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Thermomechanical bending study for functionally graded sandwich plates using a simple quasi-3D shear deformation theory

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Abstract. In this article, a simple quasi-3D shear deformation theory is employed for thermo-mechanical bending analysis of functionally graded material (FGM) sandwich plates. The displacement field is defined using only 5 variables as the first order shear deformation theory (FSDT). Unlike the other high order shear deformation theories (HSDTs), the present formulation considers a new kinematic which includes undetermined integral variables. The governing equations are determined based on the principle of virtual work and then they are solved via Navier method. Analytical solutions are proposed to provide the deflections and stresses of simply supported FGM sandwich structures. Comparative examples are presented to demonstrate the accuracy of the present theory. The effects of gradient index, geometrical parameters and thermal load on thermo-mechanical bending response of the FG sandwich plates are examined.

Keywords: sandwich plate; thermo-mechanical; quasi-3D HSDT; functionally graded material

1. Introduction

Plates composed of functionally graded material (FGM) are widely used in different fields of engineering such as civil, mechanics, aerospace, chemistry, electricity, etc (Ahmed 2014, Yaghoobi *et al*. 2014, Belkorissat *et al*. 2015, Yahia *et al*. 2015, Kar and Panda 2016, Bousahla *et al*. 2016, Bellifa *et al*. 2016, Boukhari *et al*. 2013, Aldousari 2017, Akbas 2017, Sekkal *et al*. 2017a, Kolahchi *et al*. 2017, Avcar 2015, 2019, Mohammadimehr *et al*. 2018, She *et al*. 2018, Faleh *et al*. 2018, Hussain and Naeem 2018, Farokhi *et al*. 2018, Attia *et al*. 2018, Karami and Shahsavari 2019, Chaabane *et al*. 2019, Berghouti *et al*. 2019). The benefits of the FGM plates are the high thermal resistance and the gradual change in material properties in the desired direction. The concept of FGM was examined for the first time in Japan in 1984 during a project of space plane.

Several investigations have been carried out to study the mechanical behavior of FG structures. Bouderba *et al*. (2013) examined the thermomechanical bending response of FG thick plates resting on Winkler-Pasternak elastic foundations. Tornabene *et al*. (2014) proposed the vibration analysis of double-curve shell structures employing the generalized kinematic of the unified Carrera formula, introducing the Zig-Zag influence provided by the Murakami's function. Barretta and Luciano (2014) presented a novel solution procedure, based on a principle of correspondence between a linearly elastic, homogenous and orthotropic Saint-Venant beam under torsion and an isotropic linearly viscoelastic FG Kirchhoff plate without kinematic constraints on the boundary. Tornabene *et al*. (2015) studied the recovery of through-the-thickness transverse normal and shear strains and stresses in statically deformed FG doubly-curved sandwich shell structures and shells of revolution using the generalized zigzag kinematic and the Carrera Unified Formulation. Barretta *et al*. (2015a) have developed novel analytical solutions of FG beams subjected to non-uniform torsion by detecting axial variations of longitudinal and shear modules incorporating an axially uniform warping field. Barretta *et al*. (2015b) examined the flexural problem of FG Euler-Bernoulli nanobeam base on a non-local thermodynamic formulation and proposed novel non-local models. Fantuzzi *et al*. (2016) studied the vibration response of moderately thick FGM plates with geometric discontinuities and arbitrarily curved boundaries. Hajmohammad *et al*. (2017) studied the dynamic buckling of sensor/FG-carbon nanotube-reinforced laminated plates/actuator based on sinusoidal-visco-piezoelasticity models. Karami *et al*. (2018a) presented a wave propagation analysis in FG nanoplates under in-plane magnetic field based on nonlocal strain gradient theory and

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four variable refined plate theory.

In a lot applications, the sandwich plate is a laminated construction consisting of two or more thin face sheets connected by one or more thick cores in order to obtain high properties such as lightness, high noise resistance, vibration, thermal insulation and long fatigue life, wear resistance. Although sandwich structures offer benefits over other types of structures, the sudden variation in the characteristics of the materials in the bond between the facing sheets and the core causes delamination which is the most common type of damage to the plates in sandwich. To overcome this disadvantage, it is possible to use functionally graded materials (FGMs). FGMs are a class of composite material whose properties change gradually and continuously from one surface to another. Due to the continuous variation in material characteristics of a FGM, the interfaces between two materials disappear. Because of this feature, FGMs have some benefits, such as eliminating material discontinuity and delamination failure, reducing stress and deflections. The combination of these features promotes the application of FGM in sandwich structures.

