International Journal of Engineering Science 75 (2014) 135–153

Contents lists available at ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

The effect of localized internal defects on the field distributions of electrostrictive composites

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A R T I C L E I N F O

Article history:
Received 28 August 2013
Received in revised form 12 November 2013
Accepted 14 November 2013
Available online 8 December 2013

Keywords:
Smart composites
Electrostrictive composites
Localized defects
Representative cell method
Higher-order theory
High-fidelity generalized method of cells

A B S T R A C T

The electromechanical field distributions in electrostrictive periodic composites with localized defects are determined. The composite is subjected to a combined electromechanical loading which is sufficiently far away from the localized internal defects. The present analysis forms a generalization of the linearly constitutive equations based approach for electro–magneto–elastic composites which has been recently presented. Presently, the nonlinear terms in the fully coupled constitutive relations of the phases as well as the effect of defects are combined and represented by eigen-electromechanical field terms which are a priori unknown, thus requiring an iterative procedure for establishing the solution. The analysis is based on the combined use of three approaches. In the first one, a micromechanical analysis establishes the concentration matrices needed for the determination of the far-field distributions in the composite's phases induced by the remote loading. In the second approach, the representative cell method is employed as a result of which the problem for a periodic composite, discretized into numerous identical cells, is reduced to a problem of a single cell in the discrete Fourier transform domain. The third approach consists of the application of the higher-order theory where the single cell is divided into several subcells, and the governing equations and interfacial conditions in the transform domain, imposed in an average (integral) sense, are solved. The inverse of the Fourier transform provides the actual electroelastic field at any point of the damaged composite. The offered method is verified by comparisons with analytical solutions, and several applications are presented for localized defects in the form of cavities and inclusions in an electrostrictive material subjected to combined electromechanical loadings. Next, the field distributions in two types of unidirectional composites with a missing fiber, subjected to electromechanical loadings are presented. In the first type, the composite consists of electrostrictive ceramic fibers reinforcing a polymeric matrix, whereas in the second one the electrostriction effect is enhanced by PZT fibers reinforcing an electrostrictive polymeric matrix. Comparisons between the resulting responses are discussed.

1. Introduction

Electrostriction describes the effect of generating mechanical deformation in a dielectric material as a result of the application of electric field. In some materials with sufficiently large dielectric permittivities (e.g., PMN ceramic) this effect is significant and can be utilized for sensing and actuation. Unlike piezoelectric materials, the relation between the induced strains and electric field is nonlinear of the second order. A brief discussion of electrostrictive materials is given in the book by Banks, Smith, and Wang (1996), for example, where several of their advantages and disadvantages are listed. Similarly,

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http://dx.doi.org/10.1016/j.ijengsci.2013.11.012

numerous advantages of electrostrictives over piezoelectric materials are mentioned in Moulson and Herbert (1990) such as the very low hysteresis that is exhibited by the former. Several practical applications of electrostrictive materials have been presented by Rittenmyer (1994) and Uchino (1986). A detailed account on piezoelectric and electrostrictive materials, actuators and their practical applications is given in a monograph by Uchino (1997). Like piezoelectric materials, electrostrictive materials can be utilized by combining them with polymers, thus forming a composite material that can be used in practical applications. For example, Takeuchi, Masuzawa, Nakaya, and Ito (1989) utilized electrostrictive-polymer composite as an ultrasonic probe for medical applications.

The constitutive equations of electrostrictive materials have been developed by Knops (1963) in the framework of two-dimensional problems and complex variables. This formulation has been utilized by Smith and Warren (1966) to solve the problem of a cavity, rigid inclusion and crack in an electrostrictive material subjected to a remote electric field. Based on Smith and Warren (1966) solution, the electrostrictive stresses near the crack have been extensively investigated by McMeeking (1989). In these investigations, the electric constitutive relations are not coupled to the mechanical effects. Recently, Kuang (2008) established the constitutive equations, equilibrium equations, interfacial and boundary conditions for electrostrictive materials by utilizing variational principles. He showed that in the previous investigations which were based on Knops (1963) developments, the Maxwell stresses have been ignored. The established equations by variational principles have been employed by Kuang and Jiang (2004), Jiang and Kuang (2007) and Gao, Mai, and Zhang (2010) to solve, by utilizing the complex variable technique, two-dimensional problems of inclusions and cracks in electrostrictive materials that are subjected to a far electric field. Here too, the coupling between the electric constitutive relations and the mechanical effects has been ignored.

