers [63]. Andrawes and DesRoches [64] also carried out a sensitivity study to compare the effectiveness of SMA restrainers with other retrofit devices including steel restrainer cables, metallic dampers, and viscoelastic dampers.

A few experimental studies were conducted to examine the feasibility of SMA restrainers. Johnson et al. [65] performed shake table tests to determine the effects of SMA restrainers on seismic response of multiple frame concrete bridges and to compare the performance of SMA restrainers to that of steel restrainers. The test specimen which simulates an in-span hinge.

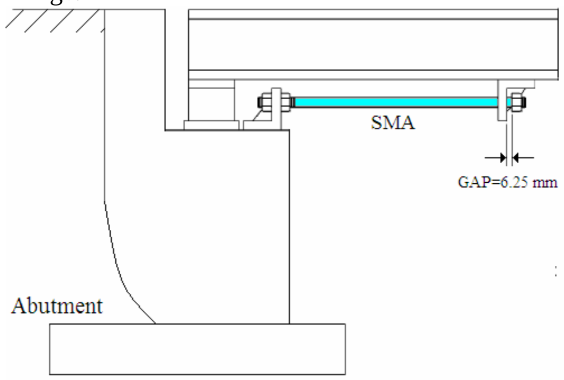


Figure 15: Schematic of the setup of SMA restrainer for a simple-supported bridge

Figure 16: Experimental test setup and SMA restrainer

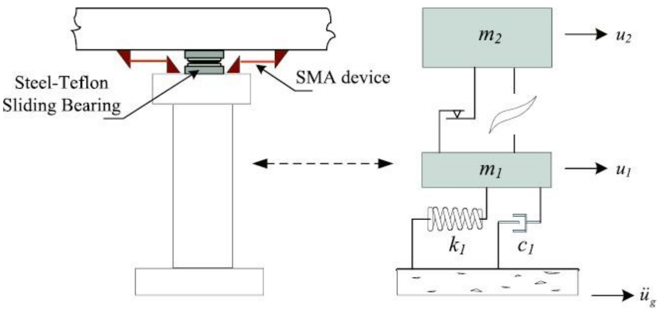


Figure 17: A bridge structure modeled with sliding bearings and SMA device

4.8 SMA reinforcement

The large displacement in concrete structures during earthquakes can cause the structural failure. This leads to permanent deformations and severe damage in the structure. SMAs have been considered as an alternative to traditional steel reinforcement in concrete columns in order to reduce permanent displacements and damage in concrete buildings. Saiidi and Wang [66] tested concrete column specimens with SMA longitudinal reinforcement in the plastic hinge zone on a shake table to determine the effectiveness of SMA bars. The test results showed that SMA reinforced columns were capable of recovering nearly all the post-yield deformations. Mohamed Omar. [67] studied the seismic response of concrete frames using SMA bars. For comparison purposes, he tested a frame with conventional concrete and steel reinforcement and a column with conventional concrete and SMA bars.

Roh and Reinhorn [68] proposed the use of SMA bars to improve hysteretic performance of the precast segmental bridge piers and insure self-centering capacity to the post-tensioned (PT) column system. They developed a new analytical model for SMA bars and numerically examined the performance of the PT segmental columns with superelastic SMA bars.

4.9 SMA as isolation devices

Isolation of structures using SMA is currently part of a lot of researchers' interest. Wilde et al. [69] proposed a base isolation system that is composed of a laminated rubber bearings and SMA device for protecting elevated highway bridges from the hazard of earthquakes. They compared the performance of the proposed isolation system with a laminated rubber bearing that has a lead core. Choi et al. [70] developed a new isolation system for seismic protection of bridges using elastomeric bearings and SMA wires. Analytical studies on a multi-span steel bridge illustrated that the combination of an SMA-rubber bearing effectively decreases relative displacement between deck and pier when compared with a conventional lead-rubber bearing. Dolce et al. [71] studied the performance of three different sliding-type isolation systems that employ rubber, steel, or SMAs as auxiliary device. They proposed two design procedures, the displacement and force approaches, to design isolation systems.

Ozbulut and Hurlebaus [72] studied the performance of a superelastic-friction base isolator (S-FBI) that combines a flat sliding bearing and a superelastic SMA device. In the proposed isolation system, the steel-Teflon sliding bearing filters out the earthquake forces by providing frictional sliding interfaces and the SMA device provides a re-centering mechanism and absorbs seismic energy through hysteresis of SMA elements. They identified the optimum design parameters of the S-FBI system for seismic protection of bridges against near-field earthquakes, Fig. 17. Ozbulut and Hurlebaus [73] also explored the effect of temperature changes on the performance of the S-FBI system and found out that changes in the ambient temperature have a modest effect on the performance of bridge structures isolated by S-FBI system. It was noted that the change in the forces generated in the sliding bearings and the SMA.

