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SHAPE MEMORY ALLOYS AS A NEW CONSTRUCTION MATERIAL

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ABSTRACT

Shape Memory Alloys (SMAs) are special materials with great potential in various civil engineering applications. The novelty of this material lies in its ability to undergo large deformations, and return to its undeformed shape through stress removal (superelasticity) or heating (shape memory effect). Among prospective SMA candidates, Ni-Ti alloys have distinct thermomechanical properties including: superelasticity, shape memory effect, and hysteretic damping. This led to numerous applications including: self-sensing, repairing of structural elements, prestressing, external post-tensioning, and developing kernel components for seismic devices (actuators, dampers, and isolators). Although the high cost of SMA is still limiting its use, researches investigating its production and processing are expected to reduce significantly its price. It is only a matter of time and SMA will emerge as an essential material in the construction industry. This paper reviews the fundamental characteristics of SMA emphasizing the factors influencing their properties and constitutive material models. The paper also presents a review of the state-of-the-art of SMA applications in the construction of civil engineering structures along with its future trends and applications.

Keywords: Shape Memory Alloy, Austenite, Martensite, Shape Memory Effect, Pseudoelasticity.

INTRODUCTION

Civil infrastructure constitutes a large portion of national wealth in most countries. Because of ageing and decay, it needs monitoring, evaluation and repairing at regular time intervals. This resulted in infrastructure management becoming a common crisis. If a structure becomes smart enough to detect its own damage, report its condition and adopt changes in the loading conditions, most problems of infrastructure management can be eliminated. This thinking has given rise to smart materials. Smart materials and smart structures are becoming increasing popular in modern design. They have the ability to adapt to the operational parameters of the surrounding environment, and thus provide optimal operating conditions, minimum energy use, and low maintenance [1]. Shape Memory Alloys (SMAs) are novel materials that have the ability to undergo large deformation and return to a predetermined shape when heated above their transformation temperature or upon removal of stress. The distinct and unique properties of SMAs have categorized them as intelligent materials. They have the potential to be used in building smart structures that respond and adapt to changes in condition or environment by integrating the functions of sense, logic, action, and control, usually in a repetitive manner [2].

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

FUNDAMENTALS OF SMA

Shape memory effect (SME) and superelasticity/pseudoelasticity (PE) are two distinct properties that make SMA a smart material. SME is the unique phenomenon by which SMAs can recover its predetermined shape by heating even after large deformations. Superelastic SMAs can restore its initial shape spontaneously even from inelastic range upon unloading. Various compositions of SMAs such as Ni-Ti, Cu-Zn, Cu-Zn-Al, Cu-Al-Ni, Fe-Mn, Mn-Cu, Fe-Pd, and Ti-Ni-Cu have been developed and their properties have been investigated. Among these Ni-Ti has been found to be the most appropriate SMA for structural applications because of its large recoverable strain, superelasticity and exceptionally good resistance to corrosion. In this paper, unless otherwise stated, SMAs are mainly referred to Ni-Ti SMA (commonly known as Nitinol).

At relatively low temperature SMA exists in the martensite phase. When heated, it experiences a transformation to the austenite phase (crystalline change). In the stress (σ) free state, SMA is characterized by four distinct transformation temperatures: martensite start (M_s), martensite finish (M_f), austenite start (A_s), and austenite finish (A_f). SMA exists in fully martensite when $T<M_f$ and austenite state when $T>A_f$. During the phase change from martensite to austenite and vice versa, both martensite and austenite phases coexist with temperatures between A_s and A_f, and M_s and M_f, respectively. In the martensite state when $T<A_s$, some residual strain will remain upon unloading as shown in the rightmost curve of Fig.1. Upon heating, the material regains its original shape, known as SME. Figure 1 (the curve on T-ε plane) shows the temperature effect on residual strain. In austenite state (T

