Available online at www.sciencedirect.com

ScienceDirect

International Journal of Solids and Structures 44 (2007) 8751–8768

INTERNATIONAL JOURNAL OF SOLIDS AND STRUCTURES

www.elsevier.com/locate/ijsolstr

Generalized layerwise mechanics for the static and modal response of delaminated composite beams with active piezoelectric sensors

Nikolaos A. Chrysochoidis, Dimitris A. Saravanos *

Department of Mechanical Engineering and Aeronautics, University of Patras, Patras GR26500, Greece

Received 16 October 2006; received in revised form 14 June 2007
Available online 3 August 2007

Abstract

A coupled linear layerwise laminate theory and a beam FE are formulated for analyzing delaminated composite beams with piezoactuators and sensors. The model assumes zig-zag fields for the axial displacements and the electric potential and it treats the discontinuities in the displacement fields due to the delaminations as additional degrees of freedom. The formulation naturally includes the excitation of piezoelectric actuators, their interactions with the composite laminate, and the effect of delamination on the predicted sensory voltage. The quasistatic and modal response of laminated composite Gr/Epoxy beams with active or sensory layers having various delamination sizes is predicted. The numerical results illustrate the strong effect of delamination on the sensor voltage, on through the thickness displacement and on the stress fields. Finally, the effect of delamination on modal frequencies and shapes are predicted and compared with previously obtained experimental results.

Keywords: Composite materials; Laminate; Delamination; Modelling; Finite element; Beams; Piezoelectrics

1. Introduction

The development of active structural health monitoring systems and techniques using piezoelectric actuator and sensor wafers or films is an area experiencing significant technical activity. Particular emphasis is placed on the active structural health monitoring methods for composite structures, as the likelihood of internal defects, and the evolution of invisible damage in the composite material during service life remains high. One candidate type of damage is delamination cracks, which are usually induced during low-velocity impact and fatigue, remain hidden and can propagate quickly leading to catastrophic failure. Among the many open issues in this field is the development of analytical and numerical models capable of capturing the effect of delaminations on the structural response, particularly on the electromechanical response components associated with the piezoelectric actuators and sensors, as such models may help understand the sensitivity of

* Corresponding author. Tel.: +30 2610996191; fax: +30 2610997234.
E-mail address: saravanos@mech.upatras.gr (D.A. Saravanos).

0020-7683/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijsolstr.2007.07.004

electromechanical response on damage parameters, and thus provide a basis for the development of damage detection and localization techniques and the design of the smart composite system. To this end, this paper presents a layerwise mechanics theory and a finite element for analyzing laminated beams with delamination cracks and active piezoelectric sensors.

Early work in the area was focused on the effects of a single delamination on the natural frequencies of composite beams (Tracy and Pardoen, 1989; Nagesh Babu and Hanagud, 1990; Paolozzi and Peroni, 1990; Shen and Grady, 1992) and plates (Tenek et al., 1993; Rinderknecht and Kroplin, 1995) using experimental results and simple analytical beam and plate models of the so-called "four-region" approach. Keilers and Chang (1995) presented experimental work for identifying a delamination in composite beams using built-in piezoelectric sensors. A generalized composite beam model for predicting the effect of multiple delaminations on the modal damping and modal frequencies of composite laminates was reported together with experimental studies (Saravanos and Hopkins, 1996), which treated the opening and sliding at the delamination interfaces as additional degrees of freedom. Barbero and Reddy (1991) used a layerwise laminate theory to describe plates with multiple delamination cracks between the layers. Di Sciuva and Librescu (2000) presented a geometrically non-linear theory of multilayered composite plates and shells with damaged interfaces, Luo and Hanagud (2000) presented a model for describing the static, modal and dynamic response of delaminated beams using a nonlinear approach based on piecewise linear spring models between the delaminated sublaminates; Thornburgh and Chattopadhyay (2001) used a higher-order theory to model matrix cracking and delamination in laminated composite structures; Hu et al. (2002) analyzed the vibration response of delaminated composite beams using a higher-order finite element with a C_0 type finite element materials; and Diaz Valdes and Soutis (1999) presented experimental work on the detection of delaminations in composite beams using piezoelectric actuator and sensor. Chrysochoidis and Saravanos (2004) investigated mainly experimentally effects of delamination on the modal parameters and frequency response functions of artificially delaminated composite beams obtained via attached piezoceramic actuators and sensors pairs and demonstrated the potential of the latter compared to other traditional sensors. Chattopadhyay et al. (1999) studied the dynamics of delaminated composite plates with piezoelectric actuators using a third-order shear theory and more recently (Chattopadhyay et al., 2004) reported a refined layerwise theory for the prediction of the vibration of delaminated plates considering the crack faces interface contact using a system of nonlinear springs.

The previous studies have shown that vibration methods based on lower vibrational modes are insensitive to detecting small size delaminations, hence, pointing to the excitation and monitoring of more localized response and higher frequency modes. The later also suggests the development of analytical and numerical models, which can capture local effects of delaminations. In the present paper, an electromechanically coupled layerwise theory is described for composite beams with piezoelectric actuators and sensors, treating interfacial sliding, crack opening and slope discontinuity across a delamination crack, as additional degrees of freedom. The generalized stiffness, mass piezoelectric, and permittivity matrices are formulated and a 2-node finite element is further developed. The new finite element capabilities are evaluated by predicting the effect of a single delamination on the modal and quasistatic response of composite beams with passive or active piezoelectric layers. The analytical predictions of the modal frequencies are further correlated with available measurements. Also the delamination mode shapes are presented showing the delamination "*breathing*". Through these model predictions, some mechanisms capable of revealing the delamination presence are further discussed with an eye toward active delamination detection.

2. Theoretical formulation

This section presents the formulated mechanics for piezoelectric laminated beams with interlaminar delamination cracks.

2.1. Governing material equations

Each ply is assumed to exhibit linear piezoelectric behavior. In the current beam case, in-plane and interlaminar shear strains are considered in the elastic field. The piezoelectric materials considered are monoclinic class two crystals with the poling direction coincident with the z-axis. The constitutive equations have the form