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Modeling and simulation of macro-fiber composite layered smart structures

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ABSTRACT

Piezo fiber composite material, macro-fiber composite (MFC), is increasingly applied in engineering, due to its high flexibility and strong actuation forces. This paper develops a linear electro-mechanically coupled finite element (FE) model for composite laminated thin-walled smart structures bonded with orthotropic MFCs having arbitrary piezo fiber orientation. Two types of MFCs are considered, namely, MFC-d31 in which the d_{31} effect dominates the actuation forces, and MFC-d33 which mainly uses the d_{33} effect. The FE model is developed based on the Reissner–Mindlin hypothesis using linear piezoelectric constitutive equations. The present results are compared with ANSYS and experimental results reported in the literature (Bowen et al., 2011). Afterwards, isotropic or composite structures with cross-ply laminates, integrated with MFC-d31 or -d33 patches having different fiber orientation, are simulated under a certain electric voltage on the MFC patches.

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1. Introduction

Structures integrated with smart materials, e.g. piezoelectric, magnetostrictive and shape memory alloy, are applied increasingly in many fields of technology for shape control, vibration control and health monitoring. Amongst them piezoelectric materials are the most widely used ones in industrial applications due to a number of beneficial properties that these materials possess. Piezoceramics, like lead zirconium titanate (PZT), have a high structural stiffness, which generates strong actuation forces. However, there are several practical limitations to implement this typically lead-based piezoceramic materials, for example the brittle nature of ceramics which makes them susceptible to fracture during handling and bonding procedures, and their extremely limited ability to fit with curved surfaces [1]. Another very frequently used piezoelectric material is polyvinylidene fluoride (PVDF), which is much more flexible than piezoceramics, but with low actuation forces.

The idea of a hybrid material consisting of piezoceramic fibrous phase embedded in epoxy matrix phase remedies many of the aforementioned limitations. The first type of this piezo fiber composite material is referred to as 1–3 composite, and is manufactured by Smart Material Corp. [2]. The second type are active fiber composite (AFC) actuators, which were originally developed by MIT and were the first composite actuators primarily used on structural actuation [1]. The third one, macro-fiber composite (MFC), was developed by NASA Langley Research Center in 1999 [1,3,4]. The flexible nature of MFC allows the material conforming to a curved surface easily. Additionally, an MFC patch even has larger actuation forces than a PZT patch, since the d_{33} effect dominates the actuation mode in MFCs. For more detailed information of active piezoelectric fiber composites, we refer to [5–7]. Because of these beneficial properties of piezoelectric fiber composites, considerable efforts have been made to integrate this material into metal structures for vibration control [8,9] and health monitoring [10–12].

Due to the complexity of MFC structure, many researchers focused on the determination of material properties for homogenized MFC patches based on experimental or numerical investigations. The very early material properties of MFC, including the basic elasticity constants for orthotropic thin-walled structures in both the linear elastic region and the nonlinear constitutive behavior, were obtained experimentally by Williams et al. [13]. Later, Park and Kim [14], predicted the material properties of MFC using classical lamination theory and uniform fields model. Furthermore, Deraemaeker et al. [15–17] proposed a representative volume

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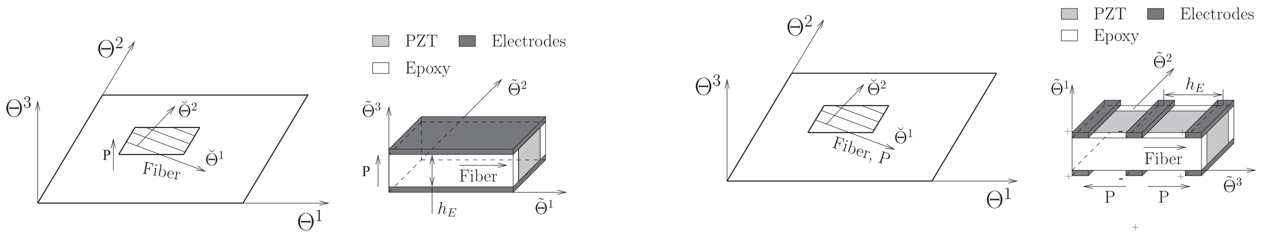

(a) MFC-d31 structure (b) MFC-d33 structure

Fig. 1. Schematic of different kinds of MFC models.

element (RVE) technique and mixing rules for the determination of equivalent material properties of both d_{31}- and d_{33}-type MFCs, while Biscani et al. [18] developed an asymptotic expansion homogenization (AEH) method for material parameters of d_{31}-type MFCs. Additionally, actuation properties for MFC under strong voltages were investigated by Williams et al. [19] using the theoretical piezoelectric constitutive model with higher-order electric field proposed in [20]. Analogously, Schröck [21] investigated experimentally the hysteresis and creep effects in structural dynamics of MFC bonded plates.

