The Realization of Driving Force Constitutive Model of Shape Memory Alloy Based on OpenSees

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Abstract: Based on the driving force test data of shape memory alloy (SMA), the constitutive model of SMA driving force is proposed, and the secondary development is carried out on the platform of OpenSees software. SMA material was added to OpenSees, and the results show that the calculation results in this paper are consistent with the experimental data. It provides a realization path for driving force finite element analysis using OpenSees platform.

1. Introduction

As a new type of civil engineering materials, Shape Memory Alloy (SMA) has attracted great attention in the field of civil engineering structure control due to its unique shape memory effect, and has achieved good application results. Wu Ruide² applied prestrain on NiTi alloy rod, tested the restoring force of the drive element, and designed a drive mechanism of the separation device; Yuan Lei³ studied the recovery force of SMA under different strain amplitudes, and designed a SMA drive device. Chen Bin⁴ studied the relationship between recovery stress and temperature after unloading different prestrain on SMA, and designed a SMA pipe joint; Li Shuangbei⁵ studied the relationship between recovery stress and temperature under different pre-strain of SMA wire, and used SMA to repair cracks in reinforced concrete beams. Deng Zongcai⁶ studied the relationship between SMA recovery force and temperature under different pre-strain to resist the bending deformation of reinforced concrete beams. Liang⁷ studied the driving force and temperature under different pre-strains for the active control of beams. However, most of the current studies focus on the application of SMA, and the constitutive study of SMA is insufficient.

The existing constitutive model of SMA driving force is mainly divided into three categories: The first category is based on thermodynamic theory model, including Tanaka model⁸, which is simple but can only be used for one-dimensional stress state of SMA force qualitative analysis; Boyd-Lagoudas model⁹ extended Tanaka one-dimensional model to three-dimensional model, but the parameters were too complex; Yang Dazhi model¹⁰ proposed martensite kinetics model, but did not involve the relationship between driving force and temperature; Liang-Rogers model¹¹ was extended to the three-dimensional stress situation, but it cannot explain the reorientation of martensite. Brinson model¹², considering the initial conditions, but it didn’t combine with martensitic transformation temperature, the
model error is large; Ivshin-Pence model, the formula is too complex, not suitable for practical engineering applications. The second type is the model proposed based on viscoplastic theory, mainly including the Achenbach-Muller model and the Graesser-Cozzarelli model, whose functional relationship is very complex and difficult to be applied in practice. The third model is based on the crystal theory, mainly including Falk model, which is only suitable for the shear deformation of SMA single crystal, and the theoretical value is far from the experimental value, which is not suitable for engineering application. Sun-Wang model, this model is only applicable to small deformation.

In this paper, starting from the actual engineering application, a driving force model which can comprehensively reflect the influence of pre-strain, initial stress and temperature is established based on OpenSees platform. OpenSees is a fully open source finite element platform, with rich civil engineering materials, but there is no SMA driving force constitutive model. Therefore, this paper adds the SMA driving force constitutive model to the OpenSees material library, which provide an implementation path for SMA application research based on OpenSees.

2. Constitutive model of SMA driving force

Based on the SMA driving force test, the constitutive model of SMA driving force is proposed. The model is divided into heating stage and cooling stage:

The first stage is before the phase transition \( T < A_s \). The driving force has a linear relationship with the temperature because there is no reverse martensitic transformation, this moment:

\[
\sigma = \theta (T - T_0) + \sigma_0 \tag{1}
\]

The second stage is the phase transition \( A_s \leq T \leq A_f \). The transformation force is affected by the initial strain \( \varepsilon_0 \), temperature \( T \). The relationship between phase change force and temperature is sinusoidal, this moment:

\[
\sigma = E (\varepsilon - \varepsilon_0) + \theta (T - T_0) - \{\Omega [1 - 58.8 (\varepsilon_0 - \varepsilon_b)^2] + \sigma_0 \} \sin \frac{\pi}{2} \frac{T - A_s}{A_f - A_s} + \sigma_0 \tag{2}
\]

The third stage is the end of phase transition \( T > A_f \) There is a linear relationship between driving force and temperature, this moment:

\[
\sigma = \theta (T - T_0) - \Omega [1 - 58.8 (\varepsilon_0 - \varepsilon_b)^2] + \sigma_0 \tag{3}
\]

In the cooling stage, the relationship between driving force and temperature can be divided into three stages:

The first stage is before the reverse phase transition \( T > M_s \) Because there is no reverse martensitic transformation, there is a linear relationship between driving force and temperature, this moment:

\[
\sigma = \theta (T - T_0) - \Omega [1 - 58.8 (\varepsilon_0 - \varepsilon_b)^2] \tag{4}
\]

