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SHAPE MEMORY ALLOY AS RETROFITTING APPLICATION IN HISTORICAL BUILDINGS AND MONUMENTS – A REVIEW IN INDIAN PERSPECTIVE

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ABSTRACT

Shape memory alloys has some unique properties including Young's modulus-temperature relations, shape memory effects, superelastic effects, and high damping characteristics leads them to numerous applications in the biomedical and aerospace industries, are currently being evaluated for applications in the area of seismic resistant design and retrofit. This paper represents a review of the general characteristics of shape memory alloys and highlights their applications in seismic resistant design worldwide and which can be implemented in India as a special reference.

Keywords: Shape memory alloy, Brittle material, Pseudoelastic behavior, RC frame, Bridge girder.

1. INTRODUCTION

SMA is a special class of material that can undergo large inelastic deformations(strain recovery upto 8%) and recover its original shape by stress removal (known as the superelastic effect) or through the application of heat (known as the shape memory effect), thus mitigating the problem of permanent deformation. These extraordinary properties are due to a temperature and stress dependent phase transformation from a low-symmetry to a highly symmetric crystallographic structure. (Those crystal structures are known as martensite and austenite.).

The series of Nickel/Titanium alloys developed by Buehler and Wiley [Buehler and Wiley, 1965] in 60' exhibited a special property allowing them to regain and remember their original shape, although being severely deformed, upon a thermal cycle. This remarkable characteristic became known as the shape memory effect, and alloys that exhibit it were named shape memory alloys. These alloys consisted of an equi-atomic composition of Nickel and Titanium (NiTi). This alloy is commonly referred to as Nitinol. Following the first SMA development 'shape memory euphoria' began. Many researchers have contributed to better understanding of this material, developing several constitutive models. Due to distinctive macroscopic behaviours, not present in most traditional materials, SMAs are the basis for innovative applications.

The biomedical field was the first to fully exploit the unique characteristics of SMAs. Since SMAs have the excellent biocompatibility and high corrosion resistance. Their unique characteristics could be utilized for the development of numerous medical tools and devices. The need to find less invasive medical procedures resulted in several medical applications of SMAs [O'Leary et al., 1990]. Included among these are medical filters [Duerig et al, 1999] and dental archwires [Sachdeva and Miyazaki, 1990]etc. The aerospace industry has adopted SMAs as a means for controling the vibration of helicopter blades [Schetky, 1999] and airplane wings during flight [eSMART, 2002].

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, Shape memory alloys can be passive, semi-active, or active components to reduce damage caused by environmental impacts or earthquakes. Those unique properties that make SMAs useful for commercial applications can also be utilized in seismic resistant design and retrofit applications.

This article summarizes the basic characteristics of shape memory alloys, highlights the factors affecting their response, summarizes the current research works on shape memory alloys as it relates to seismic applications, and illuminates the potential for seismic resistance applications for ancient structures in a developing country like India.

2. SUPER-ELASTICITY AND SHAPE MEMORY EFFECTS OF SMAS

Super-Elasticity(SE) is a distinct property that makes SMA a smart material. A superelastic SMA can restore its initial shape spontaneously, even from its inelastic range, depending upon the unloading. Among various composites, 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 [MANSIDE, 1998]. A typical stress-strain curve of austenite SMA under cyclic axial force is presented in Fig.1. In its low temperature phase ($T<M_f$ (martensite finish)), SMAs exhibit the shape memory effect (SME). Originally in its martensitic form, the SMAs are easily deformed to several percent strain. Unloading results in a residual strain, as shown in Fig. Heating the resulting specimen above the austenite start temperature (A_s) starts the phase transformation from martensite to austenite. The phase transformation is complete at austenite finish temperature (A_f), resulting in a recovering of the original shape (i.e., removal of the residual strain).

In its high temperature form ($T>A_f$), SMAs exhibit a superelastic effect. Originally in austenitic phase, martensite is formed upon loading beyond a certain stress level, resulting in the stress plateau shown in Fig. However, upon unloading, the martensite becomes unstable, resulting in a transformation back to austenite, and recovery of the original, undeformed shape.

