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ScienceDirect

Computers and Structures 84 (2006) 2385–2395

Computers & Structures

www.elsevier.com/locate/compstruc

Mathematical modelling and finite element simulation of smart tubular composites

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Received 15 December 2005; accepted 26 June 2006
Available online 31 October 2006

Abstract

This paper presents a mathematical modelling and numerical simulation method for three-dimensional smart tubular 1(0)-3 composites based on a representative composite volume (RCV) approach. For the problems we consider, numerical results show that the maximum mechanical displacement varies linearly with the applied electrical potential and grows nonlinearly with increasing the RCV height. Further, we observe that decreasing the distance between the inner and outer radii results in increasing the maximum displacement. This refers to composites with large Young's modulus of the polymer phase, whereas for "soft" polymers (i.e. for Young's modulus of the polymers of order less than GPa) no particular 'rule' is evident, in which case the Poisson's ratio is the most important parameter.

Keywords: Piezocomposites; Tubular smart composites; Advanced materials; Numerical simulation; Finite element analysis

1. Introduction

The field of smart materials technology is an emerging multidisciplinary field (see e.g. [1,2]). Smart structures are important because of their relevance to hazard mitigation, structural vibration control, structural health monitoring, transportation engineering, thermal control, energy saving, sensing and actuation, etc. Research on smart structures has emphasized the incorporation of various devices in a structure for providing sensing, energy dissipation, actuation, control and other functions. Work on smart composites has focused on the incorporation of a functional material or device in a matrix material for enhancing the smartness or durability, while that on smart materials has studied piezoelectric materials used for making relevant devices. However, relatively little attention has been given to the development of structural complex composite materials that are inherently able to provide some of the smart functions, so that the need for embedded or attached devices is reduced or eliminated, thereby lowering cost, enhancing durability, increasing the smart volume, and minimizing mechanical property degradation, which usually occurs in the case of embedded devices.

In this paper, we are concerned with hollow (tubular) piezoelectric (or piezoceramic) composite materials, the description of which give papers [3–9]. Hollow piezocomposites have many advantages over other composites, as they allow higher frequency, lower acoustic impedance, higher sensitivity, larger displacements [10]. They are attractive for applications in biomedicine, flow noise control, aerospace technology, non-destructive testing, automotive instrumentation, various acoustical and oceanographical devices, etc. Piezocomposites (or piezoelectric composites) generally consist of two phases, and are described by two numbers which designate the type (or connectivity) of the material: the first number shows the dimension of the piezoactive phase and the second

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0045-7949/$ - see front matter © 2006 Published by Elsevier Ltd.
doi:10.1016/j.compstruc.2006.06.003

the dimension of the inactive phase (e.g. a polymer, air, iron, etc.) [8]. The hollow piezocomposite materials we will consider are known as type 1(0)-3. Here "1(0)" denotes that one-dimensional ("1") hollow ("0") piezoceramic cylinders are embedded into a three-dimensional ("3") polymer matrix. These piezocomposite materials consist of many piezoelectric hollow cylinders, each with radial polarization, embedded into a passive polymer matrix [11]. The hollow cylinders have electrodes on the inner and outer surfaces, allowing for displacements in both radial and longitudinal directions, that depend on the frequency, the inner and outer radii, the length of the tubes and the material properties. The hollow 1(0)-3 piezocomposites are more attractive than the 1-3 type previously used in the applications (where piezoceramic rods with longitudinal polarization are embedded in a polymer matrix) mainly because the radial poling of cylinders is easier to process than the longitudinal poling of rods; the cylinders have lighter weight and higher sensitivity [12]. Moreover, hollow cylinders used as piezoactive elements appear in many technical devices. The range of their applicability is steadily growing [13,14].