The second stage is the phase transition \( M_f \leq T \leq M_s \). The transformation force is affected by the initial strain \( \varepsilon_0 \), temperature \( T \). There is a cosine relationship between the transformation force and temperature, this moment:

\[
\sigma = E (\varepsilon - \varepsilon_0) + \theta (T - T_0) + \Omega [1 - 58.8 (\varepsilon_0 - \varepsilon_b)^2] \sin \frac{\pi}{2} \frac{T - M_s}{M_f - M_s} \tag{5}
\]

The third stage is the end of phase transition \( T < M_f \) There is a linear relationship between driving force and temperature, this moment:

\[
\sigma = \theta (T - T_0) \tag{6}
\]

Where: \( E \) — Elastic modulus of martensitic SMA

\( M_s, M_f \) — The start and end temperatures of martensite transformation in free state;

\( A_s, A_f \) — The start and end temperatures of austenite transformation in free state;

\( \Omega \) — Phase transition coefficient;

\( \theta \) — Thermoelastic coefficient;

\( T_0 \) — Initial temperature;

\( \sigma_0 \) — Prestress;

\( \varepsilon_0 \) — Prestrain;

\( \varepsilon_b \) — The optimum prestrain.
3. Realization of SMA driving force constitutive model

3.1. Environment compilation

OpenSees is based on the back-end source code written in C / C++, FORTRAN language, uses TCL and python language to write the front-end script, and integrates Intel MKL database to provide mathematical operations. In order to add SMA uniaxial material, the integrated programming environment should be configured, as shown in Figure 1. Environment integration mainly includes:

- Download and install visual studio with C / C++ compiler;
- Download and install TCL library;
- Download Intel parallel studio Xe and install Intel FORTRAN compiler and MKL library;
- Using git to clone OpenSees source code;
- Open OpenSees / win64 with visual studio/OpenSees.sln Documents;
- Select "realease" and "x64" in the "solution configuration" drop-down list, check the dynamic library directory and header file directory in all projects, and then rebuild the solution of OpenSees and debug the error.

![Figure 1 Compilation diagram of integrated environment](image)

3.2. SMA source code addition

To add materials, it is necessary to inherit the base class of uniaxialMaterial in order to realize different new material features through polymorphism. In this paper, SMA materials inherit the base class of uniaxialmaterial and implement the virtual method. The realized virtual function is:

- setTrialStrain() is the core function, which calls the input strain parameters from the upper element object to calculate the stress position and stiffness of SMA. It is transferred to the upper layer by reference to complete a calculation;
- getTangent() to obtain the stiffness of SMA object;
- getStress() to get the stress of SMA object;
- commitState() The function is called after an iterative step converges. When the iterative algorithm moves from the previous iteration to the next step, the convergence criterion determines whether convergence can be achieved. After convergence, this function is called to replace the initial state and enter the next iteration step by step.
- When revertToLastCommit() is not convergent, call this function to go back to the initial value of the previous iteration step;
- getCopy () is called by the upper level element object and creates a copy, which is stored in the element object;
- setResponse() / getResponse() is a set of response functions, which are used to modify SMA material parameters in the process of operation. Here, the default inheritance can be set;
- sendSelf() / recvSelf() function is used to send and receive SMA data to the database, and finally form the output result;
- void* OPS_SMA () is not a member function. It is only used to generate SMA objects and judge the input parameters of TCL script;
- TclModelBuilderUniaxialMaterialCommand.cpp Add judgment of material type and Function declaration of extern void * ops_SMA().

After the above functions are added and determined correctly, the solution is generated again to realize the addition of SMA driving force model.

4. Validation of SMA constitutive model
Based on the experimental data in reference [32], a pure SMA beam model with circular section of 1m in length and 6mm in diameter is established. The dispBeamColumn element is combined with Fiber section, LoadControl loading, NormUnbalance convergence criterion and Krylov Newton iterative algorithm are used for analysis. The model is shown in Figure 2.

Figure 2. simulation model diagram

Material simulation parameters as shown in table 1:

| Parameter    | Value      |
|--------------|------------|
| $E$ / GPa    | 11.2       |
| $\theta$ / Mpa°C$^{-1}$ | 0.3       |
| $M_f$ / °C   | 32         |
| $\sigma_0$   | 10         |
| $\varepsilon_0$ | 8%        |
| $\varepsilon_b$ | 10%       |
| $\Omega$ / Mpa | $-472$   |
| $A_s$ / °C   | 90         |
| $A_f$ / °C   | 166        |
| $M_s$ / °C   | 114        |

OpenSees software is used to simulate the heating process from 10 °C to 186 °C and the cooling process from 186 °C to 32 °C. The comparison between the simulated temperature driving force curve and the experimental results is shown in Figure 3. The simulated maximum stress is 466.1Mpa, and the experimental maximum stress is 457.1Mpa. The ratio of simulation value and experimental value is 1.02, which is in good agreement.

