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Thermo-mechanical behavior of shape adaptive composite plates with surface-bonded shape memory alloy ribbons

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ABSTRACT

In this paper, thermo-mechanical analysis of rectangular shape adaptive composite plates with surface-bonded shape memory alloy (SMA) ribbons is introduced. A robust phenomenological constitutive model is implemented to predict main features of SMA ribbons under dominant axial and transverse shear stresses during non-proportional thermo-mechanical loadings. The model is capable of realistic simulations of martensite transformation/orientation, reorientation of martensite variants, shape memory effect, pseudo-elasticity and ferro-elasticity effects. A numerical process is addressed to solve the time-discrete counterpart of the model using an elastic-predictor inelastic-corrector return mapping algorithm. Considering small strains and moderately large rotations in the von Kármán sense, governing equations of equilibrium are derived based on the first-order shear deformation theory. A Ritz-based finite element method along with an iterative incremental strategy is developed to solve the governing equations of equilibrium with both material and geometrical non-linearities. The capability of the material and structural model is examined by a comparative study with numerical data available in the open literature for laminated SMA beams. Effects of the pre-strain state, temperature, length and arrangement of the SMA ribbon actuator are investigated, and their implications on the thermo-mechanical behavior of shape adaptive composite plates are put into evidence, and pertinent conclusions are outlined.

1. Introduction

In recent years, a new class of smart materials known as shape memory alloys (SMAs) has gained considerable attention in engineering community due to their unique attributes such as pseudo-elasticity (PE) and shape memory effect (SME) [1]. The distinctive behavior of SMAs is related to the martensitic phase transformation due to changes in the stress and/or temperature. At high temperatures, SMA materials behave pseudo-elastically while producing hysteresis. On the other hand, at low temperatures, SMAs exhibit shape memory effect and can recover their original size and shape upon heating. SMAs can also attain their original shape when an opposing force is applied to the material which is termed as ferro-elasticity (FE).

Over the last two decades, many macroscopic phenomenological models have been proposed to simulated martensitic phase transformation in SMAs, see for instance [2–7]. One-dimensional (1-D) models proposed by Tanaka [2], Liang and Rogers [3] and Brinson [4], and three-dimensional (3-D) model developed by Boyd and Lagoudas [5] are the most notable SMA models that researchers commonly exploited. However, it should be mentioned that the proposed models [2–5] cannot reproduce the ferro-elasticity effect of SMAs when the stress sign is changed in low temperatures. In the other words, these models are only able to simulate 1-D SMA behavior under uniaxial tensile loading. Based on the experimental observations [6,7], SMA materials under multi-axial non-proportional thermo-mechanical loadings may experience the so-called martensite variant reorientation according to loading direction. This phenomenon was not also covered in the mentioned models [2–5]. In an attempt to model variant reorientation, Panico and Brinson [6] proposed a 3-D phenomenological model with capability of the simulation of martensitic transformation and reorientation of martensite in SMAs under multi-axial non-proportional loading. Recently, Bodaghi et al. [7] developed a simple and robust model to simulate main features of SMAs under two dominant normal and shear stresses including martensitic transformation, orientation/reorientation of martensite variants, SME, PE and FE.

The shape memory effect can be employed to control the behavior of mechanical structures. One way of achieving this goal is by attaching SMA actuators in the layer form to polymeric, metallic

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or composite matrices while electrical current is normally employed to induce the thermally driven transformation. In the hybrid composite with soft matrix and eccentrically posed SMA components, shape change may be induced through SME strain recovery. On the other hand, in the hybrid composite with stiff matrix and centered or eccentrically posed SMA components, large stress may be produced through SME restrained recovery.

