Shape Control of Composite Structure with Suitably Placed Piezoelectric Sensors Under Electro-Thermo-Mechanical Condition with Non-linear Analysis

P Mani Rathnam[1], Nidhin Raj Motaboina Deepak[2]

[1]*UG Scholar, Department of Mechanical Engineering, Holy Mary Institute of Technology and Science, Keesara, Hyderabad, Telangana(State), India*
[2]*UG Scholar, Department of Mechanical Engineering, Holy Mary Institute of Technology and Science, Keesara, Hyderabad, Telangana(State), India*

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Abstract- In this paper, the application of piezoelectric actuators to the composite control card is studied statically. The electro-thermo-mechanically coupled mathematical model is used for the analysis. The main section of this paper is static control. Shape control is stated here as determining the shape control parameters, including the actuation voltage and the adjustment of the actuator orientation, so that the structure which is activated using these parameters also adapts as closely as possible to the required shape. In this paper, we have presented FE model for the control analysis of the shape of piezoelectric laminated (PZT) composite plates using Ansys. The piezoelectric layer and composite plate are modeled in the form of additional layers to be attached to the upper or lower surface or to be integrated into the laminated composite plate. Ansys finite element software is used for modeling and has been successfully validated with experimental and numerical results which are readily available in the literature. The present analysis shows that with the application of an appropriate voltage to the piezoelectric actuator, the desired shape of the composite plate can be obtained.

Keywords: Composite plate, FEM, Intelligent structure, Non-linear, piezoelectric, sensor, voltage

Abbreviations: R&D, research and development; PZT, piezoelectric; PVDF, polyvinylidene fluoride;

1.INTRODUCTION

The need for structures with self-monitoring and self-monitoring capabilities, particularly in aerospace applications, has led to notable growth in the research and development (R&D) of smart structures. An intelligent structure can be stated as a configuration made of pure elastic materials, called substrates, integrated in sensors or actuators ascend on the surface or integrated which have the capacity to detect and take corrective measures Wang et al (1997). The direct effect of piezoelectric is the capacity to produce an electrical charge proportionate to the mechanical force applied externally, and the reverse piezoelectric attain is the exact opposite of the direct effect. The laminated composite plate is chosen as the substrate for its high strength / weight and stiffness / weight ratios. These characteristics make the laminated composite board suitable for use in numerous applications, particularly in the aerospace sector.

A composite is a structural member consisting of more than combined components which are merge at the macroscopic level and which are not doable in each other. A component is called the gain phase and the one in which it is integrated is called the matrix. The material in the reinforcing phase can be in the form of fibers, particles or flakes. The materials in the matrix phase are generally continuous. Examples of composite systems include steel reinforced concrete and epoxy reinforced with graphite and wood fibers, wherein the lignin matrix is reinforced with cellulose fibers and bones in which bone salt plates composed of calcium and phosphate ions softly enhance collagen. etc. [1]

Material science and structural engineering have entered a new age brought about by the development of adoptive materials and their application in intelligent structure. Although the terms intelligent, smart and adoptive are frequently used interchanging, only a few authors have defined each term distinctly. The basic requirements of an intelligent or smart structure are the following three capabilities: sensing, processing/control, actuating. Smart structure is receiving increasing attention in biomedical field, aerospace components, civil constructions, military field, automobiles, control of flight and numerous other fields. other application is shape control where the shape of member is changed to conform to a required shape by actuating the appropriate actuators.

FE is a generic technique applied to obtain a numerical solution when the calculation of the exact solution is too tedious. Therefore, as an exact solution, FE formulations can be based on various analytical bases. Most of the intelligent structure FE approaches developed so far have not been really sophisticated in the use of an intelligent control system for distributed detection and actuation. Although the word "distributed parameter system" was used. It's an interesting challenge to optimize the location and distribution of the sensors in the structure.

The need to modify the shape of the structure, during its operation, gives rise to the form control application. By integrating adaptive materials into structures, the shape of the overall structure can be manipulated to fit certain desired shapes. Applications range from controlling the shape of aerodynamic surfaces such as aerodynamics to large flexible space structures or space antenna reflectors.

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Alik and Huges (1970) were the first to model the piezoelectric coupling in a finite element formulation. A tetrahedral solid element was derived to design a piezoceramic transducer. The electric potential was taken as a state variable with mechanical displacement and they were interpolated with the same shape functions [1]. Chendrashekara (1996) proposed modeling and controlling the shape of composite beams with integrated piezoelectric actuators. The accuracy of the model and the computer code is validated with the solution present in the available literature [2].

2. METHDOLOGY

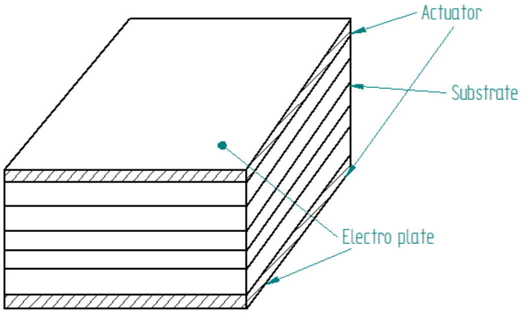

Fig. 1. Piezoelectric effect

A piezoelectric material is a substance that produces an electrical charge when physical stress is applied (the substance compresses or stretches). By contrast, mechanical deformation (the substance contracts or expands) occurs when a field of electric is applied. This effect is formed in crystals that do not have a center of symmetry.

Allik & Hughes [1] carried out one of the first works in the use of the Finite Element (FE) technique for structural modeling that included piezoelectric effects. Since the starting of the research in the field of active / intelligent structures, several authors, especially Tzou & Tseng (1988, 1990); Tzou and. Alabama. (1990); they have adopted the FE technique which is advantageous in cases where the exact analysis is too complex.

