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A nonlinear study on structural damping of SMA hybrid composite beam

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ABSTRACT

A more realistic analysis of forced and transient vibrations for a composite beam with SMA wires is provided by considering the following details: Low and high temperature vibrations are simulated by using the Panico–Brinson model which replicates the pseudo-elastic (PE) and ferro-elastic (FE) hysteresis types of martensite transformations. Besides first-order shear deformation beam theory (FOBT) and large deflection von Karman strain–displacement correlations are used to obtain more accurate estimations of stress field which consequently can result in better estimations of SMA wires hysteresis loops and their decaying characteristics. The governing equations of forced vibration in a beam under transient dynamical loading is developed and discretized by using the multiple method of differential-integral quadrature (DQ-IQ). Incremental time-domain solution of the problem is obtained by Newmark time marching technique. Nonlinear space-domain governing equations are solved by Newton-Raphson method. The results are assessed by comparing with available literature. Considering different types of boundary conditions, the influence of SMA layer position, the hysteresis behavior of pseudo-elastic and ferro-cycles, the pre-straining of SMA wires, the geometrical nonlinearities and the amplitudes of the impulsive loads are studied in detail.

1. Introduction

In past two decades, by increasing the technological request for the passive control of undesirable vibrations, motivated by impulsive or resonating loads, growing demands can be seen for the development of high damping materials and constructions [1–3]. Shape memory alloys (SMAs) possess the inherent ability to dissipate considerable portion of stored strain energy through the hysteresis behavior [4]. The behavior is a result of so-called martensitic phase transformation which occurs between the austenite (A) and martensite (M) phases in response to the change in stress and/or temperature levels. In the stress-free state, there are four different transition temperatures for an SMA material comprising M_f^0, M_S^0, A_S^0, A_f^0 which stand for martensite finish, martensite start, austenite finish and austenite start temperatures, respectively. Fig. 1 shows the schematic of different stress-strain curves for a typical SMA material at different temperature levels and load histories.

2. PE hystresis behavior (b) FE hystresis behavior (c) SME behavior

Based on PE behavior, SMA material achieves very large levels of plastic strain upon loading that can be fully recovered in unloading stage. In a cyclic loading condition with equal tensile and compressive load extremes, the behavior produces two distinctive loops of hysteresis. In FE effect, the specimen of SMA material exhibits large residual plastic strains in loading and unloading stages that can be fully recovered by applying a load opposite to the inelastic strains. But as Fig. 1b shows, in this case the center of stress-strain coordinate is located at the centroid of the hysteresis loop resulted from the cyclic loadings. Finally, the SME characteristic refers to the material ability which recovers cold-forged permanent large strains upon a mild increase in material temperature. The SME feature can be used in enhancement of critical buckling load and shape control of structural components [5,6]. Both PE and FE characteristics of SMA constructions can result in a kind of hysteresis behavior which assists the dissipation of undesirable vibrational energies. Accordingly, many researchers have studied the complex dynamical response of SMA systems, including the free and forced vibration behavior of SMA wires, bars, ribbons and beams. For instance, the free vibrations of a NiTi beam under sinusoidal and impulsive loads has been analyzed by Hashemi and Khadem [7]. They have used Auricchio model for SMA materials [8] and investigated the pseudorealistic effect (PE) of SMA materials. In a research conducted by Jafari and Ghiasvand [9], the dynamic response of pseudo-elastic SMA beam to a moving load is developed by using of Lagrange equations. They have also applied Auricchio's model to simulate the behavior of SMA pseudo-elastic material. Assuming a

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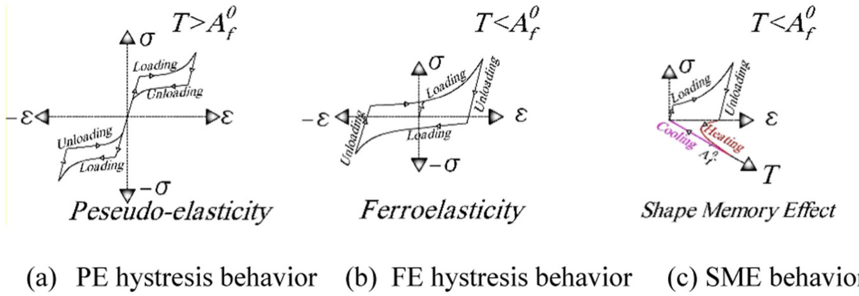

Fig. 1. The schematics of SMA material stress-strain curves at different thermo-mechanical load histories.

rheological model for the SMA materials and using the simple elastic bending beam theory, the responses of SMA beam under impulsive loads are represented by Zbiciak [10].

