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Thermal flexural analysis of anti-symmetric cross-ply laminated plates using a four variable refined theory

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Abstract. This article deals with the flexural analysis of anti-symmetric cross-ply laminated plates under nonlinear thermal loading using a refined plate theory with four variables. In this theory, the undetermined integral terms are used and the number of variables is reduced to four, instead of five or more in other higher-order theories. The boundary conditions on the top and the bottom surfaces of the plate are satisfied; hence the use of the transverse shear correction factors is avoided. The principle of virtual work is used to obtain governing equations and boundary conditions. Navier solution for simply supported plates is used to derive analytical solutions. For the validation of the present theory, numerical results for displacements and stresses are compared with those of classical, first-order, higher-order and trigonometric shear theories reported in the literature.

Keywords: refined plate theory; flexural analysis; nonlinear thermal loading; cross-ply laminated plates

1. Introduction

Nowadays, fiber reinforced composites are widely used in various domains for instance, the aerospace, automotive, marine, civil and other fields owing to their excellent mechanical and thermal properties such as high specific strength , high stiffness, corrosion resistance, light damping, temperature resistance and low thermal coefficient of expansion. In order to study the behaviour of these materials, various theories have been developed. To start with the classical plate theory (CPT) which is based on Kirchhoff assumptions that, the normal to the mid-plane remains normal and straight after deformation and do not undergo thickness stretching (Bilouei *et al*. 2016). The CPT provides acceptable results for thin plates. Nevertheless, it is inaccurate for thick plates since it neglects the effects of transverse shear deformation. Then the first-order theory has been proposed by Reissner (1945) and Mindlin (1951), this theory considers the shear deformation effect. Thus, it needs a shear correction factor to satisfy the stress free boundary conditions (Civalek and Emsen 2009, Avcar 2015, 2019, Al-Basyouni *et al*. 2015, Kolahchi *et al*. 2016, Madani *et al*. 2016, Bellifa *et al*. 2016, Arani and Kolahchi 2016, Zamanian *et al*. 2017, Amnieh *et al*. 2018, Youcef *et al*. 2018, Semmah *et al*. 2019). Further, higher-order theories have been developed in order to overcome the limitations of the previous theories (CPT and FSDT). Several higher-order shear deformation theories (HSDTs) have been proposed for the investigation of the behaviour of structures (Reddy 1984, Soldatos 1988, 1992, Touratier 1991, Kant and Swaminathan 2000, 2002, Akavci 2010, Grover *et al*. 2013, Sahoo and Singh 2013, Sayyad and Ghugal 2014, Meziane *et al*. 2014, Ahmed 2014, Yahia *et al*. 2015, Zenkour 2015, Belkorissat *et al*. 2015, Bounouara *et al*. 2016, Ahouel *et al*. 2016, Boukhari *et al*. 2016, Houari *et al*. 2016, Draich *et al*. 2016, Kolahchi and Moniri Bidgoli 2016, Abdelhak 2016, Baseri *et al*. 2016, Kolahchi *et al*. 2017a, b, Benadouda *et al*. 2017, Hachemi *et al*. 2017, Bellifa *et al*. 2017a, b, Kolahchi and Cheraghbak 2017, Kolahchi 2017, Besseghier *et al*. 2017, Abdelaziz *et al*. 2017, Belalia 2017, Avcar and Mohammed 2018, Bouhadra *et al*. 2018, Bouadi *et al*. 2018, Bakhadda *et al*. 2018, Golabchi *et al*. 2018, Fourn *et al*. 2018, Younsi *et al*. 2018, Belabed *et al*. 2018, Bourada *et al*. 2018, 2019, Adda Bedia *et al*. 2019 and Berghouti *et al*. 2019).

The mentioned-above theories have been extended or developed for the investigation of the thermal problem for laminated plates. Boley and Weiner (1960), Reddy (1997), Jones (1999), Wu and Tauchert (1980) used the CPT for the thermal stress analysis of laminated plates under thermal loading. The FSDT has been extended by Reddy (1997) in order to analyze the thermal stresses in laminated plates. Kheider and Reddy (1991) developed an exact analytical

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solution of refined plate theories, stresses and deflections of laminated plate subjected to a single sinusoidal thermal loading have been presented. The global-local higher theory has been simply derived by Zhen and Chen (2006) in order to obtain an efficient higher-order theory and finite element for laminated plates under sinusoidal thermal loading. Shinde *et al*. (2013) used the hyperbolic shear deformation theory to investigate the thermal bending of isotropic plates under uniformly distributed thermal loading. Thermal flexural analysis of cross-ply laminated plates subjected to a nonlinear sinusoidal thermal loading using trigonometric shear deformation theory has been presented by Ghugal and Kulkarni (2013a). Various plate theories have been used by Sayyad *et al*. (2014) to carry out a thermo-elastic analysis of cross-ply laminated plates under linear sinusoidal thermal loading. Thermal displacements and stresses of laminated plates subjected to a sinusoidally distributed linear thermal loading using a four-variable plate theory have been presented by Sayyad *et al*. (2015). In another article Sayyad *et al*. (2016) presented a thermal stress analysis of cross-ply laminated plate subjected to a linear thermal loading using an exponential shear deformation theory. Ghadhe *et al*. (2018) have recently presented three variables trigonometric shear deformation theory to analyze flexural behaviour of isotropic plates subjected to a single sinusoidal thermal loading. Javed *et al*. (2018) studied the free vibration of cross-ply laminated plates based on higher-order shear deformation theory.

Further, various researches interested to the response of laminated plate under combined thermo-mechanical loading, hence refined theories have been proposed. (Fares and Zankour 1999, and Fares *et al*. 2000) presented a mixed variational formula for the analysis of generally layered composite structures subjected to sinusoidal thermo-mechanical single loading. Han *et al*. (2017) proposed an enhanced first order shear deformation theory including the transverse normal strain effect for the analysis of the thermo-mechanical response of laminated composite and sandwich plates. By the use of a unified shear deformation plate theory, Zenkour (2004) investigated the static thermo-elastic response of symmetric and anti-symmetric cross-ply laminated plates under non-uniform sinusoidal mechanical and/or thermal loading. An equivalent single layer shear deformation theory has been presented by Ghugal and Kulkarni (2012, 2013b, c) using a trigonometric shear deformation theory in order to analyze displacements and stresses of cross ply laminated plates under uniformly distributed linear and nonlinear thermo-mechanical loading. Based on the layer-wise displacement field of Reddy, Cetkovic (2015) proposed a mathematical model using small deflexion linear-elasticity theory for the analysis of the thermo-mechanical bending of laminated composites and sandwich plates subjected to a uniform or a single sinusoidally distributed gradient temperature along with sinusoidal mechanical loadings. Panda and Katariya (2015) studied the stability and free vibration behaviour of laminated composite panels under thermo-mechanical loading. Zen and Xiaohui (2016) proposed a new modal to analyze the thermo-mechanical behavior of multilayered composite plates under thermo-mechanical combined loading based on Reddy-type higher order theory. An analytical model of laminated composite plates based on an inverse hyperbolic shear deformation theory (IHSDT) has been proposed by Joshan *et al*. (2017), the thermo-mechanical response of cross-ply and angle-ply laminated composite plates has been investigated. Also, Joshan *et al*. (2018) presented an assessment of non-polynomial shear deformation theories for thermo-mechanical analysis of laminated composite plates. Moreover, several investigations delved on the study of the thermal or thermo-mechanical behaviour of functionally graded plates; various refined theories have been presented by (Jabbari *et al*. 2002, Zankour and Alghamdi 2008, Bouderba *et al*. 2013, Tounsi *et al*. 2013, Zidi *et al*. 2014, Hamidi *et al*. 2015, Kar and Panda 2015, Attia *et al*. 2015, 2018, Yaghoobi *et al*. 2015, Beldjelili *et al*. 2016, Bousahla *et al*. 2016, Bouderba *et al*. 2016, Khetir *et al*. 2017, Chikh *et al*. 2017, Kolahchi *et al*. 2017b, Fahsi *et al*. 2017, Menasria *et al*. 2017, Hajmohammad *et al*. 2017, 2018a, b, c, Zghal *et al*. 2017, El-Haina *et al*. 2017, Fakhar and Kolahchi 2018, Hosseini and Kolahchi 2018, Hussain and Naeem 2019).

