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Bending Analysis of Smart Composite Laminated Plates Subjected To Electro-Mechanical Loading By Using 'HOSDT'

*P.Hemavathi[1], P.Veera Sanjeeva Kumar[2].
[1.] *P.G.Student, Department of Mechanical Engineering, C.R.Engineering College, Tirupati, A.P. (INDIA).*
[2.] *Assoc.Prof. Department of Mechanical Engineering, C.R.Engineering College, Tirupati, A.P. (INDIA).*
Corresponding Author: P.Hemavathi

Abstract: *The present paper involves the investigation of bending response of smart composite plates by using a new higher order shear deformation theory (HOSDT). A piezoelectric fiber reinforced composite materials are used as a distributed sensors or actuators to analyze the performance of the smart plates. A higher order shear deformation theory is proposed for piezoelectric laminated composite plates subjected to electro mechanical loading. The displacement model is considered and the equations of equilibrium are attained by using the principle of virtual work and the solutions are evaluated with Navier's technique. The displacements and stresses due to bending are analyzed.*

Keywords: *Smart structures, Higher Order Shear Deformation Theory, Piezoelectric fiber reinforced composites, Principle of Virtual work.*

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I. Introduction

The conventional composites especially structural composites are recently embedded with special materials especially piezoelectric materials to obtain the combined benefits. The deformations, deflections and induced stresses are excellently controlled with the consolidation of composite with piezoelectric materials .The resulted structures are treated as a smart or intelligent structures. The smart structure has a great demand in the fabrication of various engineering structures especially in air craft, naval and aerospace applications .In the previous investigations, P.Ravikanth Raju,J.Suresh Kumar,M.V.Laxmi Prakash [1] were presented a paper on Analysis of smart anti symmetric composite plates using HSDT. Tran Ich Thinh and Le Kim Ngoc [2]are studied the Static and Dynamic analysis of laminated composite plates with integrated piezoelectric s. Shiuh-Chaun Her and Chi-Sheng Lin[3] are excellently explained in their paper Deflection of cross ply composite laminates induced by Piezoelectric actuators. Chee Zho Kam and Ahmad Beng Hong Kuch [4] are studied the Bending response of cross ply laminated composite plates with diagonally perturbed localized Interfacial degeneration. Tarun Kant and S.M.Shiyeakar[5] are presented the best method of analysis of Cylindrical bending of piezoelectric laminates with a higher order shear and normal deformation theory. P.Ravikanth Raju et al [6] determined the Transient Analysis of smart material plates using Higher order theory in their paper. P.Phung –Van,M.Abdel-Wahab [7] are introduce the NURBS concept in their paper Buckling analysis of piezoelectric composite plates using NURBS-based on isogeometric finite elements and higher order shear deformation theory. Rajan L.Wankhade, Kamal M. Bajoria[8] are submitted a paper on Shape control and vibration analysis of Piezolaminated plates subjected to electro-mechanical loading. Mallikarjuna and T.Kant[9] are responsible for dynamic studies of laminate composites in their paper Dynamics of laminated composite plates with a higher order theory and finite element discritization. B.Siddareddy,J.Suresh Kumar[10] are investigated the Buckling analysis of functionally graded material using higher order shear deformation theory. Tarun Kant and Mallikarjuna [11] are developed A higher order theory for free vibration of unsymmetrical laminated composite and sandwich plates – finite element evaluation. N.D.Phan and J.N.Reddy[12] are proposed a enriched theory for laminated plates in their paper Analysis of laminated composite plates using a higher order shear deformation theory. J.N.Reddy and A.Khdeir[13] are investigated the buckling behavior of plates in the paper Buckling and vibration of Laminated composite plates using various plate theories. Md.Iftekhar Alam and Tasmeem Ahmad Khan[14]are studied various theories and presented a paper Comparative analysis of multi layered composite plates using higher order theories. Nilanjan Malik andM.C.Ray[15] are presented an Exact solutions for the analysis of piezoelectric fiber reinforced composites as distributed actuators for smart composite plates. S.M.Shiyekar and Tarun Kant[16] are analyzed and studied the Higher Order Shear Deformation effects on analysis of laminates with piezoelectric fiber reinforced composite actuators.

