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Detecting laminate damage using embedded electrically active plies – An analytical approach

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ABSTRACT

Assessment of damage initiation and progression in composite laminates with embedded electrically active plies is modeled. Utilizing electrically active layers embedded in composite laminates as damage sensors is proposed by several researchers and is mainly assessed experimentally. Sensing damage using embedded electrically active plies is generally preferred over the use of surface mounted PZT wafers since the range of the latter is limited to a very narrow area underneath the surface, while multiple damage mechanisms can generally be found in several plies of the laminate.

The solution presented invokes two levels of analysis. Firstly, on the laminate level, applied membrane loads and/or bending moments induce stresses in the plies according to some distribution factors, which depend on the elastic properties and thickness fractions of the plies. To obtain these factors, the conventional lamination theory is implemented. Secondly, on the ply level, each unidirectional composite ply, whether electrically active or inactive, is modeled using the Mori-Tanaka averaging model. Both the fiber and matrix stresses are computed and a response in the form of electrical displacement is found in the electrically active plies. Upon damage in certain plies, some eignstresses are applied such that the stress components, which invoke the damage criteria vanish. These eignstresses affect not only the failed plies but also other plies and subsequently the overall behavior of the laminate. Deviations in the electric response of electrically active plies from that found in the undamaged state serves as a damage detector.

This paper outlines a transformation field methodology which implements the above formulation and shows examples for laminates subjected to bending moments. Variation of the electric displacement with the progression of damage is examined in terms of the location of the electroactive ply within the laminate thickness.

1. Introduction

Coupled behavior of piezoelectric materials such as PZT is now a well-established tool for structure health monitoring. Nowadays, PZT is widely used to build electrically active composites by embedding PZT filaments into a resin matrix to form piezoelectric monolayers rather than using them in their bulk form [1]. Accordingly, the overall mechanical and electrical properties of the electrically active composites must be measured or estimated. This can be found for example in the work of Aboudi [2], Berger et al. [3], Challagulla and Georgiades [4], Chen [5], Hadjiloizi et al. [6,7], Della and Shu [8], and Kumar and Chakraborty [9]. Sartorato et al. [10,11] presented a numerical formulation for a finite element shell taking into account a double curvature geometry with some or all layers of piezoelectric composite. The analysis was performed under dynamic load for natural frequencies and compared with experimental results. Overall moduli of piezoelectric composites with imperfect fiber-matrix adhesion were investigated in the work of Brito-Santana el al. [12] where interface parameters to account for the interface damage were introduced. Tita et al. [13] presented the overall moduli of a smart composite utilizing the RVE approach for both undamaged composite and the composite with imperfect fiber/matrix adhesion. The authors introduced the notion of presenting the interface region in the form of springs with degradable stiffness according to imperfection level.

The use of piezoelectric wafer active sensors, PWAS, for structural health monitoring is on the rise. Many researchers have developed different techniques to utilize surface mounted PWAS for the detection of damage in composites. Among them are Giurgiutiu [14], Giurgiutiu and Soutis [15], Micheal and Bahei-El-Din [16] and Hasan and Muliana [1].

Application on utilizing surface mounted PWAS in detection of the dynamic behavior of a damaged unidirectional composite plate

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in the form of the change in frequency of the plate is an approach followed by Medeiros et al. [17]. The results were presented both experimentally and numerically. On the other hand, the use of vibration based techniques using PZT sensors to detect any change in stiffness, mass or damping due to inherent damage is found in the work of De Medeiros et al. [18] for composite cylinder and its application in automotive components.