slightly higher than A_f), six distinctive features can be recognized in the middle stress-strain curve of Fig. 1 [3]: (a) elastic response of austenite material at low strains (ε<1%) as denoted by BC; (b) stress-induced transformation from austenite to martensite with a long and constant stress plateau at intermediate strains (ε = 1-6%), indicated by CD; (c) elastic response in the stress-induced martensite state at large strain (ε>8%) represented by DE; (d) elastic recovery of strain upon stress removal as shown by EF; (e) instinctive recovery of strain at almost a constant stress path because of the reverse transformation to austenite due to instability of martensite at $T > A_f$ as depicted by FG; and finally (f) elastic recovery in austenite phase as indicated by GB. This exceptional property of SMA with the ability of recovering substantial inelastic deformation upon unloading yields a characteristic hysteresis loop, which is known as superelasticity (PE). If the temperature in austenite phase exceeds the maximum temperature at which martensite occurs (M_d) then PE of SMA is completely lost and it behaves like an elastic-plastic material as shown in the leftmost curve of Fig.1.

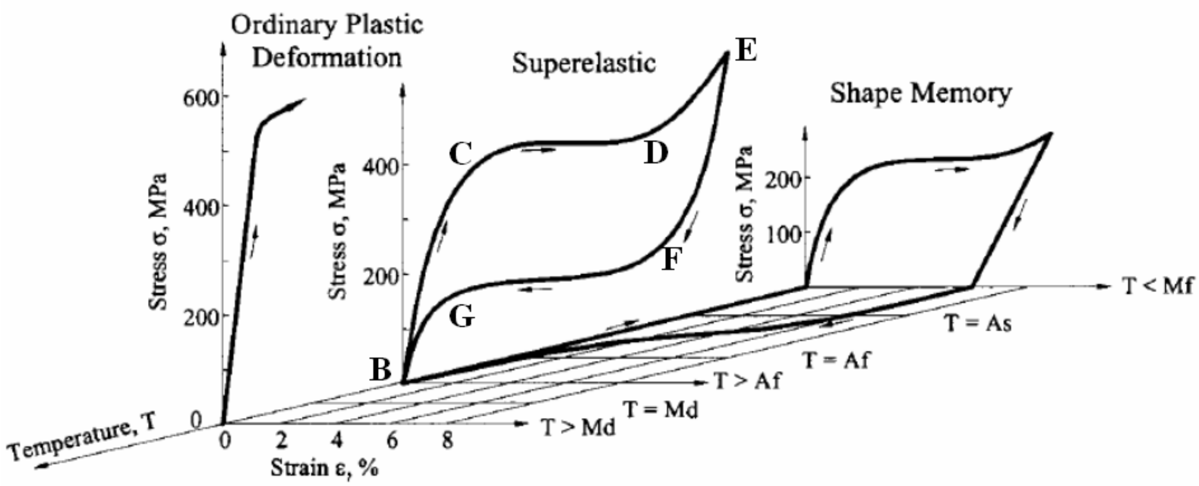

Fig. 1: 3D stress-strain-temperature (σ-ε-*T*) diagram of SMA showing SME in martensite state, PE during austenite/martensite phase transformation and elastic-plastic behaviour of austenite at higher temperature [4].

PRESTRESSING WITH SMAs

The low tensile strength exhibited by mortar and concrete makes it vulnerable to cracking. Application of prestress can produce virtually crack free products with high durability. The application of conventional prestressing requires actuators or jacking devices, which makes in non-realistic for rapid and repeated application. Prestressing with SMA strands/wires has been found to be a viable alternative, eliminating most of the shortcomings of conventional prestressing. Prestressed SMA strands/wires are embedded in concrete, then electrically heated to transform them from martensite-to-austenite phase, thus undergoing large shrinkage strains. This strain energy is used to generate a significant prestressing force in concrete. Maji and Negret [5] used Ni-Ti strands for prestressing concrete by utilizing SME. The strands were elongated beyond their plastic limit and subsequently embedded in two beam specimens: one with a single four-wire strand and the second with two four-wire strands. A three-point bending test showed the potential of creating a ‘smart bridge’ where the amount of prestressing can be increased or decreased as required to actively accommodate additional loading, or remedy prestress losses overtime. El-Tawil and Ortega-

Rosales [6] used SMA tendons of Ni-Ti and Ni-Ti-Nb alloy to permanently prestress concrete. The latter alloy proved to be a better solution for permanent prestress application.