The present research attempts to provide a refined plate theory for the analysis of the thermal response of laminated plates under nonlinear thermal loading. In this theory, the unknown number is reduced to four instead of five or more as suggested in the other theories. The obtained results are discussed and compared with those for classical, first-order, trigonometric and higher-order shear theories of published results of open literature (Ghugal and Kulkarni 2013a).

2. Theoretical formulation

Consider a rectangular cross-ply laminated plate with total thickness "*h*" composed of n orthotropic layers(see Fig. 1), which are perfectly bonded together. The material of each layer is assumed to posses on plane of elastic symmetry parallel to x-y plane. The plate is subjected to a thermal loading T(x, y, z).

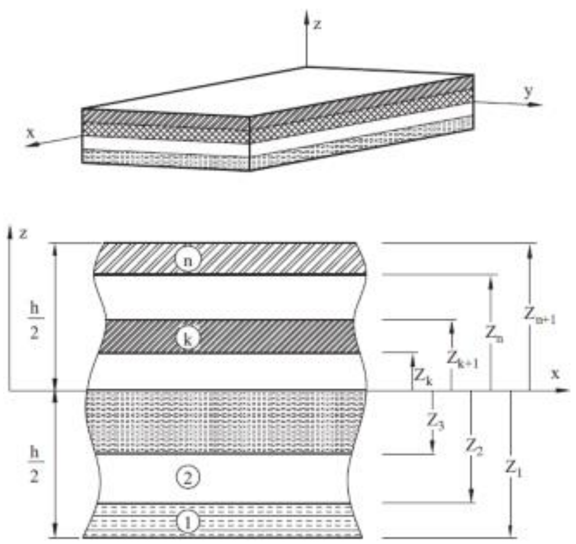

Fig. 1 Plate geometry and coordinate system

2.1 Kinematics

The displacement field of the conventional HSDT at a point in the laminated plate is expressed as

$$\begin{aligned} u(x,y,z) &= u_0(x,y) - z\frac{\partial w_0}{\partial x} + f(z)\varphi_x(x,y) \\ v(x,y,z) &= v_0(x,y) - z\frac{\partial w_0}{\partial y} + f(z)\varphi_y(x,y) \\ w(x,y,z) &= w_0(x,y) \end{aligned} \quad (1)$$

u_0, v_0, w_0, φ_x and φ_y are the five unknown displacements of a point on the mid-plane of the plate, supposing that $\varphi_x = \int \theta(x,y)dx$ and $\varphi_y = \int \theta(x,y)dy$, the displacement field mentioned above can be written in a simple form as (Bourada *et al*. 2018 and Meksi *et al*. 2019)

$$\begin{aligned} u(x,y,z) &= u_0(x,y) - z\frac{\partial w_0}{\partial x} + k_1 f(z)\int \theta(x,y)dx \\ v(x,y,z) &= v_0(x,y) - z\frac{\partial w_0}{\partial y} + k_2 f(z)\int \theta(x,y)dy \\ w(x,y,z) &= w_0(x,y) \end{aligned} \quad (2)$$

The integrals terms defined in the above equations shall be resolved by using Navier type method and the displacement field can be written as follows

$$\begin{aligned} u(x,y,z) &= u_0(x,y) - z\frac{\partial w_0}{\partial x} + k_1 A_1 f(z)\frac{\partial \theta}{\partial x} \\ v(x,y,z) &= v_0(x,y) - z\frac{\partial w_0}{\partial y} + k_2 B_1 f(z)\frac{\partial \theta}{\partial y} \\ w(x,y,z) &= w_0(x,y) \end{aligned} \quad (3)$$

Where

$$k_1 = \mu^2, \quad k_2 = \lambda^2, \quad A_1 = -\frac{1}{\mu^2}, \quad B_1 = -\frac{1}{\lambda^2} \quad (4a)$$

and

$$\mu = \frac{m\pi}{a}, \qquad \lambda = \frac{n\pi}{b} \quad (4b)$$

In the present formulation the shape function f(z) is given as follows

$$f(z) = \frac{h}{\pi} sin \frac{\pi z}{h} \quad (5)$$

The normal and shear strains associated with the displacement field (3) are as follows

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + z\begin{Bmatrix} k_x^b \\ k_y^b \\ k_{xy}^b \end{Bmatrix} + f(z)\begin{Bmatrix} k_x^s \\ k_y^b \\ k_{xy}^s \end{Bmatrix}; \quad (6a)$$

$$\begin{Bmatrix} \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} = g(z)\begin{Bmatrix} \gamma_{yz}^s \\ \gamma_{xz}^s \end{Bmatrix} \quad (6b)$$

where

$$\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} = \begin{Bmatrix} \frac{\partial u_0}{\partial x} \\ \frac{\partial v_0}{\partial y} \\ \frac{\partial u_0}{\partial y} + \frac{\partial v_0}{\partial x} \end{Bmatrix}; \quad \begin{Bmatrix} k_x^b \\ k_y^b \\ k_{xy}^b \end{Bmatrix} = \begin{Bmatrix} -\frac{\partial^2 w_0}{\partial x^2} \\ -\frac{\partial^2 w_0}{\partial y^2} \\ -2\frac{\partial^2 w_0}{\partial x \partial y} \end{Bmatrix}; \quad (6c)$$

$$\begin{Bmatrix} k_x^s \\ k_y^s \\ k_{xy}^s \end{Bmatrix} = \begin{Bmatrix} k_1 A_1 \frac{\partial^2 \theta}{\partial x^2} \\ k_2 B_1 \frac{\partial^2 \theta}{\partial y^2} \\ (k_1 A_1 + k_2 B_1)\frac{\partial^2 \theta}{\partial x \partial y} \end{Bmatrix};$$

$$\begin{Bmatrix} \gamma_{yz}^s \\ \gamma_{xz}^s \end{Bmatrix} = \begin{Bmatrix} k_2 B_1 \frac{\partial \theta}{\partial y} \\ k_1 A_1 \frac{\partial \theta}{\partial x} \end{Bmatrix} \quad (6d)$$

and

$$g(z) = \frac{df(z)}{dz} \quad (6e)$$

2.2 Constitutive equations

The stress-strain relationships, accounting for transverse shear deformation and thermal effects for a layer can be expressed as