The many benefits of sandwich structures encourage engineers to utilize them in almost every phase of the structure, from roof panels and thermally insulated walls of buildings, from spacecraft to ships. The significant increase in the use of sandwich structures requires the development of rigorous mathematical theories to predict their response in any set of conditions. To this end, several refined theories have been developed by various authors. Li *et al*. (2008) investigated the dynamic of rectangular FGM sandwich plates with simply supported and clamped edges, based on the 3D linear theory of elasticity. Brischetto (2009) examined the flexural response of several sandwich plates with an FG core, employing advanced monolayer and layer-by-layer models with fourth-order linear expansion in the thickness direction. Wang and Shen (2011) performed a nonlinear static analysis of a sandwich plate with FGM facing sheets by a two-step perturbation method. Neves *et al*. (2012) used a variant of Murakami's zig-zag model to perform bending analysis of two types of FG sandwich plates, taking into account the thickness stretching influence. Natarajan and Manickam (2012) studied flexural bending and vibration in two types of FG sandwich plates employing a flexible QUAD-8 shear element proposed on the basis of HSDT. Neves *et al*. (2013) employed a quasi 3D HSDT in order to present the static, dynamic, and buckling analysis of two types of FG sandwich plates. Mantari and Soares (2014a, b) given a four-unknown and five-unknown quasi-3D HSDT for the analysis of the flexion of FG sandwich plates. Bousahla *et al*. (2014) proposed a new higher order shear and normal deformation theory based on neutral surface position for bending analysis of FG plates. Alipour and Shariyat (2014) investigated the stress and deformation of FG annular sandwich plates under non-uniform normal and/or shear tractions. Meziane *et al*. (2014) proposed an efficient and simple refined theory for buckling and free vibration of exponentially graded sandwich plates under various boundary conditions. Alibeigloo and Alizadeh (2015) discussed bending and free vibration responses of two types of FG sandwich plates based on the 3D theory of elasticity. Hamidi *et al*. (2015) employed a sinusoidal plate model with 5-unknowns and stretching effect for thermo-mechanical bending of FG sandwich plates. Bennoun *et al*. (2016) presented a novel five variable refined plate theory for vibration analysis of FG sandwich plates. Akavci (2016) employed a novel hyperbolic shear and normal deformation plate model to investigate the bending, dynamic and buckling responses of simply supported FG sandwich plates on elastic foundation. Beldjelili *et al*. (2016) investigated hygro-thermo-mechanical bending of S-FGM plates resting on variable elastic foundations using a four-variable trigonometric plate theory. Bouderba *et al*. (2016) investigated the thermal stability of functionally graded sandwich plates using a simple shear deformation theory. Menasria *et al*. (2017) proposed a new and simple HSDT for thermal buckling analysis of FG sandwich plates. Benahmed *et al*. (2017) proposed a new quasi-3D hyperbolic shear deformation theory for FG thick rectangular plates on elastic foundation. Ait Atmane *et al*. (2017) examined the effect of thickness stretching and porosity on mechanical response of a FG beams resting on elastic foundations. El-Haina *et al*. (2017) used a simple analytical approach for thermal buckling of thick FG sandwich plates. Katariya *et al*. (2018) presented a geometrically nonlinear deflection and stress analysis of skew sandwich shell panel using HSDT. Belabed *et al*. (2018) developed a new 3-unknown hyperbolic shear deformation theory for vibration of FG sandwich plate. Abualnour *et al*. (2018) presented a novel quasi-3D trigonometric plate theory for dynamic analysis of FG plates. Meksi *et al*. (2019) given an analytical solution for static, buckling and dynamic behaviors of FG sandwich plates.

The purpose of this work is to apply a simple quasi-3D HSDT to study the thermo-mechanical bending response of FG sandwich plate. The equilibrium equations are obtained via the principle of virtual work and solved using Navier Method. The number of unknown functions involved in the governing equations is only five. Comparative studies are considered to check the accuracy of the present formulation. The influences of thermal load and other parameters on the thermo-mechanical bending response of the FG sandwich plates are examined and discussed.