II. Theory and Methodology.

In the present work for investigating the bending characteristics a rectangular laminated composite plate with all sides is simply supported has considered. A thin layer of piezoelectric fiber reinforced composite (PFRC) is attached on the top and bottom surface of the composite substrate and it is working as the distributed actuator or sensor. The geometrical dimensions of the plate are assumed as shown in the fig (1). The 'z' axis is assumed at the middle of the plate i.e. it is located at the distances +h/2 and –h/2 from the top and bottom of the laminated composite plate. The thickness of the PFRC actuator is assumed as $\mathbf{t_p}$. The in plane displacements are expanded in the thickness directions of the plate in terms of powers of 'z' axis. The respective displacement vectors u (x, y, z), v (x, y, z) and w (x, y, z) at any point in the laminate are expanded in the following form.

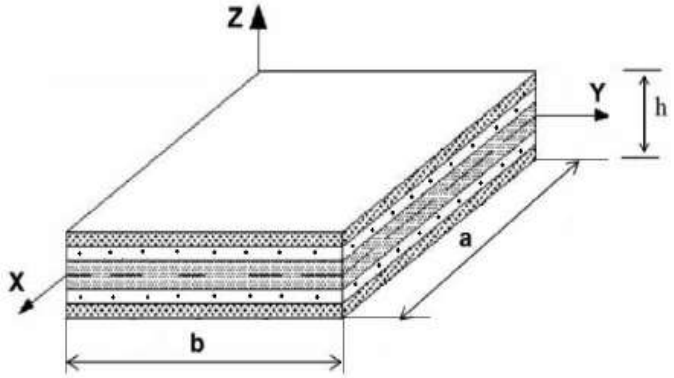


Fig.1. Geometry of piezoelectric laminated composite plate.

MODEL (HOSDT):

$$u(x, y, z) = u_0(x, y) + z\,\theta_x(x, y) + z^2 u_0(x, y) + z^3 \theta_x(x, y)$$
$$v(x, y, z) = v_0(x, y) + z\,\theta_y(x, y) + z^2 v_0(x, y) + z^3 \theta_y(x, y)$$
$$w(x, y, z) = w_0(x,) + z\theta_z(x, y) + z^2 w_0(x, y) \qquad \text{---------------------} \quad \text{Eq.}(1)$$

Where the parameters u_0, v_0 denotes the in plane displacements and w_0 is the transverse displacement at any point on the mid plane of the substrate. The functions θ x, θ yare the rotations of the normal to the mid plane about y and x –axes respectively. The remain parameters u_0, v_0, w_0, $\theta x, \theta_y$,and$\theta_z$are the respective higher order parameters related to the transverse deformation modes.

Strain -Displacement relations:

The in plane displacements (Eq.1) are substituted in the strain displacement relations of classical theory of elasticity the following relations are obtained:

$$\varepsilon_x = \varepsilon_{xo} + zk_x + z^2 \varepsilon_{xo}^* + z^3 k_x^*$$

$$\varepsilon_y = \varepsilon_{yo} + zk_y + z^2 \varepsilon_{yo}^* + z^3 k_y^*$$

$$\varepsilon_z = \varepsilon_{z0} + zk_z + z^2 \varepsilon_{z0}^*$$

$$\gamma_{xy} = \varepsilon_{xyo} + zk_{xy} + z^2 \varepsilon_{xyo}^* + z^3 k_{xy}^*$$

$$\gamma_{yz} = \phi_y + zK_{yz} + z^2 \phi_y^* + z^3 k_{yz}^*$$

$$\gamma_{xz} = \phi_x + zK_{xz} + z^2 \phi_x^* + z^3 k_{xz}^*$$

Lamina constitutive equations: The linear constitutive relations for a single piezoelectric layer couples the elastic and electric fields as given below,

$$\{\sigma\} = [Q]\{\varepsilon\} - [e]\{E\},$$
$$\{D\} = [e]^t\{\varepsilon\} - [\eta]\{E\}. \qquad \text{-----------------------} \quad (2)$$

The elastic field intensity vector E related to electrostatic potential ξ(x,y,z) in the L[th] layer is given by

$$E_X^L = \frac{\partial\xi(x,y,z)}{\partial x}; \quad E_y^L = \frac{\partial\xi(x,y,z)}{\partial y} \quad ; \quad E_z^L = \frac{\partial\xi(x,y,z)}{\partial z}$$

