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Model for piezoelectric/ferroelectric composites polarized with interdigitated electrodes

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ABSTRACT

A piezoelectric composite homogenization model (PCHM) is presented in this article. A systematic method for predicting the composite macroscopic history-dependent electromechanical response is developed and particularized for piezoelectric fiber composites polarized with interdigitated electrodes. As other composite models, the proposed PCHM requires appropriate constitutive equations describing each pure constituent namely, fiber and matrix. In this work, dielectric matrix is modeled as electromechanically linear while an existing non-linear phenomenological model is used for the fibers. Additionally, a cutting-plane algorithm is developed and implemented to integrate the fibers constitutive equation. The proposed PCHM is implemented in a previously developed ABAQUS/UEL piezoelectric shell.

To evaluate the proposed model, a representative elementary volume (REV) is analyzed with a finite element (FE) model using an ABAQUS/UEL piezoelectric brick and the same material models for each constituent of the composite. Practical examples are addressed with both, FE/REV and the proposed PCHM. Electromechanical responses predicted with both approaches are in good agreement. Numerical results illustrate the ability of the proposed PCHM to capture important aspects of piezoelectric devices such as quasi-linear range, as well as both, pressure and electric-field driven depolarization. Finally, a brief convergence analysis is performed indicating an encouraging computational performance of the proposed PCHM.

1. Introduction

Modern civilization evolution relies, to some extent, on the development of complex and efficient systems. Accordingly, several branches of science and technology are focused on developing systems with the ability of assessing a given situation and responding in a suitable manner. This functionality confers outstanding ability to fulfill the task or function for which they were designed. Despite the wide application range and diversity of the aforementioned kind of systems, some common desired features are devised e.g. optimum functionality, adaptation ability and integrated design [1]. A technological area deeply involved in active systems development is that one concerning active structures. The performance level achieved by them is very promising for numerous practical applications. The potential of these systems is reflected in the number of research papers focused on the subject published during the last decade [2–6].

Piezoelectric composites are attractive active materials. They could be used for constructing smart devices with imminent technological applications. Because of the great potential of piezoelectric composite materials in active structures and other micro-electromechanical systems, accurate material models capable of predicting their properties and response are of great interest. In structural applications, engineers and designers are generally focused on devices overall response. In those cases, the main objective of the modeling is the prediction of macroscopic material response avoiding an explicit constituent discretization. This topic has recently become the subject of intensive study. In this context, the development of reliable and efficient design and modeling tools is of main interest.

2. Literature review

Reliable and effective calculation tools for the effective properties of piezoelectric composites are highly desirable for the design of structural systems using this kind of materials. According to [7], first Maxwell [8] and Wagner [9] later, did, maybe, the initial

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attempts to theoretically predict the dependence of dielectric properties of a composite from its ceramic volume fraction. Five decades later, Buesson and Klinsberg [10] derived equations for the dielectric constants using series/parallel models. Subsequent models based on the aforementioned research were developed for piezoelectric composites. Earlier investigations were focused on deriving the properties of piezoelectric composites consisting of spherical inclusions immersed in a polymeric matrix. Later, these approaches were extended to consider piezoelectric fibers reinforced composites and others models have been proposed.

Numerous research works dealing with different approaches for the evaluation of the effective piezoelectric composite properties can be found in the specialized literature. Following [11], typical methods for the determination of the macroscopic properties of inhomogeneous media could be classified into three categories, namely effective medium theories, theoretical bounding methods and computational simulations. The former theories include the Eshelby, Mori–Tanaka [12] methods, self-consistent scheme [13,14], and other mean-field models [15]. The theoretical bounding methods consist of the Hashin–Shtrikman [16] lower and upper bounds as well as other higher-order bounds. Finally, the computationally intensive models typically use finite element or boundary element methods to calculate the response of a representative volume element of piezoelectric composites [15,17–19].

