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RESEARCH ARTICLE

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ANALYSIS OF DE-LAMINATIONS IN A LAMINATED SMART BEAM WITH MECHANICAL LOAD FOR THE DESIGN OF HEALTH MONITORING OF STRUCTURES

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ABSTRACT

The main objective of the project is to study the analysis of delamination in the smart beams under mechanical loading with the help of different mathematical equations [1]. The various equations and the fundamental principles had been used for analysis of delamination in smart beam and to develop the governing equilibrium equations and the constitutive relations. The general formulation has been applied to analyse the problem of sensing of de-lamination of a surface mounted smart beam with mechanical load. The comparison of various response quantities for the sensing and actuation problems of given smart beam has brought out the key difference in the induced shear stress between the piezo layers and the core material. Due to de-lamination, the different layers or patches of smart beam fails under the heavy mechanical loading and deflection increases. The increase in deflection notifies presence of de-lamination in structure. The sensing of this de-lamination can be used in health monitoring of structures.

Keywords: De-lamination; Electrostatics; Sensing under Mechanical loading; single patching system; laws of thermodynamics; smart beam, health monitoring of structures.

INTRODUCTION

Smart materials and structures is an emerging technology with numerous potential applications in industries as diverse as consumer, sporting, medical, computer, telecommunications, manufacturing, automotive, aerospace, as well as civil and structural engineering. Smart materials, similar to living beings, have the ability to perform both sensing and actuating functions and are capable of adapting to changes in the environment. In other words, smart materials can change themselves in response to an outside stimulus or respond to the stimulus by producing a signal of some sort. Hence, smart materials can be used as “sensors”, “actuators” or in some cases as “self-sensing actuators”. A smart structure is one which has the ability to respond adaptively in a pre-designed useful and efficient manner to changes in environmental conditions, including any changes in its own condition.

Delamination is an insidious kind of failure as it develops inside of the material, without being obvious on the surface, much like metal fatigue(Ref. [2]). Modes of failure are also known as 'failure mechanisms'. Delamination also occurs in reinforced concrete structures subject to reinforcement corrosion, in which case the oxidized metal of the reinforcement is greater in volume than

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the original metal. The cause of de-lamination is weak bonding (Ref.[3]).

Objective

The main objective of this project is analysis of smart beam under mechanical load for finite element modelling of de-lamination in laminated smart structures which facilitates health monitoring of structures.

Mathematical modelling

Analysis of the laminated smart beam involves the basic understanding of electro-magnetic phenomena, electric field mechanism, electrodynamics (Ref. [4]), thermodynamics, heat transfer (Ref. [5]), and continuum mechanics (Ref. [6]). The governing equations, constitutive equations and boundary conditions have to be obtained in a consistent manner to bring out the electro-thermo-elastic coupling effects while modeling the behaviour of the piezo continuum in a smart structure. Different equations governing the examination modeling are discussed below

ELECTROSTATICS

The concepts of electrostatics of dielectrics are used to derive the expressions for the electrostatic forces and moments acting on the polarized continuum (Ref. [7]). For a systematic formulation, the electrostatic equations are developed using Coulomb's law for point charges, system of charges, charge continuum, discrete dipoles and dipole continuum.

a. System of Charges and Electric Potential

$$\vec{E} = -\vec{\nabla}\boldsymbol{\phi}$$

Where,

$$\phi = \sum_k \frac{Q_k}{4\pi\epsilon_0 r}$$

and is known as electric potential (Newton-meter/coulomb or volt) at point $(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z})$.

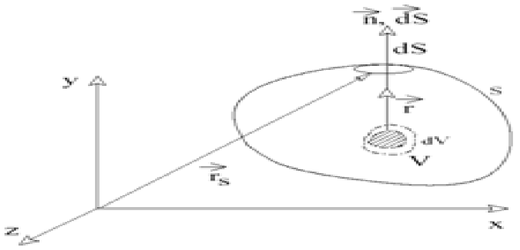


Fig. 3.1: Electrostatic force at a point due to a system of charges

b. Field due to Charge Continuum

For a surface charge continuum (for conductors), the electric field and potential are given as

$$\vec{E}(x, y, z) = \frac{1}{4\pi\epsilon_0}\int_V \frac{\rho(\xi, \eta, \zeta)}{r^3}\vec{r}\,dV$$

$$\phi(x, y, z) = \frac{1}{4\pi\epsilon_0}\int_V \frac{\rho(\xi, \eta, \zeta)}{r} r\,dV$$

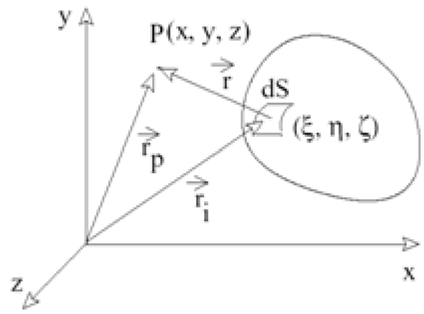


Figure 3.2: Potential and field caused by a surface charge

c. Electric Flux and Electric Displacement(Ref. [8])

