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A New Higher Order Shear Deformation Theory for bending Analysis of Isotropic and Orthotropic Plates with Linear thermal Loading

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***Abstract:* -- In this paper analytical solutions of isotropic and orthotropic laminated composite plates are analyzed by using Higher Order Shear Deformation Theory. By using Principal of virtual work we get the governing equations. A simply supported square plate is used to compare various numerical results. The shear correction factor is obviated in this theory. It observed that solution obtained from present theory make a good agreement with exact higher order shear deformation theory.**

***Keywords*: - Shear correction factor, principal of virtual work, laminated composite plates.**

I. INTRODUCTION

The composite Laminates are widely used in many engineering structures like aerospace engineering, Marin engineering etc. Due to mechanical properties of composite structure it reduces heavy weight and improves the stiffness of that structure, so these composite structures are light in weight and ease to handle. In composite materials fibers and matrix are used. According to necessity of structure orientation we can change fiber orientations. As we know, the change in environment affect to the durability and life of that structure. Therefore many engineering structures subjected to severe thermal environment due to composite attractive properties such as temperature resistance and low thermal coefficient of expansion. Due to thermal loading, thermal stresses are developed at the interface between two different materials which can be significant factor in the failure of Laminated Composite Structures. Therefore it is necessary to predict more accurately the thermal stresses in composite structures. Many theories are developed by various researchers to predict the correct behavior of composite laminates under mechanical or thermal or thermo-mechanical loading.

II. LITERATURE REVIEW

Mechab [1] presents the analytical solutions of cross-ply laminated plates under thermo-mechanical loading based on higher order shear deformation theory. The effects of plate width-to thickness ratio, thickness ratio, aspect ratio and boundary conditions on the displacement of laminated composite plates are presented. Program is developed in FORTRAN. Ghugal [2, 3] investigate the effects of nonlinear thermo-mechanical load on a composite laminated plate. Flexural stress analysis of cross-ply laminated composite plates subjected to
Transverse parabolic load and line load. Kapuria [4] present higher order zigzag theory (HZIGT) for laminated plates under thermal loading. Zenkur [5] presented unified shear deformable plate theory for buckling of fiber-reinforced viscoelastic composite plates to study the static response of laminated plates subjected to non-uniform thermal or thermo-mechanical loads. The two-dimensional analysis of composite laminated plates has been based on the classical lamination theory or the shear deformation theory [9-13]. In both of these theories, it is assumed that the displacements are continuous functions over the thickness, and the laminate is characterized as an equivalent and homogeneous layer, however, these theories predict discontinuous stress distributions at the layer interfaces due to dissimilar elastic properties of adjacent layers. Fares [6] presented thermal model accounts for First-order Reissner and Mindlin displacements and continuous stress distributions through the laminate thickness that are consistent with the surface conditions. Zhen [7] developed the global–local higher order model to analyze thermal response of laminated plates under actual temperature fields. Savoia [8] presents three dimensional solutions of rectangular multilayered plates subjected to thermo-mechanical loads within the quasi static theory of thermo elasticity. Bhaskar et al. [14] presented 3D elasticity solution for laminated cylindrical and bi directional bending considering linear thermal profile through the thickness of the symmetric

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laminate. Kirchhoff [15] gives Classical plate theory (CPT) and Mindlin [16] developed first order shear deformation theory (FSDT). Reddy [17] developed higher order shear deformation theory (HSDT). Sayyad [18] developed theory by using four variable for Thermoelastic bending analysis by assuming linear thermal variation for various aspect ratio. Sayyad [19] gives exponential shear deformation theory (ESDT) for analysis of thermal stress for laminated composite plates. Kant and Shiyekar [20] gives analytical model for thermal stress analysis of cross ply laminates subjected to gradient thermal profile across thickness of plate. Ghugal and Kulkarni [23,24] explained thermal stresses and displacements for orthotropic, two layer antisymmetric and three layer symmetric square cross ply laminated plates by considering nonlinear thermal variation across thickness of plate.

