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An overview of vibration and seismic applications of NiTi shape memory alloy

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Abstract
Shape memory alloys (SMAs) exhibit peculiar thermomechanical, thermoelectrical and thermochemical behaviors under mechanical, thermal, electrical and chemical conditions. Examples of these materials are Cu-based SMAs, NiTi SMAs, ferrous SMAs, shape memory ceramics and shape memory polymers. NiTi SMAs in particular, have unique thermomechanical behaviors such as shape memory effect and pseudoelasticity, which have made them attractive candidates for structural vibration control applications. Numerous studies have been conducted in modeling and applications of NiTi SMAs in structural vibration control. Several active, passive and hybrid energy absorption and vibration isolation devices have been developed utilizing NiTi SMAs. In this paper we present an overview of NiTi behaviors, modeling and applications as well as their limitations for structural vibration control and seismic isolation.

1. Introduction

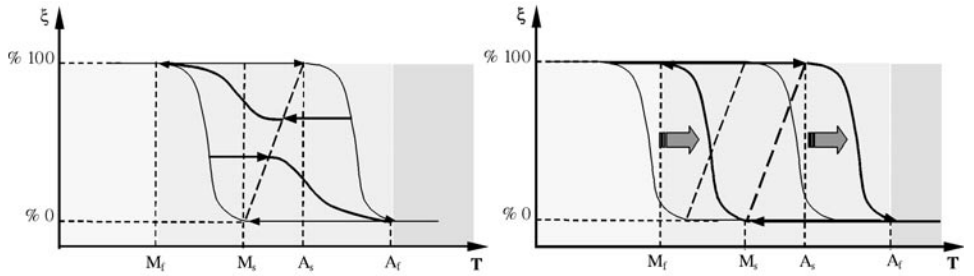
The search for non-conventional materials used as actuators to satisfy control performance requirements has been the main task during the past years. Among all shape memory materials, NiTi shape memory alloys (SMAs) with their superior thermomechanical and thermoelectrical characteristics have found many applications in different fields of engineering and science. Some examples are electrical connectors, fasteners, orthodontic wires, headbands of headphones, eyeglass frames, actuators and sensors in a variety of different devices, bone plates, active endoscopes, air conditioning vents and guide wires [1]. In what follows, a concise review of the basic aspects of NiTi SMAs thermomechanical characteristics is presented, then the modeling aspect of such thermomechanical behaviors is explored and, finally, a qualitative literature review of different applications of NiTi SMAs in structural vibration control is given.

2. Characteristics of NiTi SMAs

A comprehensive understanding of various thermomechanical behaviors of NiTi such as shape memory effect (SME) and pseudoelasticity is essential in design and implementation of NiTi-based devices, especially for seismic protection and vibration isolation applications.

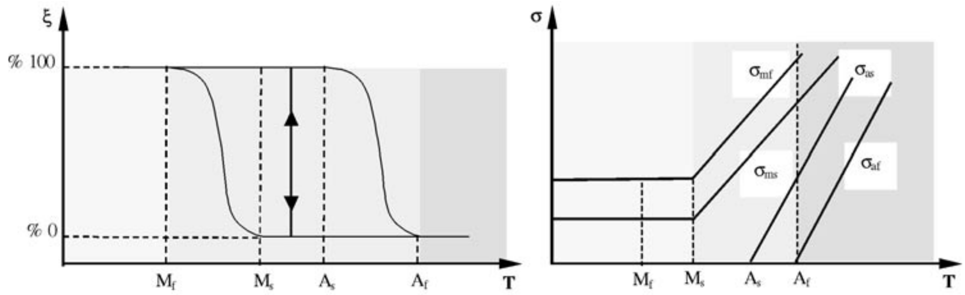
2.1. *Thermodynamics of thermoelastic martensitic phase transformation*

The martensitic phase transformation mechanism is a solid–solid diffusionless transformation accompanied by both microscopic and macroscopic deformations that can be recovered by heating in an ideal reversible cycle [2]. The dual-phase microstructure of NiTi consists of two phases: the austenite phase (A), stable in high energy levels with a body-centered cubic (bcc) structure having low strain, and the martensite phase (M), stable in low energy levels having transformation strain.



(a) (b)

Figure 1. Schematic diagrams of (*a*) stress-free temperature-induced phase transformation, and (*b*) effect of the applied stress on temperature-induced transformation.



(a) (b)

Figure 2. Schematic diagrams of (*a*) isothermal stress-induced phase transformation, and (*b*) transformation stresses versus temperature.

The driving force of the transformation is the difference between the Gibbs free energy of the two phases and depends on both the alloy temperature and the level of externally induced stress. In the forward phase transformation (A $\rightarrow$ M), the driving force is balanced by an increase in elastic strain and interfacial energies plus resistance from any internal motion, while in the reverse phase transformation (M $\rightarrow$ A) the stored elastic strain and interfacial energies are in favor of the driving force. From a thermomechanical point of view temperature and externally induced stress play equivalent roles in the transformation mechanism; this interchangeability is the origin of the SME (temperature hysteresis) and pseudoelasticity (stress–strain hysteresis) in NiTi.

The transition temperatures of a stress-free temperature-induced transformation and the transition stresses of an isothermal stress-induced transformation are material properties and depend upon the alloy composition and thermomechanical processing. Moreover, experimental results of Delaey *et al* [3] show that temperature and externally induced stress have mutual effects on transition temperatures and stresses at which forward and reverse transformations take place.

