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A Review on Prestressed Shape Memory Alloy and its Application in Civil Engineering

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***Abstract*: Now-a-days, a doubtful feeling is emerging among society regarding durability of civil structures. Modern techniques such as repairing of structural elements, prestressing, external post-tensioning, and developing kernel components for seismic devices like actuators, dampers, and isolators are accepted but still they are quite uneconomical. In order to make structures safer and stable we have come up with a material named Shape Memory Alloy. Shape memory alloys are special materials with great potential in various civil engineering applications. There are many alloys, among which Ni-Ti alloy have ability to undergo large deformations up to 6 to 8 percent, and return to its undeformed shape (from austenite to martensite) through thermo mechanical properties which includes super elasticity and shape memory effect. Until today, shape memory alloy have found very limited applications in civil engineering probably due to their cost and to limited knowledge of the material in the civil engineering industry. The paper includes the fundamental characteristic of shape memory alloy and some of its application in civil structures. This paper will provide a momentum to the running wheels of construction industry and will nullify the threatening feeling regarding durability of structures. Our project will discuss in detail the process and its successful applications.**

***Keywords*: Prestressing, Post-Tensioning, Shape Memory Alloy, Ni-Ti Alloy, Austenite, Martensite, Super elasticity.**

1. 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.

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. 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 piezo- ceramics, shape memory alloys (SMAs), magneto-rheological (MR) fluids, and electro rheological (ER) fluids. 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. 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.

2. Definitions

A shape-memory alloy is an alloy that "remembers" its original, cold-forged shape even after undergoing large deformation upto 8% and returning to the pre-deformed shape by heating. The shape memory alloys have two Stable phases - the high–temperature phase, called austenite (named after English metallurgist William Chandler Austen) and the low–temperature phase, called martensite (named after German metallographer Adolf Martens).

3. Discovery of shape memory alloy

According to Otsuka and Wayman, A. Ölander discovered the pseudo elastic behaviour of the Au-Cd alloy in 1932. Greninger and Mooradian (1938) observed the formation and disappearance of a martensitic phase by decreasing and increasing the temperature of a Cu-Zn alloy. The basic phenomenon of the memory effect governed by the thermo elastic behaviour of the martensite phase was widely reported a decade later by Kurdjumov and Khandros (1949) and also by Chang and Read (1951).

The nickel-titanium alloys were first developed in 1962–1963 by the United States Naval Ordnance Laboratory and commercialized under the trade name Nitinol (an acronym for Nickel Titanium Naval Ordnance Laboratories). Their remarkable properties were discovered by accident. A sample that was bent out of shape many times was presented at a laboratory management meeting. One of the associate technical directors, Dr. David S. Muzzey, decided to see what would happen if the sample was subjected to heat and held his pipe lighter underneath it.

Metal alloys are not the only thermally-responsive materials; shape-memory polymers have also been developed, and became commercially available in the late 1990s.

4. Fundamentals of shape memory alloy

The temperatures at which the SMA changes its crystallographic structure are characteristic of the alloy and can be tuned by varying the elemental ratios. Ms denotes the temperature at which the structure starts to change from austenite to martensite upon cooling; Mf is the temperature at which the transition is finished.

Accordingly, As and Af are the temperatures at which the reverse transformation from martensite to austenite start and finish, respectively. In Fig. 1 most of the effects related to the SMAs is visualized by means of a stress-strain- temperature diagram. The metallurgical basis of any of these effects is the reversible phase transformation from the high temperature phase austenite into the low temperature phase martensite.

The most important behavior shown by SMAs can be summarized as follows: In the absence of heating or cooling, the SMA is at ambient temperature. This temperature defines the phase state at which the alloy is stable without thermal actuation and at which phase changes can be expected under thermal actuation and mechanical loading. Below Mf the material is fully martensite. The material is showing a pseudoplastic deformation behavior. and is able to undergo large pseudoplastic deformation of up to 8% (for example NiTi alloy). On heating, transformation starts at As and is completed at Af at which the phase transformation from martensite to austenite is completed and the pseudoplastic deformation is almost fully recovered.

