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Applications of shape memory alloys in civil structures

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Abstract

Shape memory alloy (SMA) is a novel functional material and has found increasing applications in many areas. Recently, research efforts have been extended to using SMA for control of civil structures. This paper presents a review of applications of the SMA materials for passive, active and semi-active controls of civil structures. First, an overview of the characteristics of SMA is presented. The shape memory effect (SME) and pseudoelasticity, two major properties of SMA associated with the thermal-induced or stress-induced reversible hysteretic phase transformation between austenite and martensite, are reviewed. These unique properties enable SMA to be used as actuators, passive energy dissipators and dampers for civil structure control. This paper then reviews current research using SMA-based devices for passive, semi-active or active control of civil structures. The operation mechanism, design and experimental results of these SMA-based devices are also presented in the paper.

Keywords: Shape memory alloy; Structural control; Passive vibration damping; Structural rehabilitation

1. Introduction

Smart systems for civil structures are described as systems that can automatically adjust structural characteristics in response to external disturbances and/or unexpected severe loading toward structural safety, extension of the structure's life time, and serviceability [26]. One key technology toward this goal is the development and implementation of smart materials, which can be integrated into structures and provide functions such as sensing, actuation and information processes essential to monitoring, self-adapting and healing of structures. Some examples of smart materials are piezoceramics, shape memory alloys (SMAs), magneto-rheological (MR) fluids, and electro-rheological (ER) fluids.

SMAs have found applications in many areas due to their high power density, solid state actuation, high damping capacity, durability and fatigue resistance. When integrated with civil structures, SMAs can be passive, semi-active, or active components to reduce damage caused by environmental impacts or earthquakes. Though most of the research activities of SMAs' applications in civil structures are still in laboratory stage, a few have been implemented for field applications and found effective [17].

2. Basics about Nitinol shape memory alloys

2.1. Basics about shape memory alloys

In 1932, Chang and Read observed a reversible phase transformation in gold–cadmium (AuCd), which is the first record of the shape memory transformation. It was after 1962, when Buechler and co-researchers discovered the shape memory effect (SME) in nickel–titanium at Naval Ordnance Laboratory (they named the material Nitinol after their workplace), that both in-depth research and practical applications of shape memory alloys emerged.

Up to date, many types of shape memory alloys have been discovered. Among them, Nitinol possesses superior thermomechanical and thermoelectrical properties and is the most commonly used SMA [12]. In this paper, SMAs are referred to as Nitinol SMAs unless another type of SMA is specified. The following reviews two important properties of Nitinol SMAs: the shape memory effect and the superelasticity.

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2.2. Shape memory effect and superelasticity

Nitinol SMAs have two unique properties: SME and superelasticity. The SME refers to the phenomenon that SMAs return back to their predetermined shapes upon heating. The superelasticity refers to the phenomenon that SMAs can undergo a large amount of inelastic deformations and recover their shapes after unloading [12]. These unique properties are the result of reversible phase transformations of SMAs.

There are two crystal phases in SMAs: the stronger austenite phase, stable in high temperature, and the weaker martensite phase, stable in low temperature. These two phases differ in their crystal structures. The austenite has a body-centered cubic crystal structure, while the martensite has a parallelogram structure (which is asymmetric), having up to 24 variations. When SMAs in martensite are subject to external stress, they deform through a so-called detwining mechanism, which transforms different martensite variations to the particular one variation that can accommodate the maximum elongation. Due to its parallelogram structure, the martensite phase is weak and can be easily deformed. On the contrary, the austenite phase has only one possible orientation and shows relatively strong resistance to external stress [12].

2.3. Phase transformations and associated energy dissipation

The composition of SMA depends on the internal energy level. For a given temperature, the crystal structure is required to accommodate the minimum energy state. Driven by external force, the two crystal phases can be transformed: the martensitic transformation and its inverse transformation. The driving force for the phase transformation is the difference between the Gibbs free energy of the two phases, which can be provided by either temperature gradient or mechanical loading. From a thermomechanical point of view, temperature and external stress play an equivalent role in the transformation mechanism [30]. Hence, there are two types of martensite transformations: the temperature-induced transformation which causes the SME and the stress-induced transformation which results in the superelasticity.