2. Problem formulation

In this investigation, a three rectangular functionally graded sandwich plate is examined (as shown in Fig. 1). The plate has length "*a*", width "*b*" and uniform thickness "*h*". The free surfaces of the sandwich plate being defined by ($h_0 = -h / 2$, for the lower surface) and ($h_3 = +h / 2$, for the upper surface). The plate has also two intermediate surfaces (h_1, h_2) is between the faces sheets and the core, this surfaces are located at (h_1 and h_2) and depends on the layer thickness ratio as shown in Table 1.

Each FG-sandwich plate is composed of three (03) layers, namely, "Top layer", "Intermediate layer", and "Bottom layer" from top to bottom of the sandwich plate.

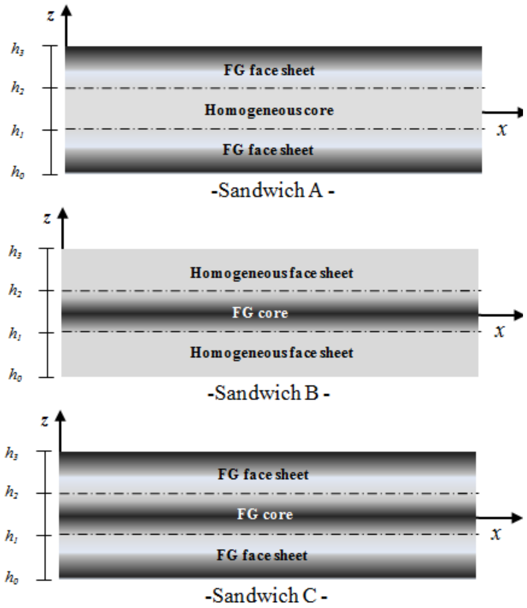

Fig. 1 geometry of FG-sandwich plates

Table 1 Various layer thickness ratio of sandwich plates

Layer thickness ratio	h_0	h_1	h_2	h_3
1-0-1		0	0	
1-2-1		$-h/4$	$h/4$	
1-1-1		$-h/6$	$h/6$	
1-3-1	$-h/2$	$-3h/10$	$3h/10$	$h/2$
2-1-2		$-h/10$	$h/10$	
3-1-3		$-h/14$	$h/14$	
2-1-1		0	$h/4$	
2-2-1		$-h/10$	$3h/10$	

The three types of FG sandwich plate considered in this study are:

- FG-sandwich plate type "A": FGM face sheets and homogeneous core
- FG-sandwich plate type "B": homogeneous face sheets and FGM core
- FG-sandwich plate type "C": both FGM faces sheets and core

2.1 Material properties of the face sheets

The volume fraction of the two layers "Top layer" and "Bottom layer" of the plate is varies as Power-law function Eq. (1), where, the "Top layer" varies from ceramic -rich surface ($z = h_2$) to a metal-rich surface ($z = h_3$) and the "Bottom layer" varies from a metal-rich surface ($z = h_0$) to a ceramic-rich surface ($z = h_1$). The volume fraction of the top and bottom layers can be given as (Zenkour and Alghamdi 2010, Bourada *et al*. 2012, Kettaf *et al*. 2013, Mantari and Monge 2016, Nguyen *et al*. 2016, Bennoun *et al*. 2016, Abdelaziz *et al*. 2017, Elmossouess *et al*. 2017)

$$V^{(1)} = \left(\frac{z-h_0}{h_1-h_0}\right)^p \qquad z \in [h_0, h_1] \tag{1a}$$

$$V^{(3)} = \left(\frac{z-h_3}{h_2-h_3}\right)^p \qquad z \in [h_2, h_3] \tag{1b}$$

Where $V^{(n)}$ is the volume fractions of the bottom layer ($n = 1$) and top layer ($n = 3$), p is a power index of the FG faces sheets with p higher or equal zero ($p \geq 0$).

The effective material properties (Young's modulus $E^{(n)}$, Poisson's ratio $\mu^{(n)}$ and thermal expansion coefficient $\alpha^{(n)}$) can be expressed as (Bourada *et al*. 2012, Bessaim *et al*. 2013, Belabed *et al*. 2014, Bounouara *et al*. 2016, Tounsi *et al*. 2016, Houari *et al*. 2016)

$$P^{(n)}(z) = P_m + (E_c - E_m)V^{(n)} \;\; with \; (n = 1, 3) \tag{2}$$

Where index c and m represent ceramic and metal respectively.