The macroscopic response to an externally applied electromechanical loading of electrostrictive composites has been micromechanically predicted by Aboudi (1999). The behavior of the constituents in the latter investigation was based on the electrostrictive constitutive relations of Hom and Shankar (1994). Due to the nonlinearity of the governing equations, an incremental procedure in conjunction with tangential formulation has been implemented. This establishes the electromechanical instantaneous concentration tensors of and the effective tangent tensor of the electrostrictive composite, see Aboudi (1999) and Aboudi, Arnold, and Bednarcyk (2013) for details. The effective electrostrictive coefficients and the effective moduli of electrostrictive composites has been recently established by Li and Rao (2004a). Here, the electrostrictive polymeric by stiff PZT fibers which possess much higher dielectric constant in order to increase the overall dielectric constant of the composite. As a result, electrostriction enhancement is achieved since higher electrostrictive strain can be obtained from the same applied electric field. In this investigation, the constitutive behavior of the electrostrictive materials is describe by Eqs. (1) and (2) that are given in the following section.

Piezoelectric materials are characterized by five elastic parameters which describe their transversely isotropic behavior, their electromechanical coupling coefficients as well as by their dielectric constants. The electrostrictive effects provides however stronger performance as compared with the piezoelectric ones. It is possible to increase the dielectric constant of electrostrictive materials adding piezoelectric PZT ceramics which are characterized by high dielectric constants. As a result, a piezoelectric/electrostrictive composite is obtained with high effective dielectric constants, thus enabling the reduction of the applied field required to generate via the electrostrictive effect large strains, Li and Rao (2004a, 2004b). It is interesting to mention here the analysis of Tzou, Chai, and Arnold (2006) for thin shells made of materials that exhibit a dual electrostrictive and piezoelectric characteristics depending on the applied temperature.

In the presence of localized defects, a micromechanical procedure cannot be implemented due to the loss of a representative volume element in the composite that can be analyzed. An overview of several approaches for the analysis of various types of localized effects in thermoelastic composites with periodic microstructure has been presented by Aboudi and Ryvkin (2013). The field distributions in electro–magneto–elastic composites with localized defects have been recently predicted by Aboudi (2013). The governing equations in this article were linear, and the defects were chosen in the form of cavities, inclusions and cracks. In the present investigation the field distributions in electrostrictive periodic composites with localized defects is established. This forms a generalization of the previous analysis to a *nonlinear* one. The adopted electrostrictive constitutive equations are those established by Kuang (2008) and a full coupling between the mechanical and electrical field is preserved. As in Aboudi (2013), a remote loading is applied and the defects are distributed over a confined region within the electrostrictive material and fiber reinforced composites.

The analysis is based on the combination of three approaches namely, the high-fidelity generalized method of cells (HFGMC) micromechanical method, Aboudi et al. (2013), the representative cell method, Ryvkin and Nuller (1997), and the higher-order theory, Aboudi et al. (2013). In the first approach, the electromechanical field in the undamaged composite's constituents, induced by the remote applied electromechanical is determined by the HFGMC which establishes the concentration tensors from which the local field can be determined. In the second one, the discrete Fourier transform is applied on the periodic composite in which the distributed defects have been included. As a result, a single representative cell problem is obtained in the transform domain. In the third approach, the solution of the governing equations, interfacial and boundary conditions in the transform domain is achieved by employing the higher-order theory that was originally developed for the analysis of functionally graded material. In the framework of this theory the representative cell is divided into several subcells in everyone of which second-order expansions of the displacements and electric potential in the transform domain are employed, and the governing equations, interfacial and boundary conditions in this domain are imposed in the average (integral) sense. Once the solution of the representative cell problem has been established for all Fourier harmonics, an inverse transform is employed to obtain the actual electroelastic field in the composite. In the present investigation, the