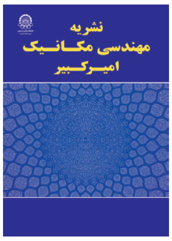

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Simulation and Optimization of Shape Memory Alloy Cables

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ABSTRACT: In this work, using a three-dimensional constitutive model and implicit solution through a user-defined subroutine in ABAQUS software, mechanical behavior of shape memory alloy cables and their constituents are investigated. Material parameters are identified by numerical simulations and available experimental data. Finite element method is first employed for analysis of an elastic steel cable and subsequently for a super-elastic cable. The simulation results for these cables show good agreement when compared with experimental data which also validates the simulation approach. The wire rope is then simulated for shape memory effect and investigating mechanical behavior and several diagrams including normal stress, shear stress, strain and temperature for both super-elastic and shape memory effect cables are presented. Moreover, utilizing the design of experiments method, shape memory effect cable is optimized to achieve the maximum specific energy. The method proposed in this study can be used for the design and optimization of shape memory alloy wire ropes.

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1- Introduction

Shape Memory Alloy (SMA) cables are a new class of structural elements that inherits many advantages of conventional wire ropes, adds new adaptive functionality (Shape Memory Effect (SME) and super Elasticity, (SE)) to structural cables. SMA cables are relatively stiff in tension and resistant to abrasion, but still flexible in bending and torsion [1]. They could have significant future applications due to the high energy absorption, large tensile strength, high mechanical energy density and more compact structural design [2]. There has been interesting in studying SMA cables in the literature. The SME helical springs under axial force are studied both analytically and numerically [3]. Moreover, in terms of experimental study, an extensive set of uniaxial tension experiments have been performed on 7×7 and 1×27 constructions, to characterize the SE behavior at room temperature [1, 2].

The present work is a finite element analysis of SMA cables, both for SE and SME. Regarding attractive features of the three-dimensional phenomenological model proposed by Souza [4], we have implemented it within a user-defined subroutine UMAT in the nonlinear finite element software ABAQUS. The mechanical behavior of SMA cables is studied and the results of SE cable are validated through comparisons with experimental data [2] and available finite element results [5]. Moreover, the finite element analysis of SME cable and its constituents are studied in details and the relationship between normal and shear stress with strain and temperature are obtained. Finally utilizing the Design of Experiments (DOE) method, SME cable is optimized to achieve the maximum specific energy.

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2- System Modeling

Constitutive equations in Souza et al. [4] are developed within the theory of irreversible thermodynamics in the realm of the small-deformation regime and is able to describe both unique effects, SE and SME.

In the model, the linear strain tensor (ε) and the Cauchy stress tensor (σ) are decomposed into volumetric and deviatoric parts as:

$$\mathring{a} = e + \frac{\theta}{3}\mathbf{I} \tag{1}$$

$$\boldsymbol{\sigma} = \boldsymbol{s} + p\mathbf{I} \tag{2}$$

where represents second-order identity tensor. θ and e are the volumetric and deviatoric parts of the strain, while p and s denote the volumetric and deviatoric parts of stress, respectively. The constitutive equations can be derived as:

$$p = K\theta \tag{3}$$

$$\boldsymbol{s} = 2G(\boldsymbol{e} - \boldsymbol{e}^{tr}) \tag{4}$$

$$\boldsymbol{X} = \boldsymbol{s} - \boldsymbol{\alpha} \tag{5}$$

$$\boldsymbol{\alpha} = \left[\hat{o}_M(T) + H\left\|\boldsymbol{e}^{tr}\right\| + \tilde{a}\right]\boldsymbol{e}^{tr} \Big/ \left\|\boldsymbol{e}^{tr}\right\| \tag{6}$$

$$\left\| e^{tr} \right\| \leq \varepsilon_L \quad (7)$$

where $\|.\|$ denotes the usual Euclidean norm and ε_L is the maximum transformation strain reached at the end of the transformation during ***a*** uni-axial test. ***X*** denotes transformation stress tensor and H is phase transformation hardening. The tensor a plays a role similar to the so-called back-stress in classical plasticity. Moreover, τ_M and γ are defined as:

$$\tau_M = \begin{cases} \beta(T - T_0) & if \ T > T_0 \\ 0 & otherwise \end{cases} \quad (8)$$

$$\begin{cases} \gamma = 0 & if \ \left\| e^{tr} \right\| < \varepsilon_L \\ \gamma \geq 0 & if \ \left\| e^{tr} \right\| = \varepsilon_L \end{cases} \quad (9)$$

where β and T_0 are a material parameter and the reference temperature, respectively. To describe e^{tr}, the limit function F takes the following form:

$$F = \left\| X \right\| - R \quad (10)$$

where the material parameter R represents the radius of the elastic domain. F is equal to zero when phase transformation may be possible, otherwise for the elastic domain, it takes a negative value.