3. MATHEMATICAL MODEL

The general formulation is based on the principle of variation of the energy of Hamilton as it is indicated in the equation

$$\int_{t_1}^{t_2} \delta\left(L+W\right)\mathrm{d}t = 0 \qquad (1)$$

The first major difference between the conventional FE and piezoelectric formulation is the presence of an electrical contribution to potential energy in Lagrangian (L) and working (W) terms. This will lead to the use of constitutive equations which connect not only the tension (s) and the tension (e) but also the electric fields (E) and displacements (D). The displacements and electric potential will be converted into nodal displacements and nodal potentials by using shape interpolation functions Equation 2.

$$u = N_u \{u_i\}$$
$$\varphi = N_\varphi \varphi_i \qquad (2)$$

The First-Order Shear Deformation Theory (FSDT)

The Reissner-Mindlin theory is used for plates in the translational displacements of the laminate with respect to a specific coordinate system using the cross sectional of the laminate in the x-z plane.

The displacement formulas on x and y direction can be written as follows,

$$u(x,y,z) = u_0 + z\phi_x, v(x,y,z) = v_0 + z\phi_y, w(x,y,z) = w_0(x,y)$$

$$\text{Where, } \frac{\partial u}{\partial z} = \phi_{x,} \frac{\partial v}{\partial z} = \phi_y$$

The strain components on the reference plane are,

$$\varepsilon^0{}_x = \frac{\partial u_0}{\partial x}, \varepsilon^0{}_y = \frac{\partial v_0}{\partial y}, \gamma^0_{xy} = \frac{\partial u_0}{\partial x} + \frac{\partial v_0}{\partial y}$$

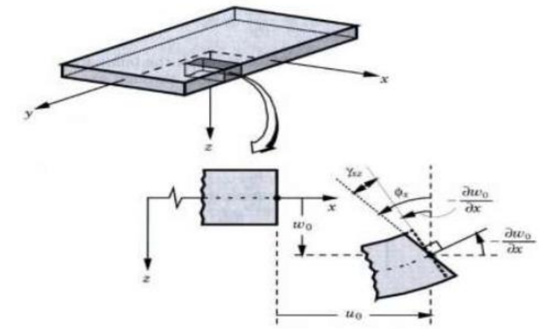

Fig. 2. Undeformed and deformed geometries of an edge of a plate under the assumptions of the first-order plate theory.

4. RESULTS AND DISCUSSION

4.1.Validation for model

The FE model developed in the previous chapter is validated in beginning and used in the rest of the analysis. To verify the accuracy of the current model, a bimorphic piezo beam shown in Figure 3 is first studied by Z Wang et al [1].

The beam member is having of two same polyvinylidene fluoride (PVDF) uniaxial beams of different polarities. The cantilever beam is designed and modeled by five same plate elements. The properties of PVDF materials are listed in Table 1

The theoretical solution to the deflection of the beam given by Tzou H. S (1989) [13]

$$W(x) = 0.375\left(\frac{e_{13}v_a}{E}\right)\left(\frac{x^2}{t^2}\right) \qquad (3)$$

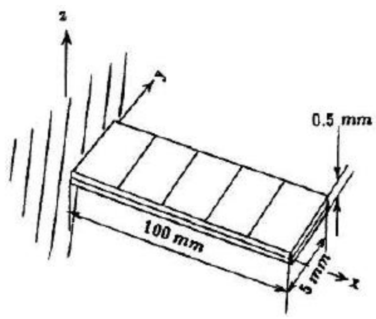

Fig.3. Piezoelectric PVDF bimorph beam

Table 1. Material properties of the main structure and piezoelectric

Property	PVDF	Epoxy/Graphite
E_1	0.2e10 N/m^2	0.98e11 N/m^2
E_2	0.2e10 N/m^2	0.79e10 N/m^2
G_{12}	0.775 e9 N/m^2	0.56e10 N/m^2
υ12	0.29	0.29
υ21	0.28	0.28
ρ	1800kg/m^3	1520 kg/m^3
e31	0.046c/m^2	0
e32	0.046c/m^2	0
e33	0	0
ε11	0.1062e-9F/m	0
ε22	0.1062e-9F/m	0
ε33	0.1062e-9F/m	0

Beam deviation is calculated for different distances between 20mm and 100mm along the beam length. The results are presented in Tables 2 with the results of Tseng [1990]. The results show the very close variations between the theoretical finish and the current one.

Table.2. Centerline deflection of PVDF Bimorph beam for unit voltage (m)

Distance (m)	RPIM Theory	Tseng (1990)	Present FEM
0.02	1.40E-08	1.50E-08	1.32E-08
0.04	5.52E-08	5.69E-08	5.23E-08
0.06	1.22E-07	1.37E-07	1.27E-07
0.08	2.21E-07	2.35E-07	2.10E-07
0.1	3.45E-07	3.60E-07	3.32E-07

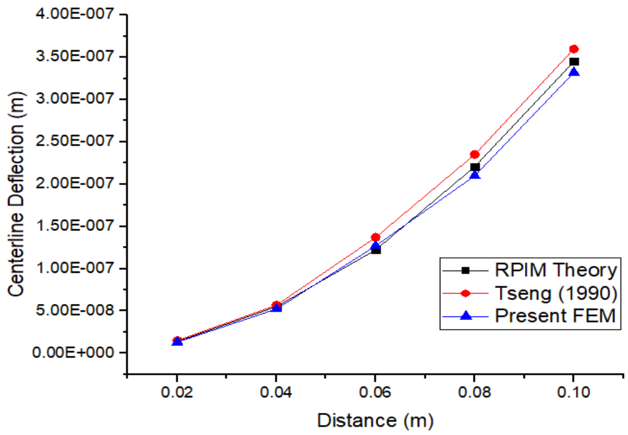

Fig.4. Centerline Deflection of PVDF Bimorph Beam (for a unit voltage) (m)

Table.3. Material Property of PZT G1195N Piezoceramics and T300/976 Graphite-Epoxy Composites

Property	PZT	T300/976
E11	6.30E+10	1.50E+11
E22	6.30E+10	9.00E+09
E33	6.30E+10	9.00E+09
υ12	0.3	0.3
υ13	0.3	0.3
υ23	0.3	0.3
G12	2.42E+10	7.10E+09
G13	2.42E+10	2.50E+09
G23	2.42E+10	7.10E+09
ρ	7600 kg/m3	1600 kg/m3
d31	22.86	
d32	22.86	
K11	15.3e-9 F/m	
K22	1.53E-08	
K33	1.50E-08	

Now for the present, the size of the plate is (0.2 m x 0.2 m). The model is having four compound layers and two layers of piezo. Total height of non-piezoelectric the composite plate is 0.001 m and the thickness of the piezoelectric layer is 0.0005 m.

