APPLICATION OF SMA IN CONCRETE STRUCTURES

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ABSTRACT
Shape memory alloys (SMAs) are increasingly becoming a topic of research in the area of ‘smart materials’. SMAs are a novel functional material, 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. 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 SMA 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 SMA materials for passive and active controls of concrete structures.

Keywords: shape memory alloys, shape memory effect, superelastic effect, structural control, smart material

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 lifetime, and serviceability [1].
In 1965, shape memory alloys (Nitinol) as a smart material derived from Nickel and Titanium were first patented by Buehler and Wiley [2] in Naval Ordnance Laboratory. Since then, tremendous effort has been infused to the utilization and study of this smart material.
In recent years, the two major properties of SMAs have attracted the attention of many researches for application to smart structural systems. One is the Supereelasticity or pseudoelastic effect (PE), which is the ability of a shape memory alloy to accommodate large strains due to stress-induced phase change at a constant, sufficiently high temperature and to recover its initial shape upon unloading. The other is the superthermal effect or shape memory effect (SME), which is the ability to deform an initially austenitic SMA by cooling under constant stress and then to recover the austenitic shape by heating. The magnitude of the
temperature-induced strains depends on the applied stress. Although SMAs have been known for decades, they have not been used in the concrete structures until rather recently. SMAs can be passive or active components in civil structures to reduce damage caused by environmental impacts or earthquakes.

This paper is divided into three main parts. The first part focuses on the basic characteristics of SMA (Section 2). The second part contains recent research on the damping properties of SMAs (Section 3). The third part presents the Application of SMAs for passive and active concrete structure control (Section 4).

2. BASICS ABOUT SHAPE MEMORY ALLOYS

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 ($T_{As}$), where the austenite starts to develop in the alloy; (b) the austenite finish temperature ($T_{Af}$), where the development of austenite in the alloy is 100% complete; (c) the martensite start temperature ($T_{Ms}$), where the development of martensite starts; and (d) the martensite finish temperature ($T_{Mf}$), where the development of martensite is 100% complete.

There are three groups of shape memory effects [3]. 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 ($T < T_{Af}$). However, this deformation can disappear by heating above $T_{Af}$ and it remains unchanged during the cooling to the start temperature (Figure 1.a).

When the start temperature is above $T_{Af}$, 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 (Figure 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 $T_{Mf} < T_{Af}$. It has to be mentioned that this effect can be produced only after a special treatment (Figure 1.c).

![Figure 1. Shape memory phenomena: one-way effect (a), pseudoelasticity (PE) (b), and two-way effect (c) [4]](image-url)
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, $A \rightarrow M$) and backward (martensite to austenite, $M \rightarrow A$) transitions and their temperatures are also illustrated.

3. RESEARCH ON THE DAMPING PROPERTIES OF SMAS

The high damping capacity is known as one of the important functional properties of shape memory alloys. Damping, in a technical context, stands for the conversion of mechanical energy to thermal energy and therefore for the ability to reduce movements or vibrations of a structure.

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 PE.

The energy dissipation of the widely-used Nitinol superelastic SMA wires was investigated [5-8]. Dolce and Cardone [9] 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. In addition, they suggested that the austenite wires should be pretensioned for larger effectiveness of energy dissipation.

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. As discovered by Liu et al [10], 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 [9] 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.

4. APPLICATION OF SMAS IN CONCRETE STRUCTURE CONTROL
The vibration suppression of concrete structures to external dynamic loading can be pursued by using 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.

4.1. 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. Indeed, martensite or austenite SMA elements as energy dissipation devices absorb vibration energy based on the hysteretic stress-strain relationship.

4.1.1. 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). 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. The combined steel–SMA type braces were also adopted by Tamai and Kitagawa [11] in their seismic resistance devices as shown in Figure 3. Cardone et al [12] proposed a design for bracings of multi-storey reinforced concrete (RC) frames with a martensitic Ni-Ti adapter as the damping element.

4.1.2. SMA Restrainers for Bridges
Bridge restrainers are elements that are commonly used to connect two adjacent bridge spans or frames and prevent them from experiencing large relative displacements during earthquakes. Superelastic SMAs can be used as damper elements or potential seismic restrainers for bridges. As shown in Figure 4, DesRoches and Delemont [13] reported their full-scale tests of 25.4 mm diameter superelastic SMA restrainer bars used for seismic retrofit of simply support bridges and their simulation analysis on a multi-span simply
supported bridge. 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. The increased stiffness of the SMA restrainers at large strains provides additional restraint to limit the relative openings in a bridge.

Moreover, Rita Johnson et al [14] conducted a large scale testing program to determine the effects of SMA restrainer cables on the seismic performance of in-span hinges of a representative multiple-frame concrete box girder bridge subjected to earthquake excitations. The SMA cable restrainer which was used in this study is shown in Figure 5. The results of the experimental testing have revealed that the SMA restrainers not only served as effective bridge retrofits, but also result in superior performance relative to equivalent traditional steel restrainer systems. Additionally, results of utilizing the analytical model revealed that using SMA restrainer cables reduced the peak hinge openings by nearly 50% for some cases.
4.1.3. 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 [11] 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 Figure 6.