Recently, the focus in health monitoring of composite structures has been on embedded sensors. This alleviates the adhesion problems found in the surface mounted ones and relays more reliable information on internal damage. This can be found in the work of Stojic et al. [19] where piezoelectric patches were embedded in concrete structures for the detection of internal cracks. The same approach has been recommended by Lin and Sodano [20] and Qing et al. [21]. The benefits of this methodology can be found in the work of De Medeiros et al. [22] where the authors present a new damage metric involving the amplitude and the phase under a certain frequency range. Bahei-El-Din and Micheal [23], on the other hand, utilized the electric displacement of PZT fibers to monitor stress concentration for a plate with a central hole. Meanwhile some research has focused on the effect of such inclusions, albeit their small dimensions, on causing stress concentrations [24].

The focus of this paper is on integrating a lamina with electrically active fibers within the layup of a composite laminate to exploit its electric response in detecting the initiation and progression of damage. The paper implements the transformation field analysis [25] to model damage in fibrous laminates. In this approach, damage is modeled by introducing transformation or eign fields to the local regions of the composite plies, which has been affected by damage based on given criteria, such the total stress is evacuated [26]. The paper starts with outlining the laminate governing equations in Section 2, the micromechanical model implemented for a unidirectional, fibrous composite in Section 3, and constitutive equations of piezoelectric materials in Section 4. The damage criterion assigned to the composite constituents is described in Section 5, and is followed in Section 6 by a description of how the electrically active lamina embedded within the laminate layup can serve as a damage detector. Finally, the method is applied to a laminate subjected to external moment in Section 7, and salient conclusions are given in Section 7.

2. Laminates

Consider a symmetric laminate of n unidirectional, fibrous composite laminas with a total thickness $2t$ and lamina thickness t_i, $i = 1, n$. The laminate global coordinate system is denoted x_j, $j = 1, 2, 3$, where x_1x_2 coincides with mid-plane of the laminate. The lamina principal material axes are denoted $\bar{x}_k$, $k = 1, 2, 3$, Fig. 1. The laminate is subjected to external membrane forces $\boldsymbol{\mathcal{N}} = [\mathcal{N}_1, \mathcal{N}_2, \mathcal{N}_{12}]$ and bending moments $\boldsymbol{\mathcal{M}} = [\mathcal{M}_{11}, \mathcal{M}_{22}, \mathcal{M}_{12}]$.

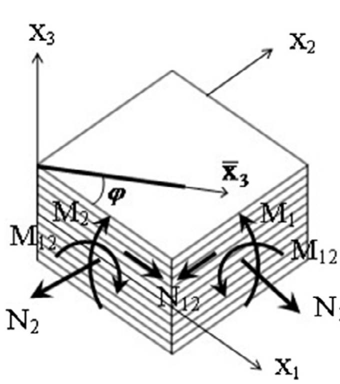

Fig. 1. Geometry and loads of a fibrous laminate.

These represent resultants of the lamina in-plane stresses $\hat{\sigma}_i = (\sigma_{11}, \sigma_{22}, \sigma_{12})$, $i = 1, n$. If in addition the laminas are subjected to transformation stresses $\hat{\lambda}_i = (\lambda_{11}, \lambda_{22}, \lambda_{12})$, $i = 1, n$, which are not removed by unloading of the external loads, membrane forces and bending moments. In analogy with the transformation field analysis developed for inelastic deformations [25,26], the lamina stresses are found as the superposition of the overall and local effects as [27]:

$$\hat{\boldsymbol{\sigma}}_i(z_i) = \boldsymbol{P}_i\boldsymbol{\mathcal{N}} + \boldsymbol{Q}_i\boldsymbol{\mathcal{M}} + \sum_{j=1,n}\boldsymbol{U}_{ij}\hat{\boldsymbol{\lambda}}_j. \tag{1}$$