III. THEORETICAL FORMULATION

Consider a square plate of length (a), width (b) and thickness (h) composed of orthotropic layers. The material of each layer is assumed to have one plane of material property symmetry parallel to x-y plane. The coordinate system is such that the mid plane of the plate coincides with x-y plane, and z axis is normal to the middle plane. The upper surface of the plate is subjected to transverse load q(x, y). The plate occupies in ((o-x-y-z) i.e. right handed Cartesian coordinate system) a region.

$$0 \le x \le a,\ 0 \le y \le b,\ -h/2 \le z \le h/2$$

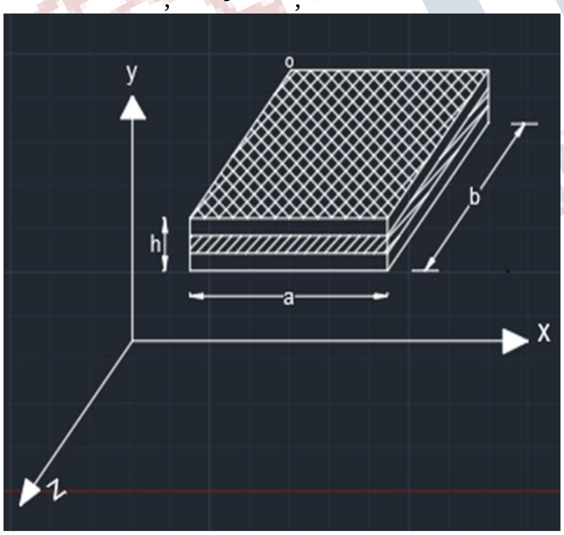

Figure 1 Coordinate system and Geometry of Laminated Plate

$$u(x,y,z) = u_0(x,y) - z\frac{\partial w(x,y)}{\partial x} + f(z)\phi(x,y) \quad (2)$$

$$v(x,y,z) = v_0(x,y) - z\frac{\partial w(x,y)}{\partial y} + f(z)\varphi(x,y)$$

$$w(x,y,z) = w_0(x,y) + \frac{\cos \pi z}{h}\xi(x,y)$$

Where $f(z) = \left(\frac{h}{\pi}\right)\sin\left(\frac{\pi z}{h}\right)$ in and u_0, v_0, w_0 are mid displacements in x, y and z directions respectively. ϕ, φ, ξ are represents rotations of given plate at neutral surface. From theory of elasticity we obtained normal strain $\varepsilon_x, \varepsilon_y, \varepsilon_z$ and shear strain $\gamma_{xy}, \gamma_{xz}, \gamma_{yz}$ in x, y and z direction.

$$\varepsilon_x = \frac{\partial u}{\partial x} \qquad \varepsilon_y = \frac{\partial v}{\partial y} \qquad \varepsilon_z = \frac{\partial w}{\partial z}$$

$$\gamma_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \qquad \gamma_{xz} = \frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}$$

$$\gamma_{yz} = \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}$$

It can be noted that transverse shear strain are zero at top and bottom of the plate. Since the laminate is made of several orthotropic layers, the constitutive relations in the kth layer are given as,

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{xy} \\ \tau_{xz} \\ \tau_{yz} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{13} & Q_{14} & Q_{15} & Q_{16} \\ Q_{21} & Q_{22} & Q_{23} & Q_{24} & Q_{25} & Q_{26} \\ Q_{31} & Q_{32} & Q_{33} & Q_{34} & Q_{35} & Q_{36} \\ Q_{41} & Q_{42} & Q_{43} & Q_{44} & Q_{45} & Q_{46} \\ Q_{51} & Q_{52} & Q_{53} & Q_{54} & Q_{55} & Q_{56} \\ Q_{61} & Q_{62} & Q_{63} & Q_{64} & Q_{65} & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x - \alpha_x \Delta T \\ \varepsilon_y - \alpha_y \Delta T \\ \varepsilon_z - \alpha_z \Delta T \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \end{Bmatrix}$$

Q_{11}, Q_{22}, Q_{33}, etc. are reduced stiffness coefficients of kth layer as given below,

$$Q_{11} = \frac{E_1}{(1-\mu_{12}\mu_{21})} \qquad Q_{22} = \frac{E_2}{(1-\mu_{12}\mu_{21})}$$

$$Q_{12} = \frac{\mu_{12}E_2}{(1-\mu_{12}\mu_{21})} \quad (5)$$

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$$Q_{66} = G_{12}, \quad Q_{44} = G_{23}, \quad Q_{55} = G_{13},$$

The temperature variation through the thickness is assumed to $T(x,y,z) = \Delta T$

IV. GOVERNING EQUATIONS

The governing equation and boundary conditions are derived using principle of virtual work, vibrational consistent differential equations and the boundary conditions for the plate under considerations are obtained. The principle of virtual work when applied to plate we get,

$$\iiint (\sigma_x \delta\varepsilon_x + \sigma_y \delta\varepsilon_y + \tau_{xy}\delta\gamma_{xy})dxdydz - \iint q\delta w dxdy = 0$$

Integrating equation by parts and collecting the coefficient of $\delta u_0, \delta v_0, \delta w_0, \delta\phi_0, \delta\varphi_0, \delta\xi_0$ the following governing equations and boundary conditions are obtained.

