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On the relationships between cellular structure, deformation modes and electromechanical properties of piezoelectric cellular solids

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ABSTRACT

Piezoelectrically active cellular solids are reminiscent of passive structural cellular solids, and therefore, depending on their inner cellular architecture, their cellular ligaments can deform locally by either bending or axial stretching. Three main cellular solid structures (i.e. hexagonal, tetragonal and triangular) that exemplify bending and stretching dominated piezoelectrically active cellular solids are considered. Three-dimensional finite element models were developed to understand the relationships between cellular structure, deformation modes and their effective electromechanical properties. The principal elastic, dielectric and piezoelectric properties of piezoelectric 3-1 cellular solids are insensitive to inner structure or topology in the longitudinally poled systems and highly sensitive to structure in the transversely poled systems. The in-plane electromechanical properties are highly sensitive to cellular architecture and connectivity as well. The effective out-of-plane elastic properties for all the three cellular structures depend linearly on relative density (i.e. stretching dominated), while the dependence of the in-plane effective elastic properties is linear for triangular and tetragonal cellular structures (i.e. stretching dominated) and generally non-linear for hexagonal honeycombs (i.e. bending dominated). Amongst the longitudinally poled systems, the triangular structures exhibit the highest in-plane stiffness properties. Amongst the transversely poled systems, the tetragonal structure exhibits the best overall combination of piezoelectric figures of merit.

1. Introduction

Piezoelectrically active materials play an instrumental role in a wide range of actuating and sensing applications such as hydrophones, ultrasound and echo-cardiogram devices, wherein they undertake the critical role of converting mechanical energy (e.g., due to vibrations or static strain) to electrical energy (i.e., charge) and vice versa. Piezoelectric materials intended for sensing applications are required to ideally possess a combination of characteristics such as high piezoelectric sensitivity (i.e. the ratio of the generated electric energy to the applied mechanical energy) and low acoustic impedance. Existing monolithic piezoelectric ceramics (e.g., lead zirconate titanate (PZT), barium titanate) and polymers (e.g., PVDF) exhibit less than ideal combined characteristics; ceramics have high piezoelectric sensitivity and high acoustic impedance while piezoelectric polymers exhibit low piezoelectric sensitivity and low acoustic impedance. Only composite piezoelectric materials, including both porous piezo-composites (e.g., Alvarez-Arenas and de Espinosa, 1996; Alvarez-Arenas and Freijo, 1996; Banno, 1987; Bast and Wersing, 1989; Bowen et al., 2004; Bowen and Topolov, 2003; Chen and Wu, 2004; Dunn and Taya, 1993b; Hikita et al., 1983; Iyer and Venkatesh, 2010, 2011; Kar-Gupta and Venkatesh, 2006, 2007c; Kara et al., 2003; Mikata, 2001; Nagata et al., 1980; Piazza et al., 2005; Ramesh et al., 2005; Ting, 1985; Zhang et al., 2007) and polymer based piezo-composites (e.g., Dunn and Taya, 1993a,c; Guinovart-Díaz et al., 2001; Hossack and Hayward, 1991; Kar-Gupta and Venkatesh, 2007a,b; Newnham et al., 1978; Pettermann and Suresh, 2000; Poizat and Sester, 1999; Ramesh et al., 2006; Richard et al., 2004; Skinner et al., 1978)., show promise in providing the required combined characteristics of high piezo-sensitivity and low acoustic impedance. Available piezoelectric composites, although having played a prominent role in sensing devices, are far from demonstrating ideal combinations of high piezoelectric sensitivity and reduced acoustic impedance. In addition, promising existing piezo composites (i.e., 3-1) is limited to one directional piezo-activity, along the piezo elements axial direction. A promising approach that allow for achieving closer to ideal combinations of characteristics, multi-dimensional piezo-sensitivity and tunable piezo crystal symmetry is to tailor the microstructure of piezo-composites.

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Continuing efforts along this path have put the spotlight on a promising subclass of piezo-porous composites, namely piezoelectric cellular solids (e.g., Bosse et al., 2012; Challagulla and Venkatesh, 2009, 2012; Kar-Gupta and Venkatesh, 2007a, b, 2008; Marcheselli and Venkatesh, 2008) and piezoelectric ferroelectret foams (Bauer et al., 2004; Fang et al., 2007)

Recently, piezoelectric cellular solids have attracted significant interest and several experimental (Arai et al., 1991; Haun and Newnham, 1986; Li et al., 2003; Marselli et al., 1999; Ting, 1985; Ueda et al., 2010) analytical (Banno, 1987; Bowen and Topolov, 2003; Dunn and Taya, 1993b; Dunn and Wienecke, 1997; Espinosa and Tarakci, 1977) and numerical-based (Bosse et al., 2012; Challagulla and Venkatesh, 2012; Challagulla and Venkatesh, 2013; Iyer and Venkatesh, 2010, 2011; Kar-Gupta and Venkatesh, 2006, 2007c; Marcheselli and Venkatesh, 2008) studies have been performed to understand their potential, characterize their electromechanical properties and elucidate the dependence of their macroscopic properties on their inner cellular architecture (i.e. property-microstructure coupling). These efforts confirmed that piezoelectric cellular solids can exhibit significantly enhanced combinations of electromechanical properties (i.e. higher piezoelectric sensitivity and reduced acoustic impedance) (Challagulla and Venkatesh, 2012), and have shown that electromechanical properties of cellular solids depend on: shape of the porosity (e.g. spheroidal or fiber-like), cellular interconnectivity (i.e. open vs. closed cells), aspect ratio of pore geometry and level of porosity.