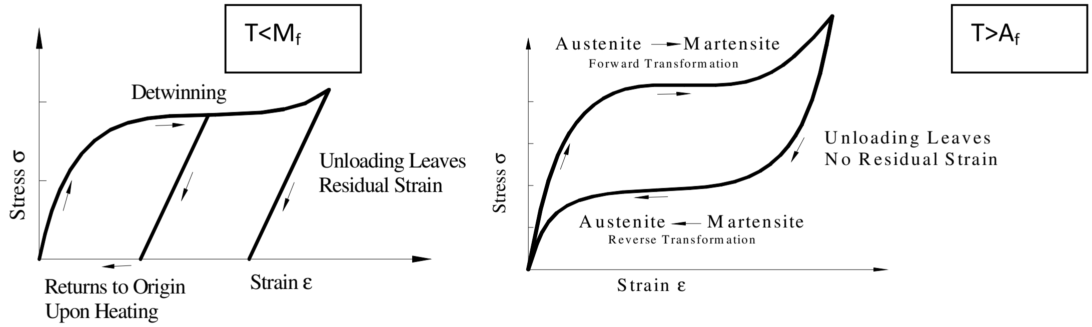

Figure 1 Idealized Stress-Strain Curve for Shape Memory (left) and Superelastic Effect (right).

3. MECHANICAL PROPERTIES OF SHAPE MEMORY ALLOYS

The mechanical properties of SMAs, as well as their behavior under different conditions, need to be understood before the potential and effectiveness of SMAs within seismic resistant design and retrofit applications. Previous studies, focusing on the cyclical properties, strain rate effects and constitutive model are discussed below.

3.1 Cyclical Properties

The cyclic behavior of SMAs are critical if they are to be used in seismic applications. Figure 2 shows a stress-strain diagram of a Nitinol SMA wire (Austenitic) subjected to cyclical loads. [Xie et al, 1998; Liu et al., 1999; Sehitoglu et al, 2001] show that residual strains and internal stresses occurs due to repeated cyclical loading. For earthquake applications, the number loading cycles, 'N' that would be considered is in the range of 5-15and according to Figure 2, this would result in an approximately 40% decrease in the stress plateau in later cycles, as compared with the first cycle [Kaounides, 1999].

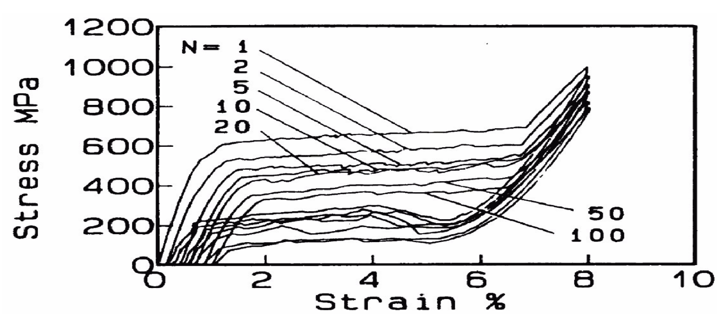

Figure 2 Stress-Strain Hysteresis of Superelastic NiTi Bars.

3.2 Strain Rate Effects

In the martensitic state, Liu and Van Humbeek [1997]and Liu et al. [1999] tested martensite NiTi bars under tension-compression cyclic deformation up to +/- 4% strain. The strain rates evaluated were from 1.6 x 10^{-3} to $8x10^{-2}$ which corresponds to an approximately 0.01Hz to 0.5 Hz for a maximum strain of 4%. Their results show that for this range of strain rates, the damping properties were insensitive to the strain rate. Several researchers have tested large diameter superelastic bars (> 12.7 mm) to evaluate the effect of loading frequency for earthquake-type loading [DesRoches et al. 2002; Dolce and Cardone, 2001]. Both studies were found that increased loading rates led to reductions in hysteresis and energy dissipation of the SMAs. In generally the rate effects during cycling are due to the heat generated while going through the transformation. However, for the higher strain rates, the energy dissipation behavior of the shape memory alloy is reduced.