In order to get the structural response of MFC integrated smart structures, some papers available in the literature discussed simulation techniques with the assistance of commercial software, e.g. ANSYS [22,23], ABAQUS [24,25], and compared the results with those from experiments. Furthermore, Bowen et al. [23] predicted the cured shape and snap-through of asymmetric bistable laminates actuated by piezoelectric macro fiber composites attached to the laminate with the help of ANSYS. A similar prediction of piezoelectric-induced snap-through of a bistable carbon fiber reinforced plastic combined with an MFC was conducted by Giddings et al. [26]. Beyond usage of commercial softwares, Bilgen et al. [27] built a linear distributed parameter electro-mechanical model for frequency response analysis of MFC actuated clamped-free thin beams, and compared their results with experiments. Similarly, Azzouz and Hall [28] developed a von Kármán nonlinear FE model based on the first-order shear deformation (FOSD) hypothesis for frequency response of a rotating MFC actuator.

From the aforementioned publications, it can be seen clearly that most of them presented various applications and experimental investigations of MFC materials, as well as homogenization of MFC using analytical solutions or experimental results. Fewer papers developed a general FE model of thin-walled smart structures bonded with d_{31}- and d_{33}-type MFC layers or patches, after the first MFC manufactured in 1999. It is well known that since 1990's the modeling and simulation of monolithic piezoelectric materials is booming. A large number of papers appeared in the literature developed linear models of thin-walled metal structures bonded with monolithic piezoelectric layers or patches using 2-dimensional (2D) finite elements based on various hypotheses, e.g. Kirchhoff–Love hypothesis [29,30], Reissner–Mindlin hypothesis [31–34], third- or higher-order shear deformation hypotheses [35,36], and zigzag hypothesis [37–39]. About one decade later, more and more researchers took geometrically nonlinear effects into account for FE modeling of piezoelectric layered smart structures undergoing large displacements, see e.g. in [40–47] among others.

However, the above mentioned study on simulation of MFC bonded structures were carried out with commercial software, and they did not take the fiber angle variation into account, which may influence significantly the structural response. Moreover, very less work has been developed and presented for modeling and simulation of MFC bonded smart structures. In order to model and simulate fiber-based MFC piezo materials with various fiber angle arrangement, this paper is to develop a linear FE model for thin-walled structures integrated with d_{31}- and d_{33}-type MFC layers or patches using 2D finite elements based on the Reissner–Mindlin hypothesis. MFC is a piezo fiber material, consisting of monotonic piezoelectric material, epoxy matrix and electrodes with a specific arrangement, which can be considered as homogenized orthotropic materials with arbitrary piezo fiber angles like composite structures. The host structures are comprised of one isotropic metal layer or composite structures with cross-ply or angle-ply laminates. The model is first validated by one example from the literature, and then used for calculation of cantilevered plates with various fiber orientation for both host structures and MFCs.

2. MFC models

Macro fiber composites mainly consist of piezoceramic fibers, epoxy matrix and electrodes, which have two different types of structures, yielding d_{31} or d_{33} modes. The first type, abbreviated as MFC-d31, has piezoelectric material polarized in the thickness direction normal to the fiber direction, thus the d_{31} effect is dominating the actuation forces. However, the second type of MFC, denoted as MFC-d33, is arranged in a specific manner such that the polarization of the piezoelectric material is along the piezo-fiber direction. Therefore, MFC-d33 can use the d_{33} effect for generation of actuation forces, which is usually much larger (about 2 times larger) than the d_{31} effect. Additionally, actuation voltages for MFC-d31 patches can be applied in the range from -60 to 360 V (with the electrode separation of 0.18 mm), while those for MFC-d33 patches can vary between -500 and 1500 V (with center-to-center interdigitated electrode spacing of 0.5 mm) [2]. The schematic of these two kinds of MFCs are shown in Fig. 1(a) and (b), respectively.

This kind of arrangement for electrodes also improves structural flexibility. Because the electric field is applied at regular intervals, any damage or fracture of the piezoceramics or electrode merely reduces the performance of a small area surrounding the defect and will not significantly reduce the overall actuation effect [23].

In the present model, three coordinate systems are employed, as can be seen in Fig. 1, namely the curvilinear coordinate system represented by Θ^i $(i = 1, 2, 3)$, the fiber coordinate system denoted by $\breve{\Theta}^i$, and the polarization coordinate system shown as $\tilde{\Theta}^i$. The curvilinear coordinate system is usually attached to thin-walled structures with the Θ^3-line defining the thickness direction, representing the geometry of the respective structures; the fiber coordinate system defines the fiber orientation, which gives the fiber angle between Θ^1 and $\breve{\Theta}^1$; and the polarization coordinate system is used for MFC material with the $\tilde{\Theta}^3$-line pointing along the direction of polarization of piezoelectric material.

From the previous study on homogenization of MFC materials, it is known that MFC can be treated as an orthotropic material, see e.g. [15–18] among others. In this paper we consider MFC

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