Finite Element Modelling and Analysis of Damage Detection Methodology in Piezo Electric Sensor and Actuator Integrated Sandwich Cantilever Beam

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Abstract. Structural health monitoring (SHM) is an essential component of futuristic civil, mechanical and aerospace structures. It detects the damages in system or give warning about the degradation of structure by evaluating performance parameters. This is achieved by the integration of sensors and actuators into the structure. Study of damage detection process in piezoelectric sensor and actuator integrated sandwich cantilever beam is carried out in this paper. Possible skin-core debond at the root of the cantilever beam is simulated and compared with undamaged case. The beam is actuated using piezoelectric actuators and performance differences are evaluated using Polyvinylidene fluoride (PVDF) sensors. The methodology utilized is the voltage/strain response of the damaged versus undamaged beam against transient actuation. Finite element model of piezo-beam is simulated in ANSYS™ using 8 noded coupled field element, with nodal degrees of freedoms are translations in the x, y directions and voltage. An aluminium sandwich beam with a length of 800mm, thickness of core 22.86mm and thickness of skin 0.3mm is considered. Skin-core debond is simulated in the model as unmerged nodes. Reduction in the fundamental frequency of the damaged beam is found to be negligible. But the voltage response of the PVDF sensor under transient excitation shows significantly visible change indicating the debond. Piezo electric based damage detection system is an effective tool for the damage detection of aerospace and civil structural system having inaccessible/critical locations and enables online monitoring possibilities as the power requirement is minimal.

1. Introduction

Structural damages such as crack in isotropic structures and debonds in composite structures are frequently observed in many structures of automotive, aerospace, marine and civil engineering applications. The damage might have originated during fabrication or functioning. The presence of such a damage significantly reduces the load carrying capacity and stiffness of the structure. Early detection of such damages in critical structures is essential for safety aspects and also for the successful completion of the intended use. Most of the fabrication stage damages can be identified with NDT techniques. But in-service damages require periodic inspection or continuous monitoring of the performance. Piezo electric based damage identification methods form a reliable damage detection strategy which combines advantages of low cost and ease of operation. In some of the crystals like quartz, tourmaline, lithium sulphate and potassium tartrate, electrical charge is generated on mechanical deformation, and also, on application of external current the material deforms. These
properties essentially make piezoelectric materials to be used as actuators to impart mechanical deformation or sensors to sense mechanical deformations (Fig.1).

![Piezo Electric Sensors and Actuators](image)