4. EXISTING APPLICATIONS OF SHAPE MEMORY ALLOYS IN SEISMIC REHABILITATION

Only a few numbers of applications of SMAs in civil engineering are available. The actually realized pilot projects, described in the following, are very important from the application point of view.

4.1 Retrofitting of the Basilica of San Francesco at Assisi, Italy

The Basilica of San Francesco was restored after being strongly damaged by an earthquake of 1997 Umbria-March earthquake (Castellano 2000).The seismic upgrade was carried out under the framework of the ISTECH project. The gable was completely disconnected from the roof and was then linked to the roof again by means of Shape Memory Alloy Devices (SMAD's). Each SMAD is designed to take both tension and compression forces, while consisting of SMA wires which are only subjected to tension.The main challenge of the restoration was to obtain an adequate safety level, while maintaining the original concept of the structure. In order to reduce the seismic forces transferred to the tympanum, a connection between it and the roof was created using superelastic SMAs. The SMA device demonstrates different structural properties for different horizontal forces. Under extremely intense horizontal loads, the SMA stiffness increases to prevent collapse. Figure 3 shows the SMAs used in the retrofit.

Figure 3 SMA Devices in the Basilica of St Francesco of Assissi [Castellano et al., 2000].

4.2 Retrofitting of the bell tower of the Church of San Giorgio at Trignano, Italy

The S. Giorgio Church, located in Trignano, Italy, was struck by a 4.8 Richter magnitude earthquake on October 15, 1996, resulting in significant damage to the bell tower within the church. Following the earthquake, the tower was rehabilitated using SMAs Indirli et al. [2001]. Retrofit design of the 17 meters tall masonry tower was carried out under the framework of the ISTECH project. The upgrade was carried out linking top and bottom of the tower by means of hybrid tendons. Four vertical prestressing steel tie bars with SMA devices were placed in the internal corners of the bell tower to increase the flexural resistance of the structure, as shown in Figure 4.

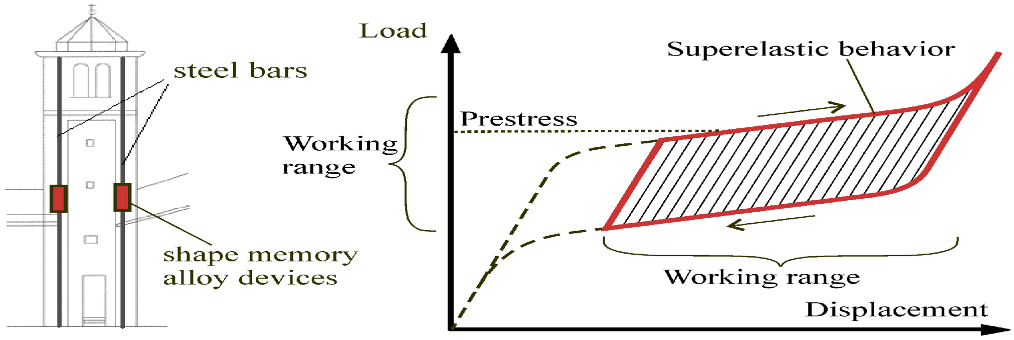

Figure 4: Bell tower with tendons and principle load-displacement behavior of incorporated SMA devices (Indirli et al, 2001).

The retrofit was tested by a minor m=4.5 Richter magnitude earthquake on June 18, 2000, with the same epicenter as the event in 1996. After the main shock, the tower was investigated and no evidence of damage was present (DESROCHES and SMITH 2003).

4.3 Retrofitting application in Bridge Engineering

The first field implementation using shape memory effect for posttensioning of a concrete structure was presented in (SOROUSHIAN, OSTOWARI et al. 2001). The shear cracks in the web of the reinforced concrete T-beam had an average width of 0.55 mm. For strengthening of the bridge girder, a harp-like assembly of shape memory alloy rods was mounted crossing the cracks at both faces of the web. Ironmanganese-silicon-chromium (FeMnSiCr) SMA was used for the rods of diameter 10.4 mm. Each rod was heated by electrical power with 1000 Ampere current to achieve 300°C. Resulting recovery stress in the rods that remained after cooling down to ambient temperature was 120 MPa, while crack width was reduced by 40%..