4.10 Experimental tests on building structures with SMA

Some researchers carried out experimental tests on building structures with SMA. Bartera and Giacchetti [74] experimentally studied the response of a single-story reinforced concrete (RC) frame that had been upgraded by different types of bracing systems. They used a high damping rubber pad and an SMA device as supplemental energy dissipation devices in series with steel braces. Free vibration and forced vibration tests were carried out to evaluate dynamic response of braced frames. Both dissipating bracing systems suppress vibration of the frame by adding a significant amount of damping. Dolce et al. [75] performed shake table tests on reduced-scale RC frames with and without special braces. In particular, they considered energy dissipating steel braces and re-centering SMA braces as passive control braces. They found that both bracing systems can significantly ameliorate the response of the RC frames subjected to seismic excitations.

Boroschek et al. [76] explored the use of SMA braces that consist of CuAlBe wires in steel frame buildings. Shake table tests were conducted on a three-story steel frame upgraded with SMA braces. The results indicated a substantial reduction in the peak relative displacements and peak accelerations of the frame. Devices counterbalance each other as the temperature varies. In another study, Ozbulut and Hurlebaus [77] compared the performance of the S-FBI system with the most commonly used seismic isolators, including lead-rubber bearings and friction pendulum systems.

As an alternative to conventional rubber isolators, Ozbulut and Hurlebaus [78] evaluated the performance of a smart rubber bearing system with SMAs. In particular, they explored the effectiveness of SMA/ rubber-based isolation systems in mitigating the response of the bridge structures subjected to near field earthquakes by performing a sensitivity analysis.

Ozbulut and Roschke [79] also examined the potential use of SMA as bracing elements in tall structures. They carried out a multiple-objective numerical optimization that simultaneously minimizes displacements and accelerations of the structure in order to optimize SMA bracing elements within the structure. After design of an optimal SMA damping system was complete, full-scale experimental shake table tests were conducted on a large-scale steel frame that was equipped with the optimal SMA devices.

Andrawes et al. [80] investigated the feasibility of using spirals made of SMAs for seismic retrofitting of RC bridge columns. They conducted uniaxial compression tests on concrete cylinders confined with 12-loop NiTi martensitic wires with a diameter of 3 mm. Using the experimental results, they developed an analytical model to represent the behavior of RC columns retrofitted with SMA spirals. The performance of the SMA retrofitted column was compared with that of carbon fiber-reinforced polymer (CFRP) retrofitted column. The analytical results showed that RC columns retrofitted with SMA spirals outperformed CFRP retrofitted column in terms of enhancing the strength and effective stiffness and reducing the residual deformations, Fig. 20.

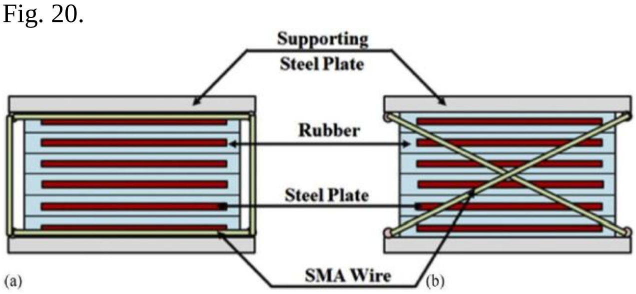
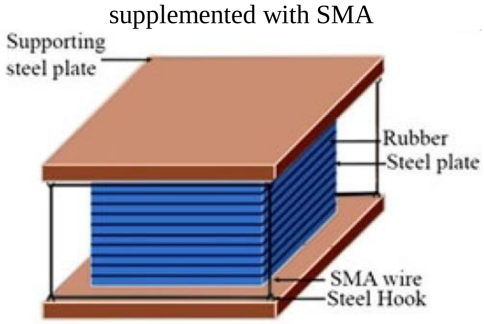
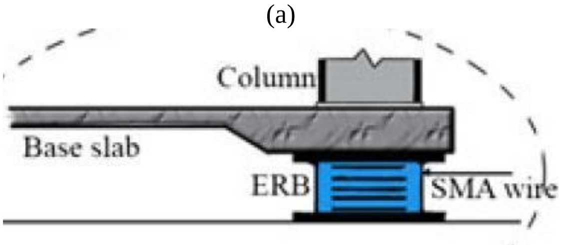


