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A Review of Applications and Research of Shape Memory Alloys in Civil Engineering

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Abstract. This article presents a timely review of thermomechanical behaviours, recent structural applications, and researches of shape memory alloys (SMAs) in civil engineering. SMAs are used in a variety of fields, such as mechanical, aeronautical and medical fields. Other fields of knowledge have been researching these materials, attracted by their superb shape memory effect and pseudoelasticity under mechanical and thermal conditions. This article not only reports a bibliographic review on the constitutive models and thermodynamic properties for SMAs, but also describes the attributes of SMAs that make them ideally suitable to structural control, intelligent structure and structural damage repair.

1. Introduction

The shape memory alloys (SMAs) have attracted the attention of scholars and engineers in various fields since they were discovered in the 1960s. Because of their shape memory effect and superelasticity of a high standard, SMAs have been widely used in mechanical, aeronautical and medical fields [1]. In addition, SMAs can also be applied in civil engineering, such as sensors and dampers due to their electrical resistance and damping properties.

SMAs can generally be classified into being Ni-Ti-based and Cu-based. Ni-Ti-based SMAs, such as Ni-Ti [2], Ni-Ti-Hf [3], Ni-Ti-Pd [4] and Ni-Ti-Fe [5], are considered most suitable for the majority of engineering applications, given its great superelastic properties and temperature variations stability. Cu-based SMAs, such as Cu-Al-Ni-Co [6], Cu-Al-Fe-Ni [7] and Cu-Al-Mn [8], have good fatigue resistance and can sustain hundreds of cycles under a high cyclic strain.

With the continuous expansion of infrastructures and high-rise buildings, higher requirements have been put forward on the performance of structures in civil engineering. Furthermore, the safety of structures under serious disasters such as earthquakes and fires has drawn constantly growing concerns. Therefore, many innovative materials [9–10], structural forms [11–12], and rehabilitation strategies [13–15] was proposed by researchers. As a new type of alloys with shape memory effect and superelasticity, SMAs have great performance in not only load-bearing capacity, but also earthquake and fire resistance, which provides themselves a wide application prospect in civil engineering.

2. Characteristics of shape memory alloys

2.1. Shape memory effect

It is important to note that SMA can transform from one phase to another over the varying temperature or loads. Furthermore, if the role of the temperature or loads is removed, the shape and mechanical properties of the SMA will return to the original phase, and such characteristic is called shape memory effect (SME) [1]. In general, SMA has two kinds of phases (martensite phase and austenite phase) and



six kinds of crystal structures. As shown in Figure 1, SMA appears as austenitic phase under high temperature or low stress, and appears as martensite phase under the low temperature or high stress. Lobo et al. [16] pointed out that SMAs are totally characterized by four phase transition temperatures from low to high: martensite transition finish temperature M_f , martensitic transition start temperature M_s , reverse martensitic transition start temperature A_s and reverse martensite phase transition finish temperature A_f , respectively. SMA exists in stable martensite when the temperature is less than M_f and in stable austenite when the temperature is greater than A_f .

Jani et al. [17] pointed out that the shape memory effect of SMA can be classified in one-way and two-way shape memory effects. One-way memory effect refers to inducing the SMA to produce deformation at low temperature and recover after heating, and two-way shape memory effect is the characteristic that SMA can be restored to the initial form at both high and low temperature.

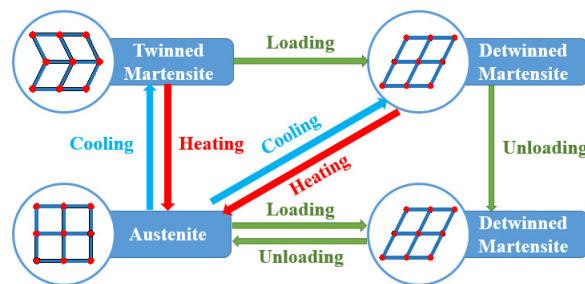


Figure 1. SMA phase transition induced by temperature or loads.

