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Mechanical performance of piezoelectric fiber composites and electroelastic field concentration near the electrode edges

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ABSTRACT

As important smart materials, piezoelectric fiber composites (PFCs) have shown excellent performance in many areas. However, the electric field strength concentration at the edge of the interdigital electrode may lead to crack propagation and eventual actuating failure of PFCs. In this paper, a novel analytical solution on the electroelastic response of PFCs is proposed to characterize the mechanical performance and obtain optimal structure parameters. The problem is converted to a singular integral equation with logarithmic kernel. By solving the resulting equation, the distributions of electric potential, electric displacement, electric field strength, and strain of PFCs fiber are obtained. The finite element method (FEM) is employed to confirm the results. The results demonstrate that the electric displacement and strain of PFCs are dramatically affected by the permittivity properties and piezoelectric constant of materials. The PFCs made by PZT-5H have higher surface electric displacement than PZT-5A and PZT-4. For a ratio of W/L = 1/4, both the electric field and strain obtained the minimal value at the electrode edges, which is better for the mechanical performance of PFCs. Moreover, when the thickness of fibers decreases, the actuating performance of PFCs improves and the probability of fracture failure lessens.

1. Introduction

Smart materials such as piezoceramics, magnetostrictives, shape memory alloys, electrostrictive polymers, ionic polymers, ferromagnetic shape memory alloys, etc., have been widely used in aerospace, aeronautic, industrial, and biomedical applications [1–5]. Piezoelectric materials are one of the most widely considered materials for smart structure design because of their light weight, compactness, and cost-effectiveness. Piezoceramics are the most commonly used piezoelectric materials. To overcome the inherent brittle nature of monolithic piezoceramic wafers, active fiber composite (AFC) was initially developed and comprised circular cross-sectional piezoceramic fibers embedded in epoxy matrices [6]. The strength, conformability, and toughness of such composites were significantly improved compared to those of monolithic piezoceramics. Polymer-based piezoelectric materials, i.e., poly(vinylidene fluoride) (PVDF) and its copolymers, have also attracted much attention in sensing applications and have also been investigated in composite structures [7–9]. Macro fiber composites (MFC) with rectangular cross-sectional fibers were later developed to improve the contact between the piezoelectric fiber and the interdigital electrodes (IDE) [10]. The two structures of AFC and MFC are referred to as piezoelectric fiber composites (PFCs), which combine excellent piezoelectric properties with good flexibility and durability offered by epoxy matrices and polyimide assembling layers [11]. Because of their improved structural integrity and actuation capability due to a stronger longitudinal piezoelectric effect along the length of the fiber, piezoelectric fiber composites have been extensively applied in the fields of actuation [12], sensing [13], structural health monitoring [14], energy harvesting [15], and more.

Although the advantage of the PFCs' integrated structure is remarkable, the application of IDE could lead to distinctly inhomogeneous electric field distribution [16], which influences the performance of PFCs. Some simulation techniques such as ANSYS [17–19] or ABAQUS [20] were used to investigate the influence of geometrical parameters to acquire the optimum actuation performance of PFCs. Bowen et al. [21] reported that when the ratio of electrode finger width to substrate thickness was 0.5, the PZT wafers could obtain the maximum strain. Beckert [22] claimed that both decreasing the electrode finger width and increasing the electrode finger spacing could improve the actuation performance of PFCs with circular fibers. These studies mainly focused on the actuation performance of PFCs with the influence of structural parameters.

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Moreover, multilayered piezoelectric actuators with IDE structure also showed the electroelastic field concentration at the edges of the electrodes, which were validated by both experiments and finite element simulations [23]. Similarly, piezoelectric fiber composites also showed high field distortion near electrode edges, which could lead to crack propagation or failure [6]. The electroelastic field concentration near electrodes has been modeled by the finite element method, and a simple semi-empirical approximation was formulated to characterize the efficiency of actuators with IDE [24]. It was observed that a crack initiated under the electrode finger and ran through the thickness; this was attributed to the accumulated electric field strength by finite element analysis [25].