We will get following boundary conditions,

$$\delta u_0 : u_{mn}(A_{11}\alpha^2 + A_{66}\beta^2) + v_{mn}(A_{12}\alpha\beta + A_{66}\alpha\beta) - w_{mn}(B_{11}\alpha^3 + B_{12}\alpha\beta^2 + 2B_{66}\alpha\beta^2) + \phi_{mn}(C_{11}\alpha^2 + C_{66}\beta^2) + \varphi_{mn}(C_{12}\alpha\beta + C_{66}\alpha\beta) - \xi_{mn}D_{13}\alpha + T_{0mn}\alpha(A_{11}^{Tx} + A_{12}^{Ty} + A_{13}^{Tz}) + T_{1mn}\alpha(B_{11}^{Tx} + B_{12}^{Ty} + B_{13}^{Tz}) + T_{2mn}\alpha(C_{11}^{Tx} + C_{12}^{Ty} + C_{13}^{Tz})$$

$$\delta v_0 : u_{mn}(A_{12}\alpha\beta + A_{66}\alpha\beta) + v_{mn}(A_{66}\alpha^2 + A_{22}\beta^2) - w_{mn}(B_{12}\alpha^2\beta + B_{22}\beta^3 + 2B_{66}\alpha^2\beta) + \phi_{mn}(C_{12}\alpha\beta + C_{66}\alpha\beta) + \varphi_{mn}(C_{22}\beta^2 + C_{66}\alpha^2)) - \xi_{mn}D_{23}\beta + T_{0mn}\beta(A_{12}^{Tx} + A_{22}^{Ty} + A_{23}^{Tz}) + T_{1mn}\alpha(B_{12}^{Tx} + B_{22}^{Ty} + B_{23}^{Tz}) + T_{2mn}\alpha(C_{12}^{Tx} + C_{22}^{Ty} + C_{23}^{Tz})$$

$$\delta w_0 : -u_{mn}(B_{11}\alpha^3 + B_{12}\alpha\beta^2 + 2B_{66}\alpha\beta^2) - v_{mn}(B_{12}\alpha^2\beta + B_{22}\beta^3 + 2B_{66}\alpha^2\beta) - w_{mn}\begin{pmatrix} E_{11}\alpha^4 + 2E_{12}\alpha^2\beta^2 + E_{22}\beta^4 + \\ 4E_{66}\alpha^2\beta^2 \end{pmatrix} - \phi_{mn}(F_{11}\alpha^3 + F_{12}\alpha\beta^2 + 2F_{66}\alpha\beta^2) - \varphi_{mn}(F_{12}\alpha^2\beta + F_{22}\beta^3 + 2F_{66}\alpha^2\beta) + \xi_{mn}(J_{13}\alpha^2 + J_{23}\beta^2) + T_{0mn}\begin{bmatrix} \alpha^2(G_{11}^{Tx} + G_{12}^{Ty} + G_{13}^{Tz}) + \\ \beta^2(G_{12}^{Tx} + G_{22}^{Ty} + G_{23}^{Tz}) \end{bmatrix} + T_{1mn}\begin{bmatrix} \alpha^2(H_{11}^{Tx} + H_{12}^{Ty} + H_{13}^{Tz}) + \\ \beta^2(H_{12}^{Tx} + H_{22}^{Ty} + H_{23}^{Tz}) \end{bmatrix} + T_{2mn}\begin{bmatrix} \alpha^2(I_{11}^{Tx} + I_{12}^{Ty} + I_{13}^{Tz}) + \\ \beta^2(I_{12}^{Tx} + I_{22}^{Ty} + I_{23}^{Tz}) \end{bmatrix}$$

$$\delta\phi_0 : u_{mn}(C_{11}\alpha^2 + C_{66}\beta^2) + v_{mn}(C_{12}\alpha\beta + C_{66}\alpha\beta) - w_{mn}(F_{11}\alpha^3 + F_{12}\alpha\beta^2 + 2F_{66}\alpha\beta^2) + \phi_{mn}(L_{11}\alpha^2 + L_{66}\beta^2) + \varphi_{mn}(L_{12}\alpha\beta + L_{66}\alpha\beta) - \xi_{mn}(P_{13}\alpha - R_{55}\alpha) + T_{0mn}\alpha(C_{11}^{6TX} + C_{12}^{6Ty} + C_{13}^{6Tz}) + T_{1mn}\alpha(F_{11}^{6Tx} + F_{12}^{6Ty} + F_{13}^{6Tz}) + T_{2mn}\alpha(L_{11}^{6Tx} + L_{12}^{6Ty} + L_{13}^{6Tz})$$

