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Influence of actuator-thickness on vibration of debonded piezoelectric sandwich beam with extension and shear actuator

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ABSTRACT : *This paper presents a finite element modelling and analysis of piezoelectric sandwich beam with extension and shear actuators using standard FE software, ANSYS. The modelling incorporates d_{31} based extension actuation mechanism (EAM) and d_{35} based shear actuation mechanism (SAM). Edge debonding of the extension actuator/face layer leads to change in dynamic behavior and substantial reduction in actuation authority. Thickness of actuators is a parameter which has considerable influence on the natural frequencies and actuation authority. These issues are addressed by carrying out investigations on a beam with clamped-free boundary conditions. Edge debonding of extension actuator/face layer is introduced at the clamped end of the beam for maximum effect on the natural frequencies and actuation authority. From the numerical experiments carried out on healthy and debonded beams, it is found that increase in thickness of actuators leads to decrease in actuation authority under EAM and increase in natural frequencies. Further, the modal analysis has revealed the fact that, for a given thickness of actuators, increase in the extent of edge debonding of extension actuator/face layer leads to decrease in natural frequencies and new modes shapes are introduced.*

Keywords: *Actuation authority, edge debonding, extension actuation mechanism (EAM), natural frequencies, piezoelectric sandwich beam, shear actuation mechanism (SAM).*

I. INTRODUCTION

Piezoelectric materials have the unique ability to interchange electrical energy and mechanical energy or strain. Due to this characteristic of the material, it has been found to be very effective as actuator and sensor, for use in static and dynamic response of various structures, involving vibration and noise control, high resolution positioning and health monitoring etc. Growing demand for piezoelectric adaptive structures with large actuation authority has led to the development of adaptive sandwich structures employing both surface bonded extension actuators and embedded shear actuators. The reported research work on the piezoelectric sandwich beam with piezoelectric actuators addressed the modelling issues with static and dynamic control applications, and investigation on actuation authority using extension and shear actuation mechanisms (EAM and SAM) ([Baz and Poh [1], Tzou, and Tseng [2], Lam et al [3] and A. Benjeddou et al [4]). There are several studies using finite element modelling and analysis. Most of these studies modelled the sandwich beam by using Euler-Bernoulli's beam theory for the faces and Timoshenko's beam theory for the core. A two noded sandwich beam finite element was developed [5] with both mechanical and electrical degrees of freedom. This element was used to develop a control scheme based on the linear quadratic regulator/independent modal space control (LQR/IMSC) method and used this to estimate the active stiffness and active damping introduced by shear and extension-bending actuators. Trindade [6] have shown that for active vibration control, simultaneous use of extension and shear actuators is very promising since EAM and SAM are complimentary, so that for modes where one of them has poor performance, the other counterbalances with a better performance.

Effectiveness of the smart structures with distributed actuators and sensors is based on perfect bonding. Therefore it is very essential to recognize the influence of debonding of actuators on the actuation authority and free vibration. Seeley and Chattopadyay [7] investigated the effect of edge debonded actuator on the mode shapes and frequencies. It was found that increase in debonded length of actuator introduces global and local deformations leading to significant changes in mode shapes and frequencies. Sun and Tong [8] developed an Eigen value problem for a composite beam with debonded actuators to study the effect of edge debonded actuators on the open loop and closed loop behavior. Though there is enough research work in the field of delamination of fiber reinforced composites, the research work in the field of edge debonding of actuators is very limited. Also the literature survey reveals the fact that the effect of thickness of actuator on actuation authority and free vibration, which is very important in the contents of closed loop vibration system has not been addressed sufficiently.

In the present work, coupled finite element modelling of adaptive cantilever sandwich beam with segmented extension and shear actuators using ANSYS is presented. Sandwich beam with debonded top extension actuator and top active face is modelled. Validation of the developed model is carried out by considering the results available in the open literature for both static and modal analysis. Performance of healthy and debonded beam is compared. The emphasis of the present work is to investigate the effect of thickness of actuators on the actuation authority and free vibration of both healthy and debonded sandwich beam.

Coupled Constitutive Equations

Elastically orthotropic and piezoelectrically orthorhombic, linear piezoelectric material with symmetry axes parallel to sandwich beam axes is considered for deriving coupled constitutive equations. Depending upon the direction of poling, two constitutive models have to be developed, one for extension actuation mechanism and other for shear actuation mechanism.