Recently, some research works have been dedicated to analyze active shape/stress/vibration control of hybrid SMA laminates with embedded or surface-bonded SMA layers. For instance, Ghomshei et al. [8] investigated thermo-mechanical deformation of a beam actuator consists of two SMA layers bonded to the sides of a matrix layer, experimentally and numerically. They developed a finite element solution for their analysis and used 1-D Brinson model [4] to predict the thermo-mechanical response of SMA layers. Results revealed that the thermal actuation is successfully achieved by applying electrical current to the SMA layers. Marfia et al. [9] proposed a finite element model to study the static behavior of elastic beams with two integrated SMA layers. They found that SMA layer actuators are able to produce large amounts of work and recover 50% of the displacement as a result of the application of external forces by performing temperature cycles on the SMA layers. Yang et al. [10] presented experimental studies on the active shape control of composite structures with SMA wire actuators attached on the surfaces of the structures using bolt-joint connectors. Using electric resistive heating, SMA actuators were activated and quite large deformation of the SMA hybrid composite structures was observed and discussed. Roh et al. [11] examined active shape control of plate and panel structures with surface-bonded SMA layers. 3-D SMA model proposed by Boyd and Lagoudas model [5] was employed to simulate the main characteristics of SMA layers. They utilized the ABAQUS finite element program with an appropriate user-defined material (UMAT) subroutine for modeling SMA layers and host elastic structure elements. Numerical results revealed that the SMA actuator could generate enough recovery force to deform the host structure and sustain the deformed shape subjected to large external load, simultaneously. Roh and Bae [12] experimentally and numerically examined the thermo-mechanical behaviors of Ni–Ti SMA ribbons, associated with stress and temperature-induced transformations. They modified 3-D Boyd–Lagoudas model [5] into a plane stress condition and implemented the two-dimensional (2-D) incremental formulation in the ABAQUS finite element program with the aid of a UMAT subroutine. For application of the developed numerical 2-D SMA model, the feasibility of a gripper actuator with surface-bonded SMA strips was numerically demonstrated. Results revealed that, when the SMA strip is activated by raising its temperature, the strain recovered in the activated SMA strip causes bending deformation due to the off-center placement of the SMA strip. Transient response of a sandwich beam with SMA hybrid composite face sheets and flexible core under dynamic loads was studied by Khalili et al. [13]. They used 1-D Brinson model to predict pseudo-elastic behavior of SMA wires and developed a finite element model to solve the non-linear governing equations. Recently, Bodaghi and his colleagues [14,15] investigated active shape/vibration control of thin homogeneous elastic beams under static/dynamic loadings with integrated SMA layers using finite element method. They employed the 3-D Panico–Brinson model [6] and reduced it to a 1-D tension–compression case to simulate 1-D behavior of SMA layers. They found that the SMA layers can be successfully used to suppress static/dynamic deformation of smart beams under mechanical loads.

The literature survey reveals that most of researches have been devoted to study active shape/vibration control of beam-like structures with integrated/embedded SMA layers. Also, it can be found that researches employed generally 1-D or 3-D models [2–5] to simulate thermo-mechanical behavior of SMA materials. As previously stated, these models are incapable of simulating the ferro-elasticity effect revealed when the pre-strained SMA materials undergo compressive stress at low temperatures. Moreover, these models do not take into account martensite variant reorientation as an important phenomenon under non-proportional thermo-mechanical loading conditions.

The aim of this work is to investigate thermo-mechanical behavior of shape adaptive composite plates with surface-bonded SMA ribbon actuators using a robust SMA model with capability of simulating ferro-elasticity and martensite variant reorientation. SMA ribbons pre-strained in a combined axial-shear state are installed onto the top surface of the composite plate to design shape adaptive composite structures. The robust phenomenological constitutive model proposed by the authors [7] is implemented to characterize main aspects of the SMA ribbons under dominant axial and transverse shear stresses during non-proportional thermo-mechanical loadings. The SMA model is able to simulate martensite transformation/orientation, pseudo-elasticity, shape memory effect and in particular reorientation of martensite and ferro-elasticity features. The first-order shear deformation theory (FSDT) and von Kármán geometrical non-linearity are assumed to describe displacement and strain fields of shape adaptive composite plates. Based on the principle of minimum total potential energy, an SMA composite plate element is first developed which is subsequently extended to the finite element equations of equilibrium. An iterative incremental strategy is introduced to solve the coupled governing equations of equilibrium with both material and geometrical non-linearities. Capabilities of the material and structural formulations are first examined through comparative study with numerical results available in the open literature for laminated SMA beams. A detailed analysis of the influence of pre-strain state, temperature, length and arrangement of surface-bonded SMA ribbons on the thermo-mechanical behavior of shape adaptive composite plates with clamped-free, clamped–clamped and simply supported-simply supported boundary conditions is carried out. Due to the absence of similar results in the specialized literature, this paper is likely to fill a gap in the state of the art of this problem.

2. Materials and methods

Consider a composite plate with length a, width b, and thickness h_c, as depicted in Fig. 1a. In order to control the structure deformation, shape memory alloys in ribbon form are perfectly bonded to the top surface of the host plate while current heating is used to activate them. SMA ribbons have rectangular cross section $d \times h_s$ with arbitrary length. For the sake of identification, some quantities associated with the composite plate will be marked by a subscript "c", while those affiliated with the SMA ribbons by a subscript "s", placed on the right of the respective quantity. The middle plane of the substrate plate is considered as a reference plane. The origin of the Cartesian coordinate system (x, y, z) is located at the upper-left corner of the host plate on the reference plane.

During non-proportional thermo-mechanical loadings, the SMA ribbons experience two dominant axial stress and transverse shear stress. The thermo-mechanical behavior of SMA materials is first studied and then governing equations of equilibrium and solution strategy are presented.

2.1. Time-continuous SMA constitutive model

In order to simulate main thermo-mechanical features of the SMA materials under combined axial-shear non-proportional loadings, the simple and robust macroscopic phenomenological