2.2. Temperature-induced transformation at constant stress

Figure 1(*a*) shows how phase transformation takes place as temperature changes in a stress-free condition. The vertical axis represents the temperature-induced martensitic phase fraction ξ. Stress-free condition means an unconstrained condition in which the resulting displacement is a function of change in phase composition during forward and reverse transformations. The transition temperatures are martensite start M_s, martensite finish M_f, austenite start A_s and austenite finish A_f respectively.

Although transition temperatures identify the beginning and the end of the forward and reverse transformations, there are possibilities that forward transformation could start at much higher temperatures than M_s and reverse transformation could start at temperatures much lower than A_s respectively. The reason is that the amount of energy required to trigger transformation is directly related to the relative mass fractions of austenite and martensite as well as the applied stress. In figure 1(*a*) the diagonal line connecting M_s to A_s is called the trigger line, which is the location of the unstable phase equilibrium on which forward and reverse transformations occur. Note that either in forward or reverse transformation the phase composition does not change prior to hitting the trigger line.

So far, it is assumed that transformation happens in stress-free conditions. However, as noted earlier, temperature and stress have mutual effects on the transformation mechanism. Figure 1(*b*) shows such an effect: as applied stress increases the hysteresis loop moves to the right; in other words the higher the applied stress the higher the transition temperatures are.

2.3. Isothermal stress-induced transformation

Isothermal stress-induced transformation suggests that any point within the hysteresis loop of figure 2(*a*) moves only up during forward (loading) and down during reverse (unloading) transformations, contrary to temperature-induced transformation. Basically, transformation starts when the mechanical energy of applied stress becomes equal to the required energy for forward or reverse phase transformations and is accompanied by heat generation. Note that, for any given temperature, both forward and reverse transformations happen over the same vertical path.

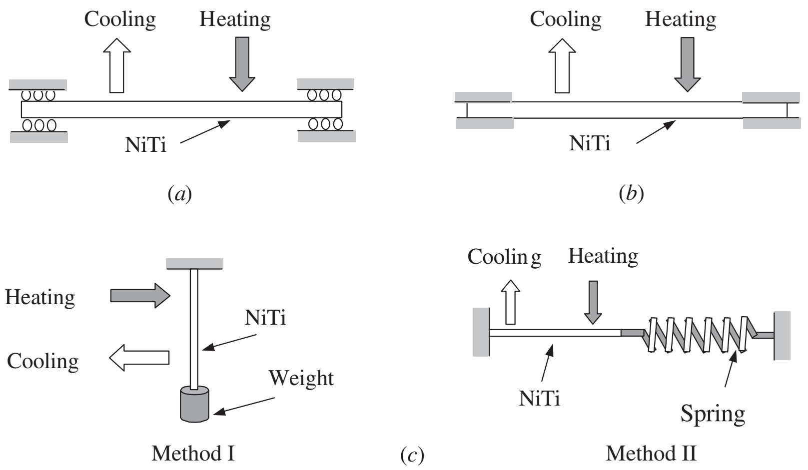


Figure 3. Schematic diagrams of (*a*) free recovery, (*b*) restrained recovery and (*c*) controlled recovery.

For the time being, it is assumed that the heat generation is negligible; therefore, the alloy temperature does not change during the transformation and there is no temperature-induced transformation. The effect of heat generation on the alloy behavior during stress-induced transformation is fully investigated in the following sections.

Figure 2(*b*) shows the variation of transition stresses as a function of temperature with the same temperature division as in figure 1. When the temperature is less than M_f, transformation is not due to any phase change but because of reorientation of martensite variants in the direction of applied stress. Successive heating to temperatures above A_f and cooling to temperatures below M_f can recover this deformation.

Within the temperature range of M_s to A_f, the alloy temperature at the end of the unloading process determines the final state of the alloy phase composition. Within this region martensite and austenite co-exist; therefore, at the end of the loading process (forward transformation) the stress-induced martensite (SIM) is stable and the phase composition of the alloy remains constant during unloading (reverse transformation). The change in phase composition results in physical deformation, which can be recovered by successive heating and cooling as mentioned before. Note that in this temperature region the forward and reverse transition stresses increase with temperature.

Above A_f austenite is the only stable phase, at zero-stress conditions. Therefore, at the end of unloading (reverse transformation), regardless of the extent of loading (forward transformation), the final phase composition of the alloy, at zero stress, is austenite again. Since the phase composition is the same at the beginning of loading (forward transformation) and at the end of unloading (reverse transformation), this indicates that there is no physical deformation associated with the transformation process.

This special case of cyclic forward and reverse transformations at temperatures higher than A_f, where the alloy can recover its original shape, is called pseudoelasticity.

2.4. Shape memory effect

The SME is a unique characteristic of NiTi that exhibits thermoelastic martensitic phase transformation. Through training, the material has the ability to memorize a very specific physical configuration or shape in either the martensite or austenite phase, which is called one-way shape memory. Also it is possible to train the material, such that it memorizes two different configurations or shapes in martensite and austenite phases, which is called two-way shape memory.

The key to the SME is the build-up of residual stress fields within the NiTi, by deforming the material plastically, then these stress fields control the phase transformation. There are two methods available for training NiTi, the conventional SME cycling and SIM training; detailed explanations of these methods can be found in [4].

When a deformed NiTi alloy recovers its original shape or switches from one shape to another, the shape recovery may fall into one of the following categories [5]. The first category is free recovery, figure 3(*a*), that simply means during the recovery process the alloy is not restrained and the amount of the residual martensite phase and recovered shape depend on the final temperature of the alloy.