4.2. Cantilever Plate with UDL

A cantilevered composite model with the lower and upper layers joined symmetrically by piezoelectric ceramic is studied. The model is having four composite layers and two piezoelectric layers. The plate consists of epoxy-graphite compounds T300 / 976 and the piezoceramic is PZT G 1195N.

Consider the composite plate $[P / -45 / 45]_{as}$ because it is originally flat and then exposed to a uniformly distributed load (UDL) of 100 N / m^2. To flatten the plate, an active voltage is gradually added until the deviation from the center line of the plate is reduced to the desired limits.

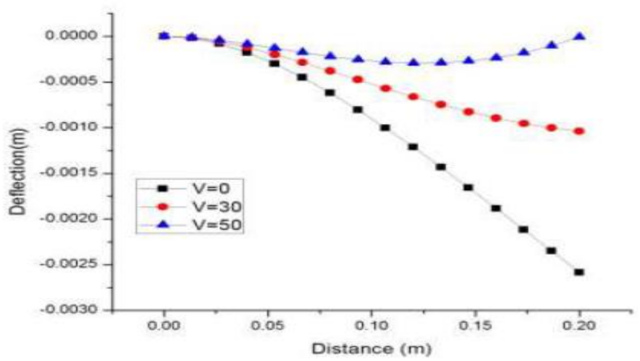

Fig.5. The centerline deflection of cantilever laminate [p/-45/45]as under uniform loading and different actuator input voltages.

In static analysis, all piezoceramics on the top and bottom layers of the plate are used as actuators or sensors. When voltages of equal amplitude with a sign opposite the thickness of the two piezoelectric layers are applied, they will come into contact or expand depending on whether the applied voltage is negative or positive and, therefore, stresses are induced to generate bending forces of the composite plate.

The two previous examples, Fig. 4 and Fig. 5 shows that the current FE model produces results which are in good agreement with the available literature.

Once the model is validated with literature results, as we can see that results are very much close to the previous results. Hence, for further study we are taking principle of present study, along with uniform distributed load, we are applying temperature for the model.

To find the suitable position for the piezoelectric layer, following cases are studied with varying voltage, UDL and temperature for cantilever beam.

Case 1: Piezoelectric layer at each corner of plate

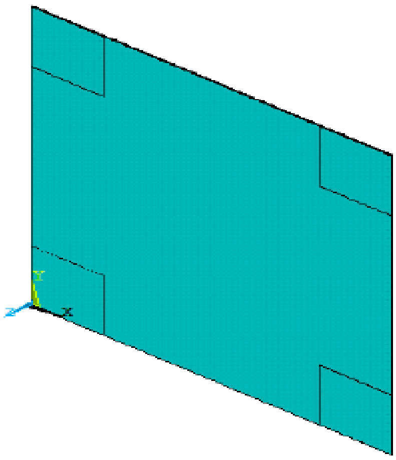

Fig .6. Piezoelectric layer at each corner of plate

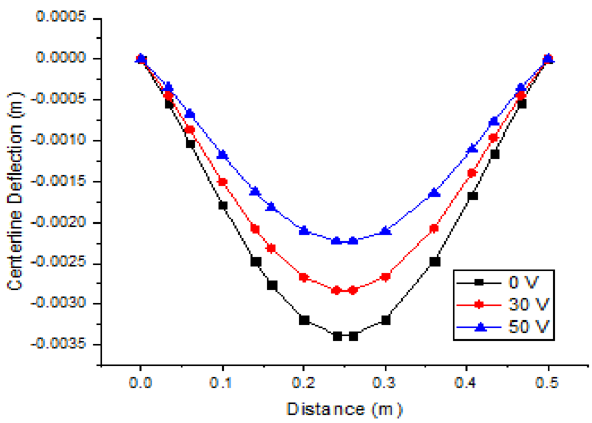

Fig.7. Centerline deflection of plate [p/-45/45]as P=100N/m^2, T=100^{0}C, V=0,30,50

Case 2: Piezoelectric layer at the center of each edge

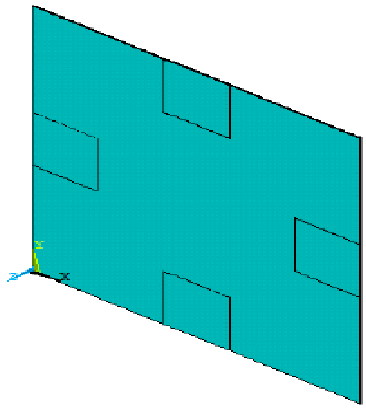

Fig.8: Piezoelectric layer at the center of each edge

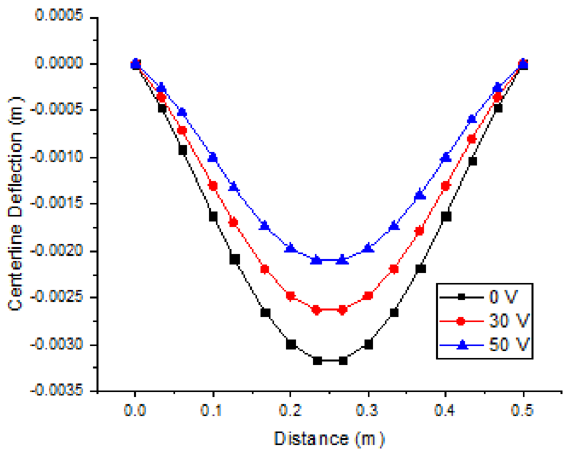

Fig.9. Centerline deflection of plate [p/-45/45]as P=100N/m^2, T=100^{0}C, V=0,30,50