List of Symbols:

As = Austenitic start temperature at zero stress
Af = Austenitic finish temperature at zero stress
ε = Uni-axial total strain
εAS = Strain corresponding to the stress finish of the martensite transformation

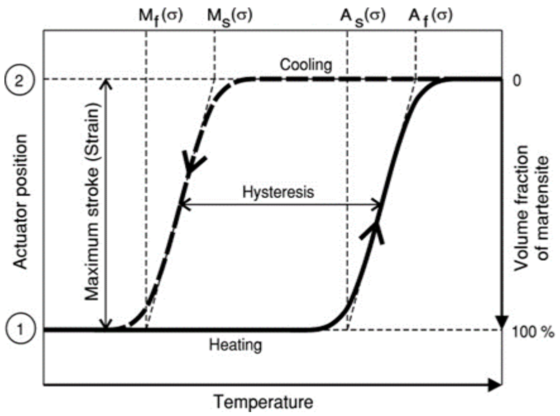


Fig. 1. Temperature – induced phase transformation

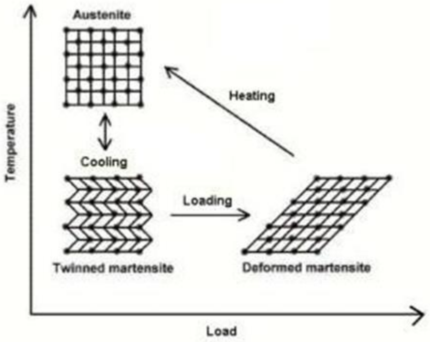


Fig. 2. Material phenomena

A. *Crystal Structure*

Many metals have several different crystal structures at the same composition, but most metals do not show this shape-memory effect. The special property that allows shape-memory alloys to revert to their original shape after heating is that their crystal transformation is fully reversible. In most crystal transformations, the atoms in the structure will travel through the metal by diffusion, changing the composition locally, even though the metal as a whole is made of the same atoms. A reversible transformation does not involve this diffusion of atoms, instead all the atoms shift at the same time to form a new structure, much in the way a parallelogram can be made out of a square by pushing on two opposing sides. At different temperatures, different structures are preferred and when the structure is cooled through the transition temperature, the martensite structure forms from the austenitic phase.

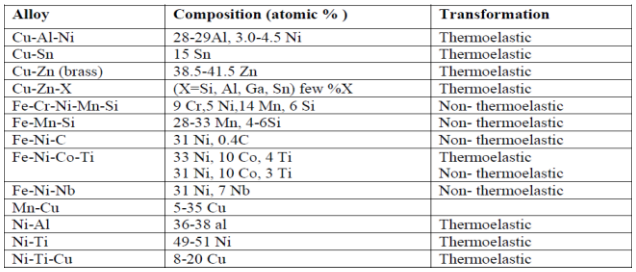
5. Types of shape memory alloy

A variety of alloys exhibit the shape-memory effect. Alloying constituents can be adjusted to control the transformation temperatures of the SMA. Some common systems include the following:

1. Cu-Al-Ni
2. Cu-Zn
3. Fe-Pt
4. Mn-Cu
5. Fe-Mn-Si
6. Ni-Fe-Ga
7. Ni-Ti approx. 55–60 wt% Ni
8. And Many More….

Up to date thirty different types of shape memory alloys have been discovered. Among them, the three main types of SMA are the copper-zinc-aluminium-nickel, copper-aluminium-nickel and nickel-titanium (Ni-Ti) alloys. The atomic composition and type of transformation for some alloys exhibiting shape memory effects are listed down in Table 1.