Electric displacement is defined as the vector flux density and is given by

$$\vec{D} = \epsilon_0 \vec{E}$$

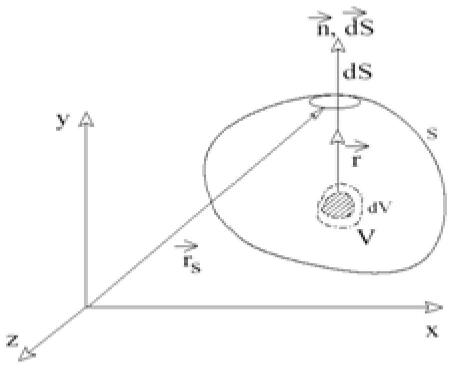


Figure 3.3: Flux due to a charge continuum

d. Energy of a Charged-Continuum/Polarized-Medium

The energy associated with bringing the free charge in to the polarized medium can be written as: (Ref. [9]):

$$\mathrm{W} = \frac{1}{2}\left(\int_V \vec{\mathrm{D}} \cdot \vec{\mathrm{E}}\,\mathrm{dV} + \int_S \phi\vec{\mathrm{D}} \cdot \vec{\mathrm{dS}}\right)$$

$$W = \frac{1}{2}\int_V \vec{D}\,.\vec{E}\,dV$$

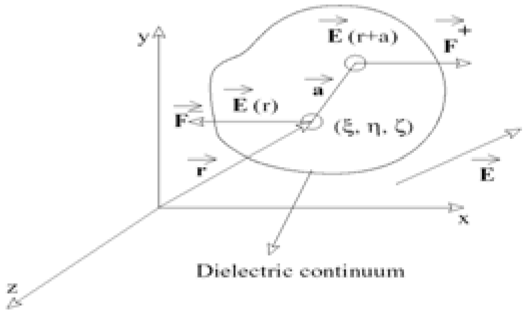


Figure 3.4: Polarized continuum in an external electric field

3.1. Description of Deformation of Body

a. STRESS

i. Stress in Non-polarized Medium (Ref. [10]).

Let us consider an elemental volume δV, If $\vec{F}$ is the force per unit volume, then total force acting on the elemental volume is equal to $\int_{\delta V} \vec{F}\,dV$.

$$\int_{\partial V} \vec{F}\,dV = \int_S (\sigma^T\ \vec{n})dS$$

ii. Maxwell's Stress (Ref. [11]).

Maxwell stress tensor can be written as:

$$[\sigma^M] = \begin{bmatrix} (E_1D_1 - \frac{1}{2}\epsilon_0E^2) & E_1D_2 & E_1D_3 \\ E_2D_1 & (E_2D_2 - \frac{1}{2}\epsilon_0E^2) & E_2D_3 \\ E_3D_1 & E_3D_2 & (E_3D_3 - \frac{1}{2}\epsilon_0E^2) \end{bmatrix}$$

3.2. Heat Transfer Constitutive Relations

The energy balance equation (first law of thermodynamics) and the rate of entropy production (second law of thermodynamics) are used for derivation of constitutive relations for the material. (Ref. [12])

3.2.1. First law of thermodynamics

a. Conservation of Energy

$$\frac{d}{dt}\int_{\delta V}\left(\frac{1}{2}\rho_m\vec{v}\,.\,\vec{v} + \rho_m U\right)dV \quad = \int_S \sigma^T\vec{n}\,.\,\vec{v}\,dS + \int_{\delta V}\vec{B}.\vec{v}\,dV - \int_S \vec{q}.\vec{n}\,dS + \int_{\delta V}\rho_m\gamma\,dV + \int_{\delta V}\dot{W}_E\,dV$$

b. Conservation of mass

Let ρ_m be the mass per unit volume of the material, then conservation of mass can be written as:

$$\frac{d}{dt}\int_{\partial V}\rho_m\,dV = 0$$

c. Conservation of charge

Conservation of charge equation can be written as:

$$\frac{d}{dt}\int_{\delta V}\rho dV = 0$$

3.2.2. Second law of thermodynamics

The second law of thermodynamics states that the rate of entropy production in the system is always greater than (irreversible process) or equal (reversible process) to the rate of entropy supplied to the system through heat, which can be written as:

$$\frac{d}{dt}\int_{\delta V}\rho_m\eta dV \geq \int_{\delta V}\frac{\rho_m\gamma}{\theta}dV - \int_S\frac{\vec{q}}{\theta}.\vec{n}\,dS$$

4. SENSING IN A SURFACE MOUNTED SMART BEAM UNDER MECHANICAL LOADING

In this section, the effect of mechanical loading will be analyzed for the sensing problem. The results of the study of sensing in a smart beam having surface mounted piezo patches/layers are presented in two sections; (i) cases corresponding to piezo layer (or single patch) and (ii) results pertaining to the case of multi-patch sensing. (Ref. [13])

4.1. Single Patch Sensing

The beam parameters are kept as under:

