Advanced Research in Design, Manufacturing and Materials

Edited by
Sandip A. Kale, Kumar D. Sapate
and Prakash S. Dabeer

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PREFACE

Research is a continuous process through which many developments take place for a better life in the world. It is this motivation which has resulted in organizing an "International Symposium on Engineering and Technology (ISET-2014), on 9-10th January 2014 at Trinity College of Engineering and Research, Pune, one of the premier technical Institutes, affiliated to University of Pune. The ISET 2014 comprised three conferences,

1. International Conference on Design, Manufacturing and Mechatronics
2. International Conference on Automotive Technology
3. International Conference on Renewable Energy and Sustainable Development

This has been the theme in bringing the Industrialists, academicians, scientists and technologists globally to a single platform through this international symposium to discuss the state of the art of technology and to make a guideline for future study and research work.

We are delighted by the enthusiastic response of both Indian and overseas authors in submitting excellent research papers to this conference. It is strongly believed that the special volume, based on papers presented in ISET 2014, entitled "Advanced Research in Design, Manufacturing and Materials" will serve to demonstrate the depth of current innovations and research and also acts as a reliable source of information for making significant advances in the this area.

Foreign delegates from Japan, South Korea, Australia, Iran, Egypt, Malaysia, Nigeria and Bangladesh added the international flavor to the symposium. The symposium featured eight invited keynote speeches.

Special gratitude is extended to all the reviewers who went through the works of the contributors meticulously to enhance the quality of the papers. The valuable advice from reputed persons in the International and National advisory committee is also gratefully acknowledged. We express sincere thanks to our KJEI's Hon, President Shri. Kalyan Jadhav, and Campus Director Dr. Ashok Ghatol for all the support for organizing this symposium.

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Vibration Control of Sandwich Plates

B. Basa[1,a] ,S. K. Sarangi [2]
Institute of Technical Education and Research (ITER), SOA University, Bhubaneswar, India
sarojksarangi@yahoo.com

Keywords: Vibration control, Active fiber composites, Finite element modeling

Abstract.This paper presents the active control of vibrations of sandwich plates using piezoelectric composites (PZC). The top surface of the plate is integrated with the patches of active constrained layer damping treatment. Active fiber composite, one of the commercially available PZCs, is used as the material of the constraining layer of the patches and the constrained layer of the patch is composed of a viscoelastic material. Considering the first order shear deformation theory individually for each layer of the sandwich plate, a three-dimensional finite element model has been developed. The performance of active fiber composite for the smart vibration control of the sandwich plates has been studied and numerical results are presented. Emphasis has also been placed on investigating the effect of variation of piezoelectric fiber orientation angle in the constraining layer on the control authority of the patches.

Introduction

Sandwich structures with laminated fiber-reinforced composite face sheets and soft low strength core material like the honeycomb are being widely used in different engineering applications. Sandwich plates are composed of two thin face sheets and a thick flexible core [1]. The face sheets of the sandwich plates are basically unidirectional laminated fiber-reinforced composites, while the core is a thick layer of low-density material, like foam polymer or honeycomb material [2]. The moment of inertia of the structure increases substantially by the separation of the face carriers from the core [3].

Expediently, it was discovered that piezoelectric materials can be used as distributed sensors and actuators for developing 'smart structures' with self-monitoring and self-controlling capabilities [4–9]. Because of the low magnitudes of the piezoelectric coefficients of the monolithic piezoelectric materials, large control voltage is required to achieve significant control of smart structures. For efficient use of these piezoelectric materials having very low control authority, the concept of active constrained layer damping (ACLD) treatment [10] was developed which has gained wide acceptability for the purpose of efficient and reliable control of flexible structures. Piezoelectric composite (PZC) materials, composed of an epoxy matrix reinforced with fibers of monolithic piezoelectric materials, are now used as distributed actuators and sensors of smart structures. These PZCs provide a wide range of effective material properties not offered by the existing monolithic piezoelectric materials. One of the commercially available PZC is the active fiber composite (AFC), developed by Bent and Hagood [11]. A lamina of AFC is composed of piezoceramic fibers horizontally aligned in the plane of the lamina while the fibers are poled along their length. The top and the bottom surfaces of the lamina are equipped with patterns of interdigitated electrode fingers which are mirror images of each other. Each pattern consists of alternatively aligned positive and negative electrode fingers and is placed transverse to the fibers such that the electric field is created along the length of the fibers. Such an arrangement of electrodes in the AFCattributes the distributed actuator made of AFCwith high in-plane actuation authority along the fiber direction.