Fig. 1 shows a typical stress-free temperature-induced martensitic transformation and its inverse transformation under a temperature excitation cycle. Four transition temperatures characterize the transformation loop: martensite start temperature (M_s), martensite finish temperature (M_f), austenite start temperature (A_s) and austenite finish temperature (A_f). These critical temperatures pinpoint the beginning and the end of the forward (martensite) and the inverse transformation. It is noticeable that the temperature-deformation loop is hysteretic due to internal phase friction.

Fig. 2 presents a typical stress–strain curve of an SMA specimen at constant low temperature ($T < M_f$). When the martensite SMA is subject to tension, the elastic deformation is followed by a large increase of strain corresponding to an almost constant stress. This yielding is due to the hysteresis-mobility of the twined variation interfaces and defects inside the martensite phase. Upon unloading, only elastic strain recovers

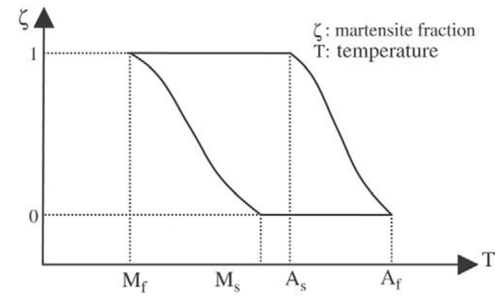

Fig. 1. Stress-free martensitic phase transformation.

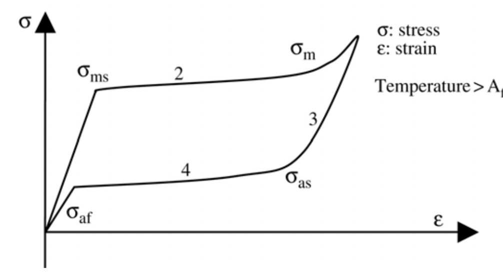

Fig. 2. Isothermal stress-induced martensitic phase transformation.

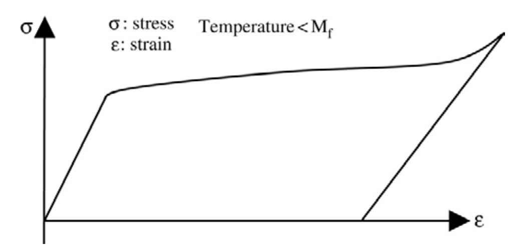

Fig. 3. Stress–strain relationship of the martensitic SMAs ($T < M_f$).

and the residual strain induced by the martensite reorientation can be recovered only by the reverse phase transformation upon heating (SME). If deformation exceeds the maximum value which martensite can sustain through the martensite reorientation mechanism, the permanent plastic deformation takes place. Hence, for practical use, the applied stress should not exceed this maximum value to avoid a permanent plastic deformation. The curve in Fig. 3 exhibits hysteresis, i.e. the released energy during unloading is significantly less than the input energy during loading. The area enclosed by the hysteresis loop is proportional to the energy dissipation and thus to the damping capacity.

Shown in Fig. 3 is the stress–strain loop of a superelastic SMA specimen undergoing a stress-induced transformation of SMA at constant temperature ($>A_f$). The four segments of the stress–strain loop (segments 1, 2, 3 and 4 shown in Fig. 2) correspond to the different phase compositions of the SMA. Before the stress reaches a critical value σ_{ms}, the SMA behaves elastically (corresponding to Segment 1). In Segment 2, stress-induced martensite transformation takes place and results in a large deformation with little increase of stress. Similarly, there are four characteristic stress values indicating the beginning and end of the transformation. Investigation has pointed out that the critical stresses are temperature dependent, and the temperature at the unloading process determines the residual strain [12]. Because of the stress–strain hysteresis, which is identified with the stress difference of the loading and unloading, the area enclosed by the loop represents the energy dissipated through the loading–unloading cycle.

3. Research on the damping properties of SMAs

Using SMAs for passive structure control relies on the SMA's damping capacity, which represents its ability to dissipate vibration energy of structures subject to dynamic loading. As reviewed in the last section, the damping capacity comes from two mechanisms: martensite variations reorientation which exhibit the SME and stress-induced martensitic transformation of the austenite phase which exhibit the superelasticity.

