A Review on Shape Memory Alloy Structures

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This paper presents a literature review on smart material NiTi shape memory alloys and their structural applications. Shape memory alloys are capable of recovering large strains as a result of martensitic transformation. The NiTi shape memory alloy is widely used because of its large memory strain, superelastic behaviour and greater thermal stability. The review includes the behaviours and the characteristics of the NiTi shape memory alloys, and also covers, in brief, structural applications and limitations.

1. INTRODUCTION

The study of smart materials and structures has received considerable attention in recent years. The advantages of incorporating these special types of materials into a structure is that the sensing and the actuating mechanism becomes part of the structure so that one can monitor structural integrity and take corrective actions. There are a number of materials that have the capability to be used as a sensor or an actuator or both. Piezoelectric materials, magnetostrictive materials, electrostrictive materials, shape memory alloys, and electrorheological fluids are widely known examples. Among these, shape memory alloys (SMAs) are metals and exhibit two very unique properties, shape memory effect and superelasticity.

Ölander[1] discovered the pseudoelastic behaviour of the Au-Cd alloy in 1932. Greninger and Mooradian[2] observed the formation and disappearance of a martensitic phase by decreasing and increasing the temperature of a Cu-Zn alloy. Chang and Read[3] reported the basic phenomenon of the memory effect governed by the thermoelastic behaviour of the martensite phase. Buehler and Wang[4] at the U.S. Naval Ordinance Laboratory discovered the shape memory effect in an equiatomic alloy of nickel and titanium, which can be considered a breakthrough in the field of shape memory materials. This alloy was named as nitinol (Nickel-Titanium Naval Ordinance Laboratory), after the Naval Ordinance Laboratory now known as the Naval Surface Weapons Center. Since that time, intensive investigations have been made to elucidate the mechanics of its basic behaviour. According to Castleman et al.[5] the first efforts to exploit the potential of NiTi as an implant material were made by Johnson and Alicandri in 1960s. In the last few years, several publications on numerical modelling and experimental studies have demonstrated the efficiency of shape memory alloys in structural applications.[6]

The term "shape memory alloy" (SMA) is applied to that group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to appropriate thermal and/or mechanical changes. The SMAs undergo a crystalline phase change when heated or cooled above the ambient temperature besides alloy composition and heat treatment, and this phase change is accompanied by a change in the elastic modulus and the critical stress. SMA materials such as, nickel titanium (NiTi), Cu-Zn-Al, Cu-Al-Ni, some ferrous alloys, shape memory ceramics and shape memory polymers have been widely used for shape and vibration control. Applications have occurred in various engineering fields viz. aeronautical, civil, mechanical. The transformation of the NiTi to an intermediate phase brings about an excellent shape memory property with small hysteresis. Also because of its better thermal stability, the NiTi has become more popular than other SMAs in engineering fields.

When the NiTi SMA is cold or below its transformation temperature, it has a very low critical stress and can be deformed quite easily into any new shape.[7] However, when the material is heated above its transformation temperature, it undergoes a change in crystal structure, which causes it to return to its original shape. If the NiTi encounters resistance during its transformation, then extremely large forces will be generated. The NiTi also recovers large strain (up to 8%), making it unique in applications, such as, actuators for active stiffness, active and passive shape control, vibration control and the flutter control of structures.[8]

2. CHARACTERISTICS OF SHAPE MEMORY ALLOYS

The characteristics of shape memory materials are marked by the low critical stress in the martensitic phase and the low modulus of elasticity at low temperatures. However these characteristics are completely changed to high critical stress, high modulus of elasticity and increased damping capacity at elevated temperatures. Cross et al.[9] presented experimental results of variation of the modulus of elasticity as shown in Fig. 1 and the variation of 2% critical stress (see Fig. 2). The nickel content in the NiTi alloy varies from 49 to 57% by weight.[10] The SMA exhibits the austenite phase, the martensite phase, and the mixture of both. In the austenite phase, the material has a high modulus of elasticity and a high critical stress. When it is cooled, it transforms to the martensite phase where it has a low modulus of elasticity and a low critical stress. The amount of the material that exists in the martensite phase is measured by the martensitic fraction (ξ) which can vary from zero to one. The temperature at which the material starts transforming from austenite to martensite is called the martensite start temperature (M_s), while the temperature at which it has a martensite fraction of one is called the martensite finish temperature (M_f). When the material is heated, it undergoes a change of phase from martensite to austenite; similarly, there exists an austenite start temperature (A_s) and an austenite finish temperature (A_f) (see Fig. 3). If an alloy is stressed above the M_s temperature, an apparent plastic deformation follows the elastic deformation of the parent phase. However this vanishes almost completely when stress is removed and such nonlinear elasticity which is capable of recovering from apparent plastic strain is called pseudoelasticity. The phase transformation of SMA with the change of alloy temperature is explained in Hodgson et al.[11] The authors discuss the applications of the SMAs and have given the typical properties of NiTi and Cu-based alloys, as well as a comparison of transformation temperatures for some alloys.