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_X - \alpha_x T \\ \varepsilon_y - \alpha_y T \\ \gamma_{xy} - \alpha_{xy} T \end{Bmatrix}; \quad (7a)$$

$$\begin{Bmatrix} \tau_{yz} \\ \tau_{xz} \end{Bmatrix} = \begin{bmatrix} Q_{44} & 0 \\ 0 & Q_{55} \end{bmatrix} \begin{Bmatrix} \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} \quad (7b)$$

where Q_{ij} are the plane stress-reduced stiffnesses that are expressed as follows

$$\begin{aligned} Q_{11} &= \frac{E_1}{1-\upsilon_{12}\upsilon_{21}}; & Q_{12} &= \frac{\upsilon_{12}E_2}{1-\upsilon_{12}\upsilon_{21}}; \\ Q_{22} &= \frac{E_2}{1-\upsilon_{12}\upsilon_{21}}; & Q_{66} &= G_{12}; \\ Q_{44} &= G_{23}; & Q_{55} &= G_{13} \end{aligned} \quad (8)$$

and E_i are Young's moduli, ν_{ij} are Poisson's rations, G_{ij} are shear moduli, α_x, α_y and α_{xy} are the thermal expansion coefficients, and $T = T(x,y,z)$ is the temperature distribution.

In the present work, the thermal loading across the thickness is supposed to be

$$T(x,y,z) = T_1(x,y) + \frac{z}{h}T_2(x,y) + \frac{f(z)}{h}T_3(x,y) \quad (9)$$

The constitutive equations of each lamina are transformed to the plate coordinates (x, y, z) and the stress-strain relationships in the plate coordinate system for thek^{th} layer is expressed as

$$\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\end{Bmatrix}_{(k)} = \begin{bmatrix}\overline{Q}_{11} & \overline{Q}_{12} & \overline{Q}_{16}\\ \overline{Q}_{12} & \overline{Q}_{22} & \overline{Q}_{26}\\ \overline{Q}_{16} & \overline{Q}_{26} & \overline{Q}_{66}\end{bmatrix}_{(k)} \begin{Bmatrix}\varepsilon_X - \alpha_x T\\ \varepsilon_y - \alpha_y T\\ \gamma_{xy} - \alpha_{xy} T\end{Bmatrix}_{(k)}, \quad (10a)$$

$$\begin{Bmatrix}\tau_{yz}\\ \tau_{xz}\end{Bmatrix}_{(k)} = \begin{bmatrix}\overline{Q}_{44} & \overline{Q}_{45}\\ \overline{Q}_{45} & \overline{Q}_{55}\end{bmatrix}_{(k)} \begin{Bmatrix}\gamma_{yz}\\ \gamma_{xz}\end{Bmatrix}_{(k)} \quad (10b)$$

Where $\overline{Q}_{ij}$ are the transformed elastic coefficient given by Reddy (1997).

2.3 Governing equations

The principle of virtual work is used in order to determine the governing equations as follows (Cherif *et al*. 2018)

$$\int_{-\frac{h}{2}}^{\frac{h}{2}}\int_0^b\int_0^a (\sigma_x\,\delta\varepsilon_x + \sigma_y\delta\varepsilon_y + \tau_{yz}\delta\gamma_{yz} + \tau_{xz}\delta\gamma_{xz} + \tau_{xy}\delta\gamma_{xy})dxdydz = 0 \quad (11)$$

The resulting stresses and moments are obtained by integrating Eq. (10) over the thickness, and are expressed as

$$\begin{Bmatrix}N\\ M^b\\ M^s\end{Bmatrix} = \begin{bmatrix}A & B & B^s\\ B & D & D^s\\ B^s & D^s & H^s\end{bmatrix}\begin{Bmatrix}\varepsilon\\ k^b\\ k^s\end{Bmatrix} + \begin{Bmatrix}N^T\\ M^{b^T}\\ M^{s^T}\end{Bmatrix}, S = A^s\gamma \quad (12)$$

Where

$$N = \{N_x, N_y, N_{xy}\}^t,\quad M^b = \{M_x^b, M_y^b, M_{xy}^b\}^t,\quad M^s = \{M_x^s, M_y^s, M_{xy}^s\}^t \quad (13a)$$

$$N^T = \{N_x^T, N_y^T, N_{xy}^T\}^t,\quad M^{b^T} = \left\{M_x^{b^T}, M_y^{b^T}, M_{xy}^{b^T}\right\}^t,\quad M^{s^T} = \left\{M_x^{s^T}, M_y^{s^T}, M_{xy}^{s^T}\right\}^t \quad (13b)$$

$$\varepsilon = \{\varepsilon_x^0, \varepsilon_y^0, \gamma_{xy}^0\}^t,\quad k^b = \{k_x^b, k_y^b, k_{xy}^b\}^t,\quad k^s = \{k_x^s, k_y^s, k_{xy}^s\}^t \quad (13c)$$

$$A = \begin{bmatrix}A_{11} & A_{12} & A_{16}\\ A_{12} & A_{22} & A_{26}\\ A_{16} & A_{26} & A_{66}\end{bmatrix},\quad B = \begin{bmatrix}B_{11} & B_{12} & B_{16}\\ B_{12} & B_{22} & B_{26}\\ B_{16} & B_{26} & B_{66}\end{bmatrix},\quad D = \begin{bmatrix}D_{11} & D_{12} & D_{16}\\ D_{12} & D_{22} & D_{26}\\ D_{16} & D_{26} & D_{66}\end{bmatrix} \quad (13d)$$

$$B^s = \begin{bmatrix}B_{11}^s & B_{12}^s & B_{16}^s\\ B_{12}^s & B_{22}^s & B_{26}^s\\ B_{16}^s & B_{26}^s & B_{66}^s\end{bmatrix},\quad D^s = \begin{bmatrix}D_{11}^s & D_{12}^s & D_{16}^s\\ D_{12}^s & D_{22}^s & D_{26}^s\\ D_{16}^s & D_{26}^s & D_{66}^s\end{bmatrix},\quad H^s = \begin{bmatrix}H_{11}^s & H_{12}^s & H_{16}^s\\ H_{12}^s & H_{22}^s & H_{26}^s\\ H_{16}^s & H_{26}^s & H_{66}^s\end{bmatrix} \quad (13e)$$

$$S = \{S_{yz}^s, S_{xz}^s\}^t,\qquad \gamma = \{\gamma_{yz}, \gamma_{xz}\}^t,\quad A^s = \begin{bmatrix}A_{44}^s & A_{45}^s\\ A_{45}^s & A_{55}^s\end{bmatrix} \quad (13f)$$