$$\delta\varphi_0 : u_{mn}(C_{12}\alpha\beta + C_{66}\alpha\beta) + v_{mn}(C_{22}\beta^2 + C_{66}\alpha^2) - w_{mn}(F_{12}\alpha^2\beta + F_{22}\beta^3 + 2F_{66}\alpha^2\beta) + \phi_{mn}(L_{12}\alpha\beta + L_{66}\alpha\beta) + \varphi_{mn}(L_{22}\beta^2 + L_{66}\alpha^2 + R_{55}) - \xi_{mn}(P_{23}\beta - R_{55}\beta) + T_{0mn}\alpha(C_{12}^{6Tx} + C_{22}^{6Ty} + C_{23}^{6Tz}) + T_{1mn}\alpha(F_{12}^{6Tx} + F_{22}^{6Ty} + F_{23}^{6Tz}) + T_{2mn}\alpha(L_{12}^{6Tx} + L_{22}^{6Ty} + L_{23}^{6Tz})$$

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$$\delta\xi_0 : -u_{mn}D_{13}\alpha - v_{mn}D_{23}\beta + w_{mn}(J_{13}\alpha^2 + J_{23}\beta^2) + \phi_{mn}(P_{13}\alpha - R_{55}\alpha) - \varphi_{mn}(P_{23}\beta - R_{55}\beta) + \xi_{mn}(R_{55}\alpha^2 - R_{55}\beta^2 + S_{33}) + T_{0mn}(D_{13}{}^{7Tx} + D_{23}{}^{7Ty} + D_{33}{}^{7Tz}) + T_{1mn}(J_{13}{}^{7Tx} + J_{23}{}^{7Ty} + J_{33}{}^{7Tz}) + T_{2mn}(P_{13}{}^{7Tx} + P_{23}{}^{7Ty} + P_{33}{}^{7Tz})$$

In this paper, We discuss three numerical non-dimensional displacement and stresses are determined for simply supported isotropic, orthotropic and three layer (0^0-90^0-0^0) symmetric cross ply laminated composite plates subjected to thermal load linearly varying across the thickness of the plate. The plate is made by graphite-epoxy composite material with following properties,

Example 1: Simply supported isotropic laminated composite plates subjected to thermal load linearly varying across the thickness of the plate with following properties,

$$\mu_{12} = \mu_{13} = \mu_{23} = \mu_{32} = \mu_{21} = \mu_{32} = 0.3$$

$$E_1 = E_2 = E_3 = 380GPa, \quad \frac{\alpha_y}{\alpha_x} = \frac{\alpha_z}{\alpha_x} = 3.0$$

$$G_{12} = G_{13} = G_{23} = 146.54GPa$$

Example 2: Simply supported orthotropic laminated composite plates subjected to thermal load linearly varying across the thickness of the plate with following properties,

$$\frac{E_1}{E_2} = 25, \quad E_2 = E_3 = 1.0GPa,$$

$$G_{12} = G_{13} = 0.5E_2, \quad G_{23} = 0.2E_2$$

$$\mu_{12} = \mu_{13} = \mu_{23} = \mu_{32} = 0.25$$

$$\mu_{21} = \mu_{31} = 0.01, \quad \frac{\alpha_y}{\alpha_x} = \frac{\alpha_z}{\alpha_x} = 3.0$$

By using Navier's solution we get governing equations and boundary conditions.

V. RESULT AND DISCUSSION

In this paper, displacements and stresses are determined for antisymmetric laminated plates subjected to linear thermal load across the thickness of plate. Results are presented in the following normalized forms for the purpose of discussion.
Normalized displacements and thermal stresses for isotropic laminated plates,

$$\bar{u} = u\frac{1}{\alpha_x T_0 h}, \quad \bar{v} = v\frac{1}{\alpha_x T_0 h}$$

$$\bar{w} = w\frac{1}{\alpha_x T_0 h}\quad \overline{\sigma_x} = \sigma_x\frac{1}{\alpha_x T_0 E_2},$$

$$\overline{\sigma_y} = \sigma_y\frac{1}{\alpha_x T_0 E_2}, \quad \overline{\tau_{xy}} = \tau_{xy}\frac{1}{\alpha_x T_0 E_2},$$