**Figure 1.** Piezo Electric Sensors and Actuators

Modelling, analysis and testing of piezo based damage detection systems are very few in literature. The variation in vibration response of the damaged and undamaged structures forms the basis of damage identification procedure. This can be measured in terms of changes in frequency, mode shape, modal strain etc. Kim *et al.* [2] studied the natural frequencies of sandwich beams with delamination between face layer and core. The theoretical results were compared with experimental ones. It was found that the face layer debond reduces the flexural bending stiffness of sandwich beams. An increase in the extent of damage leads to a greater reduction in the frequencies of the beams [5]. Pradeep *et al.* [3] conducted modal response studies on damaged and undamaged metallic sandwich beams to evaluate frequency, mode shape, modal slope, modal strain and modal strain energy. The modal strain energy is found to be the better damage indicator. The adequacy was verified by comparing with experimental data. Wahyu *et al.* [4] conducted a study to evaluate the dynamic characteristics of honeycomb sandwich structures for highway bridge applications using combined analytical and experimental study. The dynamic characteristics were measured using a PVDF sensor. Piezoelectric sensors can be used reliably for recording the response of plates, shells and composite structures [5]. The reduction in modal frequency on account of damage serves as the indication of damage in composites [6]. The optimum placement and arrangement of sensors is a critical factor governing the performance of piezoelectric patches [7]. Piezoelectric sensors have significant advantages over conventional strain gauges. Piezoelectric sensors have superior signal to noise ratio and very simple conditioning circuitry which makes them advantageous over strain gauges [8]. Murty *et al.* [9] proposed the embedded smart patches in composites to serve as interrogators and sensors to generate necessary information about the damages in laminates. Lestari *et al.* [10] demonstrated a damage identification procedure based on smart sensors using dynamic responses of healthy and damaged fibre reinforced polymer sandwich beams. Piezoelectric sensors were used for the extraction of dynamic characteristics. The study concluded that there is a reduction in frequency response function for the damaged ones and a corresponding change in mode shape. Smart sensors were found to be effective in locating damages. Rao *et al.* [11] compared the performance of Fibre Bragg Grating sensor, based on optical fibre principle, to a conventional rosette strain gauge. The results showed that FBG sensors are comparable in performance to rosette strain gauges in strain measurement. This work pointed towards the development of embedded sensors for fibre reinforced composites which are “self-evaluating”. Huang
et al. [12] studied the response characteristics of composite plate with piezoelectric layers. The effect of plate thinness ratio on dynamic properties was also investigated. The study suggested that the plate resistance increases with piezoelectric coupling. Zhang et al. [13] conducted a study to evaluate the influence of multiple piezoelectric effects (MPE) on piezoelectric sensors/actuators; Theoretical models to calculate MPE under an electric field and stress are established and validated using experiment. The study suggested that the elimination of the influence of MPE leads to improvement in the sensitivity and resolution of the piezoelectric sensors and actuators. Guirguitu [13] studied the durability and survivability of piezoelectric wafer active sensors (PWAS) under temperature cycling, outdoor environmental exposure, submersion in operational fluids, large strains, fatigue. Garcia et al. [15] suggested that the change in natural frequency is an effective identification parameter for debonds in composite plates. PVDF sensors can be effectively used for the measurement of strain [16]. Karayannis et al. [17] evaluated the damages in reinforced concrete bars using bonded piezoelectric sensors and actuators. Piezoelectric lead zirconate patches were used as sensors and actuators. Presence of damage was identified by the reduction in the amplitude of current by comparing damaged and undamaged bars. Karagulle et al. [18] investigated the suitability of closed form control loop in the vibration suppression of structures using Ansys simulation. Dong et al. [19] suggested finite element modelling as an effective means to study the vibration response of smart structures. Literature review shows that the simulation studies of the piezo sensors based damage detection is rarely attempted in the literature. This paper studies the damage detection process in isotropic and sandwich structures using piezoelectric sensors and actuators through ANSYS™ simulation. This include Numerical modelling (FEA) of piezoelectric actuation and sensing of isotropic/sandwich plates.

2. Debond Detection on Smart Sandwich Cantilever Plates

The present study aims to evaluate the transient response of the damaged and undamaged sandwich plates with piezo sensors and actuators. The sandwich structure is of isotropic aluminium skin and orthotropic aluminium honeycomb core. The length of the beam is 800mm and thickness of the core is 22.86mm and that of skin is 0.3mm (Fig. 2 & 3). The beam is bonded with piezoelectric actuator and PVDF sensor. The details of location and size are given in Fig.2 & 3. An intact configuration (Undamaged-U) and a damaged configuration (Damaged-D) are considered. Debond is of 80mm long through width type and is at the root of the cantilever between the top skin and the core. The sensor is positioned directly below the root debond, 10mm away from the root of the sandwich plate. The length of piezoelectric actuator is 50mm and thickness is 5mm. The sensor has a length of 70mm and a thickness of 0.25mm. The skin material is aluminium (AA2014T6) with a density $\rho=2800$ kg/m$^3$, Elastic Modulus $E=68670$MPa and Poisson’s Ratio $\nu=0.3$. The core material is aluminium honeycomb (AA 5056 142) of density $\rho=67$ kg/m$^3$, Shear Modulus $G_{xZ}=220$MPa, Shear Modulus $G_{YZ}=105$MPa.