The energy dissipation of the widely-used Nitinol superelastic SMA wires was investigated [9,28,18,14]. Dolce and Cardone [10] investigated the superelastic Nitinol wires subjected to tension loading. They observed the dependence of the damping capacity on temperature, loading frequency and the number of loading cycles. It is found that the mechanical behavior of the wires is stable within a useful range for seismic application. Also, they suggested that the austenite wires should be pretensioned for larger effectiveness of energy dissipation. Piedboeuf and Gauvin [28] reported that the influence of ambient temperature on the damping capacity of the superelastic Nitinol wires can be negligible. Gandhi and Wolons [14] proposed using a complex modulus approach to characterize the damping capacity of superelastic SMA wires for convenient integration with structure dynamics. A superelastic SMA wire demonstrates the damping capacity not only under tension loading, but also under cyclic bending. In 2000, Ip presented his effort to predict the energy dissipation in SMA wire under pure bending loading. His numerical results showed that the energy dissipated by the superelastic SMA wire is highly sensitive to its diameter; in detail, the thicker the SMA wire, the more energy was dissipated.

Recently, as large cross-section-area SMAs become available, studies on the properties of SMA bars or rods have attracted more attentions [22,9]. As discovered by Liu et al. [22], the damping capacity of a martensite Nitinol bar under tension–compression cycles increases with increasing strain amplitude, but decreases with loading cycles and then reaches a stable minimum value. Dolce and Cardone [10] compared the martensite damping and austenite damping of Nitinol bars subjected to torsion. They found that the damping capacity of the martensite Nitinol bar is quite a bit larger than that of the austenite Nitinol bar, although the prior cannot remain at its highest value as the residual strain accumulates. They also noticed that the martensite bar's mechanical behavior is independent of loading frequency and that of the austenite bar slightly depends on the frequency. This implies that both martensite and austenite Nitinol bars can work in a wide frequency range and have a good potential for seismic protection. An overview of the damping capacity of martensite SMAs is presented in [16].

4. Applications of SMAs in civil structure control

4.1. Classification of applications of SMAs in civil structure control

The vibration suppression of civil structures to external dynamic loading can be pursued by using active control, semi-active control, and passive control. In the active control mode, an external power source controls actuators to apply forces to the object structures. For a passive control system, no external power source is required and the impact forces are developed in response to the motion of the structures. The semi-active control devices use considerably less energy to adjust the structural properties than the active control devices.

Based on this classification methodology, the current applications of SMAs on structure control can be classified into three categories: passive structural control, active frequency tuning (semi-active) and active damage control.

4.2. SMAs for passive structural control

4.2.1. Classification of SMAs for passive structural control

The passive structural control using SMAs takes advantage of the SMA's damping property to reduce the response and consequent plastic deformation of the structures subjected to severe loadings. SMAs can be effectively used for this purpose via two mechanisms: ground isolation system and energy dissipation system [30]. In a ground isolation system, SMA-made isolators, which are installed between a super-structure and the ground to assemble an uncoupled system, filter the seismic energy transferred from the ground motion to the super-structure so that the damage of the super-structure is attenuated. On the other hand, via the energy dissipation mechanism, martensite or austenite SMA elements integrated into structures absorb vibration energy based on the hysteretic stress–strain relationship.

Although the two mechanisms are based on the damping capacity of SMAs, they are different in arrangement and function. An SMA isolator provides variable stiffness to the structure according to the excitation levels, in addition to energy dissipation and restoration after unloading. Therefore, superelastic SMAs are appropriate for isolators. On the other hand, an SMA energy dissipation element mainly aims to mitigate the dynamic response of structures by dissipating energy. Both martensite and superelastic SMAs have been studied for this case.

In general, for SMA devices for passive vibration control, martensite SMAs have a larger damping capacity; however, it requires external heat to cause a phase transformation to restore its original shape. On the other hand, superelastic SMAs have a smaller damping capacity, but they have a strong re-centering force to restore the structure's initial position and there will be little residual strain of the superelastic SMAs.

4.2.2. SMA isolation devices

The reported SMA isolation systems include SMA bars for highway bridges [37], SMA wire re-centering devices for civil buildings [8], SMA spring isolation system [19,24] and SMA

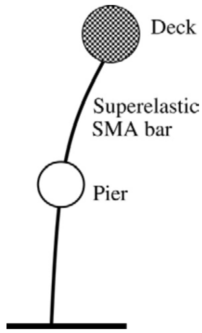

Fig. 4. Schematic of the SMA isolation device for elevated highway bridges [37].