2.2 Material properties of the face sheets

The volume fraction of the Intermediate layer of the sandwich plate $V^{(2)}$ can be given as

$$V^{(2)} = \left(\frac{2|z|}{h_2-h_1}\right)^k \qquad z \in [h_1, h_2] \tag{3}$$

Where (k) is a material index of the Intermediate layer (core) and takes values greater than or equal to zero ($k \geq 0$).

The functionally graded intermediate layer of plate has the effective material properties ($E^{(n)}$, $\mu^{(n)}$ and $\alpha^{(n)}$) vary exponentially along the thickness of the layer (Zenkour and Sobhy 2013, Asnafi and Abedi 2015, Li *et al*. 2017)

$$P^{(2)}(z) = P_m \exp(\beta V^{(2)}) \quad with \;\; \beta = \ln\frac{P_c}{P_m} \tag{4}$$

The material properties of ceramic and metal used in this investigation are summarized in Table 2.

2.3 A novel quasi-3D shear deformation plate theory

In this work, the simplifying assumptions are considered to the conventional quasi-3D theories (with stretching effect) so that the number of unknown variables is

Table 2 Material properties of Ceramic (ZrO_2) and Metal (Ti–$6Al$–$4V$)

Properties	Metal: Ti–$6Al$–$4V$	Ceramic: ZrO_2
E_i (GPa)	66.2	117.0
μ_i	1/3	1/3
α (10^{-6}/K)	10.3	7.11

diminished. The kinematic of the the existing quasi-3D theories is expressed by

$$u(x,y,z)=u_0(x,y)-z\frac{\partial w_0}{\partial x}+f(z)\phi_x(x,y) \tag{5a}$$

$$v(x,y,z)=v_0(x,y)-z\frac{\partial w_0}{\partial y}+f(z)\phi_y(x,y) \tag{5b}$$

$$w(x,y,z)=w_0(x,y)+g(z)\phi_z(x,y) \tag{5c}$$

where (u_0; v_0; w_0; ϕ_x; ϕ_y and ϕ_z) are six unknown displacements of the mid-plane of the plate, and $f(z)$ denotes shape function defining the variation of the transverse shear strains and stresses across the thickness (h). By replacing the rotations of the (yz) and (xz) caused by shear, $\phi_x = \int \theta(x,y)dx$ and $\phi_y = \int \theta(x,y)dy$, the new kinematic of the present quasi-3D theory can be obtained in a simpler form with only five variables instead of six of the other quasi-3d theories (Sekkal *et al*. 2017b, Ait Sidhoum *et al*. 2018, Benchohra *et al*. 2018, Younsi *et al*. 2018, Bouhadra *et al*. 2018, Boukhlif *et al*. 2019, Boulefrakh *et al*. 2019, Boutaleb *et al*. 2019, Bendaho *et al*. 2019, Zaoui *et al*. 2019, Khiloun *et al*. 2019) as

$$u(x,y,z)=u_0(x,y)-z\frac{\partial w_0}{\partial x}+k_1\,f(z)\int\theta(x,y)\,dx \tag{6a}$$

$$v(x,y,z)=v_0(x,y)-z\frac{\partial w_0}{\partial y}+k_2\,f(z)\int\theta(x,y)\,dy \tag{6b}$$

$$w(x,y,z)=w_0(x,y)+g(z)\phi_z(x,y) \tag{6c}$$

Where the coefficients "k_1" and "k_2" depends on the geometry. In this investigation, the proposed Quasi-3D shear deformation plate theory is determined by considering

$$f(z)=z\left(1-\frac{4z^2}{3h^2}\right) \tag{7}$$

The non-zero linear strain relations associated with the displacement model of Eq. (6) are as follows

$$\begin{Bmatrix}\varepsilon_x\\ \varepsilon_y\\ \gamma_{xy}\end{Bmatrix}=\begin{Bmatrix}\varepsilon_x^0\\ \varepsilon_y^0\\ \gamma_{xy}^0\end{Bmatrix}+z\begin{Bmatrix}k_x^b\\ k_y^b\\ k_{xy}^b\end{Bmatrix}+f(z)\begin{Bmatrix}k_x^s\\ k_y^s\\ k_{xy}^s\end{Bmatrix}$$
$$\begin{Bmatrix}\gamma_{yz}\\ \gamma_{xz}\end{Bmatrix}=g(z)\begin{Bmatrix}\gamma_{yz}^0\\ \gamma_{xz}^0\end{Bmatrix}\qquad \varepsilon_z=g'(z)\,\varepsilon_z^0 \tag{8}$$