The second category is restrained recovery, figure 3(*b*), in which the alloy is fully restrained from restoring its original shape. In this case, large internal recovery stresses are generated resulting in a large clamping force. The recovery stress is a function of temperature and residual martensitic phase. Finally, we have controlled recovery, figure 3(*c*), which means the alloy is partially restrained from recovering its original shape. Controlled recovery can further be divided into two sub-categories, according to the restraining method. In the first method, the applied load is constant regardless of recovery strain, and in the second method, the applied load is proportional to the recovery strain.

2.5. Pseudoelasticity

As elaborated earlier, it is clear that reverse stress-induced transformation depends highly on the alloy's unloading temperature, which is the key factor in determining the residual martensitic phase fraction. In figure 4(*a*), the total strain at any time consists of three components: firstly, the elastic strain caused when the alloy is either in fully austenite or fully martensite phase; secondly, the transformation strain caused when the alloy goes through the transformation process;

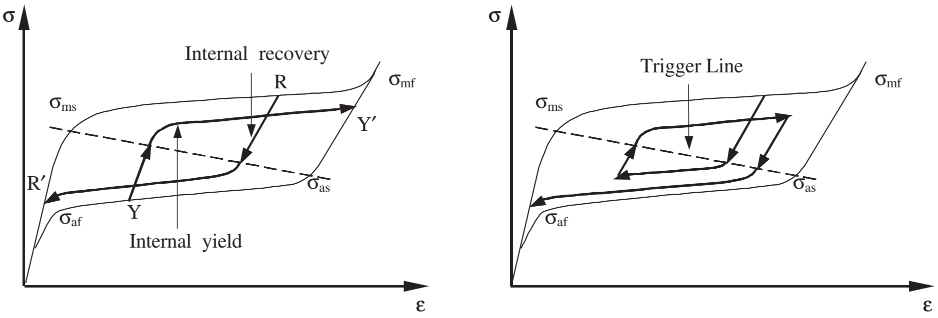


Figure 4. (*a*) Schematic of internal yield and recovery, (*b*) pseudoelastic hysteresis.

finally, plastic deformation caused by loading the alloy to stresses above the martensite yield limit.

As in temperature-induced transformation, the trigger line governs the overall behavior of the alloy when it goes through internal yield and recovery. Similar to temperature-induced transformation, the energy requirements for either forward and reverse transformations are a function of the induced martensitic phase.

If forward transformation stops at point R in figure 4(*a*) and unloading starts at this point, the alloy deforms back elastically and the phase composition as well as Young's modulus does not change until the stress level reaches the corresponding transition stress of the trigger line. Once that happens, the reverse transformation starts and finishes at point R′. Similarly, if during unloading, the unloading process reverses at point Y, then upon loading the alloy deforms elastically and there is no change in phase composition or Young's modulus until the stress level reaches the transition stress of the trigger line. Similarly, once that happens, forward transformation starts and finishes at point Y′.

Pseudoelastic hysteresis, figure 4(*b*), occurs when there are successive loading–unloading processes, in the pseudoelastic temperature range. In such a case, the trigger line controls the alloy's internal yield and recovery. Note that the area of pseudoelastic hysteresis represents the amount of energy dissipation.

3. Effects of temperature, strain rate, stress, cyclic loading and heat treatment on thermomechanical behavior of NiTi shape memory alloys

Experimental studies by Miyazaki *et al* [6], Leo *et al* [7], Wu *et al* [8], Bruno [9], Piedboeuf *et al* [10], Filip and Mazanec [11], Lim and McDowell [12], McCormick and Liu [13], Xie *et al* [14], Liu and Van Humbeeck [15] and Liu *et al* [16] have shown that although NiTi exhibits peculiar thermomechanical behaviors such as pseudoelasticity and SME, these behaviors are affected by variations in external and internal parameters such as temperature, strain rate, stress and heat treatment.

3.1. Effect of strain rate and temperature on pseudoelastic behavior

Strain rate and temperature usually account for changes in the pseudoelastic behavior of NiTi. In the pseudoelastic temperature range the size of the stress–strain hysteresis loop can be affected by a change in the alloy temperature. Either external heating or self-heating can contribute to such a change.

Bruno [9], Wu *et al* [8] and Leo *et al* [7] have shown that in the pseudoelastic temperature range, temperature and strain rate effects are coupled and greatly depend upon both the heat transfer characteristic of the surrounding media and the geometry of the alloy.

Through a set of extensive experimental and analytical studies, Leo *et al* [7] have investigated the effects of temperature and strain rate. They used two identical pseudoelastic NiTi wires of 0.652 mm in diameter at 23 °C, one loaded in air and the other in the water bath. For each wire three displacement-controlled tension loading tests at strain rates of 0.5, 5.0 and 50.0 mm min^{-1} were conducted. The temperature change, along the length of the wires, was measured via thermocouples attached at 20 mm intervals.

The results show that the heat transfer characteristics of the surrounding media controls the extent of the strain rate effect on the pseudoelasticity behavior. When the temperature of the alloy remains constant during the loading process, the effect of strain rate on the alloy's pseudoelastic behavior is negligible; otherwise, it increases the alloy's temperature that consequently affects the pseudoelastic behavior.

A set of similar experiments conducted by Wu *et al* [8] confirms the aforementioned results. However, in order to compare the effect of geometry on the heat transfer, they compared the result of their study with Witting's [17] experiment where they used an NiTi wire that was 15 times smaller in diameter. They showed that not only the heat transfer characteristics of surrounding media but also the size of the NiTi wire affect the amount of heat transfer from the wire. Bruno [9] and Piedboeuf *et al* [10] also concluded similar results through extensive experimental and analytical studies.