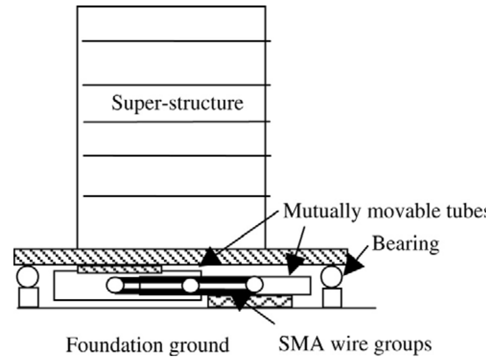

Fig. 5. Schematic of the SMA isolation system for buildings [8].

tendon isolation system for a multi-degree-of-freedom (MDOF) shear frame structure [4].

Wilde et al. [37] investigated a base isolation system with superelastic SMA bars for elevated highway bridges. The SMA bar isolation system is illustrated in Fig. 4. Comparative simulations of the SMA isolation system and a conventional isolation system were conducted with three excitation levels. The results revealed that the SMA isolation system provided variable responses to excitation as well as a notable damping. For small excitation level, the SMA isolation system firmly links the pier and the deck, while the relative motion emerges in the case of the conventional system. For a medium excitation level, the SMA bar undergoes a stress-induced martensitic transformation so that the soft stiffness allows a relative displacement comparable to that of the conventional isolation system. At severe loading, the SMA bar enters an elastic range of martensite and the maximum displacement is one-fifth as much as that of the conventional isolation system. The comparison shows that the damage energy of the bridge with the SMA isolation system is smaller than with the conventional system.

Dolce et al. [8] developed and tested the full-scale Nitinol-wire-based isolation system within the MANSIDE (Memory Alloys for New Seismic Isolation and Energy Dissipation Devices) project to study the feasibility of Nitinol wire for vibration isolation. The operation principle is schematically shown in Fig. 5. A superelastic SMA wire is so wound around three stubs which are connected to the tubes that, when there is reciprocal movement between the super-structure and the foundation, the wire is elongated and the vibration magnitude is damped by the wire. The isolation system is able to carry out up to 600 kN maximum force and to reach up to 180 mm displacement. Cyclic loading tests show that the isolation system shows a variable stiffness with the loading intensity, and a high effectiveness in filtering energy transmission. They tested the isolation system to control the free vibration of a real base-isolated building with 140 mm initial displacement. The test fully confirms the applicability of an SMA wire re-centering isolation system on passive structural control.

Khan and Lagoudas [19] analytically studied using SMA springs to isolate a single-degree-of-freedom (SDOF) system from a ground excitation simulated by a shake table. It was shown that the vibration isolation depended on the relative displacement of SMA springs, because small displacements

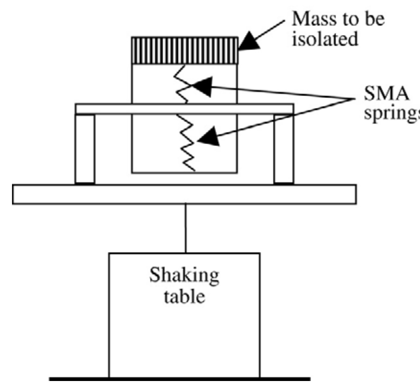

Fig. 6. Schematic of the SMA spring isolation device [19].

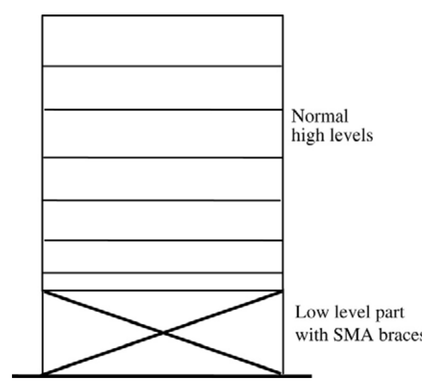

Fig. 7. Schematic of the SMA tendon isolation system for a MDOF structure [4].

did not trigger the stress-induced martensitic transformation. Moreover, the SMA springs achieved the best isolation effect only when the system vibrated at a frequency near its resonance frequency and under higher loading levels. Fig. 6 shows the experimental setup for the SMA spring isolation system developed by Mayes et al. [24], on which the experiments were conducted by the same research group. It was shown that the significant impact of SMA springs on the dynamic response of the vibration system lied on two aspects: greatly altering the system's resonance frequency and resonance amplitude.