Lamina Constitutive Relations for Extension Actuation

Extension actuator poled in the direction of imposed electric field (E_3), which is along the thickness of the extension actuator, induces membrane strain. Reduced constitutive equations for plane stress condition, involving elastic, piezoelectric and dielectric constants in the principal material coordinate system are given by,

$$\begin{Bmatrix} \sigma_1 \\ D_3 \end{Bmatrix} = \begin{bmatrix} \hat{Q}_{11} & -\hat{e}_{31} \\ \hat{e}_{31} & \hat{\eta}_{33} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ E_3 \end{Bmatrix} \tag{1}$$

where, Stiffness Coefficient $\hat{Q}_{11} = C_{11} - \frac{C_{13} C_{13}}{C_{33}}$, Piezoelectric strain coefficient $\hat{e}_{31} = e_{31} - \frac{C_{13} e_{33}}{C_{33}}$,

Dielectric Coefficient $\hat{\eta}_{33} = \eta_{33} + \frac{e_{33}\, e_{33}}{C_{33}}$, Electric Displacement D3 (thickness direction)

From the preceding equation, it is clear that electromechanical coupling between the through-thickness electric field (E_3) and membrane strain (ε_1) is established through the piezoelectric coefficient $\hat{e}_{31}$.

Lamina Constitutive Relations for shear Actuation

An essential requirement for inducing shear strain in actuation mechanism is that the poling axis and the direction of applied electric field are mutually perpendicular. Accordingly, for shear actuation mechanism transverse electric field is imposed on axially poled shear actuator. This requires the coordinate transformation on the constitutive equations such that the axial and transverse indices interchange [4]. Thus reduced constitutive equations involving electromechanical coupling of transverse electric field (E_3) and shear strain (ε_5) are,

$$\begin{Bmatrix} \sigma_1 \\ \sigma_5 \\ D_3 \end{Bmatrix} = \begin{bmatrix} \hat{Q}_{33} & 0 & 0 \\ 0 & \hat{Q}_{55} & -\hat{e}_{15} \\ 0 & \hat{e}_{15} & \hat{\eta}_{11} \end{bmatrix} \begin{Bmatrix} \varepsilon_1 \\ \varepsilon_5 \\ E_3 \end{Bmatrix} \tag{2}$$

where, $\hat{Q}_{33} = C_{33} - \frac{C_{13}\, C_{13}}{C_{11}}$, $\hat{Q}_{55} = C_{55}$, $\hat{e}_{15} = e_{15}$, $\hat{\eta}_{11} = \eta_{11}$

There is no coupling between linear stress σ_1 and through thickness electric field $E_{3.}$ The presence of $\hat{e}_{15}$ in Eq.(2) leads to electromechanical coupling between transverse electrical field and shear strain.

ANSYS Modelling of Healthy and Debonded Sandwich Beam

Adaptive Sandwich beam consisting of top and bottom elastic sfaces with transversally poled segmented surface bonded extension actuators, and core with axially poled shear actuator is modelled as shown in Fig 1. Core composed of a shear actuator and foam, is sandwiched between two elastic layers. Modelling is done using ANSYS. In ANSYS, element SOLID 5 with coupled electro-mechanical actuation capability is used for modelling of both healthy and debonded beam. Edge debonding is introduced by demerging the nodes at the interface of the top and bottom debonded regions. For the study, transverse electric field is imposed to the layers and each layer is supposed to be active. For elastic substrates, piezoelectric constants are set to zero. Healthy and debonded sandwich beams with different thicknesses of extension and shear actuators are modelled for the investigation of the influence of thickness of actuator on actuation authority and natural frequency. ANSYS model of sandwich beam with both extension and shear actuators is shown in Fig. 2.

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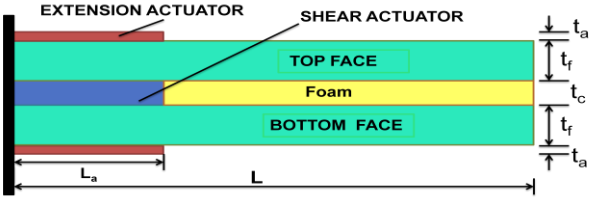


Figure 1: sandwich beam with extension and shear actuators

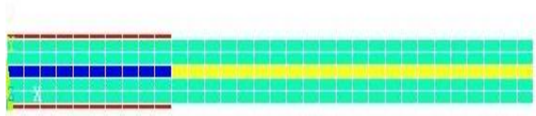


Figure 2: ANSYS model of sandwich beam

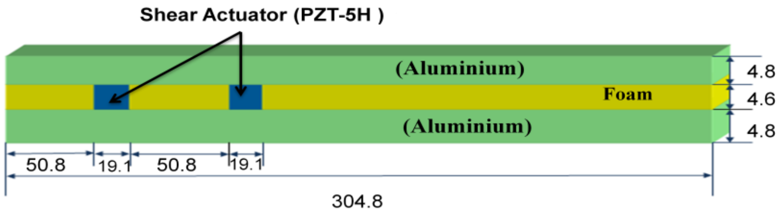


Figure 3: beam with segmented shear actuators (dimensions in mm)

Validation

Modelling of adaptive sandwich beam is verified by considering clamped-Free Sandwich beam for modal analysis. M. A. Trindade [9] has determined natural frequencies of the model shown in Fig. 3.