Where $\boldsymbol{\sigma}, \boldsymbol{Q}, \boldsymbol{\varepsilon}, \boldsymbol{e}, \boldsymbol{E}, \boldsymbol{D}$ and $\boldsymbol{\eta}$are the stress vector, elastic constant matrix, strain vector, piezoelectric constant matrix, electric field intensity vector, electric displacement vector and dielectric constant matrix respectively. From the lamina coupled constitutive equations, the elastic field can be written as two components of stresses. The first is elastic stress component (es) and second is piezoelectric stress component (pz).

i.e$\{\sigma\} = \{\sigma\}^{es} - \{\sigma\}^{pz}$, ------------------------- (3)

where

$$\{\sigma\}^{es} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} & Q_{14} & 0 & 0 \\ Q_{12} & Q_{22} & Q_{23} & Q_{24} & 0 & 0 \\ Q_{13} & Q_{23} & Q_{33} & Q_{34} & 0 & 0 \\ Q_{14} & Q_{24} & Q_{34} & Q_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & Q_{55} & Q_{56} \\ 0 & 0 & 0 & 0 & Q_{56} & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} \qquad \{\sigma\}^{pz} = \begin{bmatrix} 0 & 0 & e_{31} \\ 0 & 0 & e_{32} \\ 0 & 0 & e_{33} \\ 0 & 0 & 0 \\ 0 & e_{24} & 0 \\ e_{15} & 0 & 0 \end{bmatrix}$$

In which $\{\sigma\},\{\varepsilon\}$ are the stresses and linear strain vectors with respect to the laminate axes x, y and z, and $Q_{ij}$is the plane stress reduced elastic constants in the plate laminate axes of the L^{th} lamina.

Total stress resultants: $[Q\ S\ M\ N] = [Q\ S\ M\ N]^{es} + [Q\ S\ M\ N]^{pz}$ ------- (4)

Governing Equations of Motion:

The principle of virtual displacements is used to obtain the governing equations of motion. The general form of the dynamic version of the principle of virtual work or Hamilton's principle is:

$$\int_0^T (\delta U + \delta V - \delta K)\, dt = 0$$

The virtual strain energy δU, virtual work done by applied forces δV, and the virtual kinetic energy δK The governing equations of motion are expressed in terms of displacements for the present model and the solutions are achieved by the Navier's technique.

In Navier method the displacements are expanded in terms of unknown parameters. The choice of the trigonometric functions in the series is restricted to those which satisfy the boundary conditions of the problem. The Navier solutions can be developed for the rectangular laminates with two sets of simply supported boundary conditions. The following boundary conditions are used for the present considered model plate.

SS-1 Boundary condition: At edges x=0 and x=a;

$v_0=0$, $w_0=0$, $\theta y = 0, \theta z = 0$, Mx=0 ,Nx=0 , $v_0^* = 0$, $w_o^* = 0$,

$\theta_y^* = 0$, $M_x^* = 0$, $N_x^* = 0$, $\xi = 0$

SS-2 Boundary condition: At edges y=0 and y=b;

$u_0=0$, $w_0=0$, $\theta x = 0, \theta_z = 0$, $M_y=0$,$N_y=0$, $u_0^* = 0$, $w_o^* = 0$,

$\theta_x^* = 0$, $M_y^* = 0$, $N_y^* = 0$, $\xi = 0$

The mechanical, electrical loads and mid plane displacements are expressed in the following manner by using the Navier's technique and substituting the SS-1&SS-2 boundary conditions.

$$u_0(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} U_{mn}(t)\cos\alpha x \sin\beta y\,, \qquad v_0(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} V_{mn}(t)\sin\alpha x \cos\beta y$$

$$w_0(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} W_{mn}(t)\sin\alpha x \sin\beta y\,, \qquad \theta_x(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} X_{mn}(t)\cos\alpha x \sin\beta y$$

$$\theta_y(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} Y_{mn}(t)\sin\alpha x \cos\beta y\,, \qquad \theta_z(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} Z_{mn}(t)\sin\alpha x \sin\beta y$$

$$u_0^*(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} U_{mn}^*(t)\cos\alpha x \sin\beta y\,, \quad V_o^*(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} V_{mn}^*(t)\sin\alpha x \cos\beta y$$

$$w_0^*(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} W_{mn}^*(t)\sin\alpha x \sin\beta y\,, \quad \theta_x^*(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} X_{mn}^*(t)\cos\alpha x \sin\beta y$$