Case 3: Piezoelectric layer at the center of plate

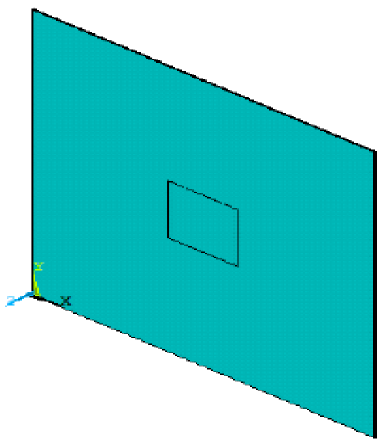

Fig.10. Piezoelectric layer at the center of plate

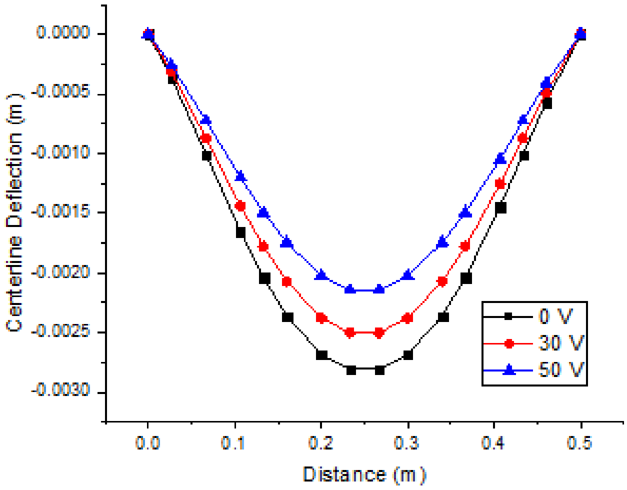

Fig.11. Centerline deflection of plate [p/-45/45]as P=100N/m^2, T=100^{0}C, V=0,30,50

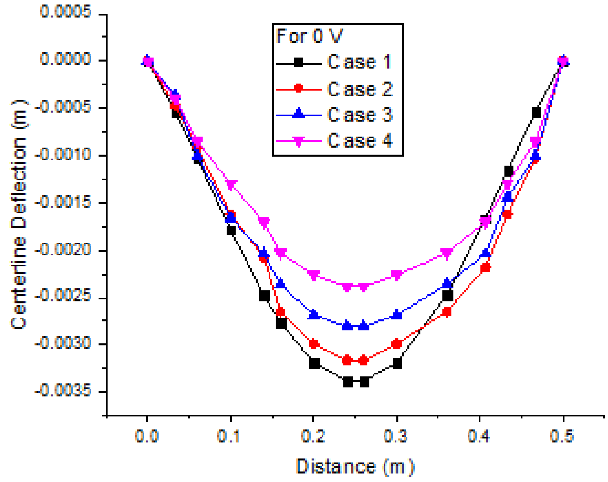

Fig.14. Centerline deflection for P=100N/m^2, T=100^{0}C, V=0 for different cases

Case 4: Piezoelectric layer throughout the plate

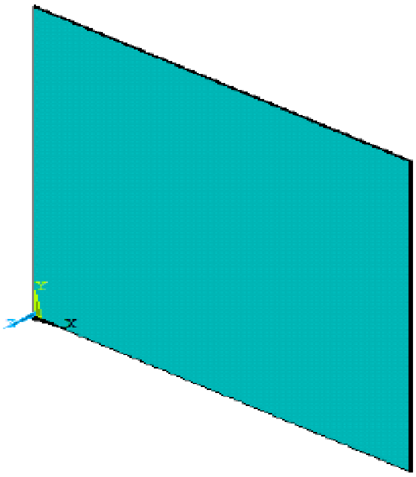

Fig.12. : Piezoelectric layer throughout the plate

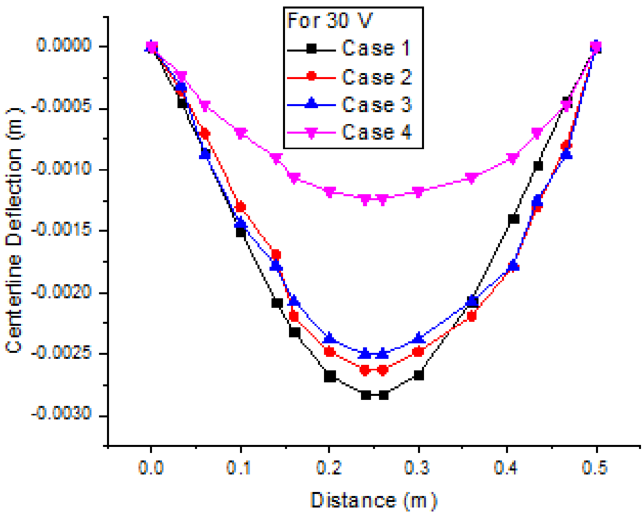

Fig.15. Centerline deflection for P=100N/m^2, T=100^{0}C, V=30 for different cases