Table 1 Validation for Modal Analysis

Mode	Experimental Frequency (Hz)	TSDT Frequency (Hz) [9]	**Present work (error %)**
1	123.06	130.53	129.45 Hz (5.19%)
2	495.71	523.84	514 Hz (3.68%)

The validation of the model is carried out and the values of natural frequencies are found to be in good agreement with the experimental values (Table 1).

Results and Discussion

Numerical experiments on the sandwich beam are carried out by considering PZT-5H material for piezoelectric actuators and aluminum layers in face. Material properties are listed in Table 2. Geometrical parameters, according to Fig.1, are L_a=50mm, L=160mm, t_f=4mm. Width of the beam is 10mm. For EAM, ±10V are applied on the top skin of top and bottom extension actuators. The thicknesses of extension actuators of the model are varied from 0.5mm to 2mm. Thickness of foam and shear actuator are maintained twice to that of extension actuator. For maximum influence on the stiffness, edge debonding of extension actuator and face are introduced at the clamped end of the beam. Different lengths of debonding 5mm, 10mm, 15mm, 20mm, and 25mm are considered.

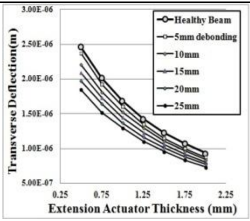
Table 2 Properties of Materials

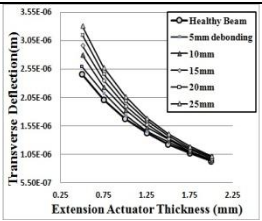
Aluminum: ρ = 2710.0Kg/m^3, E = 70.3 Gpa ν = 0.343 **Foam**: ρ = 32.0 Kg/m^3, E = 35.3 Mpa, ν = 0.33

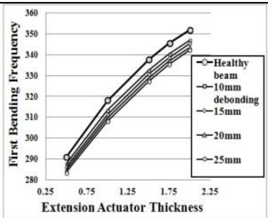
PZT-5H: ρ = 7730.0 Kg/m^3, Stiffness coefficients:C_{11} = C_{22} = 126 Gpa, C_{33} =117 Gpa, C_{12} =79.5GPa, C_{13} = 84.1Gpa, C_{44} = C_{55} = C_{66} = 23.3GPa, Piezoelectric coefficients: d_{31} = -274.0 m/V, d_{15} = 741.0 m/V, d_{33} = 593.0 m/V, Dielectric constants: η_{11} = 1.508 ×10-8 F/m, η_{33} = 1.30 ×10-8 F/m

5.1 Actuation Authority

Variation of transverse deflections of both healthy and debonded sandwich beam with thickness of extension actuator under EAM is plotted as shown in Fig. 3. For a given thickness of actuator, edge debonding of top extension actuator leads to significant loss in deflection at free end due to loss in effective length of extension actuator as shown in Fig. 3(a), whereas debonding of top active face leads to substantial loss in bending stiffness. Hence bending deflection increases with extent of debonding as shown in Fig. 3(b). It can be seen that sandwich beam with thin actuators undergoes large deflection under EAM. Transverse deflection of beam decreases with increases in thickness of actuators for both healthy and debonded beams. Effect of debonding on deflection is reduced with increase in thickness.







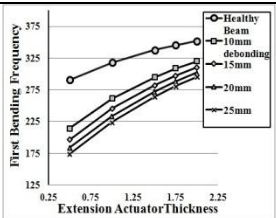


Figure 4 (a) Figure 4 (b) Figure 5 (a) Figure 5 (b)

(a) edge debonding of top extension actuator **(b)** edge debonding of top active face

Figure 4: transverse deflections of beam with different thicknesses of extension actuators under EAM

(a) edge debonding of top extension actuator (b) edge debonding of top active face

Figure 5: first bending natural frequencies-extension actuator thickness plot

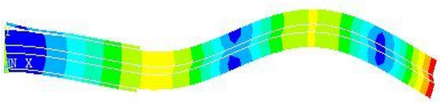
5.2 Modal Analysis

Modal analysis of cantilever healthy sandwich beam and beam with edge debonding of top extension actuator and top active face layer is carried out for obtaining natural frequencies and corresponding mode shapes. Graph of first bending natural frequencies vs thickness of extension actuator is plotted for healthy and debonded beam (Fig 5). Different extent of debonding considered are 10mm, 15mm, 20mm, 25mm.Thickness ranging from 0.5mm to 2 mm is considered.