This work proposed an analytical method to deal with the electroelastic response and to characterize the mechanical performance of PFCs. By the Fourier series technique, the problem under consideration is transformed to a weakly singular integral equation with logarithmic kernel. After solving this equation, we obtained the electric field strength and strain on the electrode edges. The effectiveness of the suggested approach is confirmed by comparing our results with those based on the finite element method. The effect of structure parameters on the distribution of electric potential, electric displacement, electric field strength, and strain on the fibers of PFC are discussed and optimal structural parameters are determined.

2. Statement of the problem and basic theory

Typically, PFCs are the composites formed of isotropic and orthotropic layers and are represented as symmetric, hybrid, cross-ply laminate or $[\mathrm{Iso}_{\mathrm{Kapton}}/\mathrm{Iso}_{\mathrm{acrylic}}/90^{\circ}_{\mathrm{copper}}/0^{\circ}_{\mathrm{PZT}}]_{\mathrm{S}}$ [10], as shown in Fig. 1. The epoxy matrix deforms due to the coupling between the piezoelectric fiber and epoxy matrix.

For simplicity, the effect of epoxy is neglected due to the relatively small elastic modulus and volume fraction compared to those of piezoelectric materials. To propose an analytical model, a unit cell comprising all relevant parameters should be defined. Because of the symmetry of the structure, a representative volume element (RVE) could simply be defined as a fiber unit between the IDE fingers, as shown in Fig. 2, where L is the invariable length of RVE, $W/2$ denotes half of the electrode finger width, P is the electrode spacing, and 2H is the piezoceramic fiber thickness in the modeling. The model is a right-handed coordinate system with 3-direction coinciding with the poling direction. The electric potential, electric field, electric displacement, stress, and strain are accordant with the same rule in every RVE. Notice that the piezoelectric properties of PFCs may not be homogeneous because the polarization direction does not necessarily coincide with the fiber direction. For simplicity, it is assumed that the direction of polarization is parallel along the 3-direction, possessing uniform material properties. This simplification has been commonly used in FEM analysis. According to the d_{33} effect, the piezoceramic fiber stretches and shrinks along the poling direction under the driving voltage.

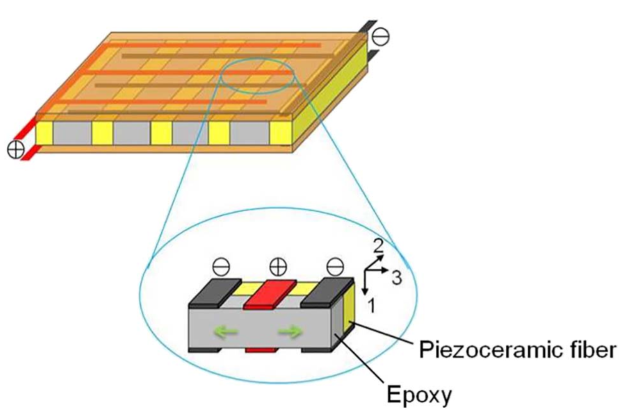

Fig. 1. Schematic view of PFCs and the representative volume element (RVE) with principal material and (1-2-3) coordinate systems.

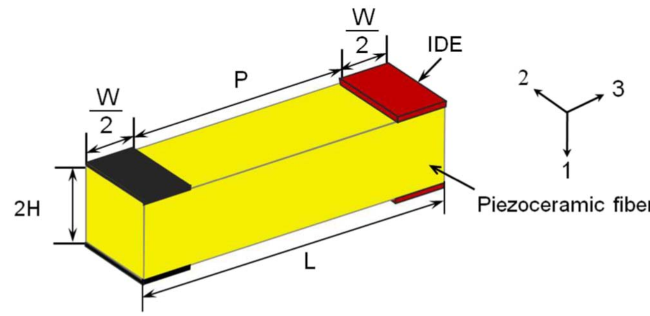

Fig. 2. The RVE modeling of PFCs and the geometry parameters.