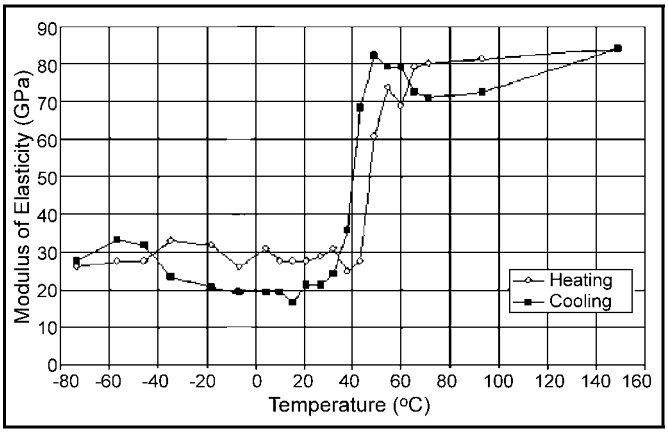

Figure 1. Variation of modulus of elasticity with temperature for NiTi alloy.

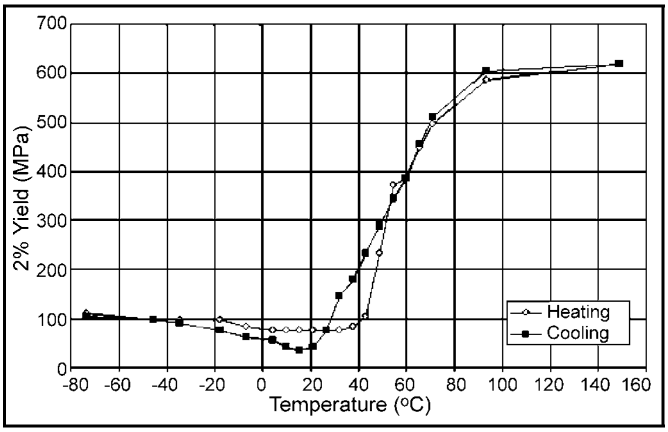

Figure 2. Variation of 2% critical stress with temperature for NiTi alloy.

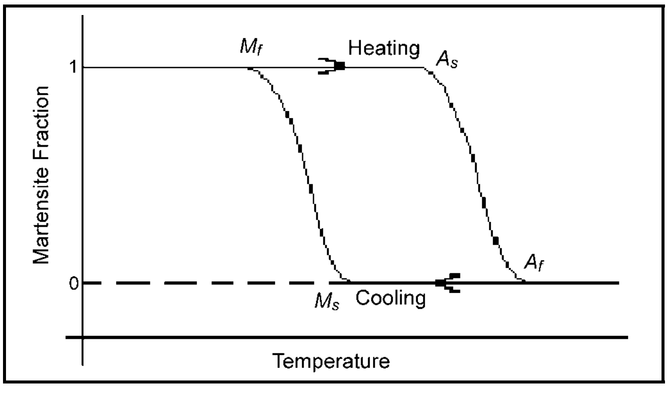

Figure 3. Phase transformation versus temperature curve for SMA.

The basic crystallography and the thermomechanical behaviour of NiTi alloys have been studied experimentally[12-17] and theoretically[18-21] for many years. There are also studies related to the mechanical behaviour of SMA and recent research in field applications.[22,23] Ortin and Planes[24] and Raniecki and Lexcellent[25] studied the thermodynamics of shape memory alloys. Vacher and Lexcellent[26] and Lexcellent and Tobushi[27] investigated experimentally the pseudoelastic behaviour of NiTi shape memory alloys. Extensive studies on the constitutive modelling of thermoelastic phase transformation of SMA have been reported.[28-34] The studies on modelling of superelastic behaviour of shape memory alloys are found in references.[35-37] Kafka[38,39] developed a mathematical model for the shape memory effect and explained the mechanism of micromechanical behaviour of shape memory materials.