where

$$\begin{Bmatrix}\varepsilon_x^0\\ \varepsilon_y^0\\ \gamma_{xy}^0\end{Bmatrix}=\begin{Bmatrix}\dfrac{\partial u_0}{\partial x}\\ \dfrac{\partial v_0}{\partial x}\\ \dfrac{\partial u_0}{\partial y}+\dfrac{\partial v_0}{\partial x}\end{Bmatrix},\quad \begin{Bmatrix}k_x^b\\ k_y^b\\ k_{xy}^b\end{Bmatrix}=\begin{Bmatrix}-\dfrac{\partial^2 w_0}{\partial x^2}\\ -\dfrac{\partial^2 w_0}{\partial y^2}\\ -2\dfrac{\partial^2 w_0}{\partial x\partial y}\end{Bmatrix}, \tag{9a}$$

$$\begin{Bmatrix}k_x^s\\ k_y^s\\ k_{xy}^s\end{Bmatrix}=\begin{Bmatrix}k_1\theta\\ k_2\theta\\ k_1\dfrac{\partial}{\partial y}\displaystyle\int\theta\,dx+k_2\dfrac{\partial}{\partial x}\displaystyle\int\theta\,dy\end{Bmatrix}, \tag{9a}$$

$$\begin{Bmatrix}\gamma_{yz}^0\\ \gamma_{xz}^0\end{Bmatrix}=\begin{Bmatrix}k_2\displaystyle\int\theta\,dy+\dfrac{\partial\varphi_z}{\partial y}\\ k_1\displaystyle\int\theta\,dx+\dfrac{\partial\varphi_z}{\partial x}\end{Bmatrix},\quad \varepsilon_z^0=\varphi_z \tag{9b}$$

The integrals used in the Eqs. (6), (9a) and (9b) shall be resolved by a Navier method and can be expressed as follows

$$\begin{aligned}&\frac{\partial}{\partial y}\int\theta\,dx=A'\frac{\partial^2\theta}{\partial x\partial y},\quad &&\frac{\partial}{\partial x}\int\theta\,dy=B'\frac{\partial^2\theta}{\partial x\partial y}\\ &\int\theta\,dx=A'\frac{\partial\theta}{\partial x},\quad &&\int\theta\,dy=B'\frac{\partial\theta}{\partial y}\end{aligned} \tag{10}$$

In this research work, the coefficients A' and B' are obtained according to the present type of solution utilized. Therefore, the coefficients A' and B' are expressed as follows

$$A'=-\frac{1}{\alpha^2},\quad B'=-\frac{1}{\beta^2},\quad k_1=\alpha^2,\quad k_2=\beta^2 \tag{11}$$

where α and β are defined in expression (26).

2.4 Constitutive equations

For the three type of functionally graded sandwich plates, the stress-strain relationships including the thermal influences ($\alpha\,T$) for the n^{th}–*layer* can be written as

$$\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{xy}\\ \tau_{xz}\\ \tau_{yz}\end{Bmatrix}^{(n)}=\begin{bmatrix}C_{11}&C_{12}&C_{13}&0&0&0\\ C_{12}&C_{22}&C_{23}&0&0&0\\ C_{13}&C_{23}&C_{33}&0&0&0\\ 0&0&0&C_{66}&0&0\\ 0&0&0&0&C_{55}&0\\ 0&0&0&0&0&C_{44}\end{bmatrix}^{(n)}\begin{Bmatrix}\varepsilon_x-\alpha\,T\\ \varepsilon_y-\alpha\,T\\ \varepsilon_z-\alpha\,T\\ \gamma_{xy}\\ \gamma_{xz}\\ \gamma_{yz}\end{Bmatrix}^{(n)} \tag{12}$$

where (σ_x, σ_y, σ_z, τ_{xy}, τ_{xz}, τ_{yz}) and (ε_x, ε_y, ε_z, γ_{xy}, γ_{xz}, γ_{yz}) are the stress and strain components respectively. The C_{ij} expressions in terms of engineering constants are given below:

The C_{ij} expressions in terms of engineering constants are given below

$$C_{11}^{(n)}=C_{22}^{(n)}=C_{33}^{(n)}=\frac{E^{(n)}(z)}{1-\left(\mu^{(n)}\right)^2}, \tag{13a}$$

$$C_{12}^{(n)}=C_{13}^{(n)}=C_{23}^{(n)}=\mu^{(n)}\,C_{11}^{(n)} \tag{13b}$$

$$C_{44}^{(n)}=C_{55}^{(n)}=C_{66}^{(n)}=\frac{E^{(n)}(z)}{2(1+\mu^{(n)})} \tag{13c}$$

The Young modulus "$E(z)$", the elastic coefficients "$C_{ij}(z)$" and the thermal expansion coefficients $\alpha^{(n)}$ change within the thickness according to Eqs. (2) and (4).

