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A Review on: Shape Memory Alloy and Its Application in Civil Structures

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Abstract: Shape memory alloy is a unique material and has found increasing application in many research areas. A shape memory alloy has an ability to undergo large deformation up to 6 to 8 percent and can also regain its undeformed shape by removal of stress or by heating. Due to this unique property, research effort has been extended by using shape memory alloy for control of civil structures. The report includes the fundamental characteristic of shape memory alloy, some of the application of shape memory alloy in civil structures, and the constitutive modeling of shape memory alloys.
Keywords: Shape memory alloy; phase transformation, constitutional model of SMA, applications of SMA.

1. Introduction
This Smart system for civil structures are described as a systems that can automatically adjust structural characteristics in response to external disturbances or unexpected severe loading towards structural safety, extension of the structures life time and serviceability [1]. Our main aim is to develop and implement smart material into our civil structures, so it can provide functions like sensing, actuation and information processes which is used for monitoring, self-adapting and healing of structures. Different types of smart materials are like piezoelectric, shape memory alloys, magneto-rheological fluids and electro-rheological fluids.
Now a day's shape memory alloys have found its application in many different areas because of its unique properties like high power density, solid state actuation, and high damping capacity, durability, fatigue resistance, shape memory effect and super elasticity. To reduce the damage caused by earthquake SMA is integrated with civil structure in the passive, active and semi-active components. Most of the research activities are still in laboratory stage, only few of its application is implemented in field and it is found effective.

2. Basics about Nitinol Shape Memory Alloy

In 1932, chang and read observed a reversible phase transformation in gold-cadmium (AuCd), which is the first record of the shape memory transformation. At Naval Ordnance Laboratory, Buechler and his co-researcher in 1962 discovered the shape memory effect in nickel-titanium. They name this material Nitinol after their workplace. Research and practical application of shape memory alloys both emerged in dept later [2].
Till now many different types of shape memory alloy have been discovered. Among them, Nitinol has excellent thermo-mechanical and thermo-electrical properties. Most commonly used SMA is Nitinol. Nitinol has two unique properties and that are:
Shape memory effect
A phenomenon that the material SMA will return to its original shape by heating a material [3].
Super elasticity
A phenomenon that the material can undergo large inelastic deformation/ plastic deformation and recover its original shape after unloading or by removal to stresses.
These unique properties are the results of reversible phase transformations of Shape memory alloy [4].

3. Phase Transformations
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 transformations. 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 thermo-mechanical point of view, temperature and external stress play an equivalent role in the transformation mechanism. There are two different types of martensite transformations:
A. Temperature-induced transformations which causes the shape memory effect
B. Stress – induced transformations which results in the super elasticity
A typical stress-free temperature-induced martensitic transformation and its inverse transformation is shown in figure1 under temperature excitation cycle. It has four different transition temperatures that characterize the transformation loop:
Martensite start temperature (M_s)
Martensite finish temperature (M_f)
Austenite start temperature (A_s)
Austenite finish temperature (A_f)

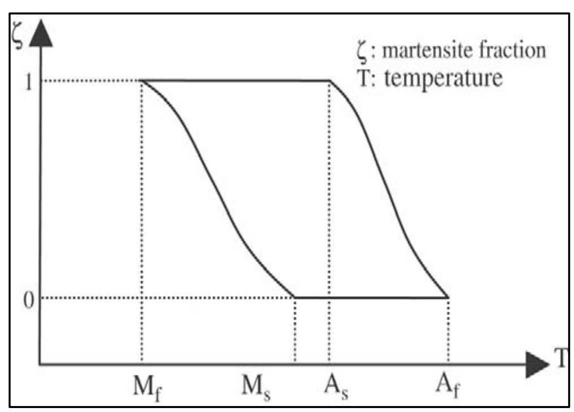

Figure 1. Temperature – induced phase transformation [2]

All these critical temperatures show the starting and the ending of the forward and reverse transformation. The temperature–deformation loop is hysteretic due to internal phase friction.

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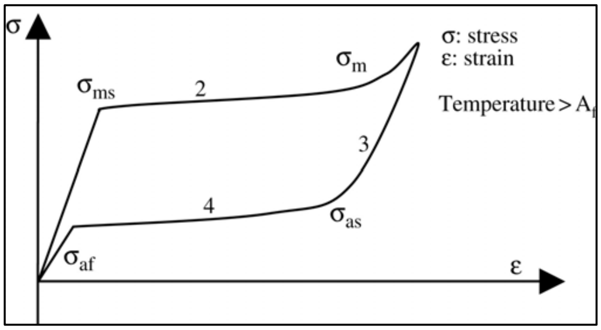


Figure 2. Stress-induced martensitic phase transformation [2]

A typical stress – strain curve of an SMA specimen at constant low temperature is shown in figure 2. When martensite SMA is subjected to tensile loading an elastic deformation takes place and it increases corresponding to constant stress. These yields takes place because of the hysteresis mobility of the twinned variation interface and defects inside the martensite phase. By unloading the elastic deformation/stain regains and the residual strain which has induces due to martensite reorientation can be recovered by reverse phase transformation i.e. by heating (SME) if this deformation exceeds the permissible value which martensite can sustain through the martensite reorientation mechanics, then a permanent plastic deformation takes place. To avoid the permanent plastic deformation, the applied stress should not exceed its permissible value.

4. Constitutive Modelling of shape memory alloys

In order to fully utilize the potential of SMAs, it is necessary to have a good understanding of their mechanical behaviour under thermal and mechanical loading. The constitutive equations of SMA are much more complicated than most of the common engineering materials. SMAs have very unusual behaviour that we have not encountered before. This unique behaviour attracts many researchers to study in this field. For this reason, the constitutive modelling of SMA has been the focus of many researchers. Several models based on various theories have been proposed so far. SMAs are usually modeled following either a phenomenological or thermodynamics approach.