Where the stiffness components are defined as

$$(A_{ij}, B_{ij}, D_{ij}) = \sum_{k=1}^{n}\int_{z_k}^{z_{k+1}}\overline{Q}_{ij}^{(k)}(1, z, z^2)dz,\quad (i,j = 1,2,6) \quad (14a)$$

$$(B_{ij}^s, D_{ij}^s, H_{ij}^s) = \sum_{k=1}^{n}\int_{z_k}^{z_{k+1}}\overline{Q}_{ij}^{(k)}(f(z), zf(z), f^2(z))dz,\quad (i,j = 1,2,6), \quad (14b)$$

$$A_{ij}^s = \sum_{k=1}^{n}\int_{z_k}^{z_{k+1}}\overline{Q}_{ij}^{(k)} g^2(z)dz,\quad (i,j = 4,5). \quad (14c)$$

By substituting Eqs. (6)-(10) into Eq. (11) and integrating through the thickness, Eq. (11) can be expressed as

$$\int_0^b\int_0^a\Big(N_x\frac{\partial\delta u_0}{\partial x} - M_x^b\frac{\partial^2\delta w_0}{\partial x^2} + k_1A_1M_x^s\frac{\partial^2\delta\theta}{\partial x^2} + N_y\frac{\partial\delta v_0}{\partial y} - M_y^b\frac{\partial^2\delta w_0}{\partial y^2} + k_2B_1M_y^s\frac{\partial^2\delta\theta}{\partial y^2} + N_{xy}\left(\frac{\partial\delta u_0}{\partial y} + \frac{\partial\delta v_0}{\partial x}\right) - 2M_{xy}^b\frac{\partial^2\delta w_0}{\partial x\partial y} + (k_1A_1 + k_2B_1)M_{xy}^s\frac{\partial^2\delta\theta}{\partial x\partial y} + k_1A_1S_{xz}^s\frac{\partial\delta\theta}{\partial x} + k_2B_1S_{yz}^s\frac{\partial\delta\theta}{\partial y}\Big)dxdy = 0 \quad (15)$$

With the integration by parts of Eq. (15) alongside collecting the coefficient of $\delta u_0, \delta v_0, \delta w_0, \delta\theta$ we can obtain the following governing equations

$$\begin{aligned}\delta u_0&: \frac{\partial N_x}{\partial x} + \frac{\partial N_{xy}}{\partial y} = 0\\ \delta v_0&: \frac{\partial N_y}{\partial y} + \frac{\partial N_{xy}}{\partial x} = 0\\ \delta w_0&: \frac{\partial^2 M_x^b}{\partial x^2} + \frac{\partial^2 M_y^b}{\partial y^2} + 2\frac{\partial^2 M_{xy}^b}{\partial x\partial y} = 0\\ \delta\theta&: k_1A_1\frac{\partial S_{xz}^s}{\partial x} + k_2B_1\frac{\partial S_{yz}^s}{\partial y} - k_1A_1\frac{\partial^2 M_x^s}{\partial x^2} - k_2B_1\frac{\partial^2 M_y^s}{\partial y^2} - (k_1A_1 + k_2B_1)\frac{\partial^2 M_{xy}^s}{\partial x\partial y} = 0\end{aligned} \quad (16)$$

By substituting Eq. (12) into Eq. (16), the governing equations can be written in terms of displacements (u_0, v_0, w_0, θ) as follows

$$A_{11}\frac{\partial^2 u_0}{\partial x^2} + 2A_{16}\frac{\partial^2 u_0}{\partial x\partial y} + A_{66}\frac{\partial^2 u_0}{\partial y^2} + A_{16}\frac{\partial^2 v_0}{\partial x^2} + A_{26}\frac{\partial^2 v_0}{\partial y^2} + (A_{12} + A_{66})\frac{\partial^2 v_0}{\partial x\partial y} - B_{11}\frac{\partial^3 w_0}{\partial x^3} \quad (17a)$$

$$
\begin{aligned}
&-B_{26}\frac{\partial^3 w_0}{\partial y^3}-3B_{16}\frac{\partial^3 w_0}{\partial x^2\partial y}-(B_{12}+2B_{66})\frac{\partial^3 w_0}{\partial x\partial y^2}\\
&+k_1A_1B_{11}^s\frac{\partial^3\theta}{\partial x^3}+k_2B_1B_{26}^s\frac{\partial^3\theta}{\partial y^3}+k_2B_1B_{12}^s\frac{\partial^3\theta}{\partial x\partial y^2}\\
&+(2k_1A_1+k_2B_1)B_{16}^s\frac{\partial^3\theta}{\partial x^2\partial y}\\
&+(k_1A_1+k_2B_1)B_{66}^s\frac{\partial^3\theta}{\partial x\partial y^2}-\frac{\partial N_x^T}{\partial x}-\frac{\partial N_{xy}^T}{\partial y}=0
\end{aligned}
\tag{17a}
$$

$$
\begin{aligned}
&A_{12}\frac{\partial^2 u_0}{\partial x^2}+A_{26}\frac{\partial^2 u_0}{\partial y^2}+(A_{12}+A_{66})\frac{\partial^2 u_0}{\partial x\partial y}\\
&+A_{22}\frac{\partial^2 v_0}{\partial y^2}+2A_{26}\frac{\partial^2 v_0}{\partial x\partial y}+A_{66}\frac{\partial^2 v_0}{\partial x^2}-B_{16}\frac{\partial^3 w_0}{\partial x^3}\\
&-B_{22}\frac{\partial^3 w_0}{\partial y^3}-B_{12}\frac{\partial^3 w_0}{\partial x^2\partial y}-3B_{26}\frac{\partial^3 w_0}{\partial x\partial y^2}\\
&-2B_{66}\frac{\partial^3 w_0}{\partial x^2\partial y}+k_1A_1B_{16}^s\frac{\partial^3\theta}{\partial x^3}+k_2B_1B_{22}^s\frac{\partial^3\theta}{\partial y^3}\\
&+k_1A_1B_{12}^s\frac{\partial^3\theta}{\partial x^2\partial y}+(k_1A_1+2k_2B_1)B_{26}^s\frac{\partial^3\theta}{\partial x\partial y^2}\\
&+(k_1A_1+k_2B_1)B_{66}^s\frac{\partial^3\theta}{\partial x^2\partial y}-\frac{\partial N_y^T}{\partial y}-\frac{\partial N_{xy}^T}{\partial x}=0
\end{aligned}
\tag{17b}
$$