2.1. Shape Memory Effect

The shape memory alloy materials can be severely deformed at a relatively low temperature and upon exposure to a higher temperature will return to their preprogrammed shape prior to the deformation. While SMA is soft and easily deformable in its lower temperature form (martensite), it resumes its original shape and rigidity when heated to its higher temperature form (austenite). This is called the one-way shape memory effect.[40] The ability of a shape memory alloy to recover a preset shape upon heating above its transformation temperatures (T) and return to an alternate shape upon cooling is known as two-way shape memory.[41,42] Figure 4 shows the shape memory effect during loading and heating the alloy after unloading conditions. Thermomechanical training will induce the two-way shape memory effect.

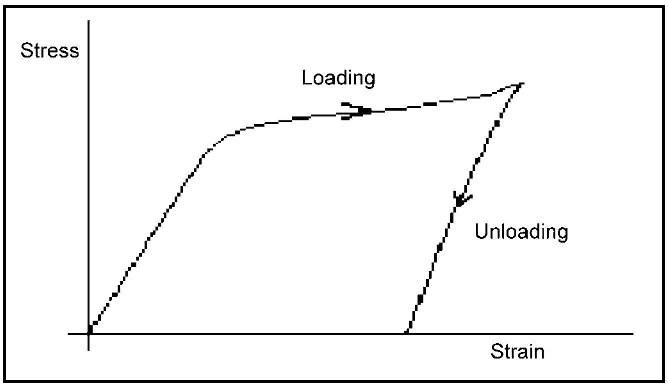

Figure 4. Shape memory effect: stress-strain hysteresis loop ($T < A_s$).

The use of the shape memory or pseudoelastic property of SMA for a specific application requires a piece of SMA to be moulded into the desired shape. The characteristic heat treatment is then performed to set the specimen to its final shape. The heat treatment methods used to set shapes in both the shape memory and the superelastic forms of SMA are similar. Adequate heat treatment parameters (temperature and suitable time) are needed to set the shape and the properties of the item.[7] They must usually be determined experimentally for the requirements of each desired part.

2.2. Superelastic Behaviour

The shape memory effect is not observed if the alloy temperature is above the transformation temperature. In such cases, the material shows a superelastic behaviour if deformed at a temperature, slightly above the transformation temperature.[43] This effect is caused by the stress-induced formation of some martensite above its normal temperature. Because it has been formed above its normal temperature, the martensite reverts immediately to undeformed austenite as soon as the stress is removed.[44] This stress-strain response of the material is termed superelastic behaviour. The stress-strain variation of NiTi SMA showing superelasticity is shown in Fig. 5.[11] Vacher and Lexcellent[26] and Lexcellent and Tobushi[27] studied the effect of cyclic loading for isothermal cases to model internal loops of superelasticity. The constitutive model was developed to describe the internal loops of pseudoelasticity in the isothermal loading condition.[32] From experimental investigations, Coleman and Noll[45] found that with proper thermo-mechanical treatment it is possible to stabilise the superelastic behaviour of NiTi under cyclic loading.

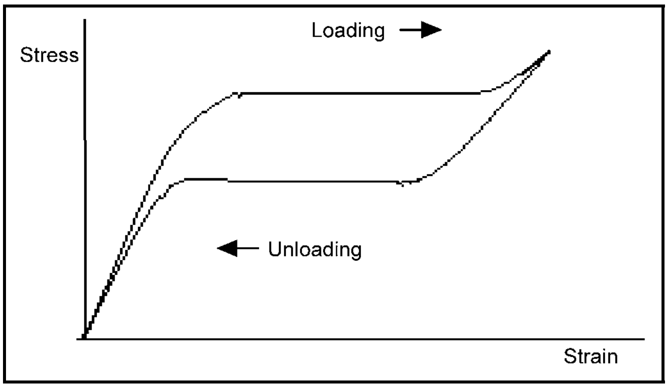

Figure 5. Superelasticity: stress-strain hysteresis loop ($T > A_f$).