Figure 18: Configuration of the isolation system supplemented with SMA



(a)



(b)

Figure 19: (a) SMA supplement elastomeric rubber bearing (SMARB) and (b) Installation of SMARB at the base isolated building frame

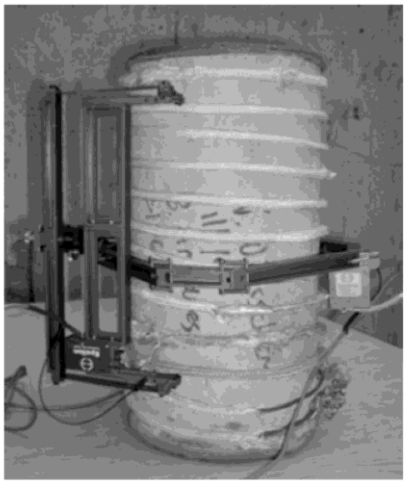


Figure 20: Concrete specimen with SMA spirals

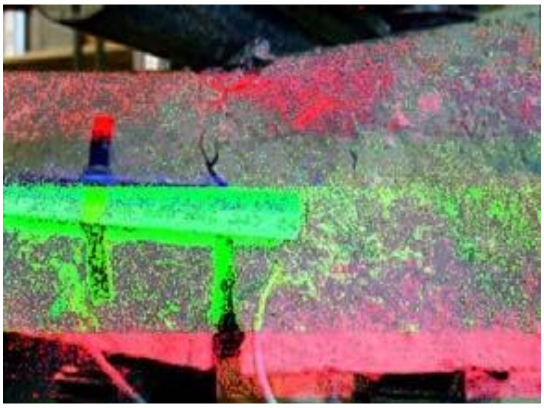


Figure 21: A large crack during a loading test

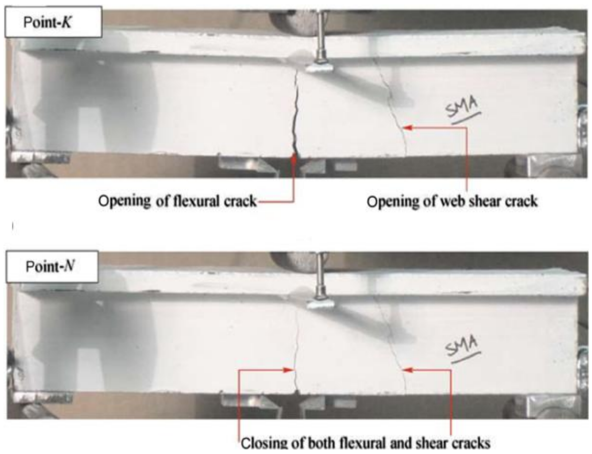


Figure 22: Reinforcement details of SMA-reinforced beams

5. Conclusions

Nowadays, during earthquakes, infrastructures sustain a large amount of damage. This leads to extra repair costs of structures. In engineering design, the trend now is moving from the strength-based design approach to a performance-based approach to enhance the behavior of structures during earthquakes. The performance-based approach, direct displacement-based design (DDBD) is being used more than the traditional strength-based design approach due to there being a reliable hysteresis, large energy dissipation and low stiffness. Therefore, the new materials and new techniques are in need to enhance the seismic behavior of structures.

SMAs as a smart materials have some unique properties which make them appealing for different applications in engineering field. These properties include large energy dissipation capacity and excellent re-centering ability. In civil engineering, there have been extensive researches on the use of SMAs in civil structures for the control of seismic responses.

The aim of this report is to present a review of the smart materials and techniques capable of enhance the behavior of structures at seismic events.

The unique mechanical and thermal properties of shape memory alloy are explained such as its behaviour during changes in temperature and stress. The mechanical properties of NiTi SMAs and their dependence on various variables such as temperature and loading rate are briefly presented. According to the fundamental information on mechanical properties and modeling techniques of SMAs, a variety of seismic applications of SMAs are presented. In particular, the applications of SMAs in civil structures as energy dissipation device, bracing system, beam-column connector, and isolation device are presented.

