Research Article

A Constitutive Model for Superelastic Shape Memory Alloys Considering the Influence of Strain Rate

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Shape memory alloys (SMAs) are a relatively new class of functional materials, exhibiting special thermomechanical behaviors, such as shape memory effect and superelasticity, which enable their applications in seismic engineering as energy dissipation devices. This paper investigates the properties of superelastic NiTi shape memory alloys, emphasizing the influence of strain rate on superelastic behavior under various strain amplitudes by cyclic tensile tests. A novel constitutive equation based on Graesser and Cozzarelli's model is proposed to describe the strain-rate-dependent hysteretic behavior of superelastic SMAs at different strain levels. A stress variable including the influence of strain rate is introduced into Graesser and Cozzarelli's model. To verify the effectiveness of the proposed constitutive equation, experiments on superelastic NiTi wires with different strain rates and strain levels are conducted. Numerical simulation results based on the proposed constitutive equation and experimental results are in good agreement. The findings in this paper will assist the future design of superelastic SMA-based energy dissipation devices for seismic protection of structures.

1. Introduction

Shape memory alloys (SMAs) are a unique class of materials that have the ability to undergo large deformations, up to 8~10%, that is, at least one order of magnitude greater than common metals and alloys, and revert back to their original and undeformed shape or dimension through either applications of heat, that is, the shape memory effect (SME), or removal of stress, that is, the superelastic effect.

The particular properties of SMAs were first discovered by Chang and Read in 1951; however, it was not until after 1962 when Buechler and his colleagues found the shape memory effect in nickel-titanium (NiTi) at the Naval Ordnance Laboratory that both in-depth research and practical applications emerged. At present, SMAs have been widely implemented in biomedical, aerospace, mechanical, and civil engineering areas [1–5], making it necessary to have a precise understanding of the special mechanical behavior of SMAs in order to fully develop and exploit their potential.

The unique mechanical behaviors of SMAs are made possible by reversible martensitic phase transformation (MPT) induced by temperature or mechanical stress between the austenitic phase (*A*) and martensitic phase (*M*). Austenite has a body-centered cubic crystal structure (crystallographic high symmetry), stable at high temperatures and low stress values, while the martensite has a parallelogram structure (low symmetry), stable at low temperatures and high stress values, having up to 24 variations. In the stress-free state, the material is characterized by four transition temperatures, namely, martensite start temperature M_s , martensite finish temperature M_f , austenite start temperature A_s , and austenite finish temperature A_f . Below the martensite finish temperature, M_f , residual deformations induced by the martensite reorientation due to applied stresses can be recovered by heating the material above the austenite finish temperature, A_f , resulting in the shape memory effect (SME). Above the austenite finish temperature, A_f , martensite is formed associated with forward MPT (from

austenite to detwinned martensite) induced by stress when load exceeds the forward transformation stress; however, the material reverts to austenite at a lower stress without residual deformation associated with inverse MPT (from detwinned martensite to austenite) after unloading, resulting in the superelastic behavior.

Over the past decades, there has been a significant amount of research dedicated to the martensitic phase transformation [6, 7] and the factors that induce the MPT [8–10]. Meanwhile, some constitutive models have been proposed. A short review of the existing models is presented here:

- (1) phenomenological macroscopic constitutive models in terms of stress, strain, and temperature with assumed phase transformation kinetics described by preestablished simple mathematical functions proposed by Tanaka [11], Liang and Rogers [12], Brinson [13], Boyd and Lagoudas [14, 15], Li et al. [16], Tobushi et al. [17], and Sun and Rajapakse [18]; among others.
- (2) one-dimensional polynomial models based on Devonshire's theory with an assumed polynomial-free energy potential, which allows superelasticity and SME description, presented by Falk et al. [19, 20];
- (3) thermodynamic models based on the free energy and dissipation potential developed by Patoor et al. [21], Sun and Hwang [22, 23], Huang and Brinson [24], and Boyd and Lagoudas [25];
- (4) plastic flow models based on dislocation theories of solid state physics proposed by Graesser and Cozzarelli [26, 27], lately improved by Wilde et al. [28], Zhang and Zhu [29], and Ren et al. [30].

