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Parameter identification of a thermodynamic model for superelastic shape memory alloys using analytical calculation of the sensitivity matrix

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ABSTRACT

This paper presents an identification procedure for the parameters of a thermodynamically based constitutive model for Shape memory Alloys (SMAs). The proposed approach is a gradient-based method and utilizes an analytical computation of the sensitivity matrix. For several loading cases, including superelasticity, that are commonly utilized for the model parameters identification of such a constitutive model, a closed-form of the total infinitesimal strain is derived. The partial derivatives of this state variable are developed to find the components of the sensitivity matrix. A Levenberg–Marquardt algorithm is utilized to solve the inverse problem and find the best set of model parameters for specific SMA materials. Moreover, a pre-identification method, based on the second derivative of the total strain components is proposed. This provides a suitable initial set of model parameters, which increases the efficiency of the inverse method. The proposed approach is applied for the simultaneous identification of the non-linear constitutive parameters for two superelastic SMAs. The comparison between experimental and numerical curves obtained for different temperatures shows the capabilities of the developed identification approach. The robustness and the efficiency of the developed approach are then experimentally validated.

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1. Introduction

Shape memory Alloys are now utilized in a wide range of applications, especially in aerospace, biomedical and energy industrial fields (Otsuka and Wayman, 1999). This success is attributed to their ability to recover substantial deformation when subjected to particular thermomechanical input. Among the number of thermomechanical loading paths that can lead to the appearance of these important deformations, two remarkable paths are often utilized in industrial applications. The first one is an isothermal path at sufficiently high temperature, which induces a superelastic behavior, where significant strains are developed and recovered upon an isothermal mechanical cycling loading. The second typical loading path is an isobaric cooling–heating cycle, where seemingly permanent strains appear during cooling under stress and are recovered upon heating (Lagoudas, 2008). When the temperature is controlled, an SMA component can be actuated, for example to modify the geometry of a structure for morphing applications (Hartl et al., 2010a, 2010b). These two effects are obtained for a specific loading path, but the thermomechanical behavior of SMA is more general and a wide variety of effects can be obtained for different loading paths. This has motivated the development of constitutive models based on the expression of a thermodynamic potential, which allows the description of the material state for all different kinds of loadings. A review of these models for SMAs can be found in Patoor et al. (2006) for the behavior of the single crystal and Lagoudas et al. (2006) for the constitutive modeling of polycrystals.

The design of SMA structures and the optimization of their characteristics are conducted now with the use of numerical simulations, most of them based on finite element analysis (FEA). Most of the three-dimensional constitutive models for SMAs are nowadays implemented in FEA codes. The accuracy of a numerical simulation of the SMA structural behavior relies on the model ability to accurately predict the constitutive behavior but also on the correct estimation of the model parameters, characteristic of a specific alloy. The common way to determine the material parameters related to the phase transformation is defined in two ASTM Standards (F2004, 2005, 2010, F2082, 2006). This methodology, useful to characterize the quality and to get specification acceptance

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for Nickel–Titanium in the biomedical industry, is not suitable for the identification of a model that aims at performing the numerical simulation of SMA structures. Indeed, the methodology is restricted to the determination of the transformation temperatures. Moreover, this determination may differ according to the method utilized (F2082, 2006).

The development of a reliable method to identify the parameters for SMA constitutive models is thus an important step to be able to perform reliable numerical simulations for the design of SMA structures, regardless of the choice of a constitutive model. The methodology applied to identify the parameters of the constitutive models based on the thermodynamics of the phase transformation often requires the construction of the phase diagram (Lagoudas, 2008; Hartl et al., 2010a, 2010b; Chemisky et al., 2011), instead of following the ASTM standards that does not give indication on the characterization of the complete set of parameters for these models. Several material parameters are obtained based on this phase diagram, which are now well utilized in the SMA community. The most common procedure is a manual procedure where the transformation points are obtained using a tangent intersection method (Stebner et al., 2011). However, several issues are associated to this methodology, since no objective criterions are utilized to assess the efficiency of the method. This can lead to potential error when estimating the model parameters of a SMA material. In this work, an identification approach is proposed to obtain the suitable model parameters that will be utilized for the simulation of the shape memory alloys thermomechanical behavior. This method is focused on the identification of the material parameters to simulate the superelastic response of SMA structures. This kind of behavior is indeed widely utilized in industrial applications (e.g. dentistry, surgical instruments, stents and micro-actuators).