2.1. Modelling of Smart Structure

Two dimensional model of piezo-structural problems can be generated in ANSYS™ using any of the coupled field planar finite elements available in the finite element library. Literatures suggest PLANE 13 element for 2D piezoelectric problems. However, it is better to use a higher order element such as PLANE223 so as to avoid erroneous results. The name coupled field indicates that the single element can be used to model structural as well as piezoelectric part. In modelling the structural part, the piezoelectric nature of the elements is suppressed by giving very low piezoelectric stress coefficients. The aspect ratio of the components is to be accounted during finite element meshing process of structure to result in an accurate model of the system. The sandwich beam has a depth of 23.46mm and the thickness of actuator is 5mm, but the sensor has a thickness of only 0.25mm. The thickness of the PVDF sensor is negligibly small compared to that of the plate, which demands for a very refined mesh. Thus the finite element model is generated as a plane stress case with PLANE223 element. The transient voltage is applied on top nodes of the actuator. The bottom nodes are grounded to creating a
potential difference. Further, the VOLT degrees of freedom are coupled at the outer nodes of PVDF sensor for uniform outputs.

Figure 2. Sandwich Plate Intact Configuration (Undamaged- U)

Figure 3. Sandwich Plate Configuration with details of Root Debond (Damaged D)

The finite element model of the intact sandwich structure with PZT actuator and PVDF sensor configuration is shown in Fig. 4 & 5. The same configuration is provided for the damaged sandwich configurations D. Damage is induced by keeping the nodes unmerged at the skin-core boundary to the required length (length of damage). A 1mm mesh is provided for the entire structure except at the skin and sensor. Since the thickness of the PVDF sensor and skin is negligible compared to that of the core, the mesh is provided in such a way that there is at least two elements across the thickness.

Figure 4 Finite Element Model of Beam

Figure 5. Finite Element Model of Sandwich beam in sensor and actuator regions
2.2. Validation of Finite Element Model

To validate the model, the voltage-strain relation obtained from the finite element model is compared with the theoretical voltage–strain relation. For a unit load (1N) in the tip of cantilever beam, the maximum strain in the skin of the plate directly below the sensor is noted from the strain contour plot. The corresponding voltage reading in the PVDF sensor is obtained from the electric potential contour plot. The contour strain plot of the skin directly below the sensor is shown in Fig. 6 and the contour plot of electric potential obtained for the PVDF sensor is shown in Fig. 7. The maximum voltage reading is observed at the outer nodes of the PVDF sensor. Based on the material property, the theoretical relation between volts developed with strain is 105mV/micro strains.

Figure 6. Contour Strain Plot for the Skin
Figure 7. Contour Plot of Electric Potential in PVDF Sensor

Maximum value of strain at skin of plate = 0.37 με
Maximum value of voltage obtained in PVDF at root of isotropic plate = 0.041 V
Therefore, voltage to strain ratio obtained for the PVDF sensor (FEA) =110mV/με
The voltage strain correlation for 0.25mm thick PVDF sensor (Theory) =105mV/με
Percentage variation in volt-strain correlation for PVDF sensor from theoretical value = 4.7%. The percentage variation falls below 5%.

3. Modal and Transient Finite Element Analysis

The finite element analysis is a coupled field type incorporating structural and electrical fields. A modal analysis is carried out to determine the fundamental frequency of sandwich plate configurations to decide the time step required for transient analysis. A coupled field transient analysis is carried out to evaluate the strain response of the sandwich structure to a transient excitation of 200V for 0.001 seconds. A time step equal to 1/20 of natural frequency of beam is considered for transient analysis, which is approximately 0.001 seconds. The strain responses from the damaged beam and intact were evaluated for a time period of 0.2 seconds. The load curve for the transient analysis is given in Fig. 8.

3.1. Results and Discussions

The fundamental frequencies of the plate for both damaged and undamaged configurations are shown in Fig. 9 and the differences are insignificant. The transient voltage responses from the PVDF sensor were evaluated from the coupled field analysis. Fig. 10 represents the transient voltage response in PVDF sensor for the sandwich plates U and D.
The voltage response from the damaged structures is significantly higher than that of the undamaged and this gives a visible indication of the presence of damage. Hence it is a suitable tool for debond detection in sandwich cantilever plates. One of the limitation of the present study is that the plane strain or plane stress assumption leads a through width piezo patches and also damage. This may be solved with a 3D analysis but as the PVDF sensor has a negligible thickness (20-25µm) compared to that of the whole structure, the mesh refinement requirement in the sensor locations leads to increase in computational time and model handling difficulties.