Corbi [4] proposed using the SMA tendon associated low level part of a multi-story shear frame (shown in Fig. 7) to isolate the ground excitation. The numerical simulation showed that the SMA tendon isolation device decisively improves the

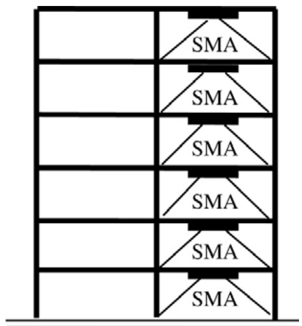

Fig. 8. Schematic of the setup of the SMA brace reinforced frame structure [3].

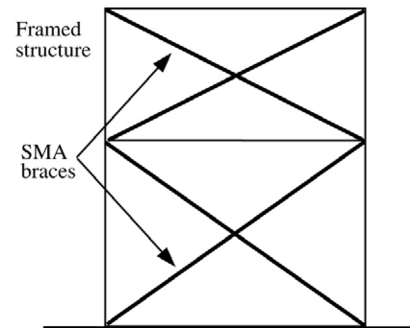

Fig. 9. Schematic of the SMA braces for a two-story steel frame [15].

dynamic response capacity of the structures either in terms of response reduction or re-centering capacity.

It should be emphasized that for isolation devices only superelastic SMA has been studied due to its zero residual strain after unloading. However, to improve the damping effect of the superelastic SMA isolation devices, martensite SMA elements can be introduced to help dissipate more energy. The re-centering device by Dolce et al. [8] is a good example of combining the superelastic and martensitic SMAs.

4.2.3. *SMA energy dissipation devices*

The SMA energy dissipation devices have been seen in the forms of braces for framed structures [3,15,7,8,29,11,36,34,1,32,13], dampers for cable-stayed bridges [21] or simply supported bridges [6,2], connection elements for columns [35,36,20] and retrofitting devices for historic buildings [17,5]. Experiments or simulations or both have been carried out to explore the potentials of the SMA-based energy dissipation devices in passive structure control. That research focused on three aspects: modeling for dynamic response of the structures with SMA devices, experimentally verifying the feasibility of the SMA devices and optimizing the SMA devices' design in terms of vibration suppression using experimental and numerical methods.

A. SMA braces for frame structures

The SMA wire braces are installed diagonally in the frame structures. As the frame structures deform under excitation, SMA braces dissipate energy through stress-induced martensite transformation (in the superelastic SMA case) or martensite reorientation (in the martensite SMA case).

Clark et al. [3] conducted a study on a six-story two-bay by two-bay steel frame which was installed with the Nitinol-wire energy dissipation devices (shown in Fig. 8). 210 loops of Nitinol wire were wrapped around two cylindrical support posts to assemble the braces. A similar configuration of the wire brace can also be seen in the Nitinol wire re-centering braces proposed by [7,8]. Several different scale prototypes of the devices were designed, implemented and tested. They showed that the proposed devices have characteristics of great versatility, simplicity of functioning mechanism, self-centering capability, high stiffness for small displacements and good energy dissipation capability. In the work by Han et al. [15], eight damper devices made of the SMA wires and steel wires were diagonally installed in a two-story steel frame structure, as shown in Fig. 9. Both experimental analysis and numerical verification were conducted to demonstrate the effectiveness of the SMA dampers on vibration reduction. Experimental comparisons of the frame responses with and without dampers showed that the vibration of the controlled frame decayed very much faster than that of the uncontrolled frame. The simulation has demonstrated that the largest displacement of the controlled frame is only 15% of that of the uncontrolled case. The combined steel–SMA type braces were also adopted by Tamai and Kitagawa [36] in their seismic resistance devices as shown in Fig. 10.

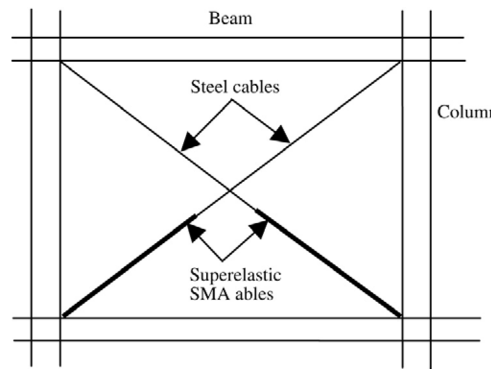

Fig. 10. Schematic of the SMA braces for a frame structure [36].