3.2. Effect of heat treatment on pseudoelastic behavior

Another important factor in the pseudoelastic behavior of NiTi is its thermomechanical treatment. Experimental studies by Miyazaki *et al* [6] show that by proper thermomechanical treatment it is possible to stabilize the pseudoelastic behavior of NiTi under cyclic loading.

3.3. Effect of cyclic loading (tensile) on pseudoelastic behavior

As mentioned by Melton and Mercier [18, 19], Perkins and Sponholz [20] and Miyazaki *et al* [6] the main reason for the change in the thermomechanical behavior of NiTi is the generation of defects in the alloy's microstructure. Metallurgical observations have shown that pile-up of dislocations around the microstructural defects causes the accumulation of residual martensitic fractions which in turn change the alloy's thermomechanical behavior. For more information regarding the mechanism of cyclic loading in accumulation of residual martensitic phase fraction, see [21].

Based on observations made by Lim and McDowell [12], Miyazaki *et al* [6,22], Contardo and Cuenin [23] and Filip and Mazanec [11], the characteristic features of the cyclic uniaxial loading of pseudoelastic NiTi under constant amplitude strain are

(1) reduction in forward phase transformation stresses,
(2) work hardening during forward phase transformation,
(3) increase in reverse phase transformation stresses,
(4) accumulation of residual strain in the direction of loading, which stabilizes with further loading, and
(5) reduction in the area of the pseudoelastic hysteresis.

Moreover, experimental results from Miyazaki *et al* [6] show that cyclic loading within the elastic range of austenite phase, low-strain range, does not have any effect on the pseudoelastic behavior at further pseudoelastic cyclic loading, high-strain range.

3.4. Path dependence of the pseudoelastic behavior

Lim and McDowell [12] showed that pseudoelastic behavior of NiTi greatly depends on the maximum transformation strain in loading cycle. They concluded that, once pseudoelastic behavior is stabilized for a given cyclic strain amplitude, further cyclic loading with smaller strain amplitude does not change the pseudoelastic behavior of the alloy. However, once pseudoelastic behavior is stabilized at the larger strain amplitude, the alloy loses its previous memory, which was stabilized at the lower strain amplitude. The results show that the pseudoelastic behavior of lower strain amplitudes is always contained within the stabilized pseudoelastic behavior of larger strain amplitudes.

3.5. Effect of strain rate on martensitic damping capacity

Studies by Liu and Van Humbeeck [15] and Lin *et al* [24] have shown that NiTi possesses a high damping capacity in both austenite and martensite phases due to stress-induced martensitic phase transformation and reorientation of martensitic variants. The high damping capacity of the martensite phase seems to be related to the hysteresis-mobility of the twined phase interfaces and defects inside the martensite phase.

Liu and Van Humbeeck [15] have shown that the damping capacity of the martensite phase is a function of both annealing temperature and strain amplitude. At temperatures below 550 °C martensite damping capacity increases with increasing annealing temperature while above 550 °C it decreases with increasing annealing temperature. Also, martensite damping capacity increases with the increase of strain amplitude. They showed that the martensite damping capacity decreases with an increasing number of loading cycles and approaches a stable limit, and austenite damping capacity is smaller than that of martensite.

4. Thermomechanical modeling of NiTi shape memory alloys

Since the first publication by Chang and Read [25] on SMAs, much has been done in characterization of NiTi behaviors, such as SME and pseudoelasticity. Scientific advances in different engineering branches over the last decade, along with peculiar characteristics of NiTi, have created opportunities for these alloys to be used in a variety of applications, ranging from medical to civil, mechanical and aerospace engineering. Consequently, modeling of the peculiar thermomechanical behaviors of NiTi, such as SME and pseudoelasticity, has been an active area of research over the past decade. During this period a handful of different approaches have been used to model these behaviors, which in general can be categorized into phenomenological and thermodynamical approaches.

Some of the relevant works in modeling over the last decade, yet are not limited to, are [26–49].

4.1. Phenomenological modeling

Tanaka [44] developed a set of explicit equations in terms of stress, strain, temperature and a set of exponential equations for evolution of kinematics of martensitic phase fraction. Niezgodka *et al* [50], Niezgodka and Sprekels [51,52], Hoffman and Sprekels [53] and Hoffman and Zheng [54] suggested similar models. Based on Tanaka's work, Liang and Rogers [37] proposed a new set of empirical equations for kinematics of phase transformation. They simplified Tanaka's model by introducing a simpler kinetic relation in cosine form for the martensitic phase fraction. But their model could not represent the behavior of NiTi at temperatures between M_s and M_f. Brinson [28] improved the model of Liang and Rogers so that it could represent the material's behavior over the full range of temperature, by introducing the temperature- and stress-induced martensitic fractions into the kinetic relations. It has been shown that Brinson's model is more versatile and simpler to use. However, her model does not take into account the effect of cyclic loading and accumulation of residual martensitic fraction.

In another paper by Tanaka *et al* [55] the uniaxial stress–strain temperature hysteresis loops due to incomplete transformations are explained. The martensite and austenite start temperatures are taken into account phenomenologically as functions of residual martensite or austenite at the start of transformation.

4.2. Thermodynamics-based modeling

The common ground among all thermodynamical models is the free energy and dissipation potentials. It has been demonstrated by Edelen [56] that there exists a vector decomposition theorem such that the generalized fluxes appearing in the entropy production inequality can be decomposed into a dissipative component and a non-dissipative component. The dissipative fluxes must be derivable from dissipation potential.