Investigations developed by Wang [20], Dunn and Taya [21], Chen [22] and Shodja et al. [23] extend the Eshelby classical solution for an infinite medium with ellipsoidal inclusions, in order to include the piezoelectric aspect. These approaches do not take into account the interactions between inclusions. The model presented by Odegard [24] is based on the self-consistent Mori–Tanaka method and the extensions proposed by Dvorak and Srinivas [25]. Other models were proposed for the analysis of history dependent non-linear effects in piezoelectric composite materials. The model proposed by Tan and Tong [26] uses uniform field model to capture the response to moderate and monotonic electric fields. Aboudi [27,28] uses a homogenization micro-mechanic based model for the study of the hysteretic response of a composite reinforced with ferroelectric fiber with periodic structure. Muliana [29] presents a simplified micro-electromechanical model averaging the field variables inside the volume. The model includes the hysteretic phenomena, repolarization of the fibers and the viscoelastic matrix effects. For this purpose, the model considers the electric field as a constant parameter, expressing the non-linear electromechanic coupling relations in terms of mechanic stress and electric field components.

Computational intensive approaches analyze the composite response identifying a representative elementary volume (REV), typically denoted as unit cell. The unit cell is identified in such a way that it exhibits the more relevant properties of the composite microstructure. Then, it is explicitly modeled and, by imposing suitable boundary conditions, the effective electromechanical properties are calculated. The electric field pattern and the ability to explode different coupling modes of piezo-composites are closely related to electrodes configuration. Bent and Hagood [15] propose a material model for piezoelectric composite laminates polarized with interdigitated electrodes. The model uses the uniform field method to obtain the effective material properties. The investigation includes comparisons with a finite element model for different constituent material properties, volume relations and electrodes geometric aspects. Based on this last model, Luccioni [30] proposes a formal, systematic approach in order to make series and parallel combinations of mechanical non-linear models. Martinez and Artemev [18] present a computationally intensive analysis of actuators and sensors constructed with piezoelectric laminates polarized with interdigitated electrodes. The analysis considers the presence of damaged fibers and the depolarization near the damaged zones. The authors present a quantification of the performance degradation associated with the fiber damage, reporting degradation levels up to 10%. Jayendiran and Arockiarajan [31] and Lin and Muliana [32] present simplified microelectromechanical models and physical tests for overall hysteretic response of active, 1–3 and 0–3 piezocomposites samples polarized with plate-type electrodes.

Interdigitated electrode pattern allows to exploit the maximum piezoelectric coupling [33] when in-plane actuation is needed, mainly in thin walled structures. Therefore, a numerical material model for composites reinforced with piezoelectric fibers polarized with interdigitated electrodes is presented in this paper. Based on the general composite materials mechanical model proposed by Luccioni [30], a systematic method for predicting the history dependent electromechanical material behavior and properties is developed in this work, emphasizing its relatively easy implementation and inclusion in a variety of general purpose finite element codes within an incremental analysis framework.

3. Proposed piezoelectric composite material model

As stated in the preceding section, the proposed piezoelectric composite homogenization model (PCHM) combines and extends existing approaches [15,30] introducing the electromechanical fields that take place in the considered piezoelectric composites in order to obtain their macroscopic properties, state and internal variables.

As other composite models, the proposed PCHM requires appropriate constitutive equations (CEs) of each pure constituents namely, fiber and matrix. A variety of constitutive models for the piezoelectric fibers, either linear or non-linear, can be included in the proposed model structure. In the context of this paper, the phenomenological ferroelectric model proposed by Huber and Fleck [34] is implemented along with a cutting plane algorithm, proposed in this work, to integrate the CE. This phenomenological model performs quite well for uni-axial loading states, which is consistent with fibers immersed in a soft matrix and far enough from electrodes zones. It exhibits good balance between implementation effort and ability to capture most of the main features of ferroelectric materials, e.g. independent evolution of both, strain and polarization states, as well as electric field and stress driven depolarization. The proposed homogenization model admits, certainly, the possibility of including other, more complex and reliable models.

Since various ideas and models from previous works are employed, it is convenient to state that the main contribution of this article is the combination of existing models, extending one of them to be able to handle electromechanical fields and the numerical implementation in the general purpose finite element package ABAQUS [35]. Fig. 1 underlines the fundamental models, ideas and their interrelations contributing to the proposed model.

3.1. Composite idealized representation

A piezoelectric composite lamina has the appearance depicted in Fig. 2. The lamina response is the result of various phenomena and processes taking place at different scales inside it. These scales definition are rather arbitrary and conveniently adopted for the analysis being performed. The fibers behavior could be analyzed with an approach characterized by a length scale called micro-electromechanical. The combination of fibers with a polymeric matrix forms the lamina whose analysis corresponds to the meso-scale. Finally, the macro-electromechanical scale is related to the behavior of piezoelectric laminate at structural level, when disposed as actuator or sensor.