$\theta_y^*(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} Y_{mn}^*(t)\sin\alpha x\cos\beta y$, $\quad q(x,y,t) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} Q_{mn}(t)\sin\alpha x\sin\beta y$

$\xi(x,y,z) = \sum_{m=1,}^{\infty}\sum_{n=1}^{\infty}\xi_{mn}(z)\sin\alpha\ \mathrm{x}\sin\beta x$,

Where, $Q_{mn}(z,t) = \frac{4}{ab}\int_0^a\int_0^b q(x,y,t)\sin\alpha x\sin\beta y\,dxdy$, $\alpha = \frac{m\pi}{a}$ and $\beta = \frac{n\pi}{b}$

The above expansions are substituted in to the governing equation of motions and which gives the required system equations as per the S.M.Shiyekar and Tarun Kant [16].

III. Results and Discussions.

In this work a simply supported rectangular laminated composite substrate at all edges is to be used. The substrate is bidirectional orthotropic and is having polymer based matrix contains graphite/epoxy layers. The top and bottom of the substrate is embedded in distributed manner with PFRC layer. The following are the various material properties to be taken for the present work.

*Elastic Substrate: E_1= 172.9 Gpa; E_1/E_2 = 25; G_{12} =0.5 E_2; ; G_{22} =0.2 E_2;$\nu 12=\nu 22$=0.25;

**PFRC Layer: C_{11}=32.6 Gpa, $C_{12}=C_{21}$=4.3 Gpa ; $C_{13}=C_{31}$=4.76 Gpa ; $C_{22}=C_{33}$=7.2 Gpa; C_{23}=3.85Gpa; C_{44}=1.05 Gpa; $C_{55}=C_{66}$=1.29 Gpa; e_{31}= -6.76 C/m^2;

$\eta_{11} = \eta_{22}$ = 0.037 E-9 C/Vm; η_{33} =10.64 E -9 C/Vm;

The applied mechanical and electrical loads are in sinusoidal form of loading as per the literature and are to be taken as:

$$q_z^+ = \sum_{m=1,3,5}^{\infty}\sum_{n=1,3,5}^{\infty} -40\sin\boldsymbol{\alpha x}\cos\boldsymbol{\beta x} \quad ;\xi\left(x,y,\frac{h}{2}+t_p\right) = \sum_{m=1,3,5}^{\infty}\sum_{n=1,3,5}^{\infty} \pm 100\sin\boldsymbol{\alpha x}\cos\boldsymbol{\beta x} ,$$

The substrate is three layer type symmetric composite laminated plate ($0^0/90^0/0^0$) and each layer is with 1 mm thickness. The thickness of piezoelectric layer is assumed as 250 micro meters. In the present testing analysis is performed for the substrate with different aspect ratios such as(S=a/h), S=10, S=20 and S=100 under different electrical loadings such as V=0, V=100 and V=-100. The numerical results are tabulated in non-dimensional manner for displacements, different normal and shear stresses. The obtain results are compared with the S.M.Sheyekar & T.Kant results [16].

The Table.1 contains the numerical results obtained for normalized in plane and transverse displacements of a square cross ply substrate laminate ($0^0/90^0/0^0$) under different voltages with different aspect ratios. It is observed that under the applied voltages the results are very close agreement with the literature results [16]. It is also noticed that under the applied voltages response in the thick laminated plates are very good with comparison of thin laminated plates. The variation of normalized in plane and transverse displacement with different aspect ratios are shown in fig(1) & fig(2). It is also noticed from the figures that for large aspect ratios (S>20) the displacements are varied linier and almost constant with the thickness of the plate. For low aspect ratios(S<10) the displacements are drastically increased to a maximum value, it is due to the thickness of plate is very thin.