$$
\begin{aligned}
&B_{11}\frac{\partial^3 u_0}{\partial x^3}+B_{26}\frac{\partial^3 u_0}{\partial y^3}+3B_{16}\frac{\partial^3 u_0}{\partial x^2\partial y}+B_{12}\frac{\partial^3 u_0}{\partial x\partial y^2}\\
&+2B_{66}\frac{\partial^3 u_0}{\partial x\partial y^2}+B_{16}\frac{\partial^3 v_0}{\partial x^3}+B_{22}\frac{\partial^3 v_0}{\partial y^3}+B_{12}\frac{\partial^3 v_0}{\partial x^2\partial y}\\
&+3B_{26}\frac{\partial^3 v_0}{\partial x\partial y^2}+2B_{66}\frac{\partial^3 v_0}{\partial x^2\partial y}-D_{11}\frac{\partial^4 w_0}{\partial x^4}-D_{22}\frac{\partial^4 w_0}{\partial y^4}\\
&-2D_{12}\frac{\partial^4 w_0}{\partial x^2\partial y^2}-4D_{16}\frac{\partial^4 w_0}{\partial x^3\partial y}-4D_{26}\frac{\partial^4 w_0}{\partial x\partial y^3}\\
&-4D_{66}\frac{\partial^4 w_0}{\partial x^2\partial y^2}+k_1A_1D_{11}^s\frac{\partial^4\theta}{\partial x^4}+k_2B_1D_{22}^s\frac{\partial^4\theta}{\partial y^4}\\
&+k_2B_1D_{12}^s\frac{\partial^4\theta}{\partial x^2\partial y^2}+(3k_1A_1+k_2B_1)D_{16}^s\frac{\partial^4\theta}{\partial x^3\partial y}\\
&+(k_1A_1+3k_2B_1)D_{26}^s\frac{\partial^4\theta}{\partial x\partial y^3}+k_1A_1D_{12}^s\frac{\partial^4\theta}{\partial x^2\partial y^2}\\
&+2(k_1A_1+k_2B_1)D_{66}^s\frac{\partial^4\theta}{\partial x^2\partial y^2}-\frac{\partial^2 M_x^{b^T}}{\partial x^2}\\
&-\frac{\partial^2 M_y^{b^T}}{\partial y^2}-2\frac{\partial^2 M_{xy}^{b^T}}{\partial x\partial y}=0
\end{aligned}
\tag{17c}
$$

$$
\begin{aligned}
&-k_1A_1B_{11}^s\frac{\partial^3 u_0}{\partial x^3}-k_2B_1B_{26}^s\frac{\partial^3 u_0}{\partial y^3}-k_2B_1B_{12}^s\frac{\partial^3 u_0}{\partial x\partial y^2}\\
&-(2k_1A_1+k_2B_1)B_{16}^s\frac{\partial^3 u_0}{\partial x^2\partial y}\\
&-(k_1A_1+k_2B_1)B_{66}^s\frac{\partial^3 u_0}{\partial x\partial y^2}-k_1A_1B_{16}^s\frac{\partial^3 v_0}{\partial x^3}\\
&-k_2B_1B_{22}^s\frac{\partial^3 v_0}{\partial y^3}-k_1A_1B_{12}^s\frac{\partial^3 v_0}{\partial x^2\partial y}\\
&-(k_1A_1+2k_2B_1)B_{26}^s\frac{\partial^3 v_0}{\partial x\partial y^2}\\
&-(k_1A_1+k_2B_1)B_{66}^s\frac{\partial^3 v_0}{\partial x^2\partial y}\\
&+k_1A_1D_{11}^s\frac{\partial^4 w_0}{\partial x^4}+k_2B_1D_{22}^s\frac{\partial^4 w_0}{\partial y^4}+k_1A_1D_{12}^s\frac{\partial^4 w_0}{\partial x^2\partial y^2}\\
&+k_2B_1D_{12}^s\frac{\partial^4 w_0}{\partial x^2\partial y^2}+(3k_1A_1+k_2B_1)D_{16}^s\frac{\partial^4 w_0}{\partial x^3\partial y}\\
&+(k_1A_1+3k_2B_1)D_{26}^s\frac{\partial^4 w_0}{\partial x\partial y^3}
\end{aligned}
\tag{17d}
$$

$$
\begin{aligned}
&+2(k_1A_1+k_2B_1)D_{66}^s\frac{\partial^4 w_0}{\partial x^2\partial y^2}\\
&-(k_1A_1)^2H_{11}^s\frac{\partial^4\theta}{\partial x^4}-(k_2B_1)^2H_{22}^s\frac{\partial^4\theta}{\partial y^4}\\
&+(k_1A_1)^2A_{55}^s\frac{\partial^2\theta}{\partial x^2}+(k_2B_1)^2A_{44}^s\frac{\partial^2\theta}{\partial y^2}\\
&+2k_1A_1k_2B_1A_{45}^s\frac{\partial^2\theta}{\partial x\partial y}-2k_1A_1k_2B_1H_{12}^s\frac{\partial^4\theta}{\partial x^2\partial y^2}\\
&-2k_1A_1(k_1A_1+k_2B_1)H_{16}^s\frac{\partial^4\theta}{\partial x^3\partial y}\\
&-2k_2B_1(k_1A_1+k_2B_1)H_{26}^s\frac{\partial^4\theta}{\partial x\partial y^3}\\
&-(k_1A_1+k_2B_1)^2H_{66}^s\frac{\partial^4\theta}{\partial x^2\partial y^2}+k_1A_1\frac{\partial^2 M_x^{s^T}}{\partial x^2}\\
&+k_2B_1\frac{\partial^2 M_y^{s^T}}{\partial y^2}+(k_1A_1+k_2B_1)\frac{\partial^2 M_{xy}^{s^T}}{\partial x\partial y}=0
\end{aligned}
\tag{17d}
$$

3. Analytical solutions for anti-symmetric cross-ply laminated plates

By using Navier approach, the closed form solution of Eq. (17) is determined for simply-supported rectangular plates.

For anti-symmetric cross-ply laminates, the following stiffnesses are equal to zero

$$
\begin{aligned}
&A_{16}=A_{26}=D_{16}=D_{26}=D_{16}^s\\
&=D_{26}^s=H_{16}^s=H_{26}^s=0\\
&B_{12}=B_{16}=B_{26}=B_{66}=B_{12}^s\\
&=B_{16}^s=B_{26}^s=B_{66}^s=0
\end{aligned}
\tag{18}
$$

and for anti-symmetric plates, the thermal expansion coefficient equals zero, $\alpha_{xy}=0$.

The boundary condition for simply-supported edges could be expressed as

$$
v_0=w_0=\frac{\partial\theta}{\partial y}=N_x=M_x^b=M_x^s=0 \quad \text{at} \quad x=0,a \tag{19a}
$$

$$
u_0=w_0=\frac{\partial\theta}{\partial x}=N_y=M_y^b=M_y^s=0 \quad \text{at} \quad x=0,b \tag{19b}
$$

We assume that the thermal loadings are expanded in double Fourier series as

$$
\begin{Bmatrix}T_1\\T_2\\T_3\end{Bmatrix}=\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\begin{Bmatrix}T_{1mn}\\T_{2mn}\\T_{3mn}\end{Bmatrix}\sin\mu\, x\sin\lambda\, y \tag{20}
$$

Where the coefficients $T_{1mn}, T_{2mn}, T_{3mn}$ are expressed as follows

$$
\begin{Bmatrix}T_{1mn}\\T_{2mn}\\T_{3mn}\end{Bmatrix}=\frac{4}{ab}\int_0^a\int_0^b\begin{Bmatrix}T_1\\T_2\\T_3\end{Bmatrix}\sin\mu\, x\sin\lambda\, y\,dxdy \tag{21}
$$

The coefficients $T_{1mn}, T_{2mn}, T_{3mn}$ can be evaluated by integrating Eq. (21) as:

$T_{1mn}, T_{2mn}, T_{3mn} = T_0$ for m = n = 1, and for a single sinusoidal thermal loading, and $T_{1mn}, T_{2mn}, T_{3mn} = \frac{16T_0}{\pi^2 mn}$ for m, n odd, in case of uniformly distributed thermal loading, where T_0 represents the intensity of thermal loading.