2.5 Governing equations

The Virtual Work is used herein to derive the governing equations for thermo-mechanical bending problem of the FG sandwich plate. The Virtual Work principle can be stated in analytical form as (Al-Basyouni *et al*. 2015, Bourada *et al*. 2015, 2016, 2018, Attia *et al*. 2015, Bellifa *et al*. 2017a, b, Ahouel *et al*. 2016, Benadouda *et al*. 2017, Besseghier *et al*. 2017, Cherif *et al*. 2018, Adda Bedia *et al*. 2019)

$$\delta U + \delta V = 0 \tag{14}$$

where δU and δV are the virtual strain energy and the external virtual works due to an external load q applied to the FG sandwich plate, respectively.

The virtual strain energy δU is given as (Tounsi *et al*. 2013, Zidi *et al*. 2014, Hebali *et al*. 2014, Zemri *et al*. 2015, Khetir *et al*. 2017, Fahsi *et al*. 2017, Hachemi *et al*. 2017, Zidi *et al*. 2017, Fourn *et al*. 2018, Bourada *et al*. 2019)

$$\delta U = \int_{-h/2}^{h/2}\int_{\Omega}\begin{bmatrix}\sigma_x\delta\varepsilon + \sigma_y\delta\varepsilon_y + \sigma_z\delta\varepsilon_z + \tau_{xy}\delta\gamma_{xy}\\ +\tau_{xz}\delta\gamma_{xz} + \tau_{yz}\delta\gamma_{yz}\end{bmatrix} d\Omega dz \tag{15a}$$

The external virtual works δV can be expressed as

$$\delta V = -\int_{\Omega} q\delta w d\Omega \tag{15b}$$

The principle of virtual work can be rewritten as

$$\int_{\Omega}\begin{pmatrix} N_x\delta\varepsilon_x^0 + N_y\delta\varepsilon_y^0 + N_z\delta\varepsilon_z^0 + N_{xy}\delta\gamma_{xy}^0\\ +M_x^b\delta k_x^b + M_y^b\delta k_y^b + M_{xy}^b\delta k_{xy}^b + M_x^s\delta k_x^s\\ +M_y^s\delta k_y^s + M_{xy}^s\delta k_{xy}^s + S_{yz}^s\delta\gamma_{yz}^s + S_{xz}^s\delta\gamma_{xz}^s - q\delta w\end{pmatrix} d\Omega = 0 \tag{16}$$

where (Ω) is the top surface and the stress resultants (N, M and S) are given by

$$\begin{Bmatrix} N_x, & N_y, & N_{xy},\\ M_x^b, & M_y^b, & M_{xy}^b,\\ M_x^s, & M_y^s, & M_{xy}^s,\end{Bmatrix} = \int_{h_{n-1}}^{h_n}(\sigma_x,\sigma_y,\tau_{xy})^{(n)}\begin{Bmatrix}1\\ z\\ f(z)\end{Bmatrix}dz \tag{17a}$$

$$N_z = \int_{h_{n-1}}^{h_n}\sigma^{(n)}{}_z g'(z)dz \tag{17b}$$

$$\left(S_{xz}^s, S_{yz}^s\right) = \int_{h_{n-1}}^{h_n}(\tau_{xz},\tau_{yz})^{(n)} g(z)dz \tag{17c}$$

where h_n and h_{n-1} are the top and bottom z-coordinates of the nth layer of the FG sandwich plate.