Research activities on the active damping of smart composite structures using AFCmaterialwith interdigitated electrodes are very limited. Recently, Zhang and Shen [12] analyzed the performance of AFC actuator for the vibration suppression of laminated plates. From the open literature on active control of smart structures, it seems that, the performance of AFC material, which is commercially available, has not yet been studied for the purpose of active control of laminated composite sandwich plates.

In this paper, the authors intend to investigate the performance of AFC material as the material of the constraining layer of the ACLD treatment for active control of thin laminated sandwich plates. For such investigation, a three-dimensional analysis of the ACLD of thin laminated composite sandwich plates integrated with the patches of ACLD treatment has been carried out by finite element method. The effect of variation of piezoelectric fiber orientation angle in the constraining AFC layer on the control authority of the ACLD patches has also been studied.

1. Finite Element Model

Figure 1 illustrates a smart laminated composite sandwich plate. The top and the bottom faces of the sandwich plate are composed of number of orthotropic layers. The top surface of the top face of the sandwich plate is integrated with the patches of the ACLD treatment. The constraining layer of the ACLD treatment is made of the AFC material and the constrained layer of the treatment is made of a viscoelastic material. Since the elastic properties of the adjacent continua of the overall structure differ in orders, a single displacement theory cannot be used to describe the kinematics of deformations of the overall structure and thus five sets of displacement fields describing the kinematics of deformation and satisfying the boundary conditions are used. These are expressed as follows:

For the core, the top layer, the viscoelastic layer and the PZC layer

$$u_i(x,y,z,t) = u_{0i}(x,y,t) + \lambda_1(z)\theta_i(x,y,t) + \lambda_2(z)\alpha_i(x,y,t) + \lambda_3(z)\beta_i(x,y,t) + \lambda_4(z)\gamma_i(x,y,t)$$

where $\lambda_1(z) = z - \langle z - h/2 \rangle$, $\lambda_2(z) = \langle z - h/2 \rangle - \langle z - h_{N+1} \rangle$, $\lambda_3(z) = \langle z - h_{N+1} \rangle - \langle z - h_{N+2} \rangle$, $\lambda_4(z) = \langle z - h_{N+2} \rangle$ and for the bottom layer

$$u_i(x,y,z,t) = u_{0i}(x,y,t) - \frac{h}{2}\theta_i(x,y,t) + \left(z + \frac{h}{2}\right)\Phi_i(x,y,t) \quad (1)$$

The in-plane displacements, u and v and the transverse displacement w are expressed corresponding to $i = x, y$ or z. The generalized displacement variables are grouped into translational $\{d_t\}$ and rotational $\{d_r\}$ variables as $\{d_t\} = [u_0 \ v_0 \ w_0]^T$ and

$$\{d_r\} = [\theta_x \ \theta_y \ \theta_z \Phi_x \Phi_y \Phi_z \ \alpha_x \alpha_y \ \alpha_z \ \beta_x \ \beta_y \ \beta_z \gamma_x \gamma_y \gamma_z]^T$$

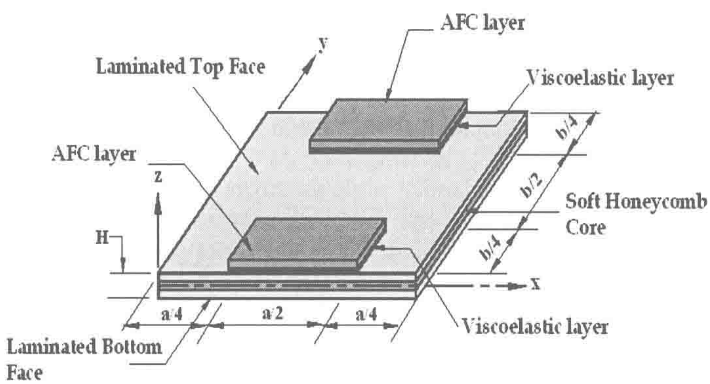

Fig. 1.Schematic representation of a Sandwich plate integrated with the patches of ACLD treatment composed of AFC constraining layer.