Tanaka and Nagaki [46] were evidently the first researchers to discuss martensitic transformations within the context of Edelen's formalism. Using the above framework, Patoor *et al* [57], Sun and Hwang [42] and others developed different models for NiTi. Raniecki and Lexcellent [41] developed three models with ideal pseudoelastic flow and recovery, isotropic linear and non-linear transformation hardening, which account for the most significant features of the pseudoelastic behavior of SMAs.

Boyd and Lagoudas [58] also developed a thermodynamics-based model of pseudoelasticity and SME, which accounts for phase transformation and reorientation in the martensitic phase. It also accounts for non-proportional loading as well as both isothermal and adiabatic transformations.

4.3. Other relevant modeling works

Falk [59] proposed a one-dimensional constitutive model based on the classical Devonshire theory in which the SME and pseudoelasticity are represented via a sixth-order polynomial form of free energy as a function of temperature and one-dimensional strain. This model does not consider energy dissipation and experimental results show that it cannot represent the mechanical behavior of NiTi for small strains. Falk's model was modified by Savi and Kouzak [60], but lack of enough experimental data to determine material constants of the model and linear dependence of the elastic modulus on temperature is the main drawback of this model.

Müller and Xu [39] developed a model for pseudoelastic behavior of NiTi using a total potential energy approach. Patoor *et al* [57] and Berveiller *et al* [61] also developed local constitutive equations for the pseudoelastic behavior using micromechanical analysis based on a kinematics description of the physical strain mechanism and definition of the local thermodynamic potential.

Other models have been developed which can take into account the effect of cyclic loading on NiTi behavior. Bo and Lagoudas [62] developed a thermodynamical model for NiTi under cyclic loading. Their model takes into account the influence of plastic residual stresses on martensitic phase transformation, isotropic hardening during phase transformation due to an increase of elastic energy, plastic strains on two-way SME and change in hysteresis as a function of loading cycles.

Lexcellent and Tobushi [63] analyzed the effect of cyclic loading for isothermal cases and presented a thermodynamic framework for modeling of internal loops of pseudoelasticity. Delobelle and Lexcellent [64] used a unified viscoplastic model with internal kinematics variables to improve the description of the uniaxial and proportional loading in the pseudoelastic range. They developed a set of constitutive equations for a description of internal loops of pseudoelasticity in isothermal loading conditions.

By introducing the concept of instantaneous residual martensite and developing appropriate kinematics equations for the new state variable, Lexcellent and Bourbon [65] developed a thermodynamics-based model in terms of free energy, for cyclic behavior of NiTi under isothermal conditions for specific strain ranges. However, this model cannot accommodate the strain and stress rate effects. Graesser and Cozzarelli [31] modified an existing one-dimensional model of hysteresis to include the macroscopic characteristics of NiTi, but their model over-estimates the NiTi behavior by up to 35%.

5. Applications of NiTi shape memory alloy

NiTi has numerous applications, such as medical, dental and industrial. The first large-scale application of NiTi was in 1971 to connect titanium hydraulic tubing in the Grumman F-14 aircraft. Since then it has been used in a wide range of applications such as enhancing buckling characteristics of composite panels, active acoustic control, active control of flow-induced vibrations, electrical connectors, thermal protection valves, switches, actuators, dental arch wire, dental implants, partial dentures, bone plates, thermostatic mixing valves, air flow controllers and so on. For a list of such citations the reader is referred to Birman [66].

In the following sections the mechanisms behind active, passive and hybrid applications are explained.

5.1. Active control

The active control scheme is based on SME characteristics. Once NiTi is trained to achieve a specific shape via thermal activation (temperature-induced transformation), it can be used as an actuator in active control or shape control schemes. Meanwhile, the response time and mechanical stroke of the NiTi actuator to thermal activation greatly depend on the heat transfer characteristics of the alloy and surrounding media. At low heat dissipation rates, after each actuation it would take a long time for the NiTi actuator to return to its initial shape and be ready for another actuation cycle. Therefore, the higher the heat dissipation rate from the alloy the faster it returns to its initial shape and the shorter the response time of the actuator. On the other hand, for a fixed actuation frequency the mechanical stroke of the actuator decreases as the alloy's average temperature increases. Note that in temperature-induced phase transformation the amount of temperature-induced austenite phase directly depends on the temperature. The higher the temperature the higher the temperature-induced austenite phase and consequently the higher the macroscopic change in the alloy's structure, leading to bigger mechanical strokes within the transformation temperature range. However, in most active applications an on–off control scheme is used. In what follows some, yet not all, of the active control applications of NiTi are presented.

Baz *et al* [67] conducted a set of theoretical and experimental studies, studying the feasibility of utilizing NiTi actuators in controlling the flexural vibrations of a flexible cantilevered beam. The actuator used in their study was merely a NiTi wire used to control only the first bending mode of the beam. At the time of activation the actuator shrinks, going through forward transformation, and exerts a force which provides the restoring control moment. In order to increase the performance of the controller and reduce the overshoot, they take into account the effect of beam velocity. Therefore actuators may switch off/on, even though the beam is not in the horizontal configuration. Their study shows that NiTi actuators are feasible for vibration control applications and can be extended to control higher mode shapes via implementing sophisticated control strategies such as time-sharing strategy.

Seelecke and Büskens [68] have investigated the active structural shape control using NiTi actuators. Their experimental setup is a pin-jointed beam with a NiTi actuator attached in parallel to a partial length of the beam. A discretized optimal control scheme is used in which the restriction is the desired configuration of the beam, represented in terms of actuator length.

Rediniotis *et al* [69] experimentally and analytically investigated the feasibility of using NiTi actuators in an active hydrofoil. Using two sets of embedded actuation elements, thin NiTi wires, they developed a two-dimensional hydrofoil, which can be used not only for control of underwater vehicles but also is capable of generating trust.