Considering PE and FE capabilities of SMA wires embedded in composite structures, these materials can be used to improve several structural characteristics such as fatigue attenuation, impact resistance and passive control of vibrations. Despite several explorations on the vibrational analysis of SMA hybrid composite plates and shells such as Refs. [11–18], there are few publications on dynamical investigation of SMA hybrid composite beams. In this framework, Ghomshei et al. [19] examined the transient response of thick elastic beams with an embedded SMA layer using Finite Element Method (FEM). They used 1-D model of Brinson [20] to model the behavior of SMA material. The nonlinear dynamic analysis of sandwich beam with SMA hybrid composite skin under impulsive loads is conducted by Khalili et al. [21]. In their research, using high order sandwich panel theory, a new type of elements is utilized. They investigated the influence of SMA wires upon the damping capacity of a sandwich beam by considering the phase transformations resulted from the PE behaviors of 1-D Brinson model. In a similar work, Khalili et al. [22] provided the dynamic analysis of a continuous SMA hybrid composite beam subjected to impulsive loading.

It worth mentioning that, in the aforesaid investigations on dynamic response of SMA beams and composite hybrid beams, some limitations are considered. First of all, these studies are limited to high-temperature vibration damping which results from PE characteristics of SMA materials. While, in practical investigations, usually the vibration of SMA structures are happening in low-temperatures, and the presence or occurrence of high temperatures are not essential. Secondly, in most of these researches, some simplified theories such as the elastic bending beam theory which merely considers the bending effects or Euler-Bernoulli beam theory (EBT) which ignores the shear deformations are employed for the derivation of governing equation. It is clear that in case of composite beams without SMA reinforcements, using the aforementioned beam theories may not considerably guarantee the accuracy of the results. While owing to the dependence of SMA material hysteresis loops on the dominating stress fields, choosing more accurate beam models which enables us predict more reliable stress fields is an essential necessity. Finally, most important of all limitations, in previous studies only small strain–displacement expressions are considered. While, in practical problems the capability of SMA materials such as PE and FE behaviors are manifested better at large displacement conditions and analyses.

There are few researches which consider some of these limitations. For instance, Damanpack et al. [23] have investigated the transient dynamic behavior of thin elastic aluminum beam reinforced with SMA layer. They employed 3-D SMA model developed by Panico and Brinson [24] and reduced the model to uniaxial loading. Their employed model enables the dynamical analysis of SMA embedded beams at high and low temperatures. However, their works have some limitations. Their investigations are limited to the homogeneous materials implemented by SMA layers and the solutions only consider the clamped-clamped types of beams. The most important limitation is that in their work the governing equations are simplified by employing EBT theory. Recently, Dehkordi et al. [25], proposed mixed LW (Layer- wise)/ESL (Equivalent single layer) models for nonlinear dynamic analysis of sandwich plate with flexible core and laminated composite face sheets embedded with shape memory alloy (SMA) wires. Although, their work benefits the accuracy of mixed LW/ESL model, it solely considers the linear terms of strain-displacement equation and the analysis is limited to high temperature behaviors of SMA materials. Consequently, to the best knowledge of the authors, there is not a comprehensive study for composite beams reinforced with SMA wires which covers all of the abovementioned limitations.

In the present work, the nonlinear transient vibration analysis of composite beam embedded with SMA wires at the high and low temperature is presented for the first time. The first order beam theory is employed for the transient dynamic analysis. Moreover, the von Karman strain–displacement relations are used to account for the large deflection effects. In order to simulate the constitutive behavior of SMA wires, 3-D SMA model developed by Panico and Brinson is adapted and reduced to 1-D case which enables us to reproduce pseudo-elastic, martensite transformation/orientation. Considering the effect of a concentrated transient load, the governing equations are linearized by Newton- Raphson method and discretized by combined method of differential quadrature – integral quadrature (DQ-IQ) which is recently developed by Eftekhari [26]. Incremental solution of the problem is obtained by Newmark time marching technique. The results are assessed by comparing with available literature. The effect of boundary conditions on the location of SMA wires, the effect of SMA wire prestringing and nonlinearity effect at the high amplitude loading conditions are explored in detail.

3. Constitutive equations

3.1. SMA constitutive model

In order to model the mechanical behavior of SMA wires, similar to those reported by Damanpack et al. [23], the 3-D macroscopic phenomenological constitutive model of Panico and Brinson [24] is reduced to 1-D form and employed in uniaxial tension-compression conditions. Accordingly, the total martensite volume fraction (ξ) is divided into two distinctive parts comprising temperature-induced martensite volume fraction (ξ_T) and stress-induced martensite volume fraction (ξ_S). That is,

$$\xi = \xi_S + \xi_T \tag{1}$$

Assuming small strain conditions, total strain (ε) is also divided into elastic strain (ε^e) and inelastic transformation strain (ε^{tr}) resulted from the austenite-to-martensite transformations. It means that,

$$\varepsilon = \varepsilon^e + \varepsilon^{tr} \tag{2}$$

In Eq. (2), ε^{tr} varies in region $0 \le |\varepsilon^{tr}| \le \varepsilon^L$ where ε^L is a material parameter corresponding to maximum transformation strain reached at