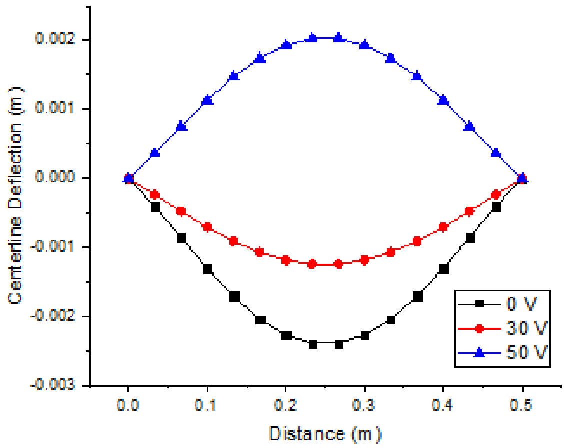

Fig .13. Centerline deflection of plate [p/-45/45]as P=100N/m^2, T=100^{0}C, V=0,30,50

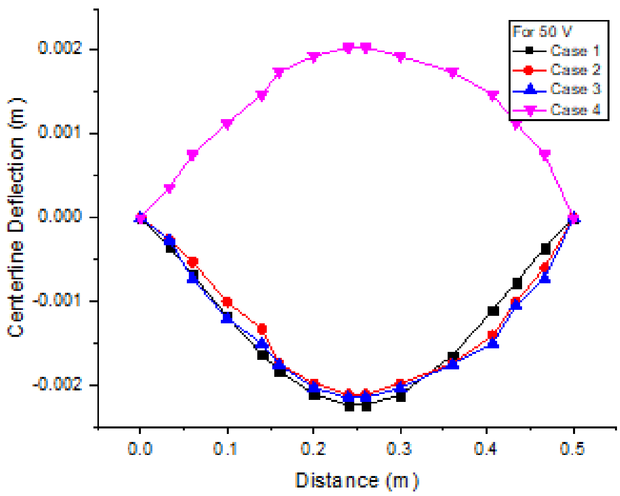

Fig.16. Centerline deflection for P=100N/m^2, T=100^{0}C, V=30 for different cases

By comparing the above three comparisons graphs i.e. 14,15,16, we can give conclusions that the centerline deviation of plate is continuous to decrease as the voltage is increased for the piezo patch at the center and throughout the plate. The deviation from the center line is very minimal for the piezo patch on the entire board. Therefore, for further study, we prefer a piezo patch throughout the plate.

4.3. EFFECT OF INCREASING NUMBER OF LAYERS

4.3.1 Cross Ply Laminates for Cantilever Plate

Cross-layer antisymmetric / symmetric plates subject to evenly distributed loads, temperature and various voltages are applied to study the behavior and effect of the layer on nonlinear centerline deviation. Figure 17-33 presents the graphs of the deviation from the center line depending on the distance for a different number of layers and it can be seen that, as the number of layers increases, the deviation from the center line decreases.

Case 1: $(0/90)_2$

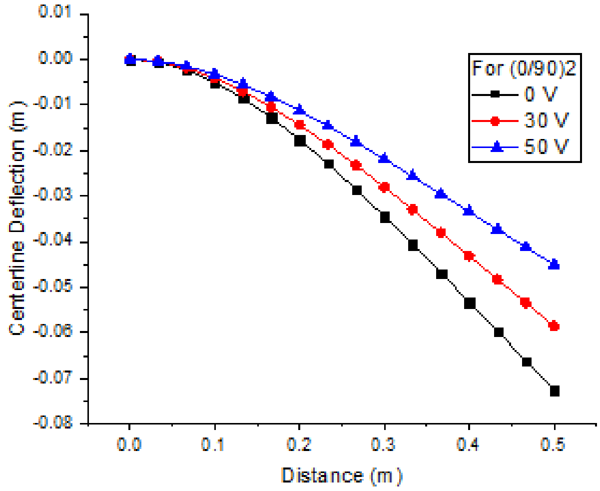

Fig.17. Effects on numbers of layer on Centerline deflection for cross ply (0/90) subjected to the load P=100N/m^2, T=100^{0}C and different voltages.

Case 2: $(0/90)_3$

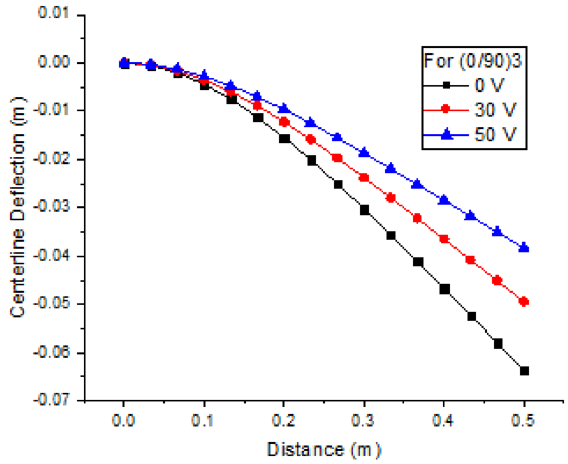

Fig.18. Effects on numbers of layer on Centerline deflection for cross ply (0/90) subjected to the load P=100N/m^2, T=100^{0}C and different voltages.

Case 3: $(0/90)_4$

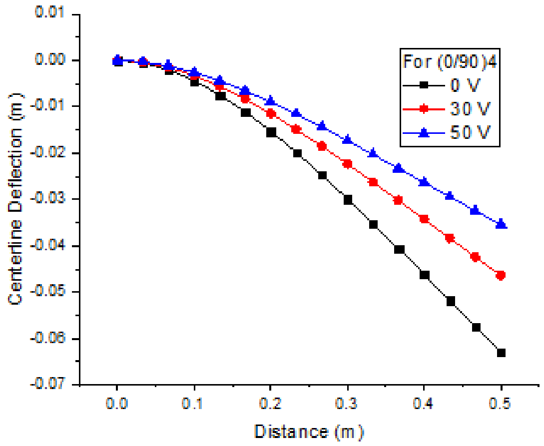

Fig.19. Effects on numbers of layer on Centerline deflection for cross ply (0/90) subjected to the load P=100N/m^2, T=100^{0}C and different voltages.