A single NiTi wire, as a basic actuator, loaded by a mass, was studied by Benzaoui *et al* [70] to develop a model for controlling the NiTi using Joule's effect. The dynamic behavior of a NiTi wire under coupled stress and temperature actions for different thermal inputs was analyzed. The transformation behavior of a NiTi/epoxy composite was studied and compared with that of plain NiTi fibers. They confirmed that NiTi could be used to control the vibrational behavior of composites by heating/cooling the embedded NiTi fibers using electric current. The importance of this work is the control synthesis of a NiTi actuator.

In another study, Gotthardt and Bidaux [71] explored the use of in-plane NiTi actuators in the vibration control of composite plates. They studied the effects of interactions between NiTi actuators and matrix material on NiTi behavior and the feasibility of using embedded NiTi wires in controlling the vibrational response of the NiTi composite. They used simple beam bending theory to predict the bending stiffness and the damping capacity of the NiTi composite beam. They concluded that NiTi wires could be used to control the vibrational behavior of composite beams and they used NiTi fibers to actively modify the vibration frequencies of a polymer beam.

5.2. Passive control

The passive control scheme uses the pseudoelastic behavior of NiTi, which is the stress-induced phase transformation at temperatures higher than A_f. NiTi is very attractive for passive vibration control, because in contrast to regular metallic materials it can sustain large amounts of inelastic deformation and recover that deformation. In the pseudoelastic temperature range, NiTi devices not only dissipate energy but also provide the system with restoring force, not to mention that both damping and restoring forces of NiTi are non-linear. In a passive control scheme, the NiTi element response time is the same as the external applied stress frequency. In what follows some of the passive control applications of NiTi, yet not all, are presented.

Birman [72] studied the effect of NiTi dampers on non-linear vibration of elastic structures. He used NiTi wires at constant temperature within the pseudoelastic temperature range. He assumed that the wire does not affect the motion of the structure and only acts as an energy dissipater. He concluded that NiTi is attractive for increasing structural damping, when used within the pseudoelastic temperature range. At the same time he identified two drawbacks: relatively large deformations are necessary to trigger a stress-induced phase transformation, and degradation in thermomechanical behavior of the material because of cyclic loading.

In another attempt, Clark *et al* [73] developed a passive damping device using NiTi superelastic wires. Their device simply consisted of multiple loops of NiTi wire wrapped around cylindrical support posts. They fabricated single- and double-sided devices using two different wire diameters and in order to prevent the wires from slipping at unloaded configuration small rubber blocks were pressed onto the wires at the support posts.

They tested the device by an in-plane test machine, using a special test setup which allows for controlling the ambient temperature around the wires. A set of experiments was conducted at different strain amplitudes, ambient temperatures and loading frequencies to investigate the effect of the aforementioned factors on device performance and behavior. The results show that NiTi dampers exhibit stable hysteresis with minor variations due to loading frequency and device configuration (single wires versus multiple layers of wire). Their study shows that it is feasible to use NiTi in designing passive damping devices.

Thomson *et al* [74], experimentally and theoretically, studied the dynamic response of an aluminum four-story flexible space-truss structure augmented with NiTi wires. The structure represents a typical large flexible space structure and the passive element consists of two NiTi wires in parallel and collocated with an actuator in the third story. A knob provides a simple mechanism to pre-stress the wires and the symmetric configuration of the wires avoids imposing a bending moment on the actuator. They used the model of Müller and Xu [39] for pseudoelastic behavior of NiTi. They concluded that the damping contribution of NiTi wires is high at the lower modes of the structure.

Eaton [75] demonstrated the benefit of using the superelastic properties of NiTi in a passive energy-absorbing device. A single-degree-of-freedom secondary system is housed in a three-story prototype building and subjected to a base excitation. Each story of the building and the secondary system are modeled as lumped masses, connected by linear springs and viscous dampers, respectively. In the secondary system the NiTi absorber is attached mechanically in parallel with the secondary spring and viscous damper.

Their study demonstrated that an NiTi damper can be effectively used to suppress the dynamic response of a secondary system, and that an NiTi damper may dissipate more energy than a viscous damper especially at large strain. The reduction in the secondary system response can be attributed to two mechanisms, shifting the secondary system from its resonance frequency, and dissipating energy through pseudoelasticity hysteresis.

5.3. Hybrid control

In the hybrid control scheme both the SME and pseudoelastic characteristics of NiTi can be utilized in conjunction with conventional methods. Although a hybrid control scheme utilizing NiTi is possible this type of application has not been seen in the literature very often.

The work of Shahin *et al* [76] is the best example of hybrid control, using NiTi SMAs. They analytically demonstrated the passive and active vibration control of a one-story scaled-model. Active control was based on temperature-induced transformation, by heating the tendon opposing the structure's motion. The tendon acts as an actuator, applying restoring force on the structure, assuming that the structural stiffness remains constant. The passive control was based on stress-induced transformation as the tendon was loaded because of the structure's relative displacement.

Brailovski *et al* [77] introduced a design methodology for NiTi actuators that takes into account thermal and mechanical effects. They used two models: a mechanical model that represents the thermomechanical behavior of the actuator and a thermal model that computes the activation times of the actuator. Liang and Rogers [5] introduced a similar approach for designing NiTi actuators. Their approach couples a thermomechanical constitutive model of the material with a transient thermal analysis.

Regelbrugge *et al* [78] utilized NiTi material in developing a passive load-adaptive damping device. The device, called an active vibration canceller, consists of passive and active isolation stages. In the passive stage NiTi sheets have been used in a composite leaf spring while the active stage uses a motion-amplified electrostrictive stack actuator to augment attenuation of transmitted vibrations in the 10–120 Hz band. Their result showed the efficiency of adaptive materials systems for mitigating vibratory disturbances in certain spacecraft applications.