Figure 3. Comparison of simulation results and experimental results

5. Conclusion and foresight
Based on the driving force test data of reference [21], this paper uses Visual Studio to build the compiler environment based on OpenSees platform. The SMA driving force constitutive model inherits the characteristics of UniaxialMaterial basis class, and the constitutive model is added by modifying the virtual function method. The calculation results are compared with the experimental results. The results are as follows:

1. The driving force model of SMA is proposed in OpenSees for the first time, which can comprehensively reflect the influence of pre-strain, initial stress and temperature.
(2) The calculation results show that the simulation results in this paper are basically consistent with the experimental data.

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Reference
[1] Niu, X.R., Wang, N., Huang, N.X., Cui, Z.K., Wang, L., Zhao, C. (2021) Review of shape memory alloys. J. Jiangsu building materials, (01): 22-23.
[2] Wu, R.D., Chang, Y.K., Chen, X.S., Zhang, T., Guo, X.R., Chen, W.L. (2020) Research on driving mechanism of separation device based on shape memory alloy. J. Pyrotechnics, (05):10-13.
[3] Yuan, L. (2015) Shaking Table Test of Spatial Structure Seismic Response Controlled by SMA. D. Xi’an University of Architecture and Technology.
[4] Chen, B. (2013) Study on Macro-Meso Mechanical Behavior of Ni-Ti-Nb Shape Memory Alloy. D. Chongqing University.
[5] Li, S.B., Mo, C.M., Liang, Q.G. (2015) Study on Recovery Performance of Shape Memory Alloy and Its Application in Crack Repair of Concrete Beam. J. Concrete, (04):68-73.
[6] Deng, Z.C., Li, Q.B. (2002) Analysis of Driving Effect of Shape Memory Alloy on Concrete Beam. J. China civil engineering journal, (02):41-47.
[7] C. Liang. (1997) One-Dimensional Thermomechanical Constitutive Relations for Shape Memory Materials. J. Journal of Intelligent Material Systems and Structures ,8(4).
[8] K. Tanaka. (1986) A Thermomechanical Sketch of Shape Memory Effect: One-dimensional Tensile Behavior Research Mechanical, RES MECHANICA, 18(3): 251-263.
[9] J.G. Boyd, D.C. Lagoudas. (1996) A Thermodynamical Constitutive Model for Shape Memory Materials. Part I. The Monolithic Shape Memory alloy. J. International Journal of Plasticity, 12(6): 805-842.
[10] Yang, D.Z., (1987) Shape Memory Alloy. J. Science, (03):188-193+235+239.
[11] Liang, C. and Rogers, C.A. (1997) One-dimensional Thermomechanical Constitutive Relations for Shape Memory Materials. J. Journal of intelligent material systems and structures, 8(4), pp.285-302.
[12] Brinson, L. C. and M. S. Huang. (1996) Simplifications and Comparisons of Shape Memory Alloy Constitutive Models. J. Journal of Intelligent Material Systems & Structures, 7: 108-114.
[13] Ivshin, Yefim, and Thomas J. Pence. (1994) A Thermomechanical Model for A One Variant Shape Memory Material. J. Journal of intelligent material systems and structures 5, 4: 455-473.
[14] Achenbach, M., T. Atanackovic and I. Muller. (1986) A Model for Memory Alloys in Plane Strain. J. International Journal of Solids and Structures, 22(2):171-193.
[15] Graesser, E.J. and F.A. Cozzarelli. (1991) Shape Memory Alloys as New Materials for Asiesmic Isolation. J. Journal of Engineering Mechanics, ASCE, 117(11):2590-2608.
[16] Falk F. (1983) Ginzburg-Lndau theory of static domain w allsin shape-memory alloys. J. Zeit Phys B,51: 177-185.
[17] Sun Q. P., Lexcellent C. (1996) On the Unified Micro-mechanics constitutive Description of One-way and Two-way Shape Memory Effect. J. Dephysy IVCl:367-376.
[18] Pacific Earthquake Engineering Research Center. OpenSEES[CP/DK]. 1999. https://Opensees.berkeley.com
[19] Gu, Q., Huang, S.R. (2016) OpenSees practical course. Science Press, Beijing.
[20] Chen, X.W., Lin, Z. (2020) Principle and implementation of structural elastoplastic analysis program OpenSees. China Construction Industry Press, Beijing.
[21] Liu, Z.Y. (2009) The Seismic Behavior and Smart Repairment on Precast Concrete Frame. D. School of Civil Engineering Tongji University.