RETROFITTING WITH SMAs

Soroushian et al. [7] used Fe-based SMA bars to rehabilitate deficient bridge girders. SMA bars were tested in the laboratory and the results showed that after elongation and heating of iron-based SMA wires, about 80% of the original restraining force could be recovered. This approach was verified by testing a damaged reinforced concrete (RC) beam after repairing it with post-tensioned SMA rods. This repairing scheme was then applied to a deficient bridge in Michigan. This involved local post-tensioning of the cracked region with twenty-four 10.4 mm diameter SMA rods and five 22.2 mm diameter high-strength anchorage rods. This rehabilitation scheme successfully reduced the average crack width by about 40%.

PRESERVING AND PROTECTING HISTORICAL STRUCTURES USING SMAs

The first practical use of SMAs in the rehabilitation of real structures is the work of Indirli et al. [8]. A masonry column supporting Bell Tower of Trignano S. Giorgio Church in Italy was seriously damaged by a 4.8 Richter magnitude earthquake on October 15, 1996. To increase its flexural resistance, four vertical prestressing steel tie bars anchored at their two ends were inserted in the internal corners of the column. Four post-tensioned SMA devices were inserted in-series in each tie bar, with the aim of maintaining the force applied to the masonry column constant at a value below 20 kN. Each SMA device included sixty superelastic SMA wires of 1 mm diameter and 300 mm length. The performance of the innovative rehabilitation scheme was positively verified after the tower was subjected to another 4.5 Richter magnitude earthquake. No forms of distress or damage were noticed after this earthquake.

SELF-SENSING AND REPAIRING CAPABILITIES OF SMA

Bolted joints are often the weakest elements in most structures. They might wear, leak, slip, or tear apart. The superelastic property of SMA may be utilized to regain the preload drop in bolted joints, and thus provide the necessary clamping force to keep the joined members together. The concept of smart bolt was presented by Peairs et al. [9] where they addressed the necessity of preload recovery. Park et al. [10] employed piezoelectric and SMA elements for self-sensing and repairing of bolted joints. When damage occurred, the SMA washers could automatically regain lost torque, and thus allowed the structure to continue its operation. Hesse et al. [11] used compressed SMA rings as clamping force actuators in bolted joints. In case of any drop in the preload, the ring could be heated between its austenite starting and finishing temperature to increase its axial dimension. An intelligent reinforced concrete structure (IRCS) was developed by Song et al. [12] using SMAs and piezoceramics. The IRCS had multiple functions, which included self-rehabilitation, self-vibration damping, and self-structural health monitoring. The IRCS was reinforced with post-tensioned martensite SMA cables, which significantly increased concrete's damping property and its ability to accommodate large impacts. Piezocermaic patches were embedded in concrete to detect the occurrence of cracks. By monitoring the electric resistance change of the SMA cables, the crack width could be estimated. In three-point bending tests cracks up to 11.9 mm could be closed by load removal and heating the SMA cables. During loading, the electrical resistance value of SMA cables changed up to 27%, and this phenomenon was used to monitor crack width.