The shape memory effect is characterized by temperature changes of SMA in a zero-stress state. That is, its ability to be deformed below a certain temperature (Mf), have the deformations remain until it is reheated, then assumes its original shape upon heating once the temperature increases above Af. This feature makes SMA suitable in civil engineering applications such as post-tensioning, strengthening, and active confinement. The other important phenomenon discussed is pseudoelasticity. This phenomenon sees austenitic SMA above temperatures Af follow a linear loading curve until it reaches a stress plateau. If it is continued to be loaded, it reaches another linear loading curve. At any point, if it is unloaded, it follows another unloading curve, transitions back to austenite and recovers almost all deformations. Civil engineering applications of this feature include; load-isolating, re-centering and dampening which are all relevant in minimizing damage to structures after an earthquake.

Traditional new construction and repair techniques are discussed and compared to innovated techniques. Traditionally, new construction involves using passive or active systems to dissipate seismic energy. For seismic repairs, fiber reinforced polymers are being used to strengthen and repair damaged structures after being exposed to an earthquake. These traditional methods do save material from being damaged or replaced, but are expensive and inefficient. This leads researchers to explore the possibility of using SMA to improve the performance of structures in seismic areas due to its re-centering ability and the ability to dissipate energy.

With the increasing demands for high performance of structural systems, the unique capabilities of SMAs can be exploited in the design, construction, and retrofit of civil infrastructure systems for the vibration control of structures. Although the analytical and experimental studies have proven that the structures with SMA devices improve the seismic response, further research is needed to evolve design guidelines for the SMA-based seismic protection systems.

Even though successful applications of SMAs demonstrated a significant potential for the development of these materials in structural engineering, several technological draw- backs actually limit their wider implementation. From the SMA material side, SMAs are very sensitive to compositional variations: small changes to the constituents of an alloy may significantly modify the mechanical properties of the material, requiring quality control to ensure suitable properties. In addition, due to the thermomechanical sensitivity of the material, SMA properties are dependent on the ambient and in-service temperatures.

Another impediment to actual implementation has been cited as the high cost of SMA material over the past years. It should be noted that the current applications of SMAs are mostly in the biomedical and aerospace industries, which requires considerably small quantities of material compared to the amounts needed in a civil engineering application. The cost of the alloy will be largely lowered once a large amount of material is consumed with the actual implementation of SMAs in civil structures. In addition, several researchers have investigated the ferrous SMAs such as FeMnSi, FeNiC, and FeNiCoTi due to their lower cost as an alternative to NiTi and Cu alloys.

In conclusion, SMA as a smart material, its application to seismic structures is still being researched. Its unique qualities, compared to classic metals, make it an ideal candidate for direct displacement-based design due to the low modulus of elasticity and large strain capabilities. If the structures can undergo larger displacements and dissipate larger amounts of energy, there will no doubt be a huge reduction in structural damage caused by earthquakes. Less structural damage results in less repair costs, structures, which can be vital to the functioning of a city, remain operational but most important of all, there is a potential to save lives that would otherwise be lost when a structure collapses.

Even though the price of SMA is still considerably higher than that of other construction materials, there has been a significant decrease in the price of NiTi over the last decade. Many efforts have been made in the use of SMAs in structural engineering involving material scientists, the civil engineering community, and manufacturers; for this reason, it is expected that significant achievements can be reached in the near future, overcoming the aforementioned obstacles.

References

[1] Rai, D.C. 2000. ‘‘Future Trends in Earthquake-Resistant Design of Structures,’’ Current Science, 79:1291—1300.
[2] R. Park and T. Paulay, "Reinforced Concrete Structures," ed. New York: John Wiley & Sons, 1975, p. 769.
[3] M. J. N. Priestley. Performance based seismic design. 12th World Conference on Earthquake Engineering (WCEE). 2000; 1(1): 22
[4] M. J. N. Priestley, G. M. Calvi, and M. J. Kowalsky. Direct

displacement-based seismic design. In: ZSEE Conference, New Zealand, 2007, vol. 23(33), pp. 1453-1460.

[5] D. Cardone, M. Dolce, and G. Palermo. Force-based vs. direct displacement-based design of buildings with seismic isolation. In: The 14th World Conference on Earthquake Engineering, 2008, vol. 1.

[6] Hurlebaus, S. and Gaul, L. 2006. ‘‘Smart Structure Dynamics,’’Mechanical Systems and Signal Processing, 20:255—281.

[7] F. Oudah and R. El-Hacha. Joint performance in concrete beam-column connections reinforced using SMA smart material. Engineering Structures. 2017; 151: 745-760 https://doi.org/10.1016/j.engstruct.2017.08.054

[8] Buehler WJ and Wiley RC, US patent 3,174,851, nickel-based alloys, 1965.

[9] Perkins J, Shape Memory Effects in Alloys, Plenum Press, New York, 1975.