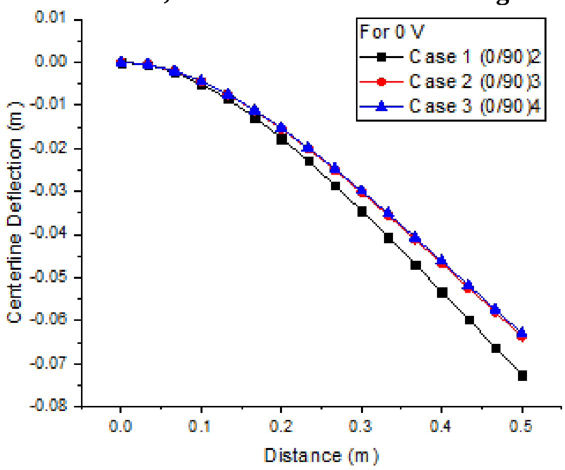

Fig.20. Effects on numbers of layer on centerline deflection for cross ply subjected to the load P=100N/m^2, T=100^{0}C and zero voltages.

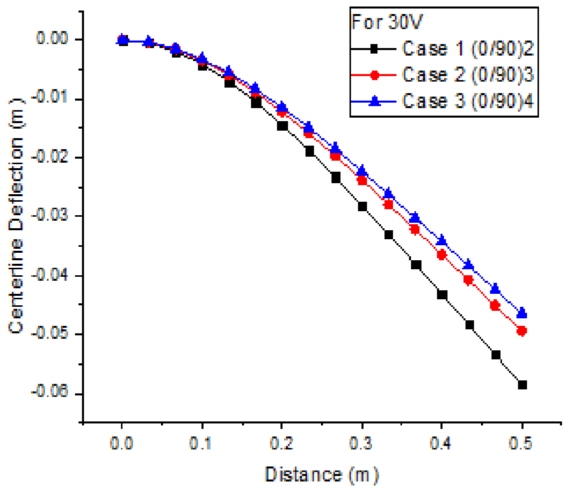

Fig.21. Effects on numbers of layer on centerline deflection for cross ply subjected to the load P=100N/m^2, T=100^{0}C and 30 voltage.

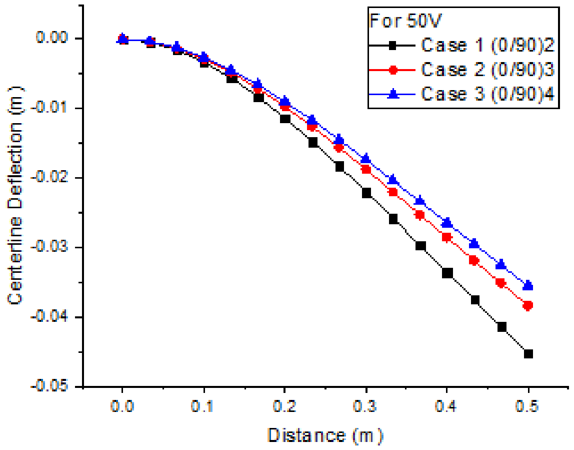

Fig.21. Effects on numbers of layer on centerline deflection for cross ply subjected to the load P=100N/m^2, T=100^{0}C and 50 voltage.

4.3.2 Cross ply laminates for clamped plate

Case 1: (0/90)$_2$

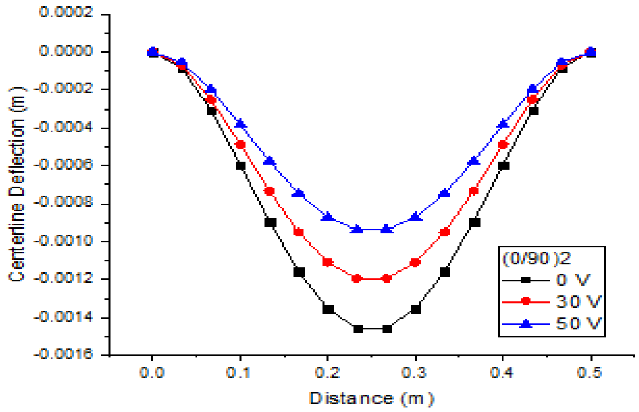

Fig.22. Effects on numbers of layer on centerline deflection for cross ply subjected to the load P=100N/m^2, T=100^{0}C and different voltages

Case 2: (0/90)$_3$

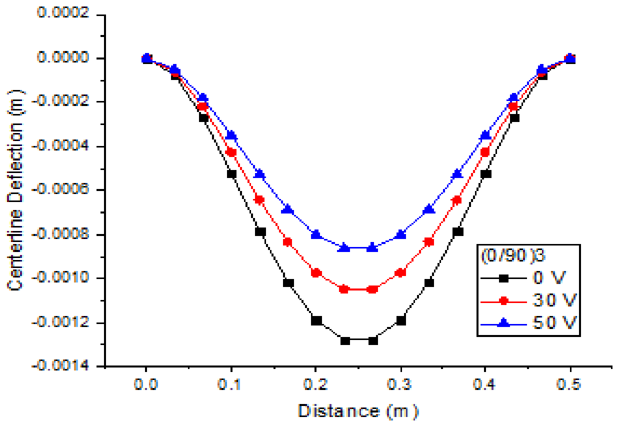

Fig.23. Effects on numbers of layer on centerline deflection for cross ply subjected to the load P=100N/m^2, T=100^{0}C and different voltages

Case 3: (0/90)$_4$

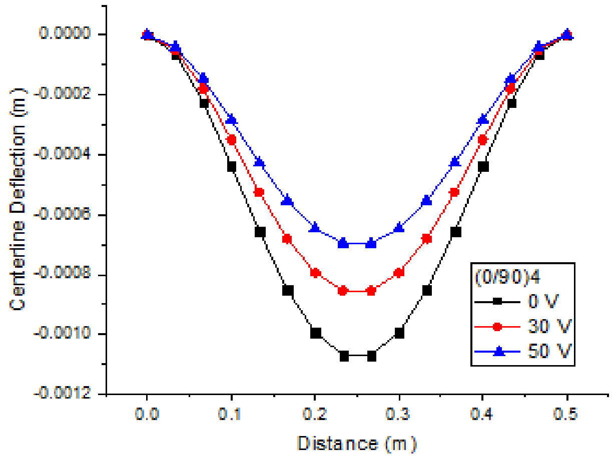

Fig.24. Effects on numbers of layer on centerline deflection for cross ply subjected to the load P=100N/m^2, T=100^{0}C and different voltages