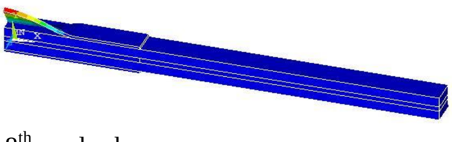
Natural frequencies of sandwich beam are found to decrease with increase in the extent of debonding of both top extension actuator (Fig. 5(a)) and top active face (Fig. 5(b)), at particular thickness. This tendency is attributed to reduction in elastic stiffness of beam due to debonding of the actuators. Debonding of top active face which consists of top extension actuator layer and top elastic face, leads to substantial loss in elastic stiffness hence results in large amount of reduction of natural frequencies. Furthermore, as can be seen, natural frequencies of sandwich beam increases with increase in thickness of extension and shear actuators.

Thickness of actuator and extent of debonding also have influence on mode shapes of sandwich beam. Lower values of thickness of actuators introduce several local mode shapes at the lower frequencies. Four mode shapes from modal analysis of 25 mm top extension actuator debonded beam with 1mm thick extension actuators are given in Fig. 6. First two mode shapes are not affected much by 25mm edge debonding of top extension actuator. Fig. 6(a,c,d) shows local modes of debonded beam, where debonded portion of actuator vibrates in bending, twisting and double bending mode respectively, while the beam doesnot vibrate. 6th mode is mixed mode, where debonded portion and beam vibrate in different mode shapes (Fig. 6(b)).

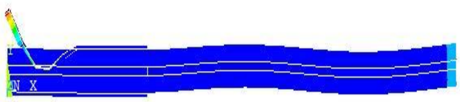
(a) 3th mode shape



(b) 6th mode shape



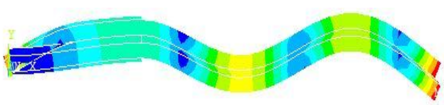
(c) 8th mode shape



(d) 10th mode shape

Figure 6: mode shapes of sandwich beam with edge debonding of top extension actuator

(a) 7th mode shape



(b) 9th mode shape

Figure 7: mode shapes of sandwich beam with edge debonding of top active face

Fig.7 shows two mode shapes from modal analysis 25mm top active face debonded beam with 1mm thick extension actuators. The mode shapes corresponding to the first six natural frequencies in both healthy and debonded beam are the same. However there is change in mode shapes from the 7th mode. At the 7th mode, face debonded portion vibrates in bending mode, the beam hardly vibrates. Fig. 7(b) shows mixed mode shape.

Conclusion

Cantilever sandwich beam with d_{31} based extension actuator and d_{35} based shear actuator, is modelled using SOLID5 element in ANSYS with coupled electro-mechanical capability. For analyzing the effect of debonding on actuation authority, sandwich beam with edge debonding of top extension actuator and top active face layer is modelled. The influence of thickness of actuator on the actuation authority and free vibration of healthy and edge debonded beam are investigated.

Edge debonding of top extension actuator in sandwich beam with segmented actuators reduces the actuator authority under EAM, due to reduction in effective length of the actuator, whereas edge debonding of top active face leads to substantial loss in bending stiffness. Hence bending deflection increases with extent of debonding.

Thickness of actuators affects the elastic stiffness of the sandwich beam. Increase in thickness of actuators in sandwich beam construction, increases elastic stiffness and hence natural frequencies. For a given thickness of actuators, increase in the extent of edge debonding of top extension actuator and top active face layer leads to decrease in natural frequencies, due to more loss of elastic stiffness of structure, and new mode shapes are introduced. Lower values of thickness of actuators of edge debonded beam, lead to more number of local mode shapes being introduced. Also the natural frequencies correspond to global mode shapes found to be reduced.

The present modelling is further useful for vibration control and health monitoring studies. The present work comprises of an extensive study on the influence of thickness of actuator on the control authority of the sandwich beam. It is necessary to carry out the open/closed loop control study in the presence of debonding of the actuators. This study will be helpful for the modification of the control scheme, in the event of debonding of actuators.

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