It is well-known that the finite element method (FEM) has the leading position in the area of numerical methods of the analysis of complex problems for media with different physical properties. For the first time it was suggested to use FEM for the piezoelectric materials in [15]. Some time later FEM development reached a stage at which this method was considered as the basis for many commercial packages. These packages (e.g. ANSYS, ABAQUS, PZFLEX, ATILA) are able to model and simulate existing piezoelectric devices with different boundary conditions. But the careful analysis of these large commercial packages shows that solutions of highly specialized problems with great number of physical and geometrical parameters and different boundary conditions are very expensive, difficult, and, generally, non-optimal. A detailed survey of the piezoelectric solid, shell, plate and beam finite elements can be found in [16,17]. These indicate that, although piezoelectric fiber composites have been well studied using the FE RCV technique (see e.g. [18]), piezoelectric tubular composites, as those considered here, have not yet been analyzed using the FE RCV method. It is then, the main objective of the present work to fill this gap.

This paper, which is an updated and extended version of Ref. [19], is organized as follows. Section 2 describes the 3D geometrical model of our object and methods we use in our computations. In Section 3 we present the specific boundary-value problem we solve. In Section 4 we present the constitutive equations for our composite object. In Section 5 we present the solution of the problem. In Section 6 we present our results in graphical form, and, finally, in Section 7 we end with our conclusions. All results are given in terms of the maximum mechanical displacement versus such parameters as applied electric potentials, thickness of the ceramic tube, ceramic volume fraction, etc.

2. 3D model

The experimental investigation of electrical and mechanical properties of tubular piezoelectric composites is generally expensive. For this reason, we resort to numerical simulation to analyze the material properties. In this project it is necessary to consider a 3D model (due to the overall non-axisymmetric nature of our problem). We will employ a finite-element-based methodology for a representative composite volume (RCV) of a typical hexagonal cell, as it is presented in Fig. 1. An additional motivation for this project is that commercial codes in existence (e.g. ANSYS, ABAQUS, PZFLEX, ATILA) are not very efficient towards axisymmetric piezoceramic applications [20]. Therefore, it is essential to introduce and develop a new methodology and to construct a code for studying our 3D model.

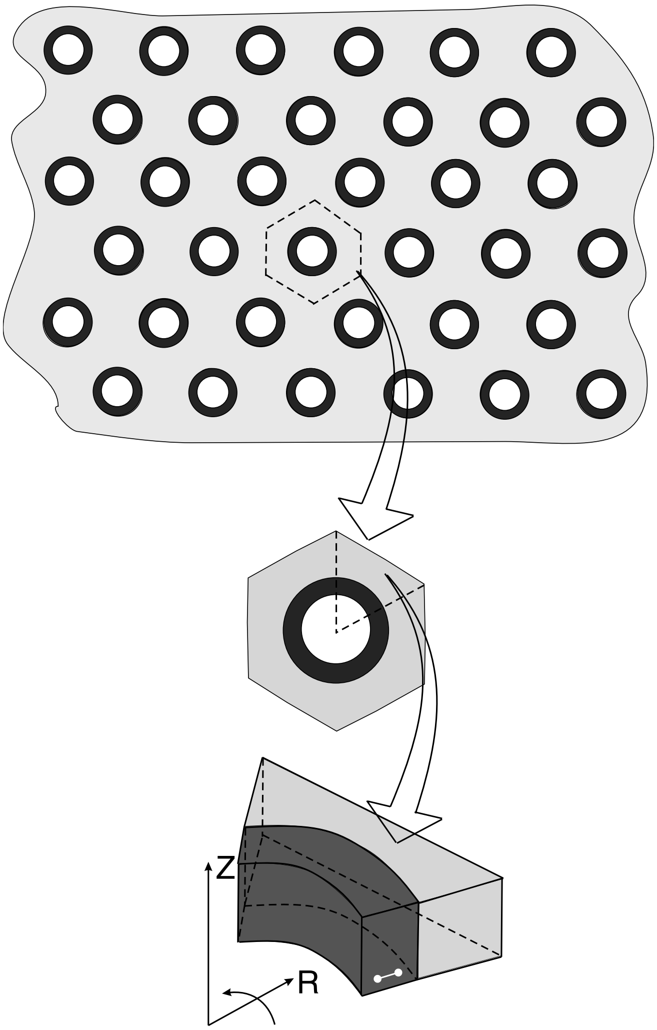

Fig. 1. A top view of 1(0)-3 piezocomposites; a model for simulation (white line is the polarization direction).