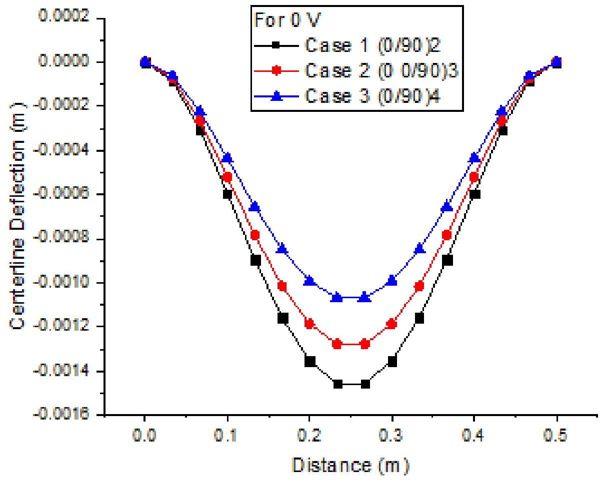

Fig.25. Effects on numbers of layer on centerline deflection for cross ply subjected to the load P=100N/m^2, T=100^{0}C and zero voltages.

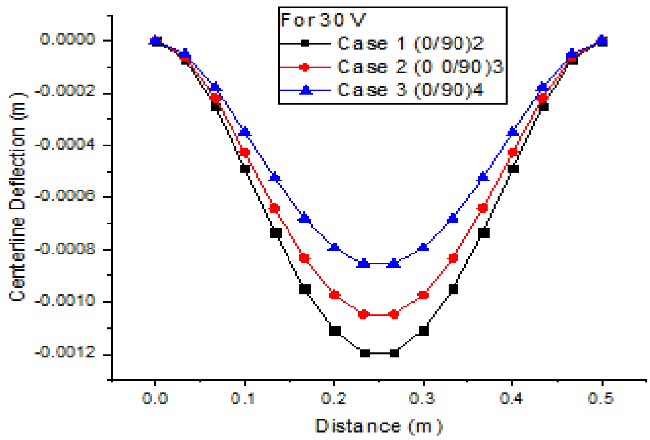

Fig.26. Effects on numbers of layer on centerline deflection for cross ply subjected to the load P=100N/m^2, T=100^{0}C and 30 voltages.

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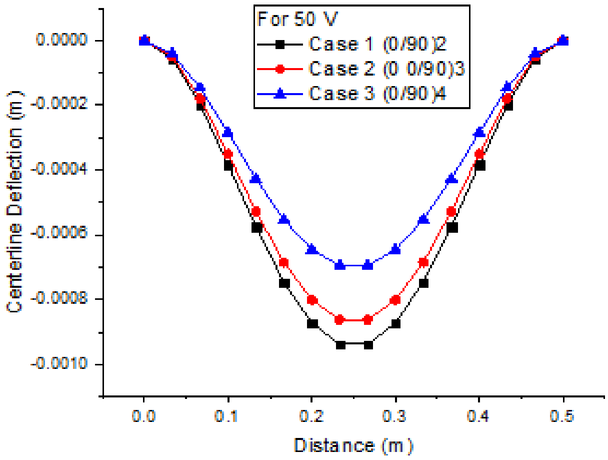

Fig.27. Effects on numbers of layer on centerline deflection for cross ply subjected to the load P=100N/m^2, T=100^{0}C and 50 voltages.

4.3.3 Cross ply laminates for Simply Supported Plate

Case 1: (090)$_2$

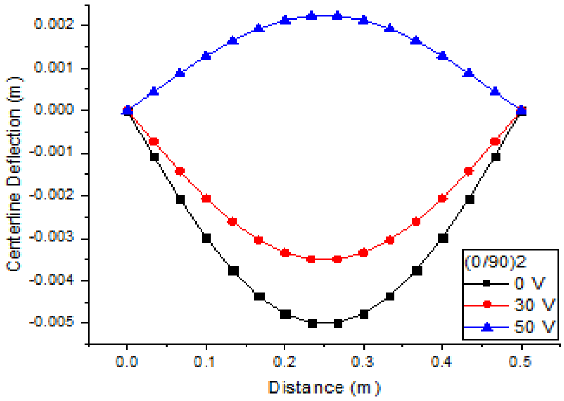

Fig.28. Effects on numbers of layer on centerline deflection for cross ply (0/90) subjected to the load P=100N/m^2, T=100^{0}C and different voltages.

Case 2: (090)$_3$

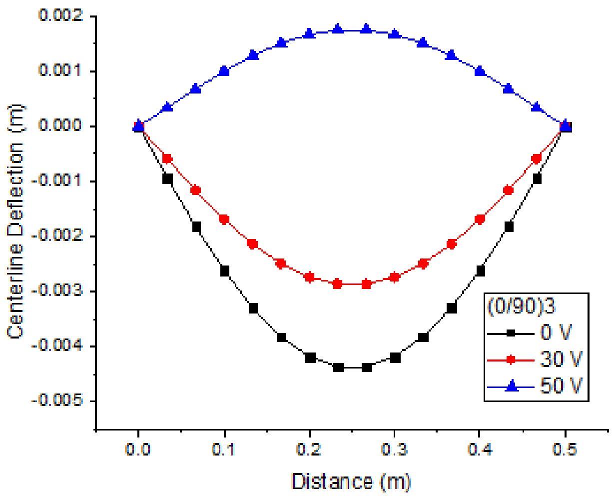

Fig.29. Effects on numbers of layer on centerline deflection for cross ply (0/90) subjected to the load P=100N/m^2, T=100^{0}C and different voltages.