The shape memory effect and the superelastic behaviour of the SMAs are affected by variations in parameters such as stress, temperature, strain rate and heat treatment. The strain rate and temperature usually account for the changes in the superelastic behaviour of NiTi SMA by changing the alloy microstructure. Within the temperature range the size of the stress-strain hysteresis loop can be affected by a change in the alloy temperature.[46] Either the external heating or the self-heating can contribute to this change. Within the superelastic temperature range, the combined effect of the temperature and the strain rate effects are greatly dependent upon both the heat transfer characteristic of the surrounding media and the alloy geometry.[47,48] Through a set of extensive experimental and analytical studies, Wu et al.[49] and Leo et al.[50] investigated the effects of temperature and strain rate on the superelastic behaviour of SMAs. The effect of strain rate on the SMA's superelastic behaviour is negligible when the temperature of the alloy remains constant during the loading process. Piedboeuf et al.[51] showed that not only the heat transfer characteristics of the surrounding media but also the size of the NiTi wire affects the amount of heat transfer from the wire.

3. APPLICATIONS OF SHAPE MEMORY ALLOYS

The NiTi SMA is widely used in many engineering and other fields owing to its special characteristics and behaviour. Some of the applications are briefly discussed below.

3.1. Structural Damping Applications

The NiTi shape memory alloys are attracting increasing interest for use as smart materials both for the passive as well as active structural damping applications. The passive high damping capacity occurs in the thermoelastic martensitic phase due to the hysteretic mobility of martensite variants. The damping capacity increases with increasing amplitude of the applied vibration. Moreover, there is special interest in damping extremely large displacements. This can be realised by applying the mechanical hysteresis occurring during the superelastic/pseudoelastic loading. Presently, this aspect is employed as a tool for protecting buildings against earthquakes in seismically active regions. Active damping can be obtained in hybrid composites by controlling the recovery stresses or strains of embedded shape memory alloy wires. This controls the internal energy of a structure that allows modal modification and tuning of the dynamic properties of structural elements.[52-54] Inaudi and Kelly[55] explored the use of NiTi in a perpendicular direction to the motion in a mass-tuned damper and showed that it could provide an effective non-linear damping mechanism. Birman[56] studied the effect of NiTi dampers on nonlinear vibration of elastic structures. When used within the pseudoelastic temperature range, NiTi is effective for increasing structural damping. Recently, Seelecke[57] presented nonlinear vibration analysis for damping using a model developed by Achenbach and Muller.[16]

3.2. Vibration Control of Structures

At low temperatures, the nitinol microstructure is found to be in the martensitic phase, while at high temperature an austenitic phase governs the microstructure. When NiTi SMA is subjected to heat, several of its properties, such as stiffness and damping, are changed. Normally, at a low temperature, NiTi SMA is a very flexible material, allowing for easy deformation. However, at higher temperature, while undergoing microstructure transformation, the stiffness and the modulus of elasticity increase significantly. This increased stiffness will decrease the amplitude of sway under a base vibration. The increased stiffness will also change the frequency of the structure and prevent it from reaching resonance or pushing it away from resonance.[58] Baz et al.[59] conducted a set of theoretical and experimental studies to find the feasibility of utilising NiTi actuators in controlling the flexural vibrations of a flexible cantilevered beam. A NiTi wire was used as the actuator to control the first bending mode of the beam. At the time of activation, the actuator shrinks and exerts a force, which creates the restoring moment. In order to increase the performance of the controller and reduce the overshoot, the effect of beam velocity was considered. Chen and Levy[60] presented a mathematical model for a flexible beam covered with SMA layers for vibration control. Tylikowski and Hetnarski[61] proposed a technique for the dynamic stability analysis of SMA activated hybrid rotating shafts under a compressive axial force varying with time. Graesser and Cozzarelli[62] studied the application of NiTi SMA for seismic applications. The vibration control and the modification of vibration characteristics of the structure are studied using the SMA layers in combination with a combined viscoelastic layer.[63] In one case, the increase in natural frequency of the beam was observed from 21 Hz at room temperature to 62 Hz when the actuators were heated to 148°C.[64] Ostachowicz et al.[65] also reported a shift in natural frequencies by simple heating with the Joule effect. Rogers et al.[66] and Pietrzakowski[67] reported a comprehensive study on the eigen frequencies and the eigen functions of SMA hybrid adaptive panels with uniformly- and piecewise-distributed actuation. With the numerical investigations it was shown that the activation by the temperature effectively changes the eigen frequencies, mode shape of the plate, and sound transmission through the composite.