2.1. Basic equations

Choosing the strain and electric field strength components as the primary unknowns, the static equilibrium equations and constitutive equations for piezoelectric materials [26] are as follows:

$$\begin{aligned} &\sigma_{ji,j}=0,\ D_{i,i}=0,\ in\quad V,\\ &\sigma_{ij}=c_{ijkl}S_{kl}-e_{kij}E_k,\ D_i=e_{ikl}S_{kl}+\varepsilon_{ik}E_k,\ in\ \ V,\\ &S_{ij}=(u_{i,j}+u_{j,i})/2,\ E_i=-\varphi_{,i}=-\frac{\partial\varphi}{\partial i},\ in\ \ V. \end{aligned} \tag{1}$$

where u denotes the mechanical displacement vector, σ is the stress tensor, S is the strain tensor, E is the electric field strength, D is the electric displacement, φ is the electric potential, $\sigma_{ji,j}$ is the abbreviation of $\frac{\partial\sigma_{ji}}{\partial j}$, and so on. The coefficients c_{ijkl}, e_{kij}, and ε_{ik} are the elastic, piezoelectric, and dielectric constants, respectively. Consider the problem in a state of plane strain; that is, there is no stress coupling effect between the piezoelectric layer and the epoxy layer, and the epoxy layer thickness is assumed to be thin enough.

Because of the plane strain assumption, the in-plain displacements are only related to the 1- and 3-direction and are independent of the 2-direction. Thus, we have $u_2=$ constant, $u_1=u_1(x,z)$, $u_3=u_3(x,z)$, and $\varphi=\varphi(x,z)$, which leads to nontrivial stress and electric displacement of $\sigma_1,\sigma_2,\sigma_3,\sigma_{13},D_1,D_3$ through the above constitutive equations, which become

$$\begin{aligned} &\sigma_1=c_{11}u_{1,1}+c_{13}u_{3,3}+e_{31}\varphi_{,3}\\ &\sigma_2=c_{12}u_{1,1}+c_{13}u_{3,3}+e_{31}\varphi_{,3}\\ &\sigma_3=c_{13}u_{1,1}+c_{33}u_{3,3}+e_{33}\varphi_{,3}\\ &\sigma_{13}=c_{44}(u_{1,3}+u_{3,1})+e_{15}\varphi_{,1}\\ &D_1=e_{15}(u_{3,1}+u_{1,3})-\varepsilon_{11}\varphi_{,1}\\ &D_3=e_{31}u_{1,1}+e_{33}u_{3,3}-\varepsilon_{33}\varphi_{,3} \end{aligned} \tag{2}$$

where the stiffness coefficients are simplified due to the crystal structure of the piezoceramics.

Under such circumstances, the equilibrium equations reduce to $\sigma_{1,1}+\sigma_{13,3}=0$, $\sigma_{13,1}+\sigma_{3,3}=0$, and the Gauss equation simplifies to $D_{1,1}+D_{3,3}=0$. Substituting the above constitutive equations into the equilibrium equations, the Gauss equation yields [27]:

$$\begin{aligned} &c_{11}u_{1,11}+c_{44}u_{1,33}+(c_{13}+c_{44})u_{3,13}+(e_{31}+e_{15})\varphi_{,13}=0\\ &(c_{13}+c_{44})u_{1,13}+c_{44}u_{3,11}+c_{33}u_{3,33}+e_{15}\varphi_{,11}+e_{33}\varphi_{,33}=0\\ &(e_{15}+e_{31})u_{1,13}+e_{15}u_{3,11}+e_{33}u_{3,33}-\varepsilon_{11}\varphi_{,11}-\varepsilon_{33}\varphi_{,33}=0 \end{aligned} \tag{3}$$

2.2. Boundary conditions

Because the problem is symmetric with respect to the $z=0$ plane, only the right half part of the medium needs to be considered, and the vertical displacement and shear stress on the middle plane ($x=H$)