[10] Árpád Peth˝o, Constitutive modeling of shape memory alloys based on a finite strain description, Periodica poly technical ser. Mech. Eng. 2000, Vol. 44, No. 1, pp. 115-126.

[11] Shahin, A., Alu, R., Meckl, P.H. and Jones, J.D. 1997. ‘‘Modeling of SMA Tendons for Active Control of Structures,’’ Journal of Intelligent Material Systems and Structures, 8:51—70.

[12] McGavin, G. and Guerin, G. 2002. ‘‘Real-time Seismic Damping and Frequency Control of Steel Structures Using Nitinol Wire,’’ Proceedings of SPIE, 4696:176—184.

[13] Ocel, J., DesRoches, R., Leon, R.T., Hess, W.G., Krumme, R., Hayes, J.R. and Sweeney, S. 2004. ‘‘Steel Beam-Column Connections using Shape Memory Alloys,’’ Journal of Structural Engineering, 130:732—740.

[14] Ma, H., Wilkinson, T. and Cho, C. 2007. ‘‘Feasibility Study on a Self- Centering Beam-to-Column Connection by Using the Superelastic Behavior of SMAs,’’ Smart Material and Structures, 16:1555—1563.

[15] Youssef, M.A., Alam, M.S. and Nehdi, M. 2008. ‘‘Experimental Investigation on the Seismic Behaviour of Beam-Column Joints Reinforced with Superelastic Shape Memory Alloys,’’ Journal of Earthquake Engineering, 12:1205—1222.

[16] Alam, M.S., Youssef, M.A. and Nehdi, M. 2008. ‘‘Analytical Prediction of the Seismic Behaviour of Superelastic Shape Memory Alloy Reinforced Concrete Elements,’’ Engineering Structures, 30:3399—3411.

[17] DesRoches, R., Taftali, B. and Ellingwood, B.R. 2010. ‘‘Seismic Performance Assessment of Steel Frames with Shape Memory Alloy Connections, Part I — Analysis and Seismic Demands,’’ Journal of Earthquake Engineering, 14:471—486.

[18] Ellingwood, B.R., Taftali, B. and DesRoches, R. 2010. ‘‘Seismic Performance Assessment of Steel Frames with Shape Memory Alloy Connections, Part II — Probabilistic Seismic Demand Assessment,’’ Journal of Earthquake Engineering, 14:641—645.

[19] M. S. Speicher, R. DesRoches, and R. T. Leon. Experimental results of a NiTi shape memory alloy (SMA)-based recentering beam-column connection. Engineering structures. 2011; 33(9): 2448- 2457

[20] W. Wang, C. Fang, and J. Liu. Self-centering beam-to-column connections with combined superelastic SMA bolts and steel angles. Journal of Structural Engineering. 2017; 143(2).

[21] H. Roh and A. M. Reinhorn. Modeling and seismic response of structures with concrete rocking columns and viscous dampers. Engineering Structures. 2010; 32(8): 2096-2107.

[22] F. Oudah and R. El-Hacha. Plastic hinge relocation in concrete structures using the double- slotted-beam system. Bulletin of Earthquake Engineering. 2016; 15(5): 2173-2199 http://doi.org/10.1007/s10518-016-0055-9

[23] Mohamed OMAR, Toshiro HAYASHIKAWA and Shehata E. ABDEL RAHEEM, Seismic Nonlinear Analysis of Cable Stayed Bridge Steel Towers with Shape Memory Alloy Connection, JSSC Journal of Construction Steel, Vol.14, 2007.

[24] Krumme, R., Hayes, J. and Sweeney, S. 1995. ‘‘Structural Damping with Shape-Memory Alloys: One Class of Devices,’’ Proceedings of SPIE, 2445:225—240.

[25] Higashino, M. and Aizawa, S. 1996. ‘‘Experimental and Analytical Studies of Structural Control System using Shape Memory Alloy,’’ In: Second International Workshop on Structural Control, 18—20 December, Hong Kong, pp. 221—232.

[26] Aizawa, S., Kakizawa, T. and Higasino, M. 1998. ‘‘Case Studies of Smart Materials For Civil Structures,’’ Smart Materials and Structures, 7:617—626.

[27] Salich, J., Hou, Z. and Noori, M. 2001. ‘‘Vibration Suppression of Structures using Passive Shape Memory Alloy Energy Dissipation Devices,’’ Journal of Intelligent Material Systems and Structures, 12:671—680.

[28] Suduo, X. and Xiongyan, L. 2007. ‘‘Control Devices Incorporated with Shape Memory Alloy,’’ Earthquake Engineering and Engineering Vibration, 6:159—169.