5.4. Structural applications of NiTi shape memory alloy

The unique constitutive behaviors of NiTi have attracted the attention of researchers in the civil engineering community. A survey of the literature provides a wide range of studies from fundamental and small scale to elaborate and full scale. The collective results of these studies suggest that NiTi can be used effectively for vibration control of structures through vibration isolation and energy absorption mechanisms.

Aiken and Kelly [79] developed a cross-bracing damping mechanism, which increased the structural damping from 0.5 to 3.0% and reduced all other structural responses. Inaudi and Kelly [80] explored the use of NiTi in the perpendicular direction to the motion of a tuned mass damper and showed that it can provide an effective non-linear damping mechanism.

Savi and Mamiya [81] studied passive vibration control using pseudoelastic behavior of NiTi via using a simple oscillator and showed that NiTi can be used for vibration control near the resonant condition. Whittaker *et al* [82] developed a technical base for the design of NiTi energy dissipation devices for building structures through characterization of material behavior, device development and experimental studies.

In another extensive study, Krumme *et al* [83] reviewed the passive control of civil structures using NiTi damping devices. In a set of experiments, they studied such behaviors as hysteretic energy dissipation, hardening at large strains, thermomechanical processing, the temperature effect, the pre-stressing effect and the effect of progressive engagement. By progressive engagement, different bundles of NiTi wire are loaded at different strain levels such that the damping capacity of the passive device may increase according to the strain level. The results show temperature insensitivity, frequency independence, excellent low- and high-cyclic-fatigue properties, negligible creep and highly reliable energy dissipation.

Attanasio *et al* [84] developed a passive energy-dissipater device consisting of a frame, three vertical legs and a horizontal beam made of NiTi. The middle leg is connected to the vibrating foundation while the other two are connected to the isolator. The relative movement of the legs exerts a torque on the NiTi beam resulting in shear stresses. Energy dissipates once the relative movement is big enough to induce stress-induced transformation in the beam then by proper heating the original shape of the beam is recovered. They emphasized the advantage of reaching large strains and of recovering most of the deformation with a relatively simple thermal cycle.

Davoodi *et al* [85] studied the feasibility of using NiTi for controlling the amplitude and natural frequency of structures during high-level excitations by developing different types of NiTi-based device. First, they studied the effect of temperature on SME and damping of NiTi, then they designed and experimentally studied two single-degree-of-freedom models. In the first model, NiTi was used as a structural member where in the second model it was used as an energy-absorbing device. Their study shows that NiTi could be used to shift the natural frequency of a structure away from its exciting frequency and control the amplitude of the structure's motion during vibration.

The most comprehensive and up to date study on passive vibration isolation of structures using SMAs and in particular NiTi is the MANSIDE project [86]. Researchers from four member countries of the European Union including Italy, Greece, Belgium and Sweden contributed to the MANSIDE project. Within the framework of the project the following important issues are fully addressed: the mathematical modeling, damping capacity, stability of pseudoelastic behavior with respect to abrupt temperature change, seismic device design, development, testing guidelines and requirements, performance comparison of different seismic protection strategies using NiTi-based and conventional base isolation devices, and finally cost analysis.

Bernardini and Brancaleoni [87] studied the constitutive modeling aspects related to seismic applications. Conducting a set of different mechanical tests at different temperatures and strain rates as well as calorimetric measurements, they concluded that for seismic excitation the NiTi response is mainly composed of sub-loops internal to the main pseudoelastic hysteresis loop. Also, since NiTi is mainly used in wire form, uniaxial constitutive models, that capture the rate dependence of the NiTi response under arbitrary mechanical loads, are the most suitable. Moreover, earthquake excitation can induce high temperature variation in the NiTi, resulting in a non-isothermal condition that affects the response of NiTi drastically.

Cardone *et al* [88] investigated the behavior of various NiTi elements mainly wires and bars under torsion, tension and shear-bending. The result of torsion tests suggests that mechanical behavior depends on the loading frequency. The results of tensile tests reveal that mechanical behavior depends on strain amplitude, strain rate, temperature and number of loading cycles. As a result, on one hand similar behaviors have been detected for martensite elements both in torsion and in bending. On the other hand, important variations have been detected in the pseudoelastic behavior of austenite elements with respect to loading frequency and temperature. They concluded that supplemental dissipating mechanisms or elements must be added since in the frequency range of interest for civil structures the energy dissipation capacity of NiTi is quite low.

Dolce and Marnetto [89] designed, implemented and tested two families of passive energy dissipating and re-centering devices for seismic isolation of buildings and braces of framed structures. Due to their simplicity and reliability over time, passive protection techniques are more suitable for civil engineering applications. Their study shows that NiTi proved to be the best candidate for passive application as compared with CuAlNi, CuZnAl, FeMn[Si] and MnCu. Based upon their constitutive behavior, martensite components are suitable for energy dissipation and austenite components for re-centering devices.

One of the proposed devices [89] is a hybrid solution where a bundle of NiTi wires provides the re-centering capability and steel elements provide the main dissipation effect. By calibrating the number and characteristics of NiTi wires and steel elements an optimal configuration can be achieved. Another proposed device is a NiTi-based bracing device. The amount of restoring force and energy dissipation provided by the device depends on the number of NiTi wires and induced displacement. Full-scale experiments [89] show that re-centering devices gain the best mechanical characteristics of both quasi-elastic devices such as rubber isolators, and elasto-plastic devices such as hysteretic dampers.