The Table.2 and Table.3 contains the numerical results for the in plane and transverse normal stresses as well as shear stresses respectively. The results are obtained for different aspect ratios (S=10, 20 and 100) under various applied voltages (V=0, +100 and -100).The fig(3) & (4) shows the variation of in plane normal stresses and transverse shear stresses for different aspect ratios under sinusoidal loading. It is observed that from fig(4) the transverse shear stresses are linearly increased between the aspect ratio 20 to 100 and drastically increased for low aspect ratios (S<20), it may be due to thick plates.

IV. Conclusions

The present investigation produces an excellent solution for laminated composite plates integrated with piezoelectric material layers in distributed form on top and bottom surface of it and subjected to electro-mechanical loading. The Navier's technique is used to find the solution of the proposed HOSDT. The obtained results gives the good agreement with the literature results[16]. The present results are more effective and reliable one with others. The piezo effects are in the case of thick laminates (Low aspect ratio) compared with thin laminates (High aspect ratio). The effects of various displacements, stresses in the laminates are satisfactorily studied.

Table 1: Normalized in plane and transverse displacements of $(\bar{u}, \bar{w})$ of symmetric substrate $(0^0/90^0/0^0)$ without and with sinusoidal electric voltages at top of the PFRC actuator surface.

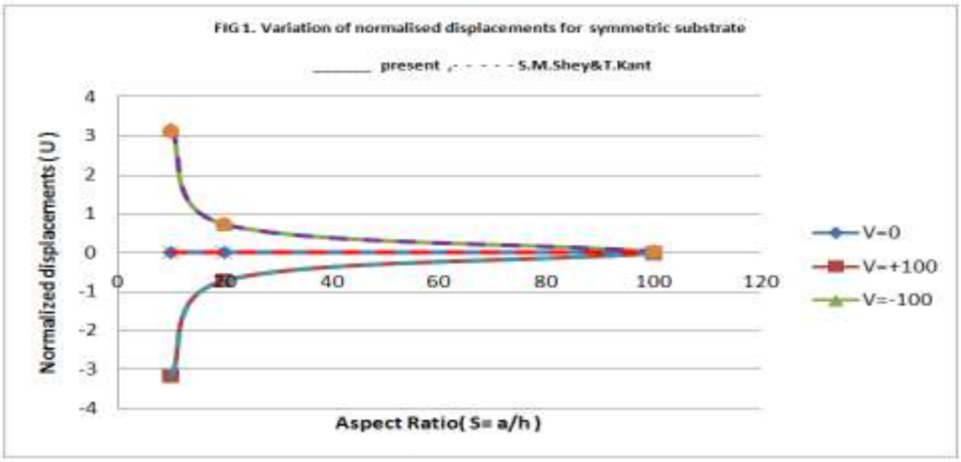
Theory	S=10			S=20			S=100		
	V=0	V=+100	V=-100	V=0	V=+100	V=-100	V=0	V=+100	V=-100
$\bar{u} = \left(0, \frac{b}{2}, \pm\frac{h}{2}\right)$ Present	0.0040	-3.1623	3.1704	0.0056	-0.7147	0.7349	0.0063	-0.0222	0.0345
S.M.Shiyekar &T.Kant	0.00632	-3.11842	3.13105	0.00617	-0.7147	0.72709	0.00613	-0.02191	0.03416
$\bar{w} = \left(\frac{a}{2}, \frac{b}{2}, 0\right)$ Present	-0.6817	130.55	-131.9	-0.476	30.1152	-31.06	-0.407	0.7854	-1.601
S.M.Shiyekar &T.Kant	-0.66806	129.05	-130.39	-0.47112	29.772	-30.7146	-0.40432	0.77533	-1.58397

Table 2: Normalized in plane and transverse normal stresses of $(\bar{\sigma}_x, \bar{\sigma}_y, \bar{\sigma}_z)$ of symmetric substrate ($0^0/90^0/0^0$) without and with sinusoidal electric voltages at top of the PFRC actuator surface.