Table 1: Some of the Alloys exhibiting Shape Memory Effect



Alloy	Composition (atomic %)	Transformation
Cu-Al-Ni	28-29Al, 3.0-4.5 Ni	Thermoelastic
Cu-Sn	15 Sn	Thermoelastic
Cu-Zn (brass)	38.5-41.5 Zn	Thermoelastic
Cu-Zn-X	(X=Si, Al, Ga, Sn) few %X	Thermoelastic
Fe-Cr-Ni-Mn-Si	9 Cr,5 Ni,14 Mn, 6 Si	Non- thermoelastic
Fe-Mn-Si	28-33 Mn, 4-6Si	Non- thermoelastic
Fe-Ni-C	31 Ni, 0.4C	Non- thermoelastic
Fe-Ni-Co-Ti	33 Ni, 10 Co, 4 Ti 31 Ni, 10 Co, 3 Ti	Thermoelastic Non- thermoelastic
Fe-Ni-Nb	31 Ni, 7 Nb	Non- thermoelastic
Mn-Cu	5-35 Cu	
Ni-Al	36-38 al	Thermoelastic
Ni-Ti	49-51 Ni	Thermoelastic
Ni-Ti-Cu	8-20 Cu	Thermoelastic

A. Different types of SMA Suitable for civil structures

The two main types of shape-memory alloys are copper-aluminium-nickel, and nickel-titanium (Ni-Ti) alloys but SMAs can also be created by alloying zinc, copper, gold and iron. Although iron-based and copper-based SMAs, such as Fe-Mn-Si, Cu-Zn-Al and Cu-Al-Ni, are commercially available and cheaper than Ni-Ti, Ni-Ti based SMAs are preferable for most applications due to their stability, practicability and superior thermo-mechanic performance. The copper-based and Ni-Ti-based shape-memory alloys are considered to be engineering materials.

B. Nitinol based shape memory alloy

Nitinol possesses superior thermo mechanical and thermo-electrical properties and is the most commonly used SMA. In this paper, SMAs are referred to as Nitinol SMA unless another type of SMA is specified. Out of all the Shape Memory Alloys that have been discovered so far, Nickel-Titanium (Ni-Ti) SMA alloys have been found to be the most flexible and beneficial in engineering applications due to its superior thermo-mechanical and thermo-electrical properties. It can recover from large amount of bending and torsional deformations as well as small amount of strain. The process of deformation and shape recovery can be repeated millions of times.

6. Manufacturing

Nickel-titanium alloys can be manufactured using a number of different techniques. These include vacuum melting techniques such as:

- Electron Beam Melting
- Vacuum Arc Melting
- Vacuum Induction Melting
- Plasma Arc Melting

Shape-memory alloys are typically made by casting, using vacuum arc melting or induction melting. These are specialist techniques used to keep impurities in the alloy to a minimum and ensure the metals are well mixed. The ingot is then hot rolled into longer sections and then drawn to turn it into wire. The way in which the alloys are "trained" depends on the properties wanted. The "training" dictates the shape that the alloy will remember when it is heated.

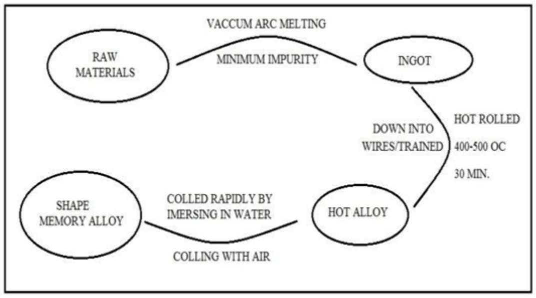


Fig. 3. Flow chart of manufacturing

7. Properties of shape memory alloy

A. One-Way Memory Effect

When a shape-memory alloy is in its cold state (below As), the metal can be bent or stretched and will hold those shapes until heated above the transition temperature. Upon heating, the shape changes to its original. When the metal cools again it will remain in the hot shape, until deformed again.