In another study using SMA devices in bridges, Adachi and Unjoh [1999] created an energy dissipation device out of a Nitinol SMA plate, designed to take the load only in bending. The proof-of-concept study is performed by fixing one end of the plate to the shake table and the other other to a large mass (representing the deck). Shake table tests and numerical models were used to confirm the feasibility of such a device. The SMA damper system reduced the seismic response of the bridge, and were found to be more effective in the martensite form than the austenite form. This is due to the improved damping properties when in the martensitic phase, as compared to the austenite phase.

DesRoches and Delemont [2001] continued the examination of SMAs in bridges. Their study presented the results of an exploratory evaluation of the efficacy of using superelastic shape memory alloy restrainers to reduce the seismic response of simple span bridges, as shown in Figure 5. The study consisted of experimental evaluations of the characteristics of SMA wires and bars, followed by analytical studies evaluating the effect that SMAs have on the seismic response of a MSSS bridge. The results show that SMA restrainers placed at the intermediate hinges can reduce the relative hinge displacement much more effectively than conventional steel cable restrainers.

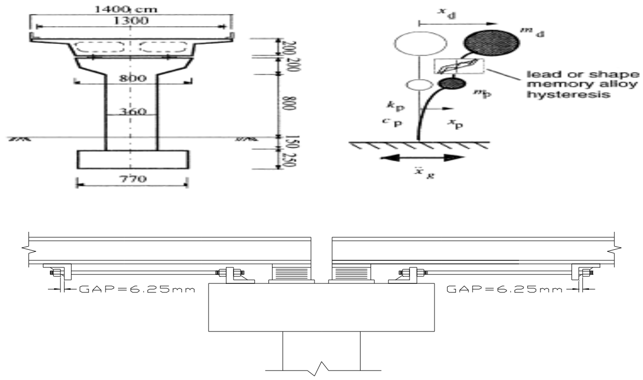

Figure 5: Application of Shape Memory Alloys to Bridge Retrofit. (Left) Variable Base Isolation System with Shape Memory Alloy[Wilde et al., 2000], and (right) Relative Hinge Displacement Comparison Using Conventional Restrainers and SMA Restrainers [DesRoches and Delemont, 2001].

5. WORLDWIDE EXPERIMENTAL PROJECTS

5.1 RC Beams reinforced with SMA rebars

A concrete beam reinforced with shape memory alloys wires was tested and compared with a conventionally reinforced concrete (RC) beam, (CZADERSKI, HAHNEBACH et al. 2006). It was possible to vary pre-stress, stiffness and strength of the SMA beam. The purpose of the study was to determine whether it is possible to combine SMA wires with concrete in order to achieve an adaptive structure that has the potential to react to a changing environment. For the tests, NiTi (Nickel/Titanium) wires approximately 4.3mm in diameter were used to reinforce the underside of a concrete beam with a span of 1.14m (Fig. 6)

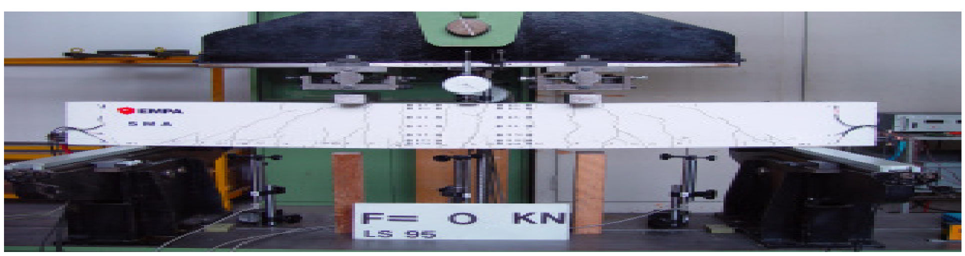

Figure 6: Beam reinforced with SMA wires in the test set-up

The test results proved that by using coated SMA wires it is possible to produce a RC beam with variable stiffness and strength. The tests also showed that a prestress in the SMA wires could be achieved by using the shape memory effect (Fig. 7).