[29] Zuo, X.B., Li, A.Q. and Chen, Q.F. 2008. ‘‘Design and Analysis of a Superelastic SMA Damper,’’ Journal of Intelligent Material Systems and Structures, 19:631—639.

[30] Ma, H. and Yam, M.C.H. 2011. ‘‘Modeling of Self-Centering Damper and its Application in Structural Control,’’ Journal of Constructional Steel Research, 67:656—666.

[31] O. E. Ozbulut and B. Silwal. Performance assessment of buildings isolated with S-FBI system under near-fault earthquakes. Smart Struct. Syst. 2016; 17(5): 16

[32] H. Qian, H. Li, and G. Song. Experimental investigations of building structure with a superelastic shape memory alloy friction damper subject to seismic loads. Smart Materials and Structures. 2016; 25(12): 125026

[33] Han, Y.L., Xing, D.J., Xiao, E.T. and Li, A.Q. 2005. ‘‘NiTi-Wire Shape Memory Alloy Dampers to Simultaneously Damp Tension, Compression, and Torsion,’’ Journal of Vibration and Control, 11:1067—1084.

[34] Ma, H. and Cho, C. 2008. ‘‘Feasibility Study on a Superelastic SMA Damper with Re-Centring Capability,’’ Materials Science and Engineering A, 473:290—296.

[35] van de Lindt, J.W. and Potts, A. 2008. ‘‘Shake Table Testing of a Superelastic Shape Memory Alloy Response Modification Device in a Wood Shearwall,’’ Journal of Structural Engineering, 134:1343—1352.

[36] Li, H., Mao, C.X. and Qu, J.P. 2008. ‘‘Experimental and Theoretical Study on Two Types of Shape Memory Alloy Devices,’’ Earthquake Engineering and Structural Dynamics, 37:407—426.

[37] Zhang, Y. and Zhu, S. 2007. ‘‘Shape Memory Alloy-Based Reusable Hysteretic Damper for Seismic Hazard Mitigation,’’ Smart Materials Structures, 16:1603—1613.

[38] Zhu, S. and Zhang, Y. 2007b. ‘‘Seismic Behaviour of Self-Centring Braced Frame Buildings with Reusable Hysteretic Damping Brace,’’ Earthquake Engineering and Structural