Saadat et al. investigated utilization of Nitinol tendons for vibration control of coastal structures. Their work was carried out on a single-degree-of-freedom structure installed with diagonal Nitinol tendons. They mainly studied the effects of the eight different configurations of the bracing system on the dynamic characteristics of the structure by simulation. They concluded that the hybrid tendons made of rigid segments and Nitinol wire can be used for vibration control of coastal structures and the proper tendon geometry plays an important role in energy dissipation. Considering the transient response of a frame with beams and SMA tendons, Sun and Rajapakse [34] numerically investigated the modeling issue of a simple frame with two diagonally installed SMA wire tendons. It was found that there is pre-strain dependency in the dynamic response of the frame and in the energy dissipation.

Seelecke et al. [32] studied the effects of geometry variations of a superelastic SMA damper on the dynamic response of a SDOF model representing a building structure to a seismic

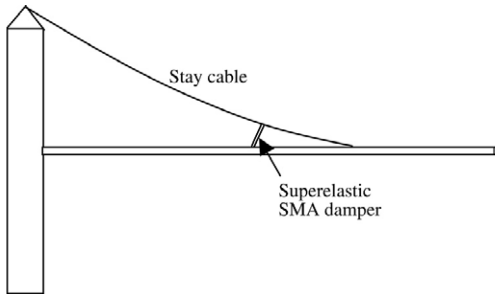

Fig. 11. Schematic of the SMA damper for a stay-cable bridge [21].

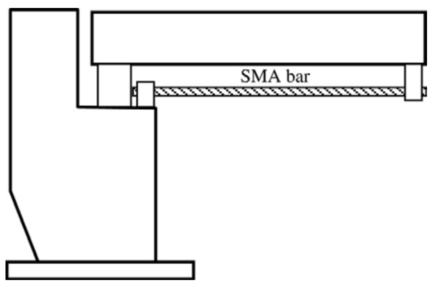

Fig. 12. Schematic of the setup of SMA restrainer for a simple-supported bridge.

excitation. They showed that a particular value of SMA diameter resulted in an optimal vibration control performance. Duval et al. [13] conducted a numerical simulation on a similar SDOF system associated with a SMA spring damper for buildings. Their work focused on the dynamic response of the system under random excitation. Their research suggested that system response could be altered by damping effect and temperature variation of SMA springs.

B. SMA damping elements for bridges

Both superelastic and martensite SMAs can be used as damper elements for bridges. Li et al. [21] theoretically studied the vibration mitigation of a combined cable–SMA damper system which can be used on a stay-cable bridge (shown in Fig. 11). The dynamic responses of the SMA damped cable were simulated as it vibrated at its first mode or at its first few modes respectively. They stated that the proposed superelastic SMA damper can suppress the cable's vibration in both cases.

As shown in Fig. 12, DesRoches and Delemont [6] reported their testing on a full-scale superelastic SMA bar used for seismic retrofit of simply support bridges and their simulation analysis on a multi-span simply supported bridge with the SMA restrainer. The results have shown that the SMA restrainer more effectively reduced relative hinge displacement at the abutment and it provided a large elastic deformation range in comparison with conventional steel restrainer cables. In addition, the SMA restrainer extremely limits the response of bridge decks to near-field ground motion.

Casciati et al. [2] studied the application of the large martensite Nitinol bar in seismic protection devices for bridges. They used a finite element model (FEM) to analyze both static and dynamic response of the devices to strong earthquakes. The following experiments were in agreement with the FEM analysis and show the applicability of the martensite Nitinol bar in energy dissipation.

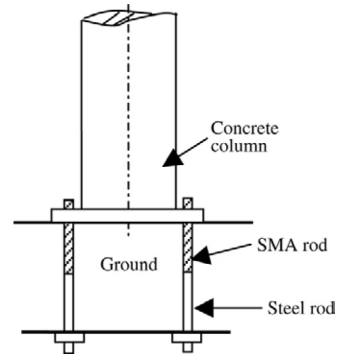

Fig. 13. Schematic of SMA bar anchorage for a column.

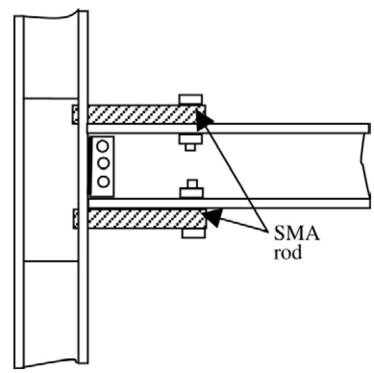

Fig. 14. Schematic of SMA connector for steel structures.