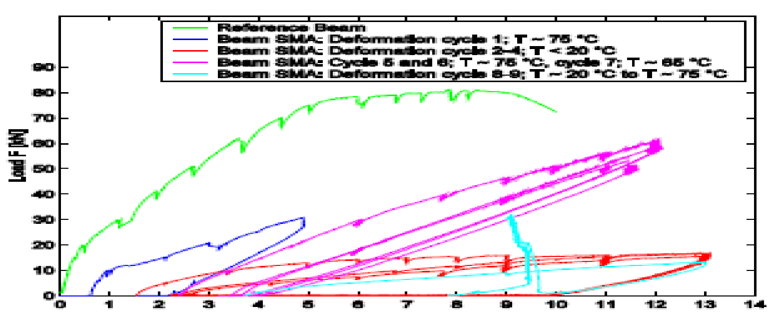

Figure 7: Test cycles on the test beams.

5.2 SMA Short Fibre Reinforced Cement Based Material

In the study (MOSER, BERGAMINI et al. 2005) shape memory alloy (SMA) wires were embedded in mortar. The wires had been shaped by inelastic elongation into loop- and star-shaped fibers (Fig. 8). After hardening of the mortar, the specimens were heated up in order to activate the tensile stress in the fibers, thereby causing a pre-stress of the surrounding mortar. The effect was monitored by length measurements both on specimens with and without fibers. Compression of some 6 MPa was reached in the experiments. It was concluded that for practical applications, alloys with suitable temperature domains of austenitic and martensitic transformation, most likely Fe-based, and efficient methods for the production of such fiber mortars are to be developed. A practical application of such internally pre-stressed cement based materials is envisioned in repair mortars, in which the differences in hygro-thermal histories of the freshly applied mortar layer and the pre-existing substrate can lead to the formation of shrinking induced cracks (Martinola 2000). The application of compressive stresses to the matrix may help overcome this problem. This approach will help meet the need for crack free rebar cover for the rehabilitation of reinforced concrete structures.

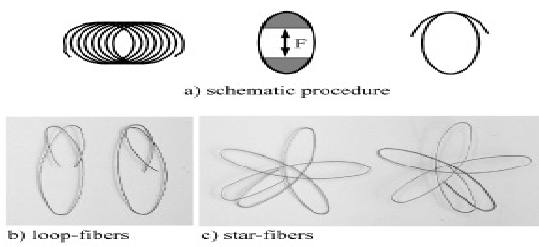

Figure 8: Production of loop- and star-fibers from annealed wire coils

6. CONCLUSIONS

Although SMAs have been known for decades, they have not been used very much in the building industry until rather recently probably due to their cost and limited knowledge of the material in the civil engineering industry worldwide.

In this present paper several field applications of SMA materials are presented such as - retrofitting of the Basilica of San Francesco at Assisi and the Bell Tower of the Church of San Giorgio at Trignano, Italy, where the superelastic behaviour and damping effects of SMA were used. A cracked highway bridge girder was repaired by SMA rods using the recovery stress of the SMA rods.

In general, shape memory alloys can be formed as wires, rods, or plates. The ability for forming various shapes for SMAs provides them with the flexibility to be used in a variety of different types of application. Superelastic and martensitic properties can be exploited in torsion and bending, as well as tension/compression.

Furthermore, a number of laboratory projects were presented which illustrate the potential of this material in the field application of civil engineering and SMAs have shown a great potential.

Particularly in large scale applications low cost SMAs are required. Although the cost of SMAs has decreased significantly, from approximately $1100 US per kilogram in 1996 to less than $111 US per kilogram today, they are still considered to be too expensive for widespread use in Civil Engineering and it is expected that the price will continue to decrease as further applications using large quantities are sought.

In India a number of historical buildings and monuments, such as Taj Mahal, Victoria Memorial, Kutub-Minar, Lal-Kella, Nizam-Palace etc. were established in different era. Those buildings were built before the ample use of reinforced buildings. So the preservation against earthquake of those structures is very essential otherwise they may lost permanently. Application of SMA as retrofitting element in India will be suitable choice with respect to the retrofitting of the Basilica of San Francesco at Assisi, Italy.

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