For application of SMAs in earthquake engineering, Graesser and Cozzarelli's model [26] will be adopted in this paper due to its advantage of simplicity. Graesser and Cozzarelli's model is capable of capturing both the superelastic effect and the martensitic hysteresis with their subloops due to partial transformation processes. Wilde et al. [28] improve the Graesser and Cozzarelli model by introducing the possibility of describing the material behavior also after phase transformation completion as well as by simulating a smooth transition between the elastic branch and the superelastic plateau. Zhang and Zhu [29] modified Wilde's model to enhance the stability of numerical simulation and speed up the computation time. However, Graesser and Cozzarelli's model and the improved editions cannot describe the strain-rate-dependent property of SMA. To consider the effect of the load path to increase its modeling accuracy, Ren et al. [30] improved Graesser and Cozzarelli's model by dividing the full loop into three parts: the loading branch, unloading branch before the completion of the reverse transformation and the elastic unloading branch after the completion of the reverse transformation, where each part adopts its respective parameters. However, the improved model can only reflect one case of hysteresis for a fixed loading rate, since when the loading rate changes, the model parameters will change. Therefore, it is not convenient to perform continuous simulation of SMA devices under seismic excitations, which involve many different loading rates.

As a further research to improve Graesser and Cozzarelli's model, this paper aims to develop a novel strain-rate-dependent constitutive model, which can simultaneously account for the effects of both strain rates and strain levels. In Section 2 of this paper, Graesser and Cozzarelli's model is improved by adding a stress variable including the influence of strain rate. To verify the effectiveness of the proposed constitutive equation, cyclic tensile tests on superelastic NiTi wires with different strain rates and strain levels are carried out, as described in Section 3, and the experimental results and analysis are given in Section 4. In Section 5, numerical simulations are conducted to demonstrate the accuracy of the improved Graesser and Cozzarelli's model.

2. Constitutive Model of Shape Memory Alloys

In this section, a uniaxial constitutive model, based on Graesser and Cozzarelli's model, is developed to capture the strain-rate-dependent property of superelastic SMA materials.

2.1. Graesser and Cozzarelli's Model. Based on Ozdemir's model [30], Graesser and Cozzarelli proposed a one-dimensional hysteretic model that produced the general macroscopic stress-strain characteristics of SMAs [26]. The equation is given as

$$\dot{\sigma} = E \left[\dot{\varepsilon} - |\dot{\varepsilon}| \left(\frac{\sigma - \beta}{Y} \right)^n \right], \quad (1)$$

where σ is the one-dimensional stress, ε is the strain, E is the elastic modulus, Y is the transformation stress, n is a constant assumed to be any positive odd real value controlling the sharpness of the transition from the elastic state to the phase transformation, $\dot{\sigma}$ and $\dot{\varepsilon}$, respectively, denote the ordinary time derivative of the stress and strain, and β is the one-dimensional back stress, given by

$$\beta = E\alpha \{ \varepsilon_{\text{in}} + f_T |\varepsilon|^c \operatorname{erf}(a\varepsilon) [u(-\varepsilon\dot{\varepsilon})] \}, \quad (2)$$

where f_T , a , and c are material constants controlling the type and size of the hysteresis, the amount of elastic recovery during unloading, and the slope of the unloading stress plateau, respectively. α is a constant controlling the slope of the σ - ε curve in the inelastic range, given by

$$\alpha = \frac{E_y}{E - E_y}, \quad (3)$$

where E_y is the slope of the σ - ε curve in the inelastic range. ε_{in} is the inelastic strain, given by

$$\varepsilon_{\text{in}} = \varepsilon - \frac{\sigma}{E}. \quad (4)$$

$u(x)$ is the unit step function defined as

$$u(x) = \begin{cases} +1 & x \geq 0 \\ 0 & x < 0. \end{cases} \quad (5)$$

$\text{erf}(x)$ is the error function defined by

$$\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt. \quad (6)$$

Graesser and Cozzarelli's model has a relatively simple expression with parameters that can be easily acquired and it is easy to implement, yet this model can still be improved. Though the equations are written in differential form, the model is essentially strain rate independent. Studies [8–10] show that the properties are strongly dependent on the strain rate. In this paper, Graesser and Cozzarelli's model will be improved to consider the influence of strain rate.