Substituting the strain of Eq. (8) into Eq. (12) and the subsequent results into Eq. (17), the stress resultants can be obtained as function of generalized displacements (u_0, v_0, w_0, θ, ϕ_y) as

$$\begin{Bmatrix} N_x\\ N_y\\ N_{xy}\\ M_x^b\\ M_y^b\\ M_{xy}^b\\ M_x^s\\ M_y^s\\ M_{xy}^s\\ N_z\end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & 0 & B_{11} & B_{12} & 0 & B_{11}^s & B_{12}^s & 0 & X_{13}\\ A_{12} & A_{22} & 0 & B_{12} & B_{22} & 0 & B_{12}^s & B_{22}^s & 0 & X_{23}\\ 0 & 0 & A_{66} & 0 & 0 & B_{66} & 0 & 0 & B_{66}^s & 0\\ B_{11} & B_{12} & 0 & D_{11} & D_{12} & 0 & D_{11}^s & D_{12}^s & 0 & Y_{13}\\ B_{12} & B_{22} & 0 & D_{12} & D_{22} & 0 & D_{12}^s & D_{22}^s & 0 & Y_{23}\\ 0 & 0 & B_{66} & 0 & 0 & D_{11} & 0 & 0 & D_{66}^s & 0\\ B_{11}^s & B_{12}^s & 0 & D_{11}^s & D_{12}^s & 0 & H_{11}^s & H_{12}^s & 0 & Y_{13}^s\\ B_{12}^s & B_{22}^s & 0 & D_{12}^s & D_{22}^s & 0 & H_{12}^s & H_{22}^s & 0 & Y_{23}^s\\ 0 & 0 & B_{66}^s & 0 & 0 & D_{66}^s & 0 & 0 & H_{66}^s & 0\\ X_{13} & X_{23} & 0 & Y_{13} & Y_{23} & 0 & Y_{13}^s & Y_{23}^s & 0 & Z_{33}\end{bmatrix} \times \begin{Bmatrix} \partial u_0/\partial x\\ \partial v_0/\partial y\\ \partial u_0/\partial y + \partial v_0/\partial x\\ -\partial^2 w_0/\partial x^2\\ -\partial^2 w_0/\partial y^2\\ -2\partial^2 w_0/\partial x\partial y\\ k_1\theta\\ k_2\theta\\ \left(k_1 A' + k_2 B'\right)\partial^2\theta/\partial x\partial y\\ \phi_z\end{Bmatrix} - \begin{Bmatrix} N_x^T\\ N_y^T\\ 0\\ M_x^{bT}\\ M_y^{bT}\\ 0\\ M_x^{sT}\\ M_y^{sT}\\ 0\\ N_z^T\end{Bmatrix} \tag{18a}$$

$$\begin{Bmatrix} S_{yz}^s\\ S_{xz}^s\end{Bmatrix} = \begin{bmatrix} A_{44}^s & 0\\ 0 & A_{55}^s\end{bmatrix}\begin{Bmatrix} k_2 B'\dfrac{\partial\theta}{\partial y} + \dfrac{\partial\varphi_z}{\partial y}\\ k_1 A'\dfrac{\partial\theta}{\partial x} + \dfrac{\partial\varphi_z}{\partial x}\end{Bmatrix} \tag{18b}$$

Where

$$(A_{ij}, A_{ij}^s, B_{ij}, D_{ij}, B_{ij}^s, D_{ij}^s, H_{ij}^s) = \sum_{n=1}^{3}\int_{h_{n-1}}^{h_n} C_{ij}^{(n)}(1, g^2(z), z, z^2, f(z), zf(z), f^2(z))dz \tag{19a}$$

and

$$(X_{ij}, Y_{ij}, Y_{ij}^s, Z_{ij}) = \sum_{n=1}^{3}\int_{h_{n-1}}^{h_n} C_{ij}^{(n)}(1, z, f(z), g'(z))g'(z)dz \tag{19b}$$

The efforts and moment resultants due to thermal loading ($N_x^T, N_y^T, M_x^{bT}, M_y^{bT}, M_x^{sT}, M_y^{sT}$ and N_z^T) are defined by

$$\begin{Bmatrix} N_x^T\\ M_x^{bT}\\ M_x^{sT}\\ N_z^T\end{Bmatrix} = \sum_{n=1}^{3}\int_{h_{n-1}}^{h_n}\frac{E^{(n)}(z)}{1-(\nu^{(n)})^2}(1+2\nu^{(n)})\alpha^{(n)}T\begin{Bmatrix}1\\ Z\\ f(z)\\ g'(z)\end{Bmatrix}dz \tag{20}$$

With $N_x^T = N_y^T$, $M_x^{bT} = M_y^{bT}$, $M_x^{sT} = M_y^{sT}$.