4. Conclusions
Piezo electric sensor and actuator based damage (debond) monitoring methodology in sandwich beam is simulated using coupled field finite elements in plane strain condition. Even though the fundamental frequencies of the damaged and undamaged cases are not showing significant differences, the transient voltage response obtained from the PVDF sensor gives a visible indication of the presence of damage. This shows that piezo electric sensors and actuators are effective in damage monitoring of sandwich structures.

5. References
[1] Worden K and Bullough W A 2003 Smart Technologies(Singapore: World Scientific Publishing) pp 15-30
[2] Kim H Y and Hwang W 2002 Effect of debonding on natural frequencies and frequency response functions of honeycomb sandwich beams Composite structures 55 pp 51-62.
[3] Pradeep K R 2013 Modelling, detection and fracture assessment of debonds in sandwich structures Ph D Thesis (Chennai, Indian Institute of Technology)
[4] Lestari W and Qiao P 2006 Dynamic characteristics and effective stiffness properties of honeycomb composite sandwich structures for highway bridge applications Journal of Composite Construction 10(2) pp148-160.
[5] Banks H T, Inman D J, Leo D J and Wang Y 1996 An experimentally validated damage detection theory in smart structures Journal of Sound and Vibration 191(5) pp 859–880
[6] Diaz S H, Valdes and Soutis C 1999 Delamination detection in composite laminates from variations of their modal characteristics *Journal of Sound and Vibration* **228**(1) pp 1-9

[7] Zou Y, Tong L and Steven G P 2000 Vibration-based model-dependent damage (delamination) identification and health monitoring for composite structures-a review *Journal of Sound and Vibration* **230**(2) pp 357-378.

[8] Sirohi J and Chopra I 2000 Fundamental understanding of strain sensors *Journal Of Intelligent Material Systems and Structures* **11**(4) pp 246-257

[9] Krishnamurthy A V, Siadha E, Niak G N and Gopalakrishnan S 2003 An experimental investigation of a smart laminated composite beam with a magneto restrictive patch for SHM *Structural Health Monitoring* **2** pp.273-292

[10] Lestari W and Qiao P 2005 Damage detection of fiber-reinforced polymer honeycomb sandwich beams, *Composite Structures* **67** pp. 365–373

[11] Baskarrao M, Bhat M R and Murthy C R L, Venumadhav K and Asokan S 2006 Structural Health Monitoring Using Strain Gauges, PVDF film and Fibre Bragg Grating (FBG) Sensors (Hyderabad: Proc National Seminar on Non-destructive Evaluation)

[12] Huang J H and Liu Y C 2006 Electrostatic response of a laminated composite plate with piezoelectric sensors and actuators *Journal of engineering mechanics* **132**(8) pp 889-897

[13] Zhang Z and Kan J 2013 Influence of multiple piezoelectric effects on sensors and actuators *Mechanical Systems and Signal Processing* **35** pp 95–107.

[14] Guirguitu V 2014 Structural health monitoring with Piezoelectric Wafer Active Sensors (Oxford; Academic Press) pp 357-394.

[15] Garcia D, Palazzetti R, Trendafilova I, Fiorini C and Zucchelli A 2015 Vibration-based delamination diagnosis and modelling for composite laminate plates *Composite Structures* **130** pp 155–162.

[16] Jacob C M 2015 Evaluation of strain in sandwich structures using PVDF sensors *Structural Health Monitoring* **15**(1) pp 20

[17] Karayannis C G, Chalioris C E, Angeli G M, Papadopoulos N A Favvata M J and Providakis C P 2016 Experimental damage evaluation of reinforced concrete steel bars using piezoelectric sensors, *Construction and Building Materials* **105** pp 227–244.

[18] Karagulle H, Malgaca L and Oklem H F 2004 Analysis of active vibration control in smart structures by ansys, *Smart Mater. Struct.* **13** pp 661–667

[19] Dong X J, Meng G and Peng J C, 2006 Vibration control of piezoelectric smart structures based on system identification technique Numerical simulation and experimental study *Journal of Sound and Vibration* **297**(6) pp. 680–693.