The solution form for (u_0, v_0, w_0, θ) to solve the problem is adopted as follows (Sekkal *et al*. 2017a)

$$\begin{Bmatrix} u_0 \\ v_0 \\ w_0 \\ \theta \end{Bmatrix} = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} \begin{Bmatrix} U_{mn}\cos(\mu x)\sin(\lambda y) \\ V_{mn}\sin(\mu x)\cos(\lambda y) \\ W_{mn}\sin(\mu x)\cos(\lambda y) \\ \theta_{mn}\sin(\mu x)\cos(\lambda y) \end{Bmatrix} \tag{22}$$

Where $U_{mn}, V_{mn}, W_{mn}, \theta_{mn}$ are arbitrary parameters to be determined, substituting Eqs. (20)-(22) into governing Eq. (17), we obtain the following operator equation

$$[K]\{\delta\} = \{F\} \tag{23}$$

Where $\{\delta\} = \{U_{mn}, V_{mn}, W_{mn}, \theta_{mn}\}$ and [K] is the symmetric matrix given by

$$[K] = \begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} \\ K_{12} & K_{22} & K_{23} & K_{24} \\ K_{13} & K_{23} & K_{33} & K_{34} \\ K_{14} & K_{24} & K_{34} & K_{44} \end{bmatrix} \tag{24}$$

In which

$$\begin{aligned}
K_{11} &= -A_{11}\lambda^2 - A_{66}\mu^2, \\
K_{12} &= -(A_{12} + A_{66})\lambda\mu \\
K_{13} &= B_{11}\lambda^3, \\
K_{14} &= -B_{11}^s\lambda^3 k_1 A_1 \\
K_{22} &= -A_{22}\mu^2 - A_{66}\lambda^2, \\
K_{23} &= B_{22}\mu^3, \\
K_{24} &= -B_{22}^s k_2 B_1 \mu^3 \\
K_{33} &= -D_{11}\lambda^4 - 2(D_{12} + 2D_{66})\lambda^2\mu^2 - D_{22}\mu^4 \\
K_{34} &= D_{11}^s k_1 A_1 \lambda^4 + D_{22}^s k_2 B_1 \mu^4 \\
&\quad + D_{12}^s \lambda^2\mu^2 (k_1 A_1 + k_2 B_1) \\
&\quad + 2D_{66}^s \lambda^2\mu^2 (k_1 A_1 + k_2 B_1) \\
K_{44} &= -H_{11}^s (k_1 A_1)^2 \lambda^4 - 2H_{12}^s k_1 A_1 k_2 B_1 \lambda^2\mu^2 \\
&\quad - H_{22}^s (k_2 B_1)^2 \mu^4 - H_{66}^s (k_1 A_1 + k_2 B_1)\lambda^2\mu^2 \\
&\quad - S_{55}^s k_1 A_1 \lambda^2 - S_{44}^s k_2 B_1 \mu^2
\end{aligned} \tag{25}$$

and $\{F\} = \{F_1, F_2, F_3, F_4\}$ is the generalized force given by

$$\begin{aligned}
F_1 &= \lambda[(L_{11} + L_{21})T_{1mn} + (P_{11} + P_{21})T_{2mn} \\
&\quad + (R_{11} + R_{21})T_{3mn}] \\
F_2 &= \mu[(L_{12} + L_{22})T_{1mn} + (P_{11} + P_{22})T_{2mn} \\
&\quad + (R_{11} + R_{22})T_{3mn}] \\
F_3 &= -\lambda^2[(S_{11} + S_{21})T_{1mn} + (F_{11} + F_{21})T_{2mn} \\
&\quad + (U_{11} + U_{21})T_{3mn}] - \mu^2[(S_{11} + S_{22})T_{1mn} \\
&\quad + (F_{11} + F_{22})T_{2mn} + (U_{11} + U_{22})T_{3mn}] \\
F_4 &= -k_1 A_1 \lambda^2[(V_{11} + V_{21})T_{1mn} + (W_{11} + W_{21})T_{2mn} \\
&\quad + (X_{11} + X_{21})T_{3mn}] - k_2 B_1 \mu^2[(V_{11} + V_{22})T_{1mn} \\
&\quad + (W_{11} + W_{22})T_{2mn} + (X_{11} + X_{22})T_{3mn}
\end{aligned} \tag{26}$$

Where

$$(L_{ij}, P_{ij}, R_{ij}) = \sum_{k=1}^{n}\int_{z_k}^{z_{k+1}} \alpha_i^{(k)}\overline{Q}_{ij}^{(k)}\left(1, \frac{z}{h}, \frac{f(z)}{h}\right), \quad (i,j = 1,2) \tag{27a}$$

$$(S_{ij}, T_{ij}, U_{ij}) = \sum_{k=1}^{n}\int_{z_k}^{z_{k+1}} \alpha_i^{(k)}\overline{Q}_{ij}^{(k)}\left(z, \frac{z^2}{h}, \frac{f(z)z}{h}\right), \quad (i,j = 1,2) \tag{27b}$$

$$(V_{ij}, W_{ij}, X_{ij}) = \sum_{k=1}^{n}\int_{z_k}^{z_{k+1}} \alpha_i^{(k)}\overline{Q}_{ij}^{(k)} f(z)\left(1, \frac{z}{h}, \frac{f(z)}{h}\right), \quad (i,j = 1,2) \tag{27c}$$

4. Numerical results and discussion

To verify the accuracy of the present theory, simply-supported two-layered (0°/90°) anti-symmetric laminated plate under nonlinear thermal loading is to be considered. In all cases, the lamina properties are assumed to be

$$\frac{E_1}{E_2} = 25, \quad G_{12} = 0{,}5E_2, \quad G_{13} = G_{12}, \quad G_{23} = 0{,}2E_2, \quad \mu_{12} = 0{,}25, \quad \frac{\alpha_1}{\alpha_2} = 3$$