4.1 Phenomenological modelling

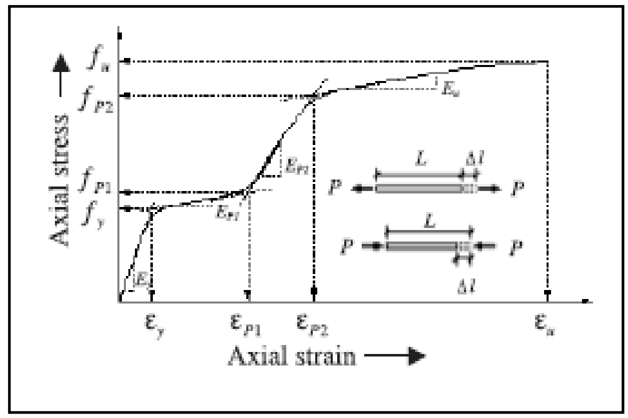
Since most civil engineering applications of SMAs are related to the use of bars and wires, one dimensional phenomenological models (PMs) are often considered suitable. In phenomenological models, the parameters shown in Figs. 3 and 4 are defined experimentally. Several researchers have proposed uniaxial phenomenological models (Tanaka and Nagaki 1982 [5]; Liang and Rogers 1990) [6]. The super elastic behaviour of SMAs has been incorporated in a number of finite element packages, e.g., ANSYS® version 10.0 (ANSYS, Inc. 2005) [7], ABAQUS 6.4 (Hibbitt et al. 2003) [8], and SeismoStruct (SeismoSoft 2004) [9], where the material models are included from Auricchio and Taylor (1996) [10&11] and Auricchio and Sacco (1997) [12], respectively. The parameters used to define the material models in FE software packages include (i) austenite to martensite starting stress (fy), (ii) austenite to martensite finishing stress (f_{P1}), (iii) martensite to austenite starting stress (f_{T1}), (iv) martensite to austenite finishing stress (f_{T2}), (v) superelastic plateau strain length or maximum residual strain (ε_l), (vi) modulus of elasticity for martensite and austenite phases (E_a and E_s), and (vii) the ratio of the transformation stresses under tension and compression.

Figure 3: Phase transformation and change in crystalline structure of shape memory alloys from martensite to austenite and vice versa as a function of temperature [13]

However, PMs seem to be more adequate for civil engineering applications involving SMA wires and bars because they can be easily incorporated in FE programs.

4.2. Thermodynamics-based modeling

Thermodynamics-based models (TMs) are built on the laws of thermodynamics and energy considerations. A number of TMs have been developed illustrating one or more aspects of SMAs. Patoor et al. (1994) [14], Goo and Lexcellent (1997) [15], Huang and Brinson (1998) [16] and others adopted micromechanics approaches and pursued closely crystallographic phenomena within the material using thermodynamics laws. TMs are much more complicated and computationally demanding than PMs because they present a highly sensible technique to derive precise three-dimensional constitutive laws.



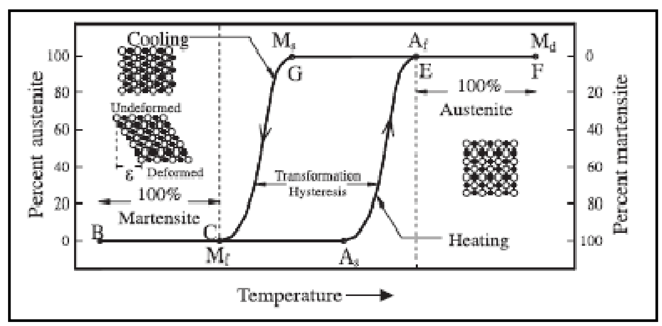


Figure 4: Typical stress-strain curve of shape memory alloy under tension-compression [13]

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5. Applications of shape memory alloys in civil structures

Shape memory alloys have load to many applications in civil engineering due to its unique characteristics. In this part application of shape memory alloy related to newly built up structures and retrofitted structures, dampers and isolators as shown below.

Use of shape memory alloy in new structures

Now many researchers has been conducted by using SMA in a new structure construction in form of reinforcement, pre-stressing strands, bracing, bolted connections and restrainers.

5.1 Reinforcement in concrete structures

Due to excessive lateral displacements several damages takes place in bridges and building are in seismic region. So, an earthquake resistant structure should be design which can behave elastically under medium earthquakes. It is not only economical possible to design structure which can perform elastically under strong earthquake. Steel is a conventional material used in seismic design and expected to yield to dissipate energy while undergoing permanent deformation. Conversely, if SMA is used as reinforcement in a reinforced concrete structure, it will yield when subjected to high seismic loads but it will recover a significant permanent deformation because of its unique characteristics.

5.2 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.

5.3 Bracings

A numerical study on a one-storey prototype building model strengthened with super elastic SMA (Ni Ti) diagonal bracing wires which are subjected to a harmonic base excitation. From the result they concluded that the additional damping is being provided by super elastic SMA hysteresis that reduces the peak displacement and also prevents the damage compared to the steel bracing with similar stiffness. Even after a large earthquake we can repair a frame easier because of its lower–level of damage.

5.4 Restrainers

One of the major problems of bridges during earthquakes is their unseating because of excessive relative hinge opening and displacement. The main limitation of unseating devices that includes small inelastic stain range limited ductility and no centering capacity. We can overcome these limitations by introducing SMA restrainers.

5.5 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.

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.

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.

6. Conclusion

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. Number of analytical and experimental studies of SMA devices proved to be effective in improving the response of civil structures under earthquake loading. 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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