Prior efforts, experimental, analytical and computational, have assessed the impact of porosity on acoustic impedance and sensitivity of piezoelectric materials. Experimental studies considered several porosity configurations, including: enclosed porosity in a piezoelectric material (i.e., 3-0 type) (Arai et al., 1991; Haun and Newnham, 1986; Li et al., 2003; Marselli et al., 1999; Ting, 1985; Ueda et al., 2010); long continuous fiber-like porosity, similar to a fiber composite (i.e., 3-1 type foam) (Bast and Wersing, 1989; Wirges et al., 2007) and open-foam like porosity (i.e., 3-3 type foam) (Lee et al., 2007; Roncari et al., 2001). Results confirmed that porosity assist in enhancing the sensitivity of piezoelectric materials.

Analytical models developed to study porous piezoelectric materials considered multiple porosity configurations (3-0 and 3-1 types), and aimed to establish predictive theories to describe the electromechanical properties of piezoelectric porous materials. These analytical models either utilized simplified geometries (Banno, 1987; Bowen and Topolov, 2003; Iyer and Venkatesh, 2014) or an Eshelby-type inclusion problem by employing a Green's function approach (Dunn and Taya, 1993b; Dunn and Wienecke, 1997). Models showed that an increase in porosity leads to an increase in the figures of merit (i.e., enhanced sensing sensitivity).

Though analytical models were useful, their predictive utility was limited as they employed simplifying assumptions (e.g., geometric), generally utilized transversely isotropic constituents and could not easily accommodate complex geometries (e.g., stochastically distributed porosity, complex 3-3, 3-0 and 3-1 geometries). To accommodate accurate details, realistic porosity configurations, material anisotropy and to study the effect of the poling direction, porosity shape and orientation, finite element based analysis proved more suitable. Efforts along this path illustrated the positive correlation between porosity, increased piezoelectric sensitivity and reduced acoustic impedance (Marcheselli and Venkatesh, 2008), and emphasized the importance of pore geometry and configuration. For instance, piezoelectric properties were found to be sensitive to porosity shape in 3-0 type foams (Iyer and Venkatesh, 2010, 2011) and porosity relative orientation to poling direction in 3-1 foams (Kar-Gupta and Venkatesh, 2006, 2007c).

The aforementioned studies of piezoelectric cellular solids highlighted the strong coupling between effective electromechanical properties and cellular architecture. As for passive cellular solids this coupling can be seen as a consequence of cellular ligaments acting as networks with admissible deformation modes (Alkhader and Vural, 2008, 2009; Evans et al., 2001; Fleck et al., 2010; Pingle et al., 2011). Theoretically, this structure-property coupling can be exploited to optimize or application-tailor piezoelectric cellular solids. However, to usefully exploit this coupling it should be understood first; in particular, geometric cellular features and associated deformation modes that strongly affect the macroscopic electromechanical properties should be identified and analyzed.

Literature from passive isotropic cellular solids suggests that one of the main issues related to structure-property coupling is the role of the dominant deformation mode (i.e., bending vs. stretching (Andrews et al., 2001; Ashby et al., 2000; Deshpande et al., 2001; Onck et al., 2001; Shi and Tong, 1995)), which in turn is influenced by nodal connectivity (i.e. the average number of ligaments connected to a vertex) and the nature of applied stresses (Alkhader and Vural, 2010; Papka and Kyriakides, 1998). For piezoelectric cellular solids, there is added complexity due to the elastic, dielectric and piezoelectric anisotropy of the cellular solids constituents, the coupled electromechanical nature of the problem, the sensitivity to the poling direction and its orientation with respect to the porosity of cellular solids. Furthermore, the relationship between deformation modes, effective electromechanical properties and geometric features such as nodal connectivity in piezoelectric cellular solids is not yet completely understood or even explored.

Hence, in this paper, we develop finite element models to characterize the effect of deformation modes (bending vs. stretching) on the complete electromechanical properties of piezoelectric active cellular solids by studying two dimensional piezoelectric cellular solids with varying cellular architectures, representative of cellular solids with bending and stretching dominant deformation modes. Representative cellular solids include perfect honeycomb (represent bending dominated cellular solids), 2D triangular structure (represent stretching dominated cellular solids) and tetragonal structure (represents cellular solids with mixed or load dependent deformation modes)

The present work has been organized as follows. Section 2 illustrates the utilized methodology and discusses the details of the developed finite element models. Results are discussed in Section 3 and principal conclusions from the present study are highlighted in Section 4.

2. Methodology

2.1. *Structure of piezoelectric cellular solids*

Three classes of two dimensional honeycomb-like piezoelectric cellular solids are considered (Fig. 1). These have been selected to represent cellular solids with low, moderate and high nodal connectivity, which can exhibit bending-dominated, mixed-mode, or stretching-dominated deformation characteristics, depending on the loading conditions. Nodal connectivity, α, is defined as the average number of ligaments connected at a node (vertex). The low connectivity class is represented by a hexagonal honeycomb structure ($\alpha = 3$) while the moderate connectivity class is represented by tetragonal structure ($\alpha = 4$), and the high connectivity class is represented by triangular structure ($\alpha = 6$).

From literature of passive cellular solids we infer that, low connectivity honeycombs generally deform in a bending mode under in-plane normal and shear loading conditions, while highly connected cellular structures, (with a connectivity of 6 in 2D), generally deform in a stretching mode under all loading conditions (Alkhader and Vural, 2008, 2009; Deshpande et al., 2001; Guo and Gibson, 1999). The tetragonal structures deform in a mixed-mode depending on the in-plane loading direction; when the load is aligned with ligaments it deforms in a stretching mode but when the load is not aligned with cellular ligaments (and for in-plane shear loading) tetragonal