2.2. Improved Graesser and Cozzarelli's Model. To simulate the strain-rate-dependent hysteretic behavior of superelastic SMAs, Graesser and Cozzarelli's model will be improved. The following assumptions are made for this purpose.

- (i) The ambient temperature is constant.
- (ii) The effect of strain rate on the properties of SMAs can be ignored when it is below $\dot{\epsilon}_0$ ($\dot{\epsilon}_0 = 1.0 \times 10^{-4}$ /s in this paper).

Based on the above assumptions, the stress is formulated here. The stress under dynamic loading can be separated into two parts; namely,

$$\sigma = \sigma_s + \sigma_k, \quad (7)$$

where σ , σ_s , and σ_k are the stress under dynamic loading, the stress under quasistatic loading, and the stress change due to the influence of the strain rate, respectively. To keep consistency with σ and σ_s in symbol style, σ_k is used to represent the stress change. Actually, the value of σ_k is equal to that of $\Delta\sigma$ which will be illustrated in Section 4.

Differentiating (7) results in

$$\dot{\sigma} = \dot{\sigma}_s + \dot{\sigma}_k, \quad (8)$$

where

$$\dot{\sigma}_s = E \left[\dot{\epsilon} - |\dot{\epsilon}| \left| \frac{\sigma_s - \beta}{Y} \right|^{n-1} \left(\frac{\sigma_s - \beta}{Y} \right) \right]. \quad (9)$$

The parameters in (9) have already been defined in Section 2.1 and can be obtained experimentally by the stress-stain curve under quasistatic loading.

The definition of σ_k depends on the relationship between $\dot{\epsilon}$ and $\dot{\epsilon}_0$. The equations capturing the relationship between σ_k and $\dot{\epsilon}$, ϵ as well as $\dot{\epsilon}_0$ can be presented from the experimental tests (presented in Sections 3 and 4) based on mathematical statistics and numerical fitting method. σ_k is given as follows.

- (1) For $-\dot{\epsilon}_0 \leq \dot{\epsilon} \leq \dot{\epsilon}_0$,

$$\sigma_k = 0. \quad (10)$$

- (2) For $\dot{\epsilon} > \dot{\epsilon}_0$,

$$\sigma_k = p \ln \left(\frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \sqrt{\epsilon} = p (\ln \dot{\epsilon} - \ln \dot{\epsilon}_0) \sqrt{\epsilon}, \quad (11)$$

where p is a material constant. If $R = -\ln(\dot{\epsilon}_0)$, then

$$\sigma_k = p (\ln \dot{\epsilon} + R) \sqrt{\epsilon}. \quad (12)$$

Differentiating (12) results in

$$\dot{\sigma}_k = p \left[(\ln \dot{\epsilon} + R) \frac{\dot{\epsilon}}{2\sqrt{\epsilon}} + \frac{\ddot{\epsilon}}{\dot{\epsilon}} \sqrt{\epsilon} \right]. \quad (13)$$

- (3) For $\dot{\epsilon} < -\dot{\epsilon}_0$,

$$\begin{aligned} \sigma_k &= q \ln \left(\frac{|\dot{\epsilon}|}{\dot{\epsilon}_0} \right) \epsilon^2 = q (\ln |\dot{\epsilon}| - \ln \dot{\epsilon}_0) \epsilon^2 \\ &= q (\ln |\dot{\epsilon}| + R) \epsilon^2. \end{aligned} \quad (14)$$

Thus, its time derivative can be written as

$$\dot{\sigma}_k = q \left[2 (\ln |\dot{\epsilon}| + R) |\dot{\epsilon}| \epsilon + \frac{\ddot{\epsilon}}{|\dot{\epsilon}|} \epsilon^2 \right], \quad (15)$$

where q is a material parameter related to the maximum strain amplitude, $\epsilon_{\max}$. Other unnoted parameters have already been defined.