With the one-way effect, cooling from high temperatures does not cause a macroscopic shape change. A deformation is necessary to create the low-temperature shape. On heating, transformation starts at As and is completed at Af (typically 2 to 20 °C or hotter, depending on the alloy or the loading conditions). As is determined by the alloy type and composition and can vary between −150 °C and 200 °C.

B. Two-Way Memory Effect

The two-way shape-memory effect is the effect that the material remembers two different shapes: one at low temperatures, and one at the high-temperature shape. A material that shows a shape-memory effect during both heating and cooling is said to have two-way shape memory. This can also be obtained without the application of an external force (intrinsic two-way effect). The reason the material behaves so differently in these situations lies in training. Training implies that a shape memory can "learn" to behave in a certain way. Under normal circumstances, a shape- memory alloy "remembers" its low-temperature shape, but upon heating to recover the high-temperature shape, immediately "forgets" the low-temperature shape. However, it can be "trained" to "remember" to leave some reminders of the deformed low-temperature condition in the high-temperature phases. There are several ways of doing this. [11] A shaped, trained object heated beyond a certain point will lose the two-way memory effect.

C. Super elasticity

Upon continued loading, the twinned martensite will begin to detwin, allowing the material to undergo large deformations. Once the stress is released, the martensite transforms back to austenite, and the material recovers its original shape. As a result, these materials can reversibly deform to very high strains – up to 8 percent.

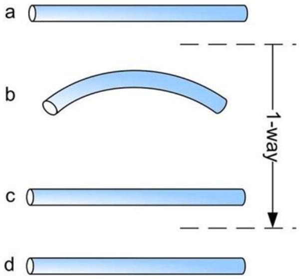


Fig. 4. One-way effect

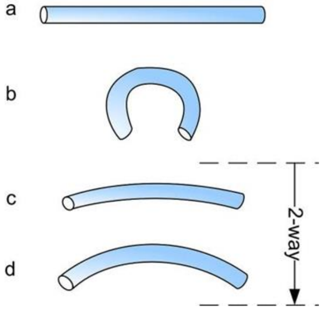


Fig. 5. Two-way effect

D. *Shape memory effect*

Shape memory effect (SME) is a 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.

8. Application of shape memory alloy in civil engineering

A. *Pre-Stressing*

Pre-stressing concrete and masonry structures with SMA strands wires are another alternative. Both pre-tensioning and post-tensioning can be done using SMAs. The benefits of using SMAs in pre-stressing are:

- Active control on the amount of pre-stressing with increased additional load-carrying capacity.
- No involvement of jacking or strand-cutting.
- No elastic shortening friction and anchorage losses over time.

1) *Pre-Tensioning*

Pre-tensioned SMA strands-wires in the martensite state are embedded in concrete, then it is heated electrically to transform the material from martensite phase to austenite phase, thus due to this it undergo large shrinkage strains; if constrained, the SMA strands-wires generate a significant pre-stressing force in concrete. Conventional pre- stressing by pre-tensioning wires requires jacking and release of pre-stressing strands, which causes crack at the end of the girders during strand cutting. So, if we use SMA for pre-stressing, than jacking or strand-cutting are not required.

2) *Post-Tensioning*

Pre-stretched SMA strands tendons in the martensite phase are passed through post-tensioning ducts after placement of concrete, and heating can conveniently induce post-tensioning. Post-tensioning requires anchoring of SMA bars, but does not require jacking and strand-cutting mitigates the possibility of friction and anchorage losses. Pre-stressing losses because of elastic shrinkage losses because of elastic shortening, creep and shrinkage are negligible and can be recovered by heating SMA bars when required induce post-tensioning. Four-point bending test on beams demonstrated that significant pre-stressing was achieved.

Fig. 6. A small concrete block post-tensioned with SMA wires

B. *Self-sensing and repairing capabilities*

Bolted joints are often the weakest elements in most structures. They might wear, leak, slip, or tear apart. The super-elastic 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. preload recovery. piezoelectric and SMA elements are employed 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.