The constitutive relations for the materials of the different layers of the top and the bottom face of the sandwich plate and that of the flexible core are given by

$$\{\sigma_b^K\}=[C_b^k]\{\varepsilon_b^k\} \text{ and } \{\sigma_s^K\}=[C_s^k]\{\varepsilon_s^k\}$$

where $[C_b^k]$ and $[C_s^k]$ are the transformed elastic coefficient matrices for a particular layer. Assuming that the viscoelastic layer is linear and isotropic, its shear modulus G and the Young's modulus E are represented as $G = G'(1 + i\eta)$ and $E = 2G(1 + \upsilon)$. The constitutive relations for the material of the viscoelastic layer are expressed employing the complex modulus approach [13].

In the present work, the electric field E_x is applied in the x direction and the constitutive equations for the AFC material are expressed as

$$\{\sigma_b^k\} = [\bar{C}_b^k]\{\epsilon_b^k\} - \{e_b^k\}E_x, \{\sigma_s^k\} = [\bar{C}_s^k]\{\epsilon_s^k\} \text{ and } D_z = \{e_b^k\}^T\{\epsilon_b^k\} + \bar{\epsilon}_{11}E_x.$$

The electric field E_x is given by $E_x = -V/d_p$ with d_p and V being the distance between the positive and the negative electrodes and the applied voltage difference between these electrodes, respectively.

The overall plate is discretized by eight noded isoparametric quadrilateral elements. The generalized displacement vectors at any point within the element can be written as

$$\{d_t\} = [N_t]\{d_t^e\} \text{ and } \{d_r\} = [N_r]\{d_r^e\}$$

in which $[N_t]$ and $[N_r]$ are the shape function matrices. Using the principle of virtual work, the open loop equations of motion of an element integrated with the ACLD treatment are obtained as

$$[M^e]\{\ddot{d}_t^e\} + [K_{tt}^e]\{d_t^e\} + [K_{tr}^e]\{d_r^e\} = \{F_{tp}^e\}V + \{F^e\} \quad (2)$$

$$[K_{tr}^e]^T\{d_t^e\} + [K_{rr}^e]\{d_r^e\} = \{F_{rp}^e\}V \quad (3)$$

in which $[K_{tt}^e]$,$[K_{tr}^e]$ and $[K_{rr}^e]$ are the elemental stiffness matrices, $\{F_{tp}^e\}$ and $\{F_{rp}^e\}$ are the elemental electro-elastic coupling vectors, $\{F^e\}$ is the elemental load vector and $[M^e]$ is the elemental mass matrix.

Since the elastic constant matrix of the viscoelastic layer is complex, the stiffness matrices of an element integrated with the ACLD treatment are complex. For an element without integrated with the ACLD treatment, the electro-elastic coupling matrices become null vectors and the elemental stiffness matrices will be real. Finally, the elemental equations of motion are assembled to obtain the open loop global equation of motion of the overall plate integrated with the ACLD patches.

The active constraining layer of the ACLD patch is activated with a control voltage proportional to the transverse velocity of a point. Thus the control voltage can be expressed in terms of the derivatives of the global nodal degrees of freedom as

$$V^j = -K_d^j\dot{w} = -K_d^j[U^j]\{\dot{X}\}$$

in which K_d^j is the control gain of the j^{th} patch and $[U^j]$ is a unit vector defining the location of sensing the velocity signal that will be fed back to this patch. Finally, the equations of motion governing the closed loop dynamics of the overall plate/ACLD system are obtained and expressed as