2.2. Pseudoelasticity or superelasticity

When the temperature of SMA exceeds A_f and the loading stress exceeds the elastic limit, martensitic transformation induced by stress will arise due to continuous loading. The reverse martensite phase transformation, however, as the stress is removed, will occur even if SMA is not heated so that the original parent phase (austenite phase) state is restored. Meanwhile, the macroscopic deformation under stress will disappear completely, and such characteristic of SMA is called pseudoelasticity or superelasticity, which is influenced by chemical composition, heat treatment method, loading and unloading cycles, cold deformation and experimental conditions.

2.3. Other characteristics

The electrical resistance of SMA is different from ordinary metals; it is affected by axial stress, martensitic fraction, phase transition temperature and strain simultaneously. When the martensitic fraction in SMA changes, the electrical resistance changes accordingly. Therefore, it is possible to induce phase transition by heating the SMA wire, thereby increasing its electrical resistance [18].

Besides, SMA has a high damping and its elastic modulus changes with the temperature. Heller et al. [19] pointed out that the damping ratio of SMA superelasticity can be measured by SMA stress-strain curve, according to the quasi-static tensile test at room temperature. In addition, Dib et al. [18] pointed out that the elastic modulus of SMA changes during phase transition, and the elastic modulus of austenite phase is higher than that of martensite phase, which can be used to make SMA actuator.

3. The constitutive models and thermomechanical behaviours

3.1. Constitutive models

The typical constitutive models of SMA include TnakaSa model, Linag-Rogers model, Brinson model, Boyd-Lagoudas model and Ivshin-penec model. These models can be roughly classified in four categories: (1) Monocrystalline theoretical model based on thermodynamic theory and free energy; (2) Mathematical model based on phase-boundary motion dynamics; (3) Phenomenological model based on thermomechanics and thermodynamics; (4) Microscopic mechanical model based on energy

dissipation theory. Among them, the one-dimensional phenomenological model proposed by Brinson [20] is widely used in civil engineering because of its simple form and experimental basis, which can be expressed as:

$$\sigma - \sigma_0 = D(\xi)\varepsilon - D(\xi_0)\varepsilon_0 + \Omega(\xi)\xi_S - \Omega(\xi_0)\xi_{S0} + \theta(T - T_0) \quad (1)$$

where σ and ε are the stress and strain of SMA, respectively, θ is the thermodynamic parameter of SMA, and the environment temperature is given by T . Subscript "S" and "0" mean stress and a reference to the initial state, respectively. $D(\xi)$ and $\Omega(\xi)$ are modulus of elasticity and phase transformation coefficient which depend on the content of martensite ξ , respectively.

On the basis of Brinson's theoretical model, a one-dimensional piecewise linear model of pseudoelasticity of SMA was proposed by Du et al. [21], and the rationality of the theoretical formula was verified by applying low-cycle reciprocating load and dynamic load to the spring-SMA system. The model is expressed as

$$\sigma = \sigma_{i0} + k_i \varepsilon, \quad i = 1, 2, 3, 4 \quad (2)$$

where σ_{i0} and k_i are the initial stress and slope at each stage, respectively.

3.2. Thermomechanical behaviours

As shown in Figure 2, relevant scholars [22-25] have studied the mechanical properties of Ni-Ti SMAs with different diameters. It is shown that the hysteresis energy dissipation (E) and damping ratio (ζ) increase with peak strain, and decrease as the cycling time increases. In addition, with the increase of the diameter of Ni-Ti SMAs, E and ζ increase at first, and then begin to decrease after the diameter is greater than 0.80 mm.

Concerning SMAs under high temperatures, which exists complex force-temperature coupling, Tian et al. [26] pointed out that martensite has a good effect of strain strengthening by studying Ti-Pd-Ni SMA, despite the austenite has higher yield strength, and their ultimate strength are close. In addition, the damping capacity of Ti-Pd SMA [27], thermomechanical behavior of Ti-Pd-Ni-W SMA [28] and cyclic stability of Ni-Ti-Hf SMA [29-31] at high temperature were studied by different researchers.