Length, L = 100 mm

Thickness of Aluminum core, t_c = 16 mm

Thickness of each piezo layer, t_p = 1 mm

Thickness of beam, $t = t_c + 2t_p$

Width of beam, b = unity

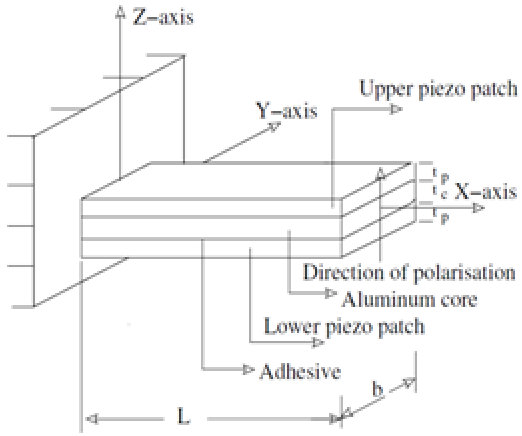


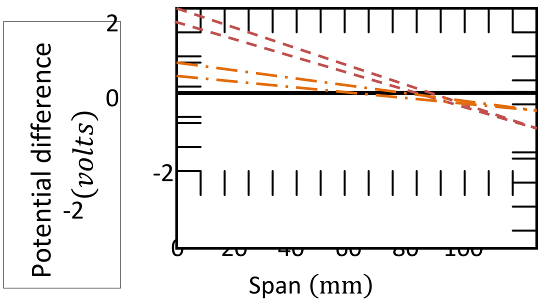
Figure 4.1: Smart cantilever in single patch sensing

In solving the single patch sensing problem (Fig. 4.1), three different cases have been considered. These are:

Case 1: The potential at a single point on the piezo patch is set to zero (i.e. the point is grounded). This point lies on the interface of the piezo layer with the core, and is chosen to be either at the fixed end or at mid-span or at the top of the beam (Fig. 4.2).

Case 2: The entire interface of the piezo patch is forced to have zero potential, or the interface is grounded (Fig. 4.3).

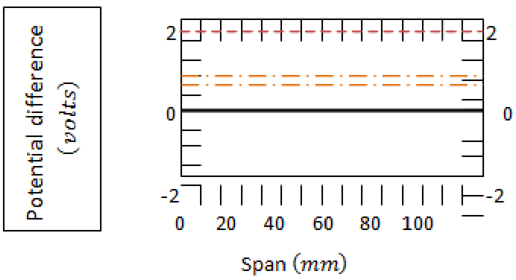
Case 3: The entire interface of the piezo patch is at zero potential and the free surface is at equipotential (Fig. 4.4).



Free surface
Middle surface
Interface

Fig.4.2; variation of induced potential along span in delaminated cantilever

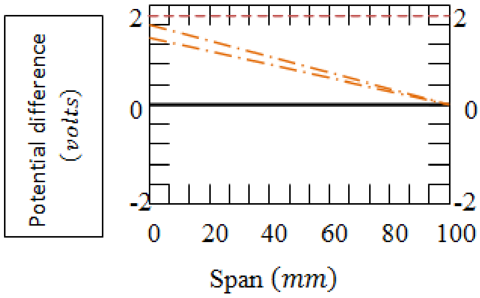
Case (i); interface of piezo patch at zero potential



Free surface
Middle surface
Interface

Fig.4.2; Variation of induced potential along span in delaminated cantilever

Case (ii); Grounded interface and equi-potential free surface



Free surface equipotential
Interface tip grounded
Interface grounded

Fig.4.3; Induced potential difference along span in delaminated cantilever

Case (iii); Grounded interface, free surface equipotential

4.2. Multi-patch Sensing Under Mechanical Loading

Figure 4.4 shows a multi-patched smart cantilever with six pairs of surface mounted piezo patches. The various dimensions are as shown in Fig. 4.4. The axis of polarization in the patches is in the z direction. Each patch is constrained to have zero potential at the interface and equi-potential at the free surface (The material properties of the core and the piezo-patches are given in Table 4.1). Assuming a tip deflection of 4.76×10^{-3}m, using formulation given in Chapter 4, the voltages induced in the six patches on the top and six patches at the bottom have been calculated in Table 7.3. It may be noted that both top and bottom piezo pairs have identical induced voltages due to symmetry. Ref. [4]

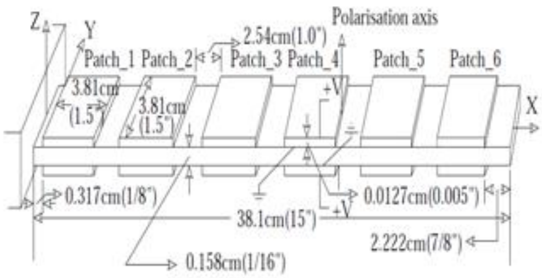


Figure 4.4: Multi-patch smart beam (Ref. 5)

Table 4.1: Material properties of PZT-5H, aluminum and steel

PZT-5H					PZT-5H			Al		Steel	
GPa					Cm^{-2}			GPa		GPa	
C_{11}^E	C_{12}^E	C_{13}^E	C_{33}^E	C_{44}^E	e_{31}	e_{33}	e_{15}	E	v	E	v
126	79.5	84.1	117	23	-6.5	23.3	17.0	70.3	0.345	68.95	0.292

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