3. Experimental Setup for Tensile Testing of Superelastic SMA Wires

In the following, cyclic tensile tests on superelastic NiTi wires with different strain rates and strain levels are carried out to verify the effectiveness of the proposed constitutive equation.

3.1. Test Specimens and Equipment. The NiTi SMA wires used for testing have a diameter of 0.5 mm. The TiNi SMA is an alloy with approximate 50.9% Ni and 49.1% Ti. Under zero external stress, the martensite start and finish temperatures and the austenite start and finish temperatures (M_f , M_s , A_s , and A_f), measured by DSC (differential scanning calorimeter), are -73°C , -55°C , -23°C , and 5°C , respectively.

Tests were conducted using an electromechanical universal testing machine. The SMA wire specimens, with a 100 mm test length between the two custom-made grips, were subjected to triangular cyclic loading under different strain amplitudes. In order to acquire reliable hysteresis behavior of SMA, three specimens were applied in each testing. The mean values were utilized for analysis. The strains were calculated from the elongation measured by a 50 mm gage length extensometer with the stress calculated from the axial force, which was measured by a 10 kN load cell. In each test, the specimen was required to follow a triangular wave with a constant strain rate. The data was recorded automatically by a PC-based data acquisition system with a 30 Hz sampling rate. All the tests were carried out at room temperature ($\approx 25^\circ\text{C}$). The experimental setup and strain loading curve are shown in Figures 1(a) and 1(b), respectively.

3.2. Test Procedure. The experimental results in references [8, 9] have shown the mechanical behaviors of the SMA trend

FIGURE 1: Experimental setup and strain loading curve for mechanical testing of SMA wires.

stable with the increasing of the cyclic number. Therefore, prior to testing, the NiTi SMA specimens were cycled 30 times at 6.5% strain amplitude and $1.0 \times 10^{-3}/s$ strain rate as a “training” process to reach a steady-state condition. The scheme of the tests is described as follows.

- (1) At quasistatic loading ($1.0 \times 10^{-4}/s$ strain rate), the NiTi SMA specimens are subjected to cyclic loading with different strain levels, ranging from 2% to 6% at an increment of 2%.
- (2) At strain rates of $5.0 \times 10^{-4}/s$, $1.0 \times 10^{-3}/s$, $2.5 \times 10^{-3}/s$, and $5.0 \times 10^{-3}/s$, the NiTi SMA specimens are subjected to cyclic loading with different strain levels, ranging from 2% to 6% at an increment of 2%.

What needs to be pointed out is that the maximum strain rate is only $5.0 \times 10^{-3}/s$ due to the limitation of the experimental condition. The range is relatively low in seismic engineering. More tests with higher strain rates will be conducted in the future.

4. Results and Analysis

Many experimental studies have shown that the superelastic behavior of SMAs strongly depends on the loading rate [8–10]; however, few quantitative relationships are provided [16–18]. In this section, a stress change variable, $\Delta\sigma$, which is a relative quantity between the dynamic loading condition and the static loading condition at an identical strain, is introduced to evaluate the effect of the strain rate on the superelastic behavior of SMAs.

4.1. Variation of Stress during Forward Martensitic Transformation at Different Strain Rates. Figure 2(a) shows the relationship between the amount of stress change, $\Delta\sigma$, and the strain obtained by the tests during the forward martensitic transformation at different strain rates. The points with different shapes represent the experimental results. As we

can see, $\Delta\sigma$ increases with an increase of strain. The rate of increase of $\Delta\sigma$ is relatively large at small strain levels; however it decreases with an increasing strain. Moreover, the stress change $\Delta\sigma$ increases with an increasing strain rate.