Theory	S=10			S=20			S=100		
	V=0	V=+100	V=-100	V=0	V=+100	V=-100	V=0	V=+100	V=-100
$\bar{\sigma}_x = \left(\frac{a}{2}, \frac{b}{2}, \pm\frac{h}{2}\right)$ Present	-0.517	247.85	-248.88	-0.498	57.043	-58.048	-0.492	1.748	-2.733
S.M.Shiyekar &T.Kant	-0.5074	247.5430	-248.558	-0.4932	56.7572	-57.743	-0.4887	1.73795	-2.7154
$\bar{\sigma}_y = \left(\frac{a}{2}, \frac{b}{2}, \pm\frac{h}{6}\right)$ Present	-0.249	40.659	-41.157	-0.186	10.251	-10.624	-0.163	0.256	-0.582
S.M.Shiyekar &T.Kant	-0.2372	39.407	-39.882	-0.1811	9.9599	-10.3222	-0.160	0.2478	-0.5678
$\bar{\sigma}_z = \left(\frac{a}{2}, \frac{b}{2}, 0\right)$ Present	-0.534	23.838	-44.907	-0.788	39.795	-41.373	-8.838	37.212	-54.88
S.M.Shiyekar &T.Kant	-0.4746	.------	-54.6788	-0.4766	.-------	.-----	-.---	---	----

Table 3: Normalized in plane and transverse shear stresses of $(\bar{\tau}_{xy}, \bar{\tau}_{yz}, \bar{\tau}_{xz})$ of symmetric substrate $(0^0/90^0/0^0)$ without and with sinusoidal electric voltages at top of the PFRC actuator surface.

Theory	S=10			S=20			S=100		
	V=0	V=+100	V=-100	V=0	V=+100	V=-100	V=0	V=+100	V=-100
$\bar{\tau}_{xy} = \left(0, 0, \pm\frac{h}{2}\right)$ Present	0.0256	-7.652	7.704	0.0213	-1.815	1.8577	0.0198	-0.0526	0.0920
S.M.Shiyekar &T.Kant	0.02473	-7.566	7.6156	0.02084	-1.7916	1.8329	0.0194	-0.0518	0.0907
$\bar{\tau}_{yz} = \left(0, \frac{b}{2}, 0\right)$ Present	-0.101	22.035	-22.23	-0.081	-12.23	------	-0.074	0.1474	-0.2959
S.M.Shiyekar &T.Kant	-0.115	23.940	-24.172	-0.0914	-14.72	------	-0.082	0.1609	-0.3255
$\bar{\tau}_{xz} = \left(\frac{a}{2}, 0, 0\right)$ Present	-0.246	19.896	-20.389	-0.258	-----	-----	-0.263	-0.0502	-0.4764
S.M.Shiyekar &T.Kant	-0.353	23.026	-23.732	-0.374	-----	------	-0.3824	-0.1241	-0.6408



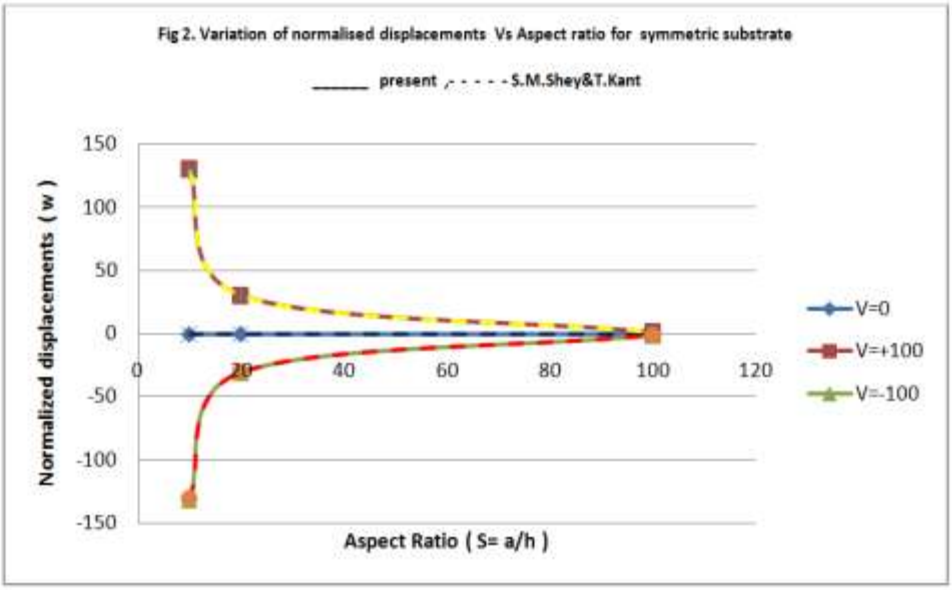


Fig 2. Variation of normalised displacements Vs Aspect ratio for symmetric substrate