Several strategies have been developed to extract directly the parameters of various constitutive laws from the measurement of displacement, strains and/or prescribed forces. The most used methods are described in the useful review work of Avril et al. (2008). The selection of a suitable identification method is dependent on the constitutive model considered and on the experimental technique utilized to characterize the material behavior. A brief review of the main identification strategies, their compatibility with different constitutive behavior and with various experimental characterization procedures is developed in the next section. This is further utilized to select a suitable identification strategy according to the set of experimental data and the constitutive model selected. Section 3 briefly reviews the thermomechanical constitutive model selected (Chemisky et al., 2011) and presents the analytical expression of the macroscopic stress/strain state as a function of the internal variables and the model parameters. Section 4 presents the identification procedure based on the inverse procedure, with the definition of the analytical sensitivity matrix. The experimental validation for different thermomechanical loadings of the proposed method is presented in Section 4. Concluding remarks are provided in Section 5.

2. Selection of the parameter identification strategy for superelastic shape memory alloys

The requirements for the identification procedure adapted to the case of superelastic SMAs are the following:

i) The identification procedure should be adapted to the standard experimental tests utilized to characterize a superelastic SMA, i.e. proportional isothermal mechanical tests; ii) The procedure should be fast enough to be of a practical interest for the analysis of homogeneous standard superelastic tests; iii) This procedure should however be easily extended to the identification of model parameters based on more complex, heterogeneous tests assuming that full kinematic field are measured at the surface of the experiment using a suitable experimental technique. According to the last statement, the identification procedure should be based on those developed when full kinematic fields are experimentally measured. Five methods have been listed in the review of Avril et al. (2008). i.e: i) The constitutive equation gap method (CEGM); ii) the virtual fields method (VFM); iii) the equilibrium gap method (EGM) iv) the reciprocity gap method (RGM) and v) the finite element model updating method (FEMU).

The constitutive equation gap consists in the measurement of the distance between a given stress field and the corresponding stress field computed through the constitutive model from a given displacement field. This method has been recently extended to elastic–plastic behaviors (Latourte et al., 2008) or elastodynamics (Banerjee et al., 2013). Moussawi et al. (2013) have revisited the concept of constitutive relation error by introducing a constitutive compatibility of stress, which defines a subspace of the classical statically admissible stress space. The virtual fields method is based on the construction of virtual fields to extract material parameters (Avril and Pierron, 2007). This technique relies on the processing of the experimental strain fields when expressing the global equilibrium of a specimen through the principle of virtual work formulated with specific virtual displacement fields. It has been successfully applied to determine the elastic and damaged anisotropic behavior of composite materials (Chalal et al., 2004, 2006). This method requires a minimization of a cost function at each loading step to find the optimal parameters characteristic of a nonlinear behavior as reported in Grédiac and Pierron (2006). The equilibrium gap method and the reciprocity gap method have been developed, to the knowledge of the authors, only in the case of linear elasticity and are thus not adapted for the identification of material parameters for SMAs.

The finite element model updating method (FEMU) (Kavanagh and Clough, 1971), a very intuitive approach, is widely utilized for the model parameters identification. This method is nowadays widely used since it can be applied to non-linear constitutive laws and a wide variety of homogeneous and heterogeneous mechanical tests (Chaparro et al., 2008; Pottier et al., 2011).

The method proposed here is first specifically developed for homogeneous superelastic tests. A cost function can be written in terms of a least square difference between the experimental and the numerically evaluated components of the mechanical field. The minimization of the cost function can be achieved using deterministic algorithms such as gradient-based Levenberg–Marquardt algorithm (Levenberg, 1944; Marquardt, 1963), real space evolutionary-inspired, genetic algorithms or Bayesian statistical approaches (Beck and Arnold, 1977). Hybrid methods are also developed, that combine several methods (e.g. genetic and gradient-based, Chaparro et al., 2008); Aguir et al. (2011) have proposed a hybrid identification strategy coupling finite elements, neural network computations and genetic algorithm.

The Levenberg–Marquardt optimization algorithm has been often adopted for the determination of material parameters for metals (Springmann and Kuna, 2005; Mahnken and Stein, 1996; Ghouati and Gelin, 1998; Cooreman et al., 2007). Moreover, it has been shown that for the identification of elastic–plastic parameters the Levenberg–Marquardt algorithm is efficient in terms of accuracy, stability and computational cost compared to other optimization algorithms, i.e. evolutionary and hybrid algorithms (de-Carvalho et al., 2011; Chaparro et al., 2008). More recently, this algorithm has been extensively used for the constitutive law parameter identification of several types of material such as biopolymer composites (Brahim et al., 2013). Spranghers et al. (2014) proposed a damped least-squares solution based on the

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