On one hand, for a fixed strain rate, the relationship between stress change $\Delta\sigma$ and strain level ε can be described using a power function with the index less than 1. In order to simplify the equation, the index selected is 1/2. On the other hand, for a fixed strain level, the relationship between stress change $\Delta\sigma$ and strain rate $\dot{\varepsilon}$ can be captured by natural logarithms function. Therefore, based on numerical fitting tools, the stress change $\Delta\sigma$, as a function of the strain level and the strain rate during the forward martensitic transformation, can be expressed by the following equation:

$$\Delta\sigma = 159.6 (\ln \dot{\varepsilon} + 9.21) \sqrt{\varepsilon}, \quad (16)$$

where ε is the strain and $\dot{\varepsilon}$ is the strain rate. The fitted curves calculated from (16) for different strain rates are shown in Figure 2(a). As seen from (16), the material constant p in (12) is equal to 159.6.

4.2. Variation of Stress during Inverse Martensitic Transformation at Different Strain Rates. Figure 2(b) shows the relationship between the amount of stress change $\Delta\sigma$ and the strain during the inverse martensitic transformation at different strain rates with the maximum strain amplitude at 6%. Likewise, the points with different shapes represent the experimental results. As opposed to the forward martensitic transformation, the rate of increase in $\Delta\sigma$ is relatively small at small strain levels; however it increases with an increasing strain. Moreover, the stress change $\Delta\sigma$ increases with an increasing strain rate. This is because the stress-strain loops of superelastic SMA translate upwards, while the branches of the curve relevant to the phase transformations harden with the increasing of strain rate, as noted in references [8, 10].

Similarly, for a given strain rate, the relationship between stress change $\Delta\sigma$ and strain level ε can be described using

FIGURE 2: Relationship between stress change and strain during. Experimental data is marked with points. The simulation of the proposed equation with the lines. (a) Forward phase transformation. (b) Inverse phase transformation.

FIGURE 3: Comparison of SMA stress-strain curve between numerical and experimental results under quasistatic loading.

a power function with the index more than 1. The index selected is 2. The relationship between stress change $\Delta\sigma$ and strain rate $\dot{\epsilon}$ is similar to that during the forward martensitic transformation. In the case of the maximum strain amplitude 6%, the stress change, $\Delta\sigma$, as a function of the strain level and the strain rate during the inverse martensitic transformation, can be expressed by the following equation:

$$\Delta\sigma = -500 (\ln |\dot{\epsilon}| + 9.21) \epsilon^2. \quad (17)$$

The fitted curves calculated from (17) for different strain rates are also shown in Figure 2(b). As seen from (17), the material constant q in (14) is equal to 500 for the strain level at 6%.

5. Numerical Simulations

In this section, the effectiveness of the improved model to reproduce the rate-dependent superelastic behavior of SMAs wire is validated by comparing numerical results with experimental data. In order to verify suitability of the model, two different conditions, static loading and dynamic loading, are investigated.

5.1. Comparison of Model Predictions and Experimental Data under Quasistatic Loading. Figure 3 shows the comparison of the model predictions and the experimental responses of the SMA wire at 2%, 4%, and 6% strain levels under quasistatic loading with a strain rate of $1.0 \times 10^{-4}/s$. The key parameters used in the models are $E = 43000$ MPa, $Y = 350$ N, $\alpha = 0.006$, $f_T = 2.3$, $c = 0.04$, $a = 400$, and $n = 6$. As can be seen from Figure 3, the numerical curves predicted by the improved model agree well with the experimental data.

To make an additional quantitative observation, comparisons of the energy dissipation per cycle, tensile stress at peak strain, and equivalent viscous damping between the experimental data and numerical results are shown in Table 1. Note that the maximum differences for energy dissipation per cycle, tensile stress at peak strain, and equivalent viscous damping are 2.9%, 1.8%, and 2.6%, respectively. Therefore, the results indicate that the mechanical behavior of superelastic SMA wire under quasistatic loading was predicted well by the improved model.