SEISMIC RETROFITTING WITH SMA BRACINGS

Salichs et al. [14] conducted a feasibility study on using SMA diagonal bracing wires as passive devices for vibration suppression of a one-storey building model. SMA superelastic hysteresis lowered the peak lateral drift compared with that for steel bracing having similar stiffness. McCormick and DesRoches [15] made an analytical evaluation of the effectiveness of using large diameter superelastic SMA bars as bracing members. The reduction in the interstorey drift and column rotation of an RC frame achieved by using SMA bracing members was more than that achieved by using steel bracing. Dolce et al. [16] conducted experimental tests on retrofitting of an old two-storey RC structure designed in the 1970's for gravity loads only with special braces. The recentering capability of these braces was determined by PE of SMA austenitic Ni-Ti wires, which were the main component of the device. Ma et al. [17] employed SMA braces to reduce the vibration of a frame structure. A shake table test simulating the 1995 Northridge earthquake was performed on a single frame structure. The results showed increased damping with SMA braces in the martensite phase than in the austenite phase. The braces also proved to be more effective at reducing vibration as compared to soft iron braces and superelastic braces.

SMA IN BEAM-COLUMN JOINTS

Ocel et al. [18] investigated the effectiveness of partially restrained steel beam-column connections using SMA elements. The connection consisted of four large diameter SMA bars connecting the beam flange to the column flange serving as the primary moment transfer mechanism. Two full-scale connections were tested. The SMA connections exhibited a high-level of energy dissipation, large ductility, and no strength degradation after being subjected to cycles of up to 4% drift. Subsequent to the initial series of tests, the tendons were heated to recover the residual beam tip displacement. After initiating the SME within the tendons, the connections were retested, displaying repeatable and stable hysteretic behaviour. An additional test was performed under dynamic loading to examine the strain rate effects on the performance of the connection. The dynamic tests showed similar behaviour, except for a decrease in energy dissipation capacity when compared to the quasi-static tests.

SMA IN COLUMN ANCHORAGE

Tamai et al. [19] investigated the possibility of using SMA rods for anchoring columns to their foundations. A column was welded to a steel base plate, which was fastened to the base with SMA anchor bolts. The seismic resisting mechanism of the column base with SMA anchorage was investigated by pulsating loading tests on cantilevers with SMA anchorage and ordinary anchorage. The test results revealed that the SMA anchorage had the ability to improve the restoring force characteristics of a column base and prevent plastic deformation and damage in the column. It was suggested that it is possible to design a column base with SMA anchorage that does not require repair after strong earthquakes.

SMA-BASED ACTUATORS

Choi and Hwang [20] experimentally investigated a sliding mode control for vibration of a building like structure with SMA wire actuators installed at an angle of 15E. It was observed that the imposed vibration was suppressed satisfactorily by the employed controller. Yuse et al. [21] developed a small-lightweight SMA/CFRP composite actuator and designed an adaptive feed-forward control system, which guarantees stable control even at large displacements. An extensive experimental program was carried out by Deng et al. [22] to investigate the behaviour of concrete specimens symmetrically embedded with SMA actuators. The prestrain SMA wires had significant effects on the recovery force induced when the initial prestrain was within 6-8%.

SMA-BASED DAMPERS

Unidirectional shake table tests on a four-storey steel frame fitted with tuned mass dampers utilizing SMA wires were conducted by Inaudi and Kelly [23]. The results of unidirectional shake table test on the frame proved SMA dampers to be an efficient nonlinear damping device. Clark et al. [24] tested two different types of reduced-scale dampers using SMA wires over a range of strain amplitudes, loading frequencies, and temperatures. They analytically studied its function by fitting it in a six-storey steel frame where the results showed good performance in reducing displacements of the structure under earthquake excitation. Han et al. [25] conducted a vibration control experiment of a two-storey steel frame installed with eight dampers based on SMA wires. The results showed that SMA was quite suitable for making damper devices for vibration control. Bartera and Giacchetti [26] investigated the dynamic response of an existing RC single storey frame upgraded with bracings of SMA wire assemblage which provided additional damping up to as much as 10 to 12.1% compared with that of the bare frame. Mao and Li [27] developed an innovative passive damping device utilizing the PE of SMA. The shake table test results demonstrated the substantial potential of SMA dampers in alleviating seismic risks. Adachi et al. [28] proposed a damping device made of SMA plate for bridge structures to absorb seismic energy and reduce the seismic force through its pseudo-yield effect. A series of shake table tests was performed to verify its effectiveness under earthquake type excitations, which showed significant reduction of seismic responses of bridge structures.