C. *Intelligent Reinforced Concrete Structure*

An intelligent reinforced concrete structure (IRCS) was developed by Song et al. 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.

Fig. 7. During loading

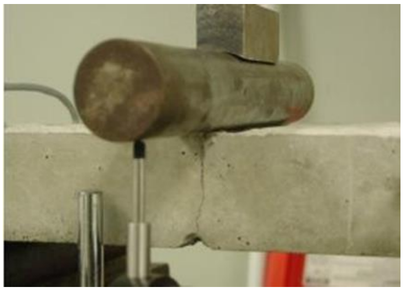


Fig. 8. After heating

D. *SMA in earthquake resistant techniques*

1) *Seismic retrofitting with SMA bracings*

Salichs et al. conducted a feasibility study on using SMA diagonal bracing wires as passive devices for vibration suppression of a one-storey building model. SMA super elastic hysteresis lowered the peak lateral drift compared with that for steel bracing having similar stiffness. An analytical evaluation shows the effectiveness of using large diameter super elastic SMA bars as bracing members. The reduction in the inter storey drift and column rotation of an RC frame achieved by using SMA bracing members was more than that achieved by using steel bracing.

2) *SMA Based Dampers*

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. Two different types of reduced-scale dampers using SMA wires over a range of strain amplitudes, loading frequencies, and temperatures. The analytically study gives 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.

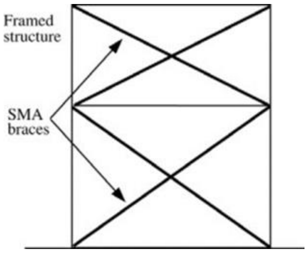


Fig. 9. SMA braces for a two-story steel frame

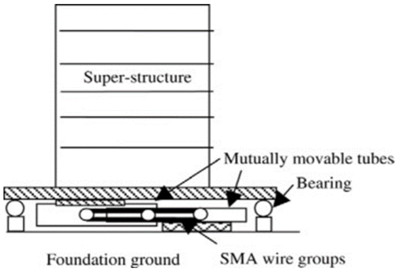


Fig. 10. SMA isolation system for buildings

3) *SMA Based Isolation Devices*

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 was done. It was found that seismic accelerations could be reduced by up to 90% using SMA devices, and the self-centering characteristics of the super elastic device resulted in negligible residual displacements.

E. *Bolted joints*

During earthquake event, beam-column and column-foundation are often weakest link of a structure. By using such super elastic shape material alloy material in a joint we can able to reduce damages by dissipating large amount of energy through large plastic deformation and then it can be recovered.

9. Advantages and disadvantages of shape memory alloy

A. *Advantages*

1. It has higher strain recovery upto 8%.
2. Higher strength of Shape memory alloy is observed.
3. Its High corrosion resistant property make it suitable for use in concrete.
4. It has Good elasticity.
5. It Resist Fatigue.
6. It does not undergo Wear and tear.
7. Easy fabrication of Shape Memory Alloy is possible
8. It is Light in weight.

B. *Disadvantages*

1. Heat energy is required to activate
2. The Property of Shape Memory Alloy.
3. Heat Dissipation - Need mechanism for cooling.
4. It Has Less Stiffness.
5. Costly as compared to other materials such as steel and aluminum.
6. It Has Poor Fatigue Properties (I.E. Structural & Functional Fatigue)

10. Conclusion and future work

This paper presents a review of the basic properties of Nitinol shape memory alloys (SMA) and their applications of shape memory alloys in civil structures. Shape memory alloys can be used in different ways to control civil structures. The SMAs can be used in different form like bars, wires, and plates, etc. Due to its unique properties of SMAs, i.e. Super elasticity and shape memory effect in has seeks more attention for researchers. SMA has opened the door of opportunities and made one of the construction materials for the future because of its self-repairing and self-healing capacity.

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