3- Simulation of 1×27 Shape Memory Alloy Cable

To simulate the behavior of SMA cable and its constituents, we have used the 3D constitutive model [4], and implicit solution through a UMAT in ABAQUS software. The experimental data reported by Shaw et al [1, 2], is used to study uniaxial behavior of SE cables. Identified material parameters are reported in Table 1.

To couple, the nodes on the cross-section of the SMA cable, the reference points located at the cable centerline, are established at a distance away from the front and back of cross-section planes [6]. Moreover, the kinematic coupling mode is employed to achieve the same displacement between the reference point and the corresponding coupled nodes. The one side of the cable ends is clamped and the other side is free. Surface to surface contact is defined and the friction coefficient is 0.115. Cross section and construction of the 1×27 SMA cable and its constituents are shown in Fig. 1.

Moreover, 185,300 C3D8 elements with dimensions of 0.05×0.03 mm2 are used for simulation of the SMA cable. (Fig. 2).

Table 1. Material parameters reported by Shaw et al.[1, 2]

Parameter	unit	value
E	GPa	40
ν	-	0.3
β	MPa°C^{-1}	5.5
H	MPa	488
R	MPa	104
T_0	°C	-25
ε_L	%	5.5

4- Results

In this section, finite element results of the 1×27 cable under uniaxial load are presented. The relation between normal (Fig. 3) and shear stress (Fig. 4) with strain for SE cable are derived and compared with experimental data [2].

It should be noticed, the difference between the results obtained in the present work and the experimental data [2] is affected by asymmetric behavior of SMA material in tension and compression, slipping off the grips and ignorance of crippling effects.

Moreover, the normal and shear stress-strain-temperature diagrams of 1×27 SME cable and each component are shown in Figs. 5 and 6, respectively.

The core wire (A) has larger normal stress compared to other wires, and then a highest portion of the normal stress is imposed on the wires in layer B to D, respectively. Layers

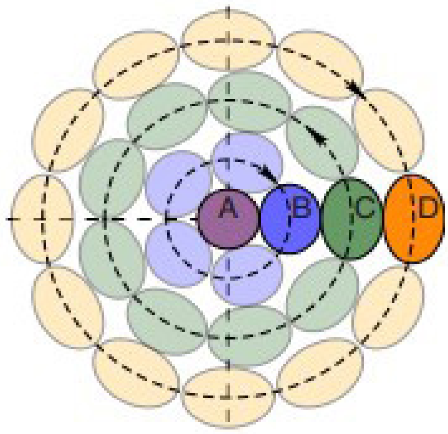

Figure 1. Cross section of 1×27 SMA cable [2].

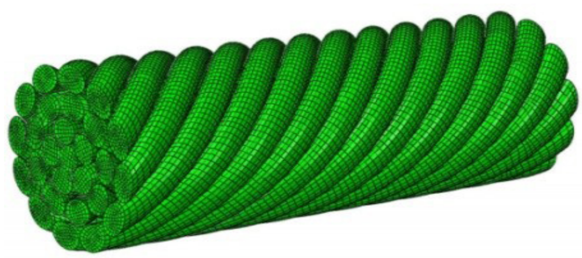

Figure 2. Mesh description of the 1×27 SMA cable.

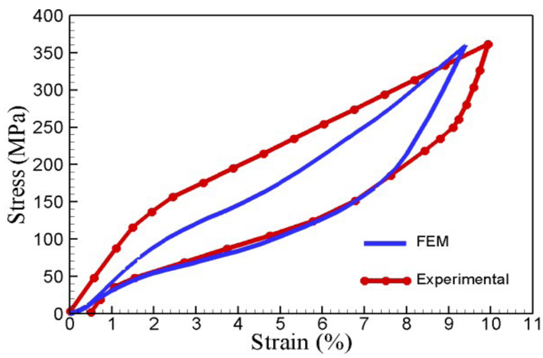

Figure 3. Comparison of normal stress-strain response in present work and experimental data [2].