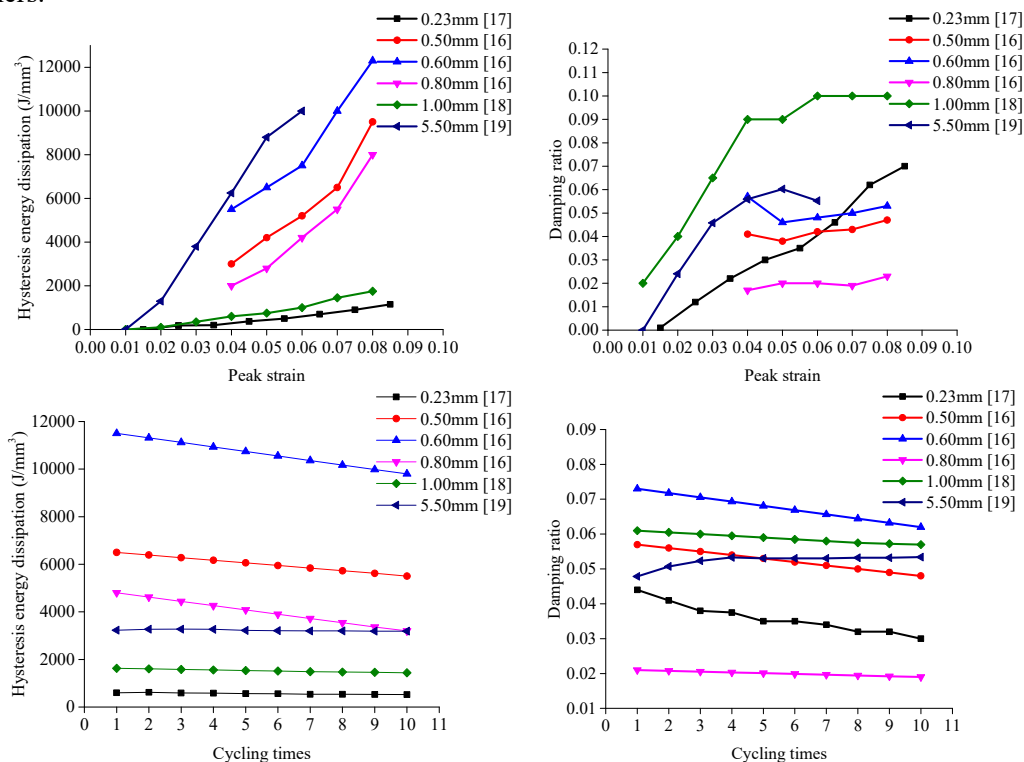
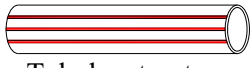
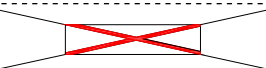
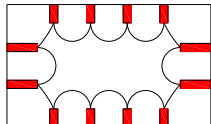


Figure 2. Hysteresis performance of Ni-Ti SMAs in different diameters measured by cycling test.

4. Applications and research in civil engineering

The applications of SMAs in civil engineering can be classified into three categories according to their mechanism as shown in Table 1: structural control, intelligent structure and structure damage repair.

Table 1. General analysis method of main SMA structure or member models

SMA model	Theoretical analysis	Numerical analysis	Test analysis
 Cantilever beam	First-order model [32] Shear lag model [46] Layerwise theory and Brinson equation [39] Thermodynamic constitutive relation model [40-42]	Phenomenological model [47]	Cyclic loading test [32] Three point bending test [31, 33, 43]
 Bridge structure		Nonlinear time history analysis [38]	
 Tubular structure		Layered optimization model [41]	
 Supporting brace		Nonlinear time history analysis [35]	Cyclic loading test [35, 37]
 End-plate connection		Auricchio's approach [36]	Cyclic loading test [36]
 Membrane structure	Thermo-Elastic Analysis [34]	Adaptive genetic algorithm [34]	