SMA-BASED ISOLATION DEVICES

Bondonet and Filiatrault [29] conducted an analytic study using a two-degree-of-freedom lumped mass model of a bridge pier/superstructure system with a single SMA device installed between the pier and the superstructure. The authors found that seismic accelerations could be reduced by up to 90% using SMA devices, and the self-centering characteristics of the superelastic device resulted in negligible residual displacements. Wilde et al. [30] proposed a smart base isolation system of an elevated highway bridge, which consisted of a simple SMA bar combined with a laminated rubber bearing. Its design was optimized based upon its performance under the Kobe earthquake (1995) scaled to different magnitudes. For the strongest excitation (0.6g), the SMA bars provided hysteretic damping and acted as a displacement control device due to hardening of the alloy after complete phase transformation. The maximum damage energy of the bridge with the SMA system was found to be 14% smaller than that with the conventional restrainer system, although the input energy to the bridge with the SMA system was 69% higher than that with the conventional one. By exploiting SME and PE of SMA, the essential parts of an isolator were developed within the MANSIDE project [31]. The full-scale device was equipped with 118 recentering 1.84 mm diameter austenite wire loops, prestrained at 2%. Cyclic sinusoidal displacements were applied to the devices. It showed an elastic nonlinear behaviour with about 160 kN supplemental recentering force. The results established SMA-based isolation systems incorporated within steel to be a very promising solution for structural vibration control.

UNSEATING PREVENTION OF BRIDGES

DesRoches and Delemont [32] investigated the efficiency of SMA restrainer bars to reduce the vulnerability of bridges to collapse due to excessive movements at intermediate hinges and abutments during earthquakes. Full-scale SMA restrainer bars of 25.4 mm diameter were subjected to cyclic loading under tension at increasing strains ranging from 0.5 to 8.0% strain. The residual strain was found to be only 1% after straining up to 8%. The SMA restrainers were capable of reducing relative hinge displacements of multispan simply supported bridges much more effectively than conventional steel restrainers. Andrawes and DesRoches [33] proposed a new technology for using SMA as unseating prevention devices. Nonlinear time history analyses were performed on a typical multiple frame RC box girder bridge using a suite of 10 ground motion records. High damping and elastic strains of superelastic elements significantly reduced relative hinge displacements compared with that in the case of conventional steel cable restrainers. During the entire time history, the SMA restrainers remained effective due to the capability of recentering and recovering the original length after deformation to a level of strain that could reach 6%-8%. SMA restrainers may be designed to offer adequate stiffness and damping to limit relative hinge displacements below a predetermined value.

CONCLUSION

This paper presents several applications of shape memory alloys in civil engineering structures. SMAs can be formed into various shapes e.g. bars, wires, plates, rings etc, and thus have the flexibility of using it into various appliances. SMAs' unique properties make them an ideal contender to be used as kernel components in seismic protection devices. A number of experimental and analytical studies of SMA devices (dampers and base isolators) prove them to be effective ways in improving the response of buildings and bridges to earthquake loadings. Especially, the recentering capability of SMA can be very efficient in reducing the cost of repairing and retrofitting of various structures even after a severe earthquake. In seismic design, if SMA can be used as reinforcement at the critical regions along with conventional steel, it can yield under strains caused by seismic loads but potentially recover deformations at the end of earthquakes. SMAs can be used in prestressing, thus can help a structure to actively accommodate additional loading, or remedy prestress losses over time. Post-tensioning with SMA wires and tendons also proves to be a better option over fiber reinforced plastics and conventional steel tendons in retrofitting works. The superelastic SMAs' self sensing and repairing capabilities may be utilized to regain the preload drop in bolted joints or other types of fasteners, and thus provide necessary clamping force to keep the joint members together.

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

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