C. SMA connectors

Connectors or connections in various structures are prone to damage during an earthquake event. SMA connectors have been designed to provide damping and tolerate relatively large deformations. Tamai and Kitagawa [36] proposed an exposed-type column base with SMA anchorage for seismic resistance. The SMA anchorages are made of the Nitinol SMA rods in 20–30 mm diameter and steel bars, as shown in Fig. 13. The results obtained from the pulsating tension loading tests and numerical simulation of the SMA rods, have shown that the SMA wires were very effective in dissipating energy and reducing the building's vibration under severe seismic ground motion. In the paper by Tamai et al. [35], they reported the pulsating tension loading tests on the exposed-type column base with SMA anchorages. It was observed that, contrary to the accumulated residual strain of ordinary anchorages, the SMA anchorages can recover their original shape after cyclic loadings and therefore their resisting performance remains the same to prevent plastic deformation and damage in the structural columns. Leon et al. [20] used martensite SMA tendons as the primary load transferring elements in steel beam–column connections (shown in Fig. 14). Based on loading tests of the two full-scale SMA enhanced connections, they concluded that the connection exhibited stable and repeatable hysteresis for rotations up to 4% and the SMA tendon was able to sustain up to 5% strain without permanent damage.

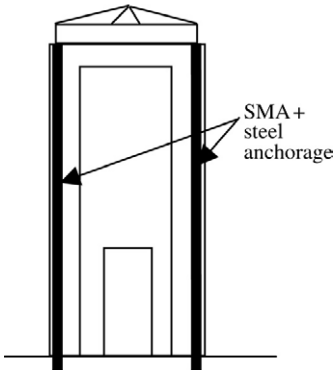

Fig. 15. Schematic of retrofit of a bell tower using SMA anchorage.

D. Structural reinforcement for earthquake retrofit

SMAs have also been used to retrofit existing or damaged structures. As seen in Fig. 15, superelastic SMA tie bars were used by Indirli et al. [17] to rehabilitate the S. Giorgio Church Bell-Tower, which was seriously damaged by the earthquake of Oct. 15th 1996. The SMA tie bars, which run through the height of the tower and are anchored at its foundation, reinforce the structure and increase its modal frequencies. This historical tower was declared intact after an similar earthquake in 2000 [17].

4.3. Shape restoration using superelastic SMAs

In the literature, there is a specific type of application of superelastic SMA wires for structural control purpose different from the aforementioned examples. This application uses the shape restoration property of superelastic SMA wires. For example, Sakai et al. [31] researched self-restoration of a concrete beam using superelastic SMA wires. The experimental results revealed that the mortar beam with SMA wires recovers almost completely after incurring an extremely large crack.

In recent work [27] at University of Houston, a more efficient way to use superelastic SMA wires to achieve a larger restoration force in the form of a stranded cable was developed. Shown in Figs. 16 and 17 is a concrete beam (24 in. × 4 in. × 6 in.) reinforced with fourteen 1/8 in.-diameter superelastic stranded cables via the method of post-tensioning to achieve a 2% pre-strain. Each cable has seven strands and each strand has seven superelastic wires. Special clamps were made to hold the superelastic strands/cables without slippage. After a load of 11,000 lbs and the appearance of a large crack (Fig. 16), the crack on this beam was closed (Fig. 17) under the elastic restoration force of the superelastic SMA cables upon removing the load. This research also demonstrates that the form of stranded cable is a new and effective way to use SMAs for civil applications.

4.4. SMAs for active structural frequency tuning

For a structure vibrating at its resonant frequency, the vibration can be reduced by actively tuning the resonant frequency of the structure. Upon heating, SMA actuators embedded or installed in structures will increase the stiffness of

Fig. 16. A large crack during a loading test.

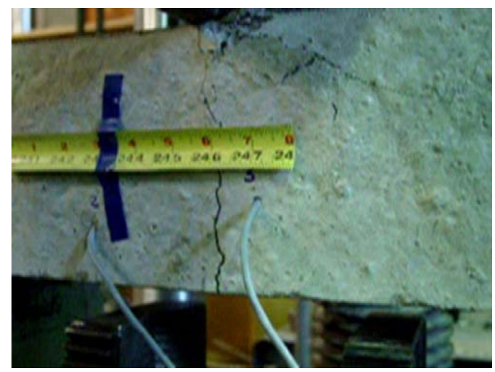

Fig. 17. The crack closes after the loading test.

the host structure so that the natural frequency of the structures can be actively tuned. By active frequency tuning, the vibration control for the structures can be achieved. This is the basic principle of SMAs for semi-active structural vibration control. For example, McGavin and Guerin [23] reported a proof-of-concept experiment in which the frequency of a steel structure is adjusted by using SMA wire actuators in real-time. They achieved about 32% change of the natural frequency.