4.1. The applications of SMAs in structural control.

For the active control of structures, Yang et al. [32] tested the end position of cantilever beams and plates with SMA actuator charged by electric current, and the results showed satisfactory control of deformation. Formentini et al. [33] pointed out that SMA yields to varying degrees at different temperatures, once the actuator is embedded in the windward surface of structures, automatic absorption or release of energy can be achieved. Wang et al. [34] pointed out that the shape of membrane structure can be maintained by use of SMA. While for the passive control of structures, Li et al. [35] designed a double X SMA damper applied to the frame bridge pier, and the damping effect was studied by cycle reciprocating test. Fang et al. [36] replaced the high strength bolt endplate connections with SMA stud, thus a "super elastic hinge" formed in the connection and the equivalent viscous damping ratio reached 17.5%. Leonardo et al. [37] made SMA support installed in shear walls for seismic reinforcement, and improvement in strength, slip performance and energy dissipation was found.

4.2. The applications of SMAs in intelligent structure

The damage curves of traditional bridges and intelligent bridges with SMA were compared obtained by Zheng et al. [38] using nonlinear time history analysis, it was found that the duration of the SMA intelligent bridge was longer. Based on the Layerwise theory and Brinson equation, the control equation of SMA beam was established and the behaviour of thermal buckling was analysed by Bayat et al. [39]. Meanwhile, the effects of anisotropy and SMA pre-strain on the buckling behaviour of SMA beam were investigated. Lagoudas et al. [40] proposed the thermodynamic constitutive relation

model of SMA to predict the residual deformation of SMA cantilever beam. Chen et al. [41] pointed out that the axial stress and radial stress of tubular structure were basically unchanged after adding SMA flakes through finite element analysis with the layered optimization model. In this case, the cyclic stress decreases by 7.9% and the shear stress decreases by 20%-30%, which can effectively avoid stress concentration. Wong et al. [42] investigated concrete beams with steel bars partially replaced by SMA. Moreover, Shajil et al. [43] conducted three point loading tests on concrete beams and beam-column joints with SMA distributed randomly inside, which proved their satisfactory self-centering ability and ductility.

4.3. The applications of SMAs in structural damage repair

Since SMA can be restored to its original form after being energized or heated, the structure with SMA can be repaired in the process of producing pretension. Choi et al. [44] fabricated twelve mortar beams with SMA and conducted three point bending test, then the damaged beams were repaired at different temperatures and the peak stress was found to reduce by 70%. SMA and calcium nitrate microcapsules were set in concrete beams by Bonilla et al. [45] to give it a dual self-healing mechanism; it was found that the stiffness of the concrete beams with SMA and calcium nitrate microcapsules could be repaired by 75%. The thermodynamic behavior of SMA concrete structure with damage was analyzed by shear lag model, and its damage evaluation criterion was given through theoretical analysis by Hu et al. [46]. Hübner et al. [47] proposed the finite element evaluation method of SMA structure considering SMA pretreatment and load conditions based on the phenomenological model.

5. Conclusions

Due to its unique shape memory effect and superelasticity, SMAs were widely used in structural control, intelligent structure, damage repair, and other fields of civil engineering. In spite of comprehensive studies of SMAs in theoretical calculation, experimental investigation, and finite element analysis were conducted, there are still some problems to be solved:

(1) The applications of SMAs in intelligent structure are mostly energized with electricity. However, it is difficult to connect the SMA embedded in the structure to electricity with wires in practical engineering. In addition, after the completion of energization, the incentive effect will suffer a serious loss.

(2) In fact, incentives can also be realized by elevated temperature. If SMA is embedded in structure members, which is in martensitic phase at room temperature, the reverse martensitic phase transition will take place when the fire occurs. Due to the shortening of the length, the pre-tightening force can be strengthened in a timely manner to reduce the loss of life and property. However, the behaviors of SMAs during and after fire still need further study.

(3) SMAs are difficult to be used in civil engineering due to their expensive costs.

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