Sun and Chen[68] investigated the effect of initial stresses on the low velocity dynamic response of laminates by the finite element method. Rogers[69] and Saunders et al.[70] investigated the application of SMA composites for vibration control and structural acoustic control. Yang[71] suggested that with the simultaneous use of SMA and a ferroelastic ceramic, the composite material could be used effectively as a sensor and actuator to reduce the structural vibration without the use of an external control.

The superelastic behaviour of NiTi is used for passive control, which utilised the stress-induced phase transformation at temperatures higher than Af. NiTi is very attractive for passive vibration control as it recovers large strain in elastic deformation. In the pseudoelastic temperature range, NiTi devices not only dissipate energy but also provide the system with a restoring force. When used for passive control, the NiTi element response time is the same as the external applied stress frequency. Savi and Mamiya[72] studied passive vibration control using the superelastic behaviour of NiTi via a simple oscillator and showed that NiTi can be used for vibration control near the resonant condition. The Muller and Xu[73] model was used for pseudo-elastic behaviour of NiTi. Eaton[74] demonstrated the benefit of using the superelastic properties of NiTi in a passive energy-absorbing device. The findings suggest that NiTi SMA can be used as a vibration damper for large strain. Wilde et al.[75] proposed a variable isolation system for elevated highway bridges consisting of laminated rubber bearings and SMA bars. The SMA base isolation system provides a stiff connection between the pier and the deck for small external loading. Ti rich NiTi alloy under stress, cyclic load would inhibit the martensite transformation.[76] Peng et al.[77] proposed a two-phase constitutive model for the polycrystalline SMA in dynamic loading. In hybrid control of structures, along with the conventional method both the shape memory effect and the pseudo-elastic characteristics of NiTi are utilised. Shahin et al.[78] developed an analytical model using hybrid control to study the vibration control of a one-story scaled model.

While manoeuvring flight vehicles at high speed, the external skin undergoes self-excited vibration, for example, panel flutter, due to the aerodynamic loading. Panel flutter, characterised by high vibration amplitudes in the third quarter length of the panel, makes it vibrate laterally.[79,80] The high in-plane oscillatory stresses induced during this vibration in turn lead to the panel failure. In these kinds of situations, NiTi alloy could be helpful to control vibrations.

3.3. Shape Control of Structures

The NiTi SMA is also employed for shape control of loaded structures. Much research effort has been made to evaluate the effect of the shape recovery force on the shape change of flexible structures. Rogers et al.[81] developed a linear analysis model for the static and dynamic control of structures. Through numerical investigation it was shown that the recovery force due to phase transformation of SMA has a direct effect on the deflection of plates. Song et al.[82] presented a simple proportional and derivative controller for the tip deflection control of composite beams reinforced with SMA wires. The model was validated through numerical and experimental studies. Baz et el.[83] developed the mathematical model for the shape control of a Nitinol-strip embedded composite beam. The results obtained from the numerical studies closely agree with the experimental results. Kim et al.[84] developed a 3-D finite-element model to study the shape control of a SMA composite beam. Numerical investigations show that the shape of the SMA/graphite/epoxy composite beam can be controlled by judicious choices of control temperatures, SMA angles and elastic tailoring. Sun et al.[85] studied the deflection of the polymeric-matrix composite plate with embedded shape memory alloy (SMA) wires subjected to uniform lateral pressure using the finite element method. The behaviour of the polymeric composite plate under the electrical heating of SMA was analysed with thermo-visco-elastic theory, and it was found that the thermo-viscoelasticity of the polymeric matrix on the actuation of SMA is significant.

Some studies on SMA related to stability control of structures have also been reported. Choi and Lee[86] made experimental and theoretical studies which show that activated embedded NiTi wires can be useful for shape control and buckling control of laminated composite beams. The buckling control of composite beams with SMA reinforced wires has also been reported.[87-89] It is possible to control the deflected shape of a composite beam reinforced with SMA wires by applying heat through electrical-resistance. The non-linear buckling analysis showed that the activation of eccentrically embedded SMA wires increases the critical buckling load when the phase transformation of SMA wires is accrued.[90] Tsai and Chen[91] studied the dynamic stability of an SMA reinforced composite beam subjected to axial applied dynamic force. The finite element method and the harmonic balance method were used to calculate the stability region of the composite beam. SMA wires have found to have significant effect on the dynamic stability regions.