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. Furthermore, 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. Additionally, it is possible to design a column base with SMA anchorage that does not require repair after a severe earthquake, when the maximum rotation responses of the base plate are less than 0.025 rad [15].
4.1.4. 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, Song and Otero [16] developed a more efficient way to use superelastic SMA wires to achieve a larger restoration force in the form of a stranded cable. Figure 7 shows 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 (Figure 7.a), the crack on this beam was closed (Figure 7.b) under the elastic restoration force of the superelastic SMA cables upon removing the load. Two quarter-scale RC column with SMA longitudinal reinforcement in the plastic hinge area were tested on the shaketable by Saiidi and Wang [17]. The exploratory study showed that the residual displacements in the SMA-reinforced columns were very small. Furthermore, Khaloo and Eshghi [18] studied numerically the response of RC columns using smart rebars under static lateral loading. It is found that by using SMA rebars in RC columns, these materials tend to return to the previous state (zero strain), so they reduce the permanent deformations and also in turn create forces known as recovery forces in the structure which lead into closing of concrete cracks in tensile zone and reduction of the eccentricity created in the concrete columns which is the result of permanent deformations.

![Figure 7. A large crack during a loading test (a), and the crack closes after the loading test (b)](image)

4.2. Smas for Active Structural Control

The SMA has the capability of recovering a previously formed shape via heat energy, which is referred to as an active property tuning when incorporated into a structural system.

4.2.1. Sma Wires in Concrete

The behavior of a simple concrete beam driven by heated SMA wires using electrical currents was investigated by Li et al [19]. Figure 8 shows the loading...
apparatus. Prior to the test, a certain pre-tension was imposed on the SMA wires, which were fixed firmly at the two ends of the specimen by the special clamps. Specimens were first loaded at the midspan to a certain deformation until the concrete was cracked. Subsequently, the SMA wires were heated using a constant electrical current of 14 A in order to drive the concrete beam. The test results indicate that recovery forces of the SMA wires can reduce mid-span deformations and compressive strains of the specimens effectively. Furthermore, the heated SMA wires can make cracks close and perform the task of emergency damage repair in civil structures. The load capacity after actuating of the SMA wires increases although the concrete is already cracked. Moreover, the specimen embedded with more SMA wires proves much better than the specimen does with fewer SMA wires.

![Set-up of the loading apparatus (a), and Instrumentation sketch (b) for concrete beam with embedded SMA wires](image)

**Figure 8.** Set-up of the loading apparatus (a), and Instrumentation sketch (b) for concrete beam with embedded SMA wires

![Active Confinement of a concrete column with a prestressed shape memory alloy wrapping for retrofitting purposes](image)

**Figure 9.** Active Confinement of a concrete column with a prestressed shape memory alloy wrapping for retrofitting purposes [20]

### 4.2.2. Active Confinement of Concrete Members with SMA

Another application of using SMAs in concrete structures is in the confinement of reinforced concrete members. The increase in load bearing capacity and also ductility by wrapping columns with bands or sheets of steel or FRP is well known. In addition,
it is well known that the strength of confined concrete is a function of the load. Utilizing the shape memory effect for tensioning the wrapping can enhance the effect of confinement. Krstulovic-Opara et al [21] carried out tests on SMA confined concrete members. They performed compression tests of the model scale with confined concrete cylinders. The specimens were jacketed with thin continuous Ni-Ti wires. Stressing of the jacket was done by putting the whole specimen in an oven. The comparison between several variants of stressed and unstressed jacketing showed that the use of SMA spirals alone effectively introduced high levels of active confinement. Concrete columns could be easily helically wrapped by continuous SMA bands. The pitch of the helix can be fitted to the aimed confinement. Figure 9 shows the setup for the tensioning by resistance heating. Obviously, this technology is suitable in particular for retrofitting, in cases where there is only limited space for mounting, e.g. in cellars of buildings or in case of double columns. The strength values under confinement can theoretical enable very high loads at very high strains. However, only compression strains of several percent are acceptable in columns in order to prevent damage to the concrete or disadvantages to the whole structural system of a building. The load bearing capacity for small strains was hence of interest for the performed calculation. The calculations showed a lower axial strain for the active SMA confined column compared to the steel or CFRP confined column at the same load. On the other hand, a higher axial load can be applied at a given ultimate strain.

5. CONCLUSIONS
This paper presents a review of the basic properties of Nitinol SMA and their applications in passive and active control of concrete structures. The SME enables martensite Nitinol materials to be used as actuators and also enables their applications in active controls of concrete structures. Structural self-rehabilitation using reinforced martensite SMAs is an example of active structural control. 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. We have seen a trend to combine the advantages of martensite and austenite SMAs to achieve optimal performance in structural control.

REFERENCES


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