Case 3: (090)$_4$

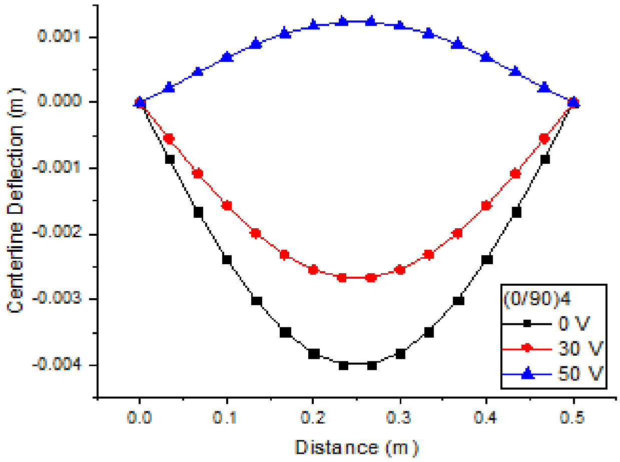

Fig.30. Effects on numbers of layer on centerline deflection for cross ply (0/90) subjected to the load P=100N/m^2, T=100^{0}C and different voltages.

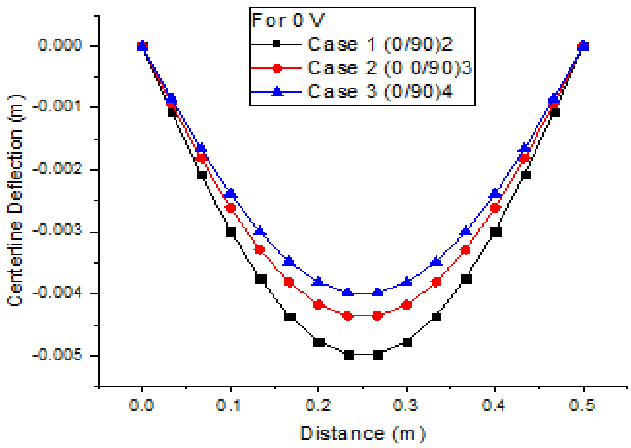

Fig.31. Effects on numbers of layer on centerline deflection for cross ply (0/90) subjected to the load P=100N/m^2, T=100^{0}C and zero voltages.

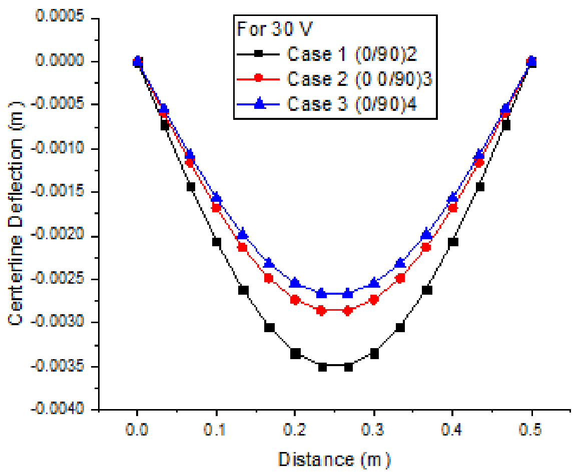

Fig.32. Effects on numbers of layer on centerline deflection for cross ply (0/90) subjected to the load P=100N/m^2, T=100^{0}C and 30 voltages.

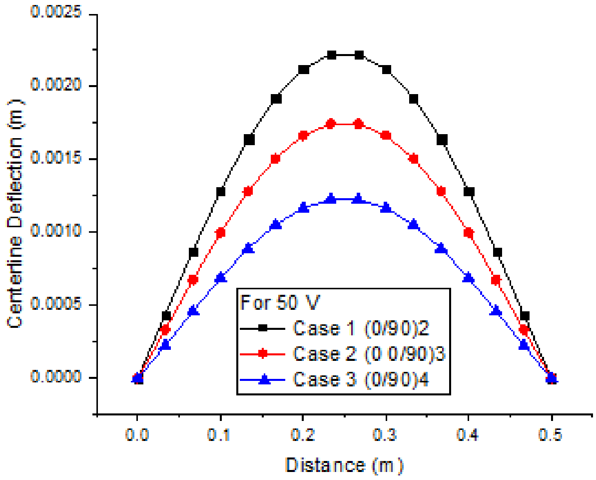

Fig.33. Effects on numbers of layer on centerline deflection for cross ply (0/90) subjected to the load P=100N/m^2, T=100^{0}C and 50 voltages.

5. CONCLUSIONS

A finite element formulation for the distributed piezoelectric plate. Sensors / actuators are presented. A piezoelectric plate element is developed. Based on the plate element, a general method for controlling the static shape of the smart structure has been developed. The present method makes it possible to obtain the input voltage and feedback gain by allowing the shape of the smart structure to achieve the desired shape. The behavior of a single support laminated piezoelectric plate is studied. In summary, the behavior of the beam subjected to electrical and mechanical loads are listed below:

1.The plate deviation decrease as the applied voltage increases.
2. It would be concluded that the deviations due to mechanical loading can be easily controlled by adding appropriate voltages to the piezo layers and can be said that piezoelectric layers are useful in controlling deflections of plate under electro mechanical loadings.
3. By studying the different cases of piezo-layer, we conclude that the piezo-layer which is in the middle of the plate and which is distributed throughout the plate has better shape control than the other two cases.
4. As the number of layers increases, the deviation from the center line continues to decrease.

6. FUTURE SCOPE

The shape control techniques developed in this study represent a possible strategy for shape control using piezoelectric actuators in an electromechanical environment. Extend the same FE formulation to include other types of structures such as shells, solids, and incorporate other physical effects such as coupling thermo-piezoelectric-magnetic effects.

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