Normalized displacements and thermal stresses for orthotropic laminated plates

$$\bar{u} = u\left(0,\frac{b}{2},\frac{-h}{2}\right)\frac{10}{\alpha_x T_0 a^2},$$

$$\bar{v} = v\left(\frac{b}{2},0,\frac{-h}{2}\right)\frac{10}{\alpha_x T_0 a^2}, \quad \bar{w} = w\left(\frac{a}{2},\frac{b}{2},0\right)\frac{10}{\alpha_x T_0 a^2}$$

$$\overline{\sigma_x} = \sigma_x\left(\frac{a}{2},\frac{b}{2},-\frac{h}{2}\right)\frac{1}{\alpha_x T_0 E_2 a^2},$$

$$\overline{\sigma_y} = \sigma_y\left(\frac{a}{2},\frac{b}{2},-\frac{h}{2}\right)\frac{1}{\alpha_x T_0 E_2 a^2}$$

$$\overline{\tau_{xy}} = \tau_{xy}\left(0,0,-\frac{h}{2}\right)\frac{1}{\alpha_x T_0 E_2 a^2},$$

$$\overline{\tau_{xz}} = \tau_{xz}\left(0,\frac{b}{2},0\right)\frac{1}{\alpha_x T_0 E_2 a^2}$$

$$\overline{\tau_{yz}} = \tau_{yz}\left(\frac{a}{2},0,0\right)\frac{1}{\alpha_x T_0 E_2 a^2}$$

Table 1 Normalized Displacements for Square Isotropic Plate Subjected To Linear Thermal Load for Aspect Ratio 10 (Example 1)

Aspect Ratio	Model	$\bar{u}$	$\bar{v}$	$\bar{w}$
10	Present	2.0915	2.0915	13.1973
	TSDT[24]	2.0690	2.0690	13.1718
	FSDT[16]	2.0690	2.0690	13.1718
	CPT[15]	2.0690	2.0690	13.1718

Table 2 Normalized stresses for square isotropic plate subjected to linear thermal load for aspect ratio 10 (Example 1)

Aspect Ratio	Model	$\overline{\sigma_x}$	$\overline{\sigma_y}$	$\overline{\tau_{xy}}$
10	Present	0.6303	0.6303	0.5054
	TSDT[24]	0.5000	0.5000	0.5000
	FSDT[16]	0.5000	0.5000	0.5000
	CPT[15]	0.5000	0.5000	0.5000

From Table 1 and Table 2, it is observed that the in plane displacements predicted by present theory, TSDT of Ghugal and Kulkarni [24], FSDT of Mindlin[16] and CPT of Kirchhoff[15]are nearly close agreement with each other.

Table 3 Normalized displacements for orthotropic plate subjected to linear thermal load for aspect ratio 5 and 10 (Example 2)

Aspect Ratio	Model	$\bar{u}$	$\bar{v}$	$\bar{w}$
5	Present	0.4759	0.3810	1.0342
	TSDT24]	0.3222	0.3729	1.0709
	FSDT[16]	0.3190	0.3812	1.0721
	CPT[15]	0.3240	0.3240	1.0312
10	Present	0.1704	0.1704	1.1295
	TSDT[24]	0.1617	0.1697	1.0439
	FSDT[16]	0.1612	0.1709	1.0440
	CPT[15]	0.1620	0.1620	1.0312

Table 4 Normalized stresses for orthotropic plate subjected to linear thermal load for aspect ratio 5 and 10 (Example 2)

Aspect Ratio	Model	$\overline{\sigma_x}$	$\overline{\sigma_y}$	$\overline{\tau_{xy}}$	$\overline{\tau_{xz}}$	$\overline{\tau_{yz}}$
5	Present	0.0449	0.1970	0.1120	0.1064	0.1183
	TSDT24]	0.0155	0.1830	0.1092	0.1120	0.1145
	FSDT[16]	0.0394	0.1806	0.1100	0.0740	0.0740
	CPT[15]	0.0053	0.1983	0.1018	-	-
10	Present	0.0029	0.1049	0.0526	0.0352	0.1571
	TSDT[24]	0.0042	0.0967	0.0521	0.0356	0.0358
	FSDT[16]	0.0080	0.0964	0.0522	0.0231	0.0231
	CPT[15]	0.0026	0.0991	0.0509	-	-

From Table 3 and Table 4, it is observed that the in plane displacements, in plane normal stresses and transverse shear stresses predicted by present theory TSDT of Ghugal and Kulkarni [24], FSDT of Mindlin[16] and CPT of Kirchhoff[15]are overestimate.

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