

EFFECTIVE MULTI-FIELD PROPERTIES OF ELECTRO-MAGNETO-THERMOELASTIC COMPOSITES ESTIMATED BY FINITE ELEMENT METHOD APPROACH**



Zhichao Zhang Xingzhe Wang*

(Key Laboratory of Mechanics on Environment and Disaster in Western China, The Ministry of Education of China; College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou 730000, China)

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ABSTRACT A finite element approach based on the micromechanics was performed to estimate the multi-field properties of electro-magneto-thermoelastic composites. The thermal field and the involved pyroelectric and pyromagnetic effect of the multi-phase composite materials were taken into account in the investigation and implemented in the finite element modeling. The multi-fields related to the electric field, magnetic field, deformation and temperature field, as well as their coupling effects of the smart composites under periodic boundary conditions were obtained numerically. Especially, by means of the homogenization approximation, the effective thermal expansion coefficients, pyroelectric coefficients, pyromagnetic coefficients and other elastic, electric, and magnetic properties for the piezoelectric material, piezomagnetic material and magnetoelectric material were calculated, respectively. Some results are compared to the theoretical predictions by the well-known Mori-Tanaka method to show good agreements.

KEY WORDS multi-field property, electro-magneto-thermoelastic composite, pyroelectric and pyromagnetic effect, FEM of micromechanics

I. INTRODUCTION

With wide potential applications in the aerospace, micro-electromechanical system, transportation and marine engineering, the smart materials and structures have evoked considerable interests in scientific and engineering communities. Due to the coupling effect between the material properties of the different constituents, the new unique effects that characterize the macroscopic composite but are absent from the constituents themselves can arise. The magnetoelectric, pyroelectric and pyromagnetic properties are known as the cross or product properties as examples of such properties. The contribution of second product effective due to the coupling of different phases plays a significant role even if the constituents of the composites exhibit intrinsic pyroelectricity properties^[1]. Pyroelectric devices have been utilized for various applications such as infrared detection, imaging systems, and thermal-medical diagnostics^[2] and have received increasing interest in recent years.

* Corresponding author. E-mail: xzwang@lzu.edu.cn

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Research on the modeling of predicting the effective property and response of smart composites can be classified into analytical and numerical approaches. Micromechanics methods are useful tool to predict effective properties of composites such as Green's function^[3,4]. Based on the dilute, self-consistent, Mori-Tanaka model (M-T) and differential micromechanics theories, Dunn and Taya^[5-7] simplified the piezoelectric Eshelby's tensor of elliptic fiber problem and extended analytical models to predict the effective electromechanical properties of piezoelectric composites. The Eshelby's tensor was further utilized in the piezoelectric-magnetic composites and the Mori-Tanaka mean field approach was developed by Li and Dunn^[8-10] to estimate effective properties of the two-phase magnetoelectric elliptic fiber composites. The expressions of effective thermal properties, including the coefficient of thermal expansion, pyroelectric coefficient and pyromagnetic coefficient, were given in their work. By the generalized Nemat-Nasser and Hori's multi-inclusion model in elasticity^[11], solutions of multi-inclusion and inhomogeneity problems that serve as basis for an averaging scheme to model the effective magnetoelectroelastic moduli of heterogeneous materials were reported^[12]. The generalized self-consistent method (GSCM) was also developed for predicting the effective properties of piezoelectric-magnetic fiber reinforced composites. The complex multi-field problem was reduced to a formal in-plane elasticity problem for which an exact closed form solution is available^[13]. Challagulla and Georgiades^[14] gave a general asymptotic homogenization model to analyze the longitudinally-layered composite material made of laminate of piezoelectric and piezomagnetic material.

Even if some analytical methods have been attempted to describe the behavior of the smart composites, the researches reported in recent literature more and more focused on two or three phase composites and the inclusions, such as elliptic fiber and cylinder fiber. Numerical methods, such as finite element method seems to be a well suited approach to describe the behavior of smart materials, as there are arbitrary geometries, material properties, size and phases involved in their analysis. Berger et al.^[15] used Representative Volume Element (RVE) method to predict the effective coefficients of periodic transversely isotropic piezoelectric fiber composites without the thermo-mechanics and thermo-electric couplings. Lee et al.^[16] developed a finite element method to calculate the effective elastic composite materials as well as electrical and magnetic properties of the magneto-electric materials. By calculating the distribution of various physical fields in the RVE they obtained effective properties of composite materials directly. In particular, the analytical Mori-Tanaka method to estimate the effective properties of multiphase composites has also been developed without consideration of the thermal effective coupling with other fields. From the viewpoint of thermodynamic potential and variation principle, Tang and Yu^[17,18] proposed a micromechanical model to calculate effective properties of periodic smart composites with piezoelectric and piezomagnetic phases. Their theoretical derivation invoked two linearized basic assumptions associated with the micromechanics concept. In recent year, the finite element method is further utilized to deal with the functionally graded materials^[19,20] and multilayered structures^[21] of smart composites.

It is necessary to develop a simple approach that is applicable to a variety of smart structures in complex fields. Additionally, there always encounters difficulties and complexity when the influence of thermal field on the pyroelectric and pyromagnetic couplings is taken into account. Our work focused on the estimation of effective multi-field properties especially the thermal coefficients in multi-phase smart composite materials. The distribution of the displacement, electric potential and magnetic potential in the RVE at a uniform temperature boundary condition were calculated. We compared our prediction results with the results of the Mori-Tanaka method in two-phase piezoelectric composites to show good agreements.

II. FUNDAMENTAL EQUATIONS AND MODEL

2.1. Governing Equation and Model Description

We consider the smart materials building up the composites which have linear coupled constitutive relations of magnetic electric elastic and temperature fields as below^[22]:

$$\begin{aligned}\sigma_{ij} &= C_{ijkl}\varepsilon_{kl} + e_{ijk}(-E_k) + q_{ijk}(-H_k) - \lambda_{ij}\theta \\ D_i &= e_{ikl}\varepsilon_{kl} - \eta_{ij}(-E_j) - a_{ij}(-H_j) - p_i\theta \\ B_i &= q_{ikl}\varepsilon_{kl} - a_{ij}(E_j) - \mu_{il}(-H_j) - m_i\theta\end{aligned}\tag{1}$$

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