5.2. Comparison of Model Predictions and Experimental Data under Dynamic Loading. Figure 4 shows the comparison of model predictions and experimental responses of the SMA wire at 4% strain under the strain rates of $5.0 \times 10^{-4}/s$, $1.0 \times 10^{-3}/s$, $2.5 \times 10^{-3}/s$, and $5.0 \times 10^{-3}/s$, respectively. The key

TABLE 1: Comparisons of model predictions and experimental data for varying peak strains: constant strain rate.

Peak strain (m/m)	Energy dissipation per cycle (MJ/m ³ /cycle)			Tensile stress at peak strain (GPa)			Equivalent viscous damping (%)		
	Experimental data	Numerical results	Difference	Experimental data	Numerical results	Difference	Experimental data	Numerical results	Difference
2.0%	2.20	2.25	2.13%	354.21	352.69	-0.43%	4.95	5.08	2.57%
4.0%	5.84	5.95	1.89%	351.20	357.82	1.88%	6.62	6.63	0.45%
5.85%	8.91	9.17	2.91%	359.32	362.57	0.91%	6.75	6.88	1.98%

FIGURE 4: Comparison of calculated stress-strain curves based on improved Graesser and Cozzarelli's model and experiment data for varying loading rates.

parameters used in the models are $E = 43000$ MPa, $Y = 350$ N, $\alpha = 0.006$, $f_T = 2.3$, $c = 0.04$, $a = 400$, and $n = 6$, $R = 9.21$, $p = 159.6$, and $q = -500$. It is obvious from Figures 4(a)–4(d) that the superelastic behavior at different strain rates is well predicted by the improved constitutive model.

Table 2 shows the comparisons of the energy dissipation per cycle, the tensile stress at peak strain, and the equivalent viscous damping between the experimental data and numerical results. It is clear that the maximum difference of energy dissipation per cycle, the tensile stress at peak strain, and the equivalent viscous damping are 6.89%, 4.01%, and

TABLE 2: Comparisons of the model predictions and experiments for varying loading rates: fixed peak strain.

Strain rate (m/m/s)	Energy dissipation per cycle (MJ/m ³ /cycle)			Tensile stress at peak strain (GPa)			Equivalent viscous damping (%)		
	Experimental data	Numerical results	Difference	Experimental data	Numerical results	Difference	Experimental data	Numerical results	Difference
5.0×10^{-4}	6.99	6.64	4.93%	400.5	409.07	−2.14%	6.94	6.46	6.93%
1.0×10^{-3}	7.45	6.94	6.89%	414.5	431.14	−4.01%	7.16	6.41	9.36%
2.5×10^{-3}	7.70	7.33	4.88%	453.8	460.32	−1.44%	6.84	6.34	7.39%
5.0×10^{-3}	7.75	7.62	1.60%	464.2	482.39	−3.92%	6.75	6.29	6.74%

9.36%, respectively. From both Figure 4 and Table 2, it can be concluded that the improved Graesser and Cozzarelli's model is able to capture the superelastic behavior in dynamic loading conditions within the range of rates tested in this study.

6. Conclusions

In this paper, the influence of the strain rate on the mechanical properties of SMAs is investigated. A one-dimensional strain-rate-dependent constitutive model based on Graesser and Cozzarelli's model is proposed to predict the hysteretic behavior of superelastic SMAs. In this model, the stress is divided into two parts: the static stress and dynamic stress change. The former is based on the original Graesser and Cozzarelli's model and describes the property under quasistatic loading. The latter one considers the effect of the strain rate. Comparisons of model predictions and experimental results at different strain levels and strain rates are performed and reveal that the improved Graesser and Cozzarelli's model can accurately predict hysteretic behavior of superelastic SMAs under both static and dynamic loading conditions within the range of rates tested in this study. In this paper, the maximum strain rate is only 5.0×10^{-3} /s due to the limitation of the experimental condition. The range is relatively low in seismic engineering. Future research will be conducted at higher strain rates to further validate the effectiveness of the model.

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