Dynamics, 36:1329—1346.
[39] Yang, C.W., DesRoches, R. and Leon, R.T. 2010. ''Design and Analysis of Braced Frames with Shape Memory Alloy and Energy-Absorbing Hybrid Devices,'' Engineering Structures, 32:498—507.
[40] Speicher, M., Hodgson, D.E., DesRoches, R. and Leon, R.T. 2009. ''Shape Memory Alloy Tension/Compression Device for Seismic Retrofit of Buildings,'' Journal of Materials Engineering and Performance, 18:746—753.
[41] Li, H., Liu, M. and Ou, J. 2004. ''Vibration Mitigation of a Stay Cable with One Shape Memory Alloy Damper,'' Structural Control and Health Monitoring, 11:21—36.
[42] Liu, M., Li, H., Song, G. and Ou, J. 2007. ''Investigation of Vibration Mitigation of Stay Cables Incorporated with Superelastic Shape Memory Alloy Dampers,'' Smart Materials and Structures, 16:2202—2213.
[43] Zuo, X.B. and Li, A.Q. 2009. ''Numerical and Experimental Investigation on Cable Vibration Mitigation using Shape Memory Alloy Damper,'' Structural Control and Health Monitoring, doi: 10.1002/stc.354.
[44] C. Qiu and S. Zhu. Shake table test and numerical study of self-centering steel frame with SMA braces. Earthquake Engineering & Structural Dynamics. 2017; 46(1): 117-137
[45] W. L. Cortés-Puentes and D. Palermo. Seismic retrofit of concrete shear walls with SMA tension braces. Journal of Structural Engineering. 2018; 144(2): 04017200-1 to 04017200-13 https://doi.org/10.1061/(ASCE)ST.1943-541X.0001936
[46] Han, Y.H., Li, Q.S., Li, A.Q., Leung, A.Y.T. and Lin, P.H. 2003.''Structural Vibration Control by Shape Memory Alloy Damper,'' Earthquake Engineering and Structural Dynamics, 32:483—494.
[47] Lafortune, P., McCormick, J., DesRoches, R. and Terriault, P. 2007. ''Testing of Superelastic Recentering Pre-Strained Braces for Seismic Resistant Design,'' Journal of Earthquake Engineering, 11:383—399.
[48] McCormick, J., DesRoches, R., Fugazza, D. and Auricchio, F. 2007. ''Seismic Assessment of Concentrically-Braced Steel Frames Using Shape Memory Alloy Braces,'' Journal of Structural Engineering, 133:863—870.
[49] Mohamed OMAR, Seismic Response of Braced Steel Frames with Shape Memory Alloy and Mega Bracing Systems, World Academy of Science, Engineering and Technology, International Journal of Civil, Architectural Science and Engineering Vol:8 No:2, 2014.
[50] Auricchio, F., Fugazza, D. and DesRoches, R. 2006. ''Earthquake Performance of Steel Frames with Nitinol Braces,'' Journal of Earthquake Engineering, 10:45—66.
[51] Zhu, S. and Zhang, Y. 2007. ''Seismic Behaviour of Self-Centring Braced Frame Buildings with Reusable Hysteretic Damping Brace,'' Earthquake Engineering and Structural Dynamics, 36:1329—1346.
[52] Torra, V., Isalgue, A., Martorell, F., Terriault, P. and Lovey, F.C. 2007. ''Built in Dampers for Family Homes via SMA: An ANSYS Computation Scheme Based on Mesoscopic and Microscopic Experimental Analyses,'' Engineering Structures, 29:1889—1902.
[53] A. Bonci, G. Carluccio, M. Castellano, G. Croci, S. Infanti, and A. Viskovic. Use of shock transmission units and shape memory alloy devices for the seismic protection of monuments: The case of the upper Basilica of San Francesco at Assisi. In: Proceedings of International Millennium Congress, More than Two Thousand Years in the History of Architecture, 2001.
[54] Seismic protection of monuments by shape memory alloy devices and shock transmitters. In: 4th International Seminar on Structural Analysis of Historical Constructions. Padova, 2004.
[55] M. Indirli and M. G. Castellano. Shape Memory Alloy Devices for the Structural Improvement of Masonry Heritage Structures. International Journal of Architectural Heritage. 2008; 2(2): 93-119 https://doi.org/10.1080/15583050701636258
[56] M. Indirli et al. Experimental tests on masonry structures provided with shape memory alloy antiseismic devices. In: 12th World Conference on Earthquake Engineering, Auckland, New Zealand, 2000; 2000.
[57] M. Indirli, M. G. Castellano, P. Clemente, and A. Martelli. Demo-application of shape memory alloy devices: the rehabilitation of the S. Giorgio Church bell tower. In: SPIE's 8th Annual International Symposium on Smart Structures and Materials, 2001, vol. 4330(11), pp. 262-272: SPIE; 2001.
[58] Casciati, S. and Hamdaoui, K. 2008. ''Experimental and Numerical Studies Toward the Implementation of Shape Memory Alloy Ties in Masonry Structures,'' Smart Structures and Systems, 4:153—169.
[59] El-Attar, A., Saleh, A., El-Habbal, I., Zaghw, A.H. and Osman, A. 2008. ''The Use of SMA Wire Dampers to Enhance the Seismic Performance of Two Historical Islamic Minarets,'' Smart Structures and Systems, 4:221—232.
[60] El-Borgi, S., Neifar, M., Ben Jabeur, M., Cherif, D. and Smaoui, H. 2008. ''Use of Copper Shape Memory Alloys in Retrofitting Historical Monuments,'' Smart Structures and Systems, 4:247—259.
[61] Indirli, M., Castellano, M.G., Clemente, P. and Martelli, A. 2001. ''Demo-Application of Shape Memory Alloy Devices: The Rehabilitation of the S. Giorgio Church Bell-Tower,'' In: Proceedings of SPIE, Smart Systems for Bridges, Structures, and Highways, 5—7 March, Newport Beach, CA, Vol. 4330, pp. 262—272.
[62] Andrawes, B. and DesRoches, R. 2005. ''Unseating Prevention for Multiple Frame Bridges Using Superelastic Restrainers,'' Smart Materials and Structures, 14:60—67.
[63] Andrawes, B. and DesRoches, R. 2007. ''Effect of Ambient Temperature on the Hinge Openings in Bridges with Shape Memory Alloy Seismic Restrainers,'' Engineering Structures, 29:2294—2301.
[64] Andrawes, B. and DesRoches, R. 2007. ''Comparison between Shape Memory Alloy Restrainers and Other Bridge Retrofit Devices,'' Journal of Bridge Engineering, 12:700—709.
[65] Johnson, R., Padgett, J.E., Maragakis, M.E., DesRoches, R. and Saiidi, M.S. 2008. ''Large Scale Testing of Nitinol Shape Memory Alloy Devices for Retrofitting of Bridges,'' Smart Materials and Structures, 17:1—10.
[66] Saiidi, M. and Wang, H. 2006. ''An Exploratory Study of Seismic Response of Concrete Columns with Shape Memory Alloys Reinforcement,'' ACI Structural Journal, 103:436—443.
[67] Mohamed OMAR, "Comparative Study on Seismic Response of Reinforced Concrete Frames with SMA in Column and Beam Plastic Hinge Zones", Advanced Materials Research, Vol 1043, pp. 247-251, Oct. 2014. https://www.scientific.net/AMR.1043.247
[68] Roh, H. and Reinhorn, A.M. 2010. ''Hysteretic Behavior of Precast Segmental Bridge Piers with Superelastic Shape Memory Alloy Bars'',' Engineering Structures,