Cardone *et al* [90] also conducted a large number of experimental tests on seismic devices employing NiTi elements. Their experiments identified that re-centering devices have the following important features: re-centering capability, high energy dissipation capability, high stiffness for small displacements and low stiffness for large displacements, insensitivity to frequency and reduced sensitivity to temperature variations.

Valente *et al* [91] have conducted a large experimental investigation on reduced-scale structural models that provided a comparative assessment between conventional and innovative NiTi-based protection devices, including fixed base non-protected structures, base-isolated structures and structures with dissipating bracings. According to their findings NiTi-based re-centering devices indicated a superior effectiveness as compared with rubber isolators and steel bracings not only in reducing the seismic vibrations and structural damage but also in improving response stability. At the same time the same conclusion cannot be stated for NiTi-based bracings as compared with steel bracings. Story drift is lower for steel bracings at high seismic intensities; however, they may need to be replaced afterwards.

6. Conclusions and future directions

It is pointed out that thermomechanical behaviors of NiTi are prone to changes in external and internal parameters; however, depending on the type of application and environmental conditions the effect of change in one or more of the external and/or internal parameters may be negligible. For instance, if the environment's heat transfer capacity is high, such as in water, then it is possible to ignore the increase in the alloy temperature as a result of cyclic loading. When the environment's heat transfer capacity is not high enough, such as in air, then we should consider the effect of increase in the alloy temperature on pseudoelastic behavior.

Meanwhile, in some applications, if the strain rate is low then one can neglect the effect of strain rate on pseudoelastic behavior and increase in alloy temperature. But for high strain rates especially in an environment with low heat transfer capacity it is necessary to consider the effect of strain rate on pseudoelastic behavior.

In seismic applications earthquake excitation can induce high temperature variation in the material over a short period of time, resulting in fully non-isothermal conditions. Since the non-isothermal behavior of NiTi is quite different from the isothermal behavior, constant temperature conditions can no longer be assumed from either theoretical or applicative points of view.

It should also be noted that in the martensite phase, higher strain rate leads to higher damping as the martensite variants change from one to another under the applied load. Apart from strain rate the strain amplitude is also important. In any particular design the pseudoelastic behavior of the NiTi should be based on the maximum critical strain amplitude that may be achieved. The pseudoelastic behavior for smaller strain amplitudes is always within the hysteresis loop of the maximum critical strain amplitude.

Cyclic loading is another important parameter that can affect the stability of pseudoelastic behavior of NiTi. It is important to know that most of the change in pseudoelastic behavior occurs during the first 10–20 cycles. However, with proper heat treatment it is possible to achieve stable pseudoelastic behavior.

Most models are developed to represent the thermo-mechanical behavior of NiTi over a specific range of temperature and loading conditions and they carry assumptions and simplifications, which result in over- or under-estimation of the material response. Some of these models are developed to represent the pseudoelastic behavior at high temperatures or the SME effect caused by thermal cycling.

In general, the phenomenological models are based upon one-dimensional non-linear elasticity models. The martensitic phase fraction is an explicit function of the stress and temperature in the transformation kinetics equations. The thermodynamic models are three-dimensional models involving both free energy and dissipation potentials. In contrast to phenomenological models, the martensitic phase fraction cannot be expressed in a closed form since it is path dependent.

The SME behavior of NiTi is utilized in actuation devices for active shape or position control such as re-centering mechanisms in seismic isolation devices. NiTi actuation devices can be divided into two different categories based on their temperature sensing capability. The first category consists of passive actuators, which provide a corrective force or movement at an appropriate working temperature such as thermal cutoff valves. The second category includes active actuators that provide a corrective force or movement on demand when heated by fluid, air or electrical current.

Passive control devices usually try to maintain the current state of the system by dissipating the energy. The pseudoelasticity behavior of NiTi especially under cyclic loading provides potential for developing auto-adaptive passive control devices such as seismic base isolation and bracing systems. Since NiTi regains its original shape at the end, it is a very good candidate for developing flexible structural components. By using such components the load carrying capacity of a structure can be increased allowing it to go through recoverable inelastic deformations.

Constitutive behaviors of NiTi such as pseudoelastic and SME behaviors present possibilities for design and development of new seismic isolation devices and bracing systems. The MANSIDE project presents a thorough analytical and experimental investigation of such devices for structural applications.

Numerous analytical and experimental studies point toward the feasibility and superiority of NiTi-based devices over conventional methods for seismic protection. However, the same studies identify that NiTi-based devices alone cannot be used as primary means of seismic protection. A hybrid device consisting of conventional devices such as rubber isolators and steel bracing systems along with NiTi-based elements can provide the optimal performance. The main characteristics of such devices are high energy dissipation and re-centering capabilities.

One must keep in mind that those constitutive characteristics of SMAs and in particular NiTi greatly depend on variations in the alloy's component and manufacturing method to begin with. Moreover, depending on the type of application, variations in external parameters such as temperature can drastically affect the response of these materials. Selecting the proper model of constitutive behaviors is also very important.

Since NiTi is used in the form of wire or a bundle of wires the design of devices will be restricted to NiTi elements subjected to uniaxial loading. This restriction limits the range of possible devices.

It is concluded that numerous analytical and experimental studies addressing different issues such as manufacturing, constitutive modeling, temperature and loading frequency sensitivity dependence and feasibility of NiTi-based seismic isolation devices have been done and the focus of the future studies must be directed toward innovative hybrid designs. NiTi-based energy absorption and vibration isolation devices cannot be used as primary components of a seismic mitigation system.

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