Dimensionless displacements $(\bar{u}, \bar{v}, \bar{w})$ and stresses $(\bar{\sigma}_x, \bar{\sigma}_y, \bar{\tau}_{xy}, \bar{\tau}_{xz}, \bar{\tau}_{yz})$ utilized for two-layer (0°/90°) anti-symmetric plate expressed as

$$\begin{aligned}
\bar{u} &= u\left(0, \frac{b}{2}, -\frac{h}{2}\right)\frac{1}{\alpha_1 T_0 a^2}, \\
\bar{v} &= v\left(\frac{a}{2}, 0, -\frac{h}{2}\right)\frac{1}{\alpha_1 T_0 a^2}, \\
\bar{w} &= w\left(\frac{a}{2}, \frac{b}{2}, 0\right)\frac{10h}{\alpha_1 T_0 a^2}, \\
\bar{\sigma}_x &= \sigma_x\left(\frac{a}{2}, \frac{b}{2}, -\frac{h}{2}\right)\frac{1}{E_2\alpha_1 T_0 a^2}, \\
\bar{\sigma}_y &= \sigma_y\left(\frac{a}{2}, \frac{b}{2}, +\frac{h}{2}\right)\frac{1}{E_2\alpha_1 T_0 a^2}, \\
\bar{\tau}_{xy} &= \tau_{xy}\left(0, 0, -\frac{h}{2}\right)\frac{1}{E_2\alpha_1 T_0 a^2}, \\
\bar{\tau}_{xz} &= \tau_{xz}\left(0, \frac{b}{2}, 0\right)\frac{1}{E_2\alpha_1 T_0 a^2}, \\
\bar{\tau}_{yz} &= \tau_{yz}\left(\frac{a}{2}, 0, 0\right)\frac{1}{E_2\alpha_1 T_0 a^2}.
\end{aligned}$$

It is to be noticed that transverse shear stresses are obtained by using three dimensional stress equilibrium equations of elasticity.

Numerical results for two-layered (0°/90°) anti-symmetric plate predicted in this work are discussed and compared with those of the classical (CPT), first-order (FSDT), higher-order (HSDT) and trigonometric (TSDT) theories obtained by Ghugal and Kulkarni (2013a).

Table 1 Normalized displacements and in-plan stresses for square two-layer (0°/90°) anti-symmetric laminated plate subjected to nonlinear thermal loading for aspect ratios 4 and 10 (T_1=0)

a/h	Theory	$\bar{u}$	$\bar{v}$	$\bar{w}$	$\bar{\sigma}_x$	$\bar{\sigma}_y$	$\bar{\tau}_{xy}$
4	Present	0.2914	0.3321	1.9460	-2.0811	2.0811	0.9794
	TSDT*	0.2914	0.3321	1.9460	-2.0811	2.0811	0.9794
	HSDT	0.2916	0.3322	1.9501	-2.0955	2.0955	0.9798
	FSDT*	0.2926	0.3325	1.9899	-2.1765	2.1765	0.9820
	CPT*	0.2926	0.3325	1.9899	-2.1765	2.1765	0.9820
10	Present	0.2924	0.3325	1.9827	-2.1609	2.1609	0.9816
	TSDT*	0.2924	0.3325	1.9827	-2.1609	2.1609	0.9816
	HSDT	0.2924	0.3325	1.9834	-2.1633	2.1633	0.9816
	FSDT*	0.2926	0.3325	1.9899	-2.1765	2.1765	0.9820
	CPT*	0.2926	0.3325	1.9899	-2.1765	2.1765	0.9820

*Ghugal and Kulkarni (2013a)

The results of in-plan displacements ($\bar{u}$, $\bar{v}$), transversenormal displacements ($\bar{w}$), in-plan normal stresses ($\bar{\sigma}_x$,$\bar{\sigma}_y$) and in-plan shear stresses ($\bar{\tau}_{xy}$) of a two-layer (0°/90°) anti-symmetric laminated plate subjected to a nonlinear thermal loading for aspect ratios 4 and 10 are shown in Table 1, whereas those of transverse shear stresses ($\bar{\tau}_{xz}$,$\bar{\tau}_{yz}$) are reported in Table 2.

The examination of Table 1 reveals that in-plane displacements ($\bar{u}$, $\bar{v}$) obtained using the present theory for two-layered anti-symmetric plate are in good agreement with those provided by TSDT, HSDT, FSDT and CPT for both aspect ratios 4 and 10. Figs. 2 and 3 display, respectively, the variation of in-plan displacement ($\bar{u}$) through the thickness for aspect ratio 4 and the variation of in-plane displacement ($\bar{v}$) through the thickness for aspect ratio 10. Transverse normal displacements ($\bar{w}$) predicted by the present formulation are similar to those given by

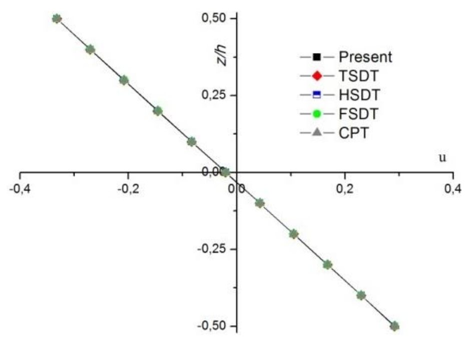

Fig. 2 Normalized in-plane displacement ($\bar{u}$) through the thickness for a two-layered (0°/90°) anti-symmetric laminated plate for aspect ratio 4

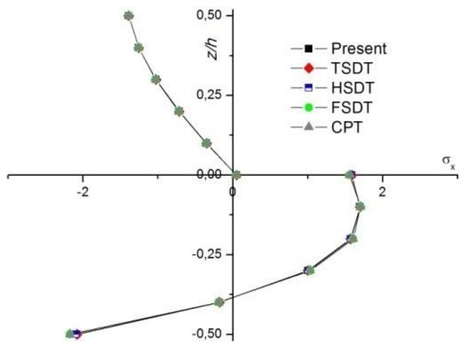

Fig. 4 Normalized in-plan normal stress ($\bar{\sigma}_x$) through the thickness of a two-layer (0°/90°) anti-symmetric laminated plate for aspect ratio 4

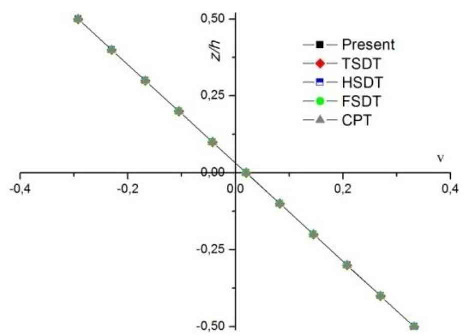

Fig. 3 Normalized in-plane displacement ($\bar{v}$) through the thickness for a two-layered (0°/90°) anti-symmetric laminated plate for aspect ratio 10

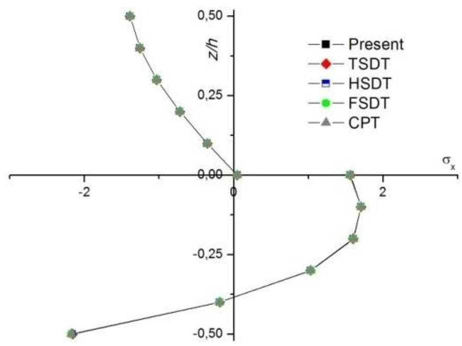

Fig. 5 Normalized in-plane normal stress ($\bar{\sigma}_x$) through the thickness of a two-layered (0°/90°) anti-symmetric laminated plate for aspect ratio 10