32:3394—3403.
[69] Wilde, K., Gardoni, P. and Fujino, Y. 2000. ‘‘Base Isolation System with Shape Memory Alloy Device for Elevated Highway Bridges,’’ Engineering Structures, 22:222—229.
[70] Choi, E., Nam, T.H., Oh, J.T. and Cho, B.S. 2006. ‘‘An Isolation Bearing for Highway Bridges using Shape Memory Alloys,’’ Material Science and Engineering, A 438—440:1081—1084.
[71] Dolce, M., Cardone, D. and Palermo, G. 2007. ‘‘Seismic Isolation of Bridges using Isolation Systems Based on Flat Sliding Bearings,’’ Bulletin of Earthquake Engineering, 5:491—509.
[72] Ozbulut, O.E. and Hurlebaus, S. 2011. ‘‘Optimal Design of Superelastic-Friction Base Isolators for Seismic Protection of Highway Bridges against Near-Field Earthquakes,’’ Earthquake Engineering and Structural Dynamics, 40:273—291.
[73] Ozbulut, O.E. and Hurlebaus, S. 2010. ‘‘Evaluation of the Performance of a Sliding-Type Base Isolation System with A NiTi Shape Memory Alloy Device Considering Temperature Effects,’’ Engineering Structures, 32:238—249.
[74] Bartera, F. and Giacchetti, R. 2004. ‘‘Steel Dissipating Braces for Upgrading Existing Building Frames,’’ Journal of Constructional Steel Research, 60:751—769.
[75] Dolce, M., Cardone, D., Ponzo, F.C. and Valente, C. 2005. ‘‘Shaking Table Tests on Reinforced Concrete Frames Without and with Passive Control Systems,’’ Earthquake Engineering and Structural Dynamics, 34:1687—1717.
[76] Boroschek, R.L., Farias, G., Moroni, O. and Sarrazin, M. 2007. ‘‘Effect of SMA Braces in a Steel Frame Building,’’ Journal of Earthquake Engineering, 11:326—342.
[77] Ozbulut, O.E. and Hurlebaus, S. 2010. ‘‘A Comparative Performance Assessment of Superelastic-Friction Base Isolators for Seismic Protection of Bridge Structures,’’ In: Proceedings of the 5th World Conference on Structural Control and Monitoring, 12—14 July, Tokyo, Japan
[78] Ozbulut, O.E. and Hurlebaus, S. 2011. ‘‘Seismic Assessment of Bridge Structures Isolated by a Shape Memory Alloy/Rubber- Based Isolation System,’’ Smart Materials and Structures, 20(1):015003.
[79] Ozbulut, O.E. and Roschke, P. 2010. ‘‘GA-based Optimum Design of a Shape Memory Alloy Device for Seismic Response Mitigation,’’ Smart Materials and Structures, 19:065004.
[80] Andrawes, B., Shin, M. and Wierschem, N. 2010. ‘‘Active Confinement of Reinforced Concrete Bridge Columns Using Shape Memory Alloys,’’ Journal of Bridge Engineering, 15:81—89.

Author Profile

Mohamed OMAR received the B.S. and M.S. degrees in Civil Engineering from Aswan University, Egypt in 2000 and 2004, respectively. During 2005-2008, he stayed in Graduate School of Engineering, Hokkaido University, Japan to study Seismic Response of Structures, He got PhD. Degree from Hokkaido University in 2008 in the field of Structural Engineering. He now works as assistant Professor in Civil Engineering Department, King Abdul-Aziz University, Saudi Arabia on leave with Aswan University, Egypt.