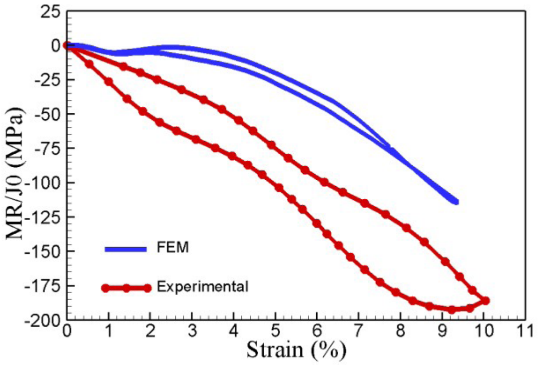

Figure 4. Comparison of shear stress-strain response in present work and experimental data [2].

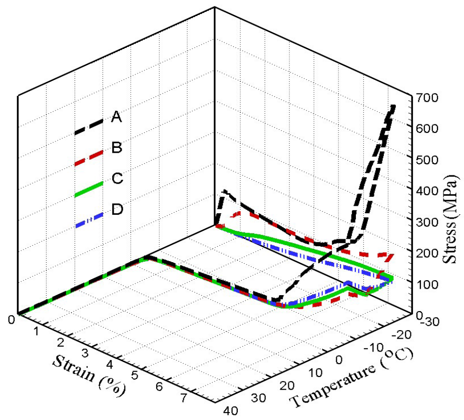

Figure 5. The normal stress-strain-temperature response of 1×27 cables components.

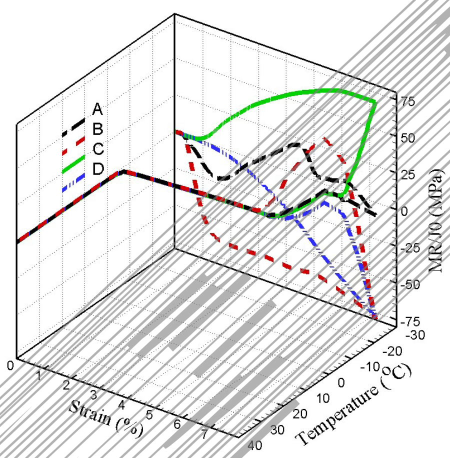

Figure 6. The shear stress-strain-temperature response of 1×27 cables components.

B, C, and D are all simple helices (first-order) in a left/right/left hand lay, respectively. Thus the sign of shear stress changes from layer wires B to D. Moreover, most of the strain recovery occurs in a short range of temperature (-10 to -5℃). According to Figs. 5 and 6, heating the cable leads to full recovery of the original shape at -5℃ and subsequent heating does not change its shape anymore.

5- Optimization of Shape Memory Effect Cable

Using the Design Of Experiments (DOE) method, SME cable with 1×6 construction (for simplicity) is optimized to achieve the maximum specific energy considered as the response variable. Moreover, the diameter and helix angle of the spiral wires are assumed as the design factors.

Analyzing the data obtained from the experiments, by increasing diameter (*D*) of the wires and helix angle (*φ*), the response variable increases and decreases, respectively. To reach the maximum response variable, the results for design factors are presented in Table 2.

Table 2. Results of the optimization in the DOE method.

Design Factors				
Parameter	*Unit*	*domain*		*Suggested level*
D	*mm*	*0.10*	*0.38*	*0.38*
φ	*degree*	*54.9*	*72.0*	*54.91*
Prediction of the response variable				
Parameter	*Unit*	*value*		
η	*J/gr*	*2.85005*		

6- Conclusion

In this paper, to study the mechanical response of SMA cables, we use a 3D constitutive model and implicit solution through a UMAT in the nonlinear finite element software ABAQUS. The results of this work show good agreement when compared with experimental data and finite element results.

Optimization of the SME cable with 1×6 constructions shows that increasing diameter and the helix angle of spiral wire, leads to increasing and decreasing the specific energy of the cable, respectively.

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