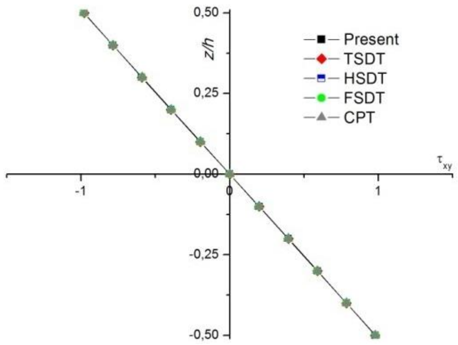

Fig. 6 Normalized in plane shear stress ($\bar{\tau}_{xy}$) through the thickness of a two-layered (0°/90°) anti-symmetric laminated plate for aspect ratio 4

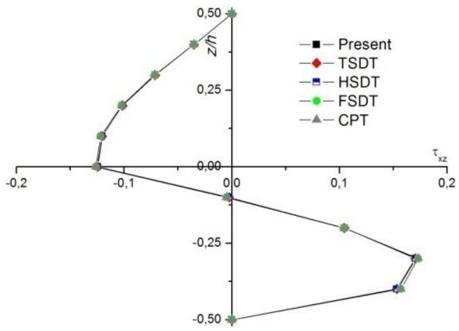

Fig. 7 Normalized transverse shear stress $(\bar{\tau}_{xz})$ through the thickness of a two-layer (0°/90°) anti-symmetric laminated plate for aspect ratio 4

Table 2 Normalized transverse shear stresses for square two-layered (0°/90°) anti-symmetric laminated plate subjected to nonlinear thermal loading for aspect ratios 4 and 10 (T_1 = 0)

a/h	Theory	$\bar{\tau}_{xz}^{EE}$	$\bar{\tau}_{yz}^{EE}$
4	Present	-0.1246	-0.1246
	TSDT*	-0.1246	-0.1246
	HSDT	-0.1250	-0.1250
	FSDT*	-0.1262	-0.1262
	CPT*	-0.1262	-0.1262
10	Present	-0.0504	-0.0504
	TSDT*	-0.0504	-0.0504
	HSDT	-0.0504	-0.0504
	FSDT*	-0.0505	-0.0505
	CPT*	-0.0505	-0.0505

*Ghugal and Kulkarni (2013a)

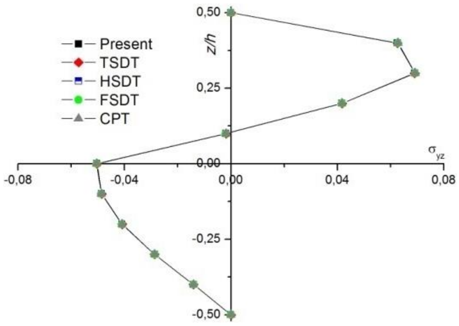

Fig. 8 Normalized transverse shear stress $(\bar{\tau}_{yz})$ through the thickness of a two-layered (0°/90°) anti-symmetric laminated plate for aspect ratio 10

TSDT, and are close to those provided by HSDT, whereas the values given by FSDT and CPT are over-predicted for the aspect ratio 4. For aspect ratio 10, the results of ($\bar{w}$) estimated using the present theory, TSDT, HSDT, FSDT and CPT are in close agreement with each other.

The results of in-plan normal and shear stresses ($\bar{\sigma}_x$, $\bar{\sigma}_y$, $\bar{\tau}_{xy}$) predicted by the present model are identical to those of TSDT, and are in good agreement with those of HSDT, whereas FSDT andCPT overestimate the in-plan stresses for both aspect ratios 4 and 10.The variation of in-plane normal stresses ($\bar{\sigma}_x$) through-the-thickness for aspect ratios 4 and 10 is shown in Figs. 4 and 5 respectively, whereas the variation of in-plane stresses $(\bar{\tau}_{xy})$ through the thickness for aspect ratio 4 is shown in Fig. 6.

From Table 2 it is observed that for aspect ratio 4, transverse shear stresses ($\bar{\tau}_{xz}$,$\bar{\tau}_{yz}$) estimated results using the present model are in close agreements with those given by TSDT and HSDT, while the values given by FSDT and CPT are overestimated. For aspect ratio 10, the results provided by the five theories presented in this paper; the present theory, TSDT, HSDT, FSDT and CPT are similar.

Figs. 7 and 8 display, respectively, the variation of normalized transverse shear stresses $(\bar{\tau}_{xz})$ for aspect ratio4 and $(\bar{\tau}_{yz})$ for aspect ratio 10 through the thickness of a two-layer anti-symmetric laminated plate.

5. Conclusions

In the present study, a refined four variables plate theory has been presented for the analysis of the response of simply supported two-layered (0°/90°) anti-symmetric laminated plates under non-linear thermal loading across the thickness of the plate. The present theory is characterized by avoiding the use of a shear correction factor and reducing the number of variables and the governing equations to four instead of five or more in the other theories. The present results are compared with those provided by the classical, first order, higher order and trigonometric theories reported in the literature. The numerical results predicted using the present formulation are found to converge extremely well with those of the trigonometric and the higher order shear deformation theories. An improvement of the present study will be considered in the future work to consider the thickness stretching effect by using quasi-3D shear deformation models (Bessaim *et al*. 2013, Belabed *et al*. 2014, Hebali *et al*. 2014, Bousahla *et al*. 2014, Bourada *et al*. 2015, Larbi Chaht *et al*. 2015, Hamidi *et al*. 2015, Bennoun *et al*. 2016, Draiche *et al*. 2016, Ait Atmane *et al*. 2017, Bouafia *et al*. 2017, Mahmoudi *et al*. 2017, Sekkal *et al*. 2017b, Benahmed *et al*. 2017, Abualnour *et al*. 2018, Karami *et al*. 2018a, b, Benchohra *et al*. 2018, Younsi *et al*. 2018, Bendaho *et al*. 2019, Boutaleb *et al*. 2019, Boukhlif *et al*. 2019, Boulefrakh *et al*. 2019, Zarga *et al*. 2019, Zaoui *et al*. 2019, Bouanati *et al*. 2019, Khiloun *et al*. 2019) and other types of materials (Mahi *et al*. 2015, Zemri *et al*. 2015, Karami *et al*. 2017, Yeghnem *et al*. 2017, Mouffoki *et al*. 2017, Zidi *et al*. 2017, Klouche *et al*. 2017, Kaci *et al*. 2018, Mokhtar *et al*. 2018, Zine *et al*. 2018, Behera and Kumari 2018, Karami *et al*. 2018c, d, e, 2019a, b, c, Ayat *et al*. 2018, Yazid *et al*. 2018, Kadari *et al*. 2018, Draoui *et al*. 2019, Bensattalah *et al*. 2019, Mekerbi *et al*. 2019, Hellal *et al*. 2019, Tounsi *et al*. 2019).

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