4.5. SMAs for structural self-rehabilitation

By utilizing the actuation property of SMA wires, Song and Mo [33] proposed the concept of Intelligent Reinforced Concrete (IRC). The IRC uses stranded martensite SMA wires for post-tensioning (as shown in Fig. 18). By monitoring the electric resistance change of the shape memory alloy wires, the strain distribution inside the concrete can be obtained. In the presence of cracks due to explosions or earthquakes, by electrically heating the SMA wires, the wire strands contracts and reduce the cracks. This self-rehabilitation can handle macro-sized cracks. The concrete structure is intelligent since it has the ability to sense and the ability to self-rehabilitate.

To demonstrate this concept, several small size specimens (dimension: 13.5 in. × 6 in. × 2 in.) were cast and tested. Some convincing preliminary results have been achieved. These small concrete blocks post-tensioned by Nitinol SMA wires were fabricated and tested at University of Houston [25]. Fig. 19 shows one specimen. Each rope has seven 0.015 in.-diameter SMA wires with 90 °C transformation temperature. A three-point bending test was conducted, as shown Fig. 20. During

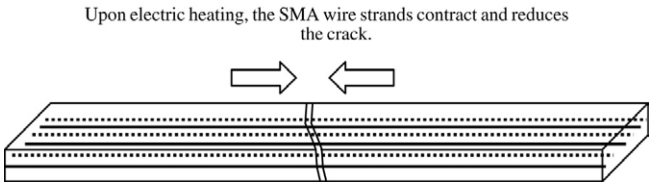

Fig. 18. Schematic of intelligent reinforced concrete specimen.

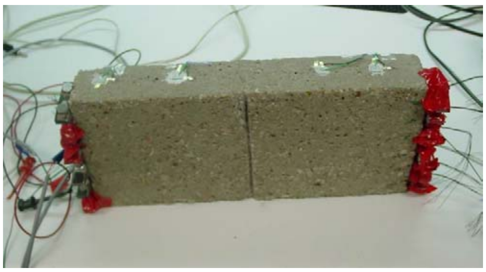

Fig. 19. A small concrete block post-tensioned with SMA wires.

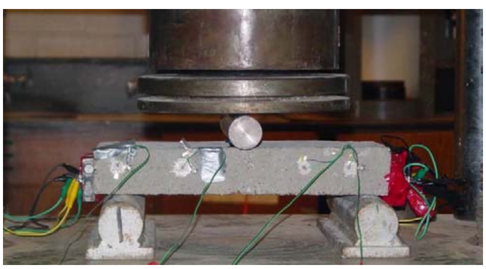

Fig. 20. The three-point bending test of the specimen.

Fig. 21. During the loading: the crack can be obviously seen.

Fig. 22. After the loading: the crack almost disappears.

the loading, a crack opened up to .32 in. (8 mm), as shown in Fig. 21. Upon removing the load and heating the SMA wires, the crack significantly reduced and it could be barely seen by naked eyes (Fig. 22). Also during the loading, the electrical resistance value of the SMA wire changed up to 15% and this phenomenon is used to monitor the crack opening without using additional sensors.

5. Conclusions

This paper presents a review of the basic properties of Nitinol shape memory alloys (SMA) and their applications in passive, active and semi-active control of civil structures. The shape memory effect (SME) enables martensite Nitinol materials to be used as actuators and also enables their applications in active and semi-active controls of civil structures. Structural self-rehabilitation using reinforced martensite SMAs is an example of active structural control. Active tuning of structural natural frequency using martensite SMA wires for vibration suppression is an example of semi-active control of civil structures. Both martensite and superelastic SMAs show strong hysteretic effects in their stress–strain curves for loading–unloading cycles and dissipate energy during these cycles. This provides the basis for developing passive structural damping devices using both martensite and superelastic SMAs. For passive structure control, SMA can be effectively used in two mechanisms: isolation system and energy dissipation system. Their similarity and difference have been stated in the paper through many applications and research examples. The effectiveness and feasibility of passive SMA devices were also demonstrated by these examples. We have seen a trend to combine the advantages of martensite and austenite SMAs to achieve optimal performance in structural control.

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