The coefficient matrices $\boldsymbol{P}_i$ and $\boldsymbol{Q}_i$ denote stress distribution factors for the membrane forces and external moments, respectively, and $\boldsymbol{U}_{ij}$ denotes stress transformation influence functions. They vary point wise along the laminate thickness, and are a function of the laminate geometry and mechanical properties of the laminas [27],

$$\boldsymbol{P}_i = L_i(\boldsymbol{A}' + z_i\boldsymbol{C}'), \tag{2}$$

$$\boldsymbol{Q}_i = L_i(\boldsymbol{B}' + z_i\boldsymbol{D}'), \tag{3}$$

$$\boldsymbol{U}_{ij} = \delta_{ij}\boldsymbol{I} - t_j\boldsymbol{P}_i - (t_jz_j)\boldsymbol{Q}_i. \tag{4}$$

where,

$$\boldsymbol{A}' = (\boldsymbol{I} - \boldsymbol{B}'\boldsymbol{B})\boldsymbol{A}^{-1}, \boldsymbol{B}' = -\boldsymbol{A}^{-1}\boldsymbol{B}\boldsymbol{D}', \boldsymbol{C}' = -\boldsymbol{D}'\boldsymbol{B}\boldsymbol{A}^{-1},$$
$$\boldsymbol{D}' = [\boldsymbol{D} - \boldsymbol{B}\boldsymbol{A}^{-1}\boldsymbol{B}]^{-1}, \tag{5}$$

$$\boldsymbol{A} = \sum_{i=1,n}t_i\boldsymbol{L}_i, \boldsymbol{B} = \sum_{i=1,n}(t_iz_i)\boldsymbol{L}_i, \boldsymbol{D} = \sum_{i=1,n}t_i\left(\frac{1}{12}t_i^2 + z_i^2\right)\boldsymbol{L}_i \tag{6}$$

Here, z_i represents the x_3 coordinate of the mid-plane of the ply, and $\boldsymbol{L}_i$ represents the lamina stiffness matrix described in the laminate global coordinate system, and under in-plane stress.

Evaluation of all the above coefficient matrices centers on defining the overall elastic moduli of the individual laminas and hence the stiffness matrix L_i. While any micromechanical model of a fibrous composite can be utilized, this is described next in terms of the averaging models.

3. Averaging model

Let $\bar{\boldsymbol{\sigma}} = (\sigma_{11}, \sigma_{22}, \sigma_{33}, \sigma_{23}, \sigma_{31}, \sigma_{12})$ and $\bar{\boldsymbol{\varepsilon}} = (\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{33}, 2\varepsilon_{23}, 2\varepsilon_{31}, 2\varepsilon_{12})$ denote the lamina stress and strain described in the material principal axes, $\bar{x}_k$, $k = 1, 2, 3$, of a unidirectional fibrous composite, such that $\bar{\boldsymbol{\sigma}} = \bar{\boldsymbol{L}}\bar{\boldsymbol{\varepsilon}}$. The elastic stiffness matrix, $\bar{\boldsymbol{L}}$, can be expressed in terms of elastic moduli of the fiber and matrix and their volume fraction using the Mori-Tanaka model [28]. This centers of Eshelby's solution of an infinitely long cylindrical inclusion embedded in a matrix of a different material [29] to find explicit forms for the fiber and matrix stress and strain concentration factors [30]. The result was utilized by Chen et al. [31] to determine the Mori-Tanaka overall moduli of a fibrous composite in the following explicit form,

$$p = \frac{2v_fp_mp_f + v_m(p_mp_f + p_m^2)}{2v_fp_m + v_m(p_f + p_m)},$$
$$m = \frac{m_mm_f(k_m + 2m_m) + k_mm_m(v_fm_f + v_mm_m)}{k_mm_m + (k_m + 2m_m)(v_fm_m + v_mm_f)}, \tag{7}$$

$$k = \frac{v_fk_f(k_m + m_m) + v_mk_m(k_f + m_m)}{v_f(k_m + m_m) + v_m(k_f + m_m)},$$
$$\ell = \frac{v_f\ell_f(k_m + m_m) + v_m\ell_m(k_f + m_m)}{v_f(k_m + m_m) + v_m(k_f + m_m)}, \tag{8}$$