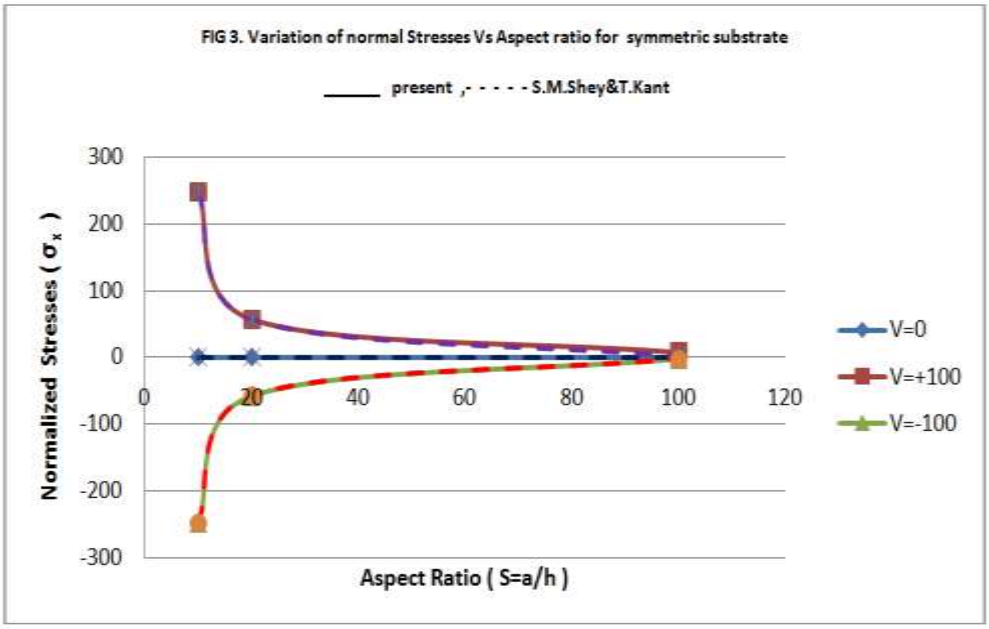


FIG 3. Variation of normal Stresses Vs Aspect ratio for symmetric substrate

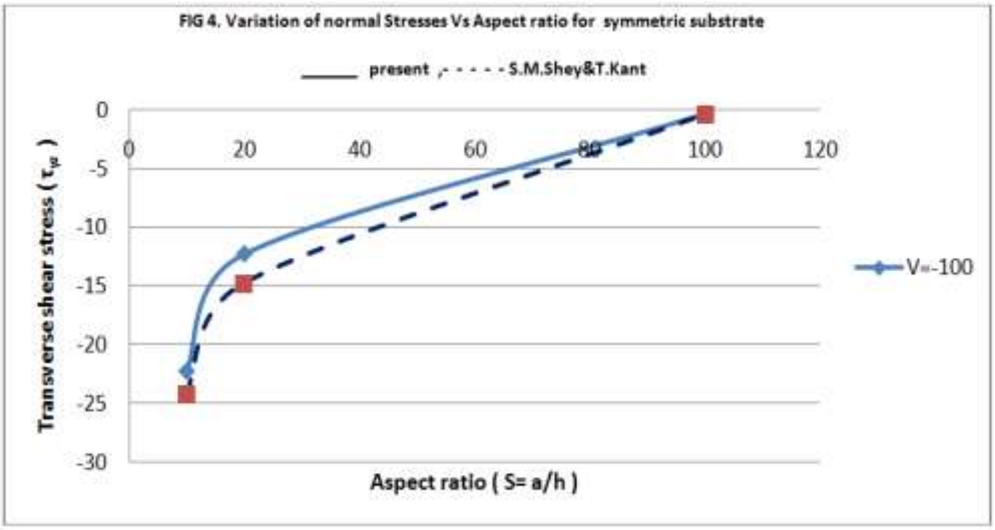


FIG 4. Variation of normal Stresses Vs Aspect ratio for symmetric substrate

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