4. OTHER STRUCTURAL APPLICATIONS

Base isolation provides a very effective passive method of protecting bridges from the hazard of earthquakes. Whittakar et al.[92] developed a technical base for the design of NiTi energy dissipation devices for building structures through characterisation of material behaviour, device development and experimental studies. Aizawa et al.[93] proposed a basic energy dissipation device model using nitinol wires. The investigation proved that the superelastic effect of shape memory alloy could be used as energy dissipating device. Wilde et al.[94] proposed smart isolation system for bridges, which combines a laminated rubber bearing with a device made of a shape memory alloy. The smart base isolation utilises different responses of the SMA at different levels of strain to control the displacements of the rubber bearing at various excitation levels. At the same time, the hysteresis of the alloy is used to increase the energy dissipation capacity. Dolce and Marnelto[95] tested passive energy dissipating devices for the seismic isolation of framed buildings. The authors proposed a hybrid device made of a bundle of NiTi wires, which can provide the dissipation effect. The number of NiTi SMA wires needed depends upon the amount of restoring force and energy dissipation required. Valente et al.[96] conducted some experimental studies on structural models with NiTi-based protection devices and compared the performance of the conventional and innovative base-isolated structures. The findings show the effectiveness of NiTi-based devices as compared to rubber isolators. The shape memory alloy also can be used for the manufacture of stents (refer to Fig. 6). These stents in their deformed shape can be inserted into damaged arteries and will expand to the appropriate diameter when human blood temperature is reached.

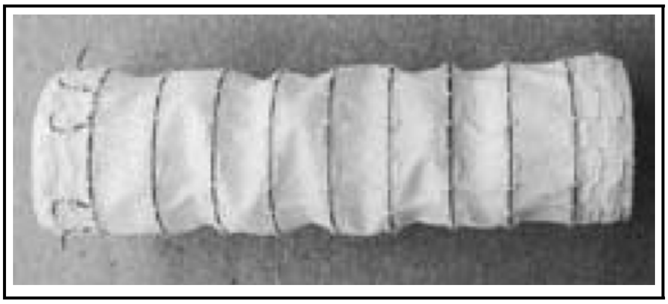

Figure 6. Stent: a reinforced graft to replace or repair damaged arteries.

5. LIMITATIONS

Though SMAs are very effective in many structural applications the researchers have reported the following disadvantages.

5.1. Degradation, Fatigue and Ageing

The failure of SMA elements is entirely different from the failure of conventional materials. During repeated actuation or during overheating, the SMAs can fail due to a decrease in the force exerted because of a shift of the transformation temperature.[97-100] Moreover, these degradation phenomena are influenced in a complex way by many parameters, including maximum temperature, maximum stress, and maximum strain, number of cycles, alloy composition, heat treatment and processing. Quantitative data on these degradation phenomena are very scarce. High strain levels in combination with high stress levels could result in failure after a few cycles.[100] Preliminary investigations on the cyclic stability of SMA composites showed positive results, but further extensive and systematic research is required.[101] Overheating of the pre-strained SMA-wires during curing of SMA-composites also require special attention in the development of SMA-composites.

5.2. Interface Strength and Durability

The SMA wires can be made as small as 50 μm in diameter, which is much greater than the size of a typical reinforcing fibre. Another important aspect of SMAs is their use for the generation of high cyclic stresses combined with changing temperatures. Therefore, the strength and the durability of the interface between the SMA and the matrix are of special importance, since the functionality and the durability of the SMA composite may be affected. Preliminary results have shown that the normal oxide layer on nitinol wires results in an adequate bonding between SMA and composite matrix.[102] Different surface treatments and coatings have been investigated but have not been found to increase the interface strength substantially. Further research is required, especially with respect to the effects of long-term cyclic activation on the interface strength and the stress analysis of structures with SMA during transformation.

6. CONCLUSIONS

The NiTi shape memory alloy has been widely used because of its unique shape memory effect and superelasticity behaviours. Though much work has been done on the identification of the material behaviour of NiTi, work in modelling of a variety of problems/applications needs to be emphasised. The NiTi shape memory alloy is used in a variety of applications, for example, shape control, vibration control, flutter control and seismic isolation.

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