$$[M]\{\ddot{X}\} + [K_{tt}]\{X\} + [K_{tr}]\{X_r\} + \sum_{j=1}^{m}\{F_{tp}^j\}K_d^j[U_t^j]\{\dot{X}\} + \sum_{j=1}^{m}\{F_{tp}^j\}K_d^j = \{F\} \quad (4)$$

$$[K_{rt}]\{X\} + [K_{rr}]\{X_r\} + \sum_{j=1}^{m}\{F_{rp}^j\}K_d^j[U_t^j]\{\dot{X}\} + \sum_{j=1}^{m}\{F_{rp}^j\}K_d^j\frac{h}{2[U_r^j]\{X_r\}} = \quad (5)$$

2. Results and Discussion

In this section, numerical results are computed using the finite element model derived in the previous section to assess the performance of the ACLD patch for causing active damping of laminated composite sandwich plates. The thicknesses of the constraining AFC layer and the viscoelastic layer are considered to be 250 μm, 200 μm, respectively. The aspect ratio (a/H)and the thickness of the substrate sandwich plate are considered as 100 and 0.003m, respectively while the orthotropic faces of the substrate plate are modeled as three layers of equal thickness. The complex shear modulus, the Poisson's ratio and the density of the viscoelastic constrained layer are used as 20(1+ i) MN/m^2, 0.49 and 1140 kg/m^3, respectively [13]. The material properties of the core and the face sheets of the sandwich plate are considered as follows [14]:

Core: $E_1=E_2=E_3=0.10363$ GPa, $G_{12}=G_{13}=G_{23}=0.05$ GPa, $\upsilon_{12}=\upsilon_{13}=\upsilon_{23}=0.33; \rho=130\ Kg/m^3$
Facings: $E_1=131$ GPa, $E_2=E_3=10.34$ GPa, $G_{12}=G_{13}=6.895$ GPa, $G_{23}=6.205$ GPa, $\upsilon_{12}=\upsilon_{13}=0.22, \upsilon_{23}=0.49, \rho=1627\ Kg/m^3$.
The effective material properties of the AFC material obtained from [15] are used here for evaluating the numerical results.

$C_{11}=138.1$ GPa, $C_{12}=71.15$ GPa, $C_{22}=148.9$ GPa, $C_{44}=C_{55}=32.35$ GPa, $C_{66}=39.14$ GPa,
$e_{11}=14.14\ C/m^2$, $e_{12}=e_{13}-3.34\ C/m^2$, $e_{16}=0$.

Two patches are used which are placed on the top of the sandwich plates as shown in fig.1. The length and the width of each patch are 50% and 25% of the length and the width of the sandwich plate respectively. The simply supported boundary conditions at the edges of the overall plate are considered for evaluating the numerical results. In order to verify the validity of the present FE model, the natural frequencies of the laminated plates integrated with the inactivated ACLD patches of negligible thickness are first computed by the present model and subsequently, compared with the existing analytical results [16]of the identical plate without integrated with the patches. Table 1demonstrates this comparison of the fundamental natural frequencies of symmetric and antisymmetric cross-ply plates. The non-dimensional frequency parameter $\bar{\omega}$ used for a particular plate has been considered according to the reference shown in Table 1with which the present result for that plate is compared. It may be observed from this table that the results are in excellent agreement validating the model derived here.

Table-1 Comparison of Fundamental natural frequencies parameters $\bar{\omega}$ of simply-supported laminated plate

Substrate laminates	Source	a/H=10	a/H=100
0°/90°/0°	Present FE soln.	12.172	15.185
	Analytical [16]	12.223	15.185
0°/90°	Present FE soln.	8.890	9.685
	Analytical [16]	8.900	9.687

Using Eqs. (4) and (5), frequency response functions are computed to study the open loop and closed loop behavior of the overall plate/ACLD system. For all frequency response functions presented in this Section, the substrate plates are excited by a transverse harmonic point load of 1 N acting at the point (a/2, b/4, H/2). The control voltages supplied to the patch 1 and the patch 2 are negatively proportional to the velocities of the points (a/2, b/4, H/2) and (a/2, 3b/4, H/2), respectively.