By substituting the non-zero linear strain relations of Eq. (8) into the virtual work principle expression (Eq. (16)), Integrating the obtained equation by parts and then collecting the five displacement coefficients (δu_0, δv_0, δw_0, $\delta\theta$ and $\delta\phi_z$), the present governing equations of FG-sandwich plate can be derived

$$\delta\, u_0: \ \frac{\partial N_x}{\partial x}+\frac{\partial N_{xy}}{\partial y}=0 \tag{21a}$$

$$\delta\, v_0: \ \frac{\partial N_{xy}}{\partial x}+\frac{\partial N_y}{\partial y}=0 \tag{21b}$$

$$\delta\, w_0: \ \frac{\partial^2 M_x^b}{\partial x^2}+2\frac{\partial^2 M_{xy}^b}{\partial x\partial y}+\frac{\partial^2 M_y^b}{\partial y^2}+q=0 \tag{21c}$$

$$\begin{aligned}\delta\, \theta: \ & -k_1 M_x^s-k_2 M_y^s-\left(k_1 A'+k_2 B'\right)\frac{\partial^2 M_{xy}^s}{\partial x\partial y}\\ & +k_1 A'\frac{\partial S_{xz}^s}{\partial x}+k_2 B'\frac{\partial S_{yz}^s}{\partial y}=0\end{aligned} \tag{21d}$$

$$\delta\, \varphi_z: -N_z+\frac{\partial S_{xz}^s}{\partial x}+\frac{\partial S_{yz}^s}{\partial y}=0 \tag{21e}$$

Substituting Eqs. (18a) and (18b) into Eqs. (21a), (21b), (21c), (21d) and (21e), the governing equations expressed in terms of displacements (u_0, v_0, w_0, θ, ϕ_z) of the present quasi-3D theory can be obtained as follows

$$\begin{aligned}& A_{11}d_{11}u_0+A_{66}d_{22}u_0+(A_{12}+A_{66})d_{12}v_0-B_{11}d_{111}w_0\\ & -(B_{12}+2B_{66})d_{122}w_0+(B_{66}^s(k_1A'+k_2B'))d_{122}\theta\\ & +(B_{11}^s k_1+B_{12}^s k_2)d_1\theta+X_{13}d_1\phi_z=p_1\end{aligned} \tag{22a}$$

$$\begin{aligned}& (A_{12}+A_{66})d_{12}u_0+A_{22}d_{22}v_0+A_{66}d_{11}v_0-B_{22}d_{222}w_0\\ & -(B_{12}+2B_{66})d_{112}w_0+(B_{66}^s(k_1A'+k_2B'))d_{112}\theta\\ & +(B_{22}^s k_2+B_{12}^s k_1)d_2\theta+X_{23}d_2\phi_z=p_2\end{aligned} \tag{22b}$$

$$\begin{aligned}& B_{11}d_{111}u_0+(B_{12}+2B_{66})d_{122}u_0+(B_{12}+2B_{66})d_{112}v_0\\ & +B_{22}d_{222}v_0-D_{11}d_{1111}w_0-2(D_{12}+2D_{66})d_{1122}w_0-\\ & D_{22}d_{2222}w_0+(D_{11}^s k_1+D_{12}^s k_2)d_{11}\theta+\\ & 2(D_{66}^s(k_1A'+k_2B'))d_{1122}\theta+(D_{12}^s k_1+D_{22}^s k_2)d_{22}\theta\\ & +Y_{13}d_{11}\phi_z+Y_{23}d_{22}\phi_z=p_3\end{aligned} \tag{22c}$$

$$\begin{aligned}& -(B_{11}^s k_1+B_{12}^s k_2)d_1u_0-(B_{66}^s(k_1A'+k_2B'))d_{122}u_0\\ & -(B_{66}^s(k_1A'+k_2B'))d_{112}v_0-(B_{12}^s k_1+B_{22}^s k_2)d_2v_0\\ & +(D_{11}^s k_1+D_{12}^s k_2)d_{11}w_0+2(D_{66}^s(k_1A'+k_2B'))d_{1122}w_0\\ & +(D_{12}^s k_1+D_{22}^s k_2)d_{22}w_0-H_{11}^s(k_1)^2\theta-H_{22}^s(k_2)^2\theta\\ & -2H_{12}^s k_1k_2\theta-(k_1A'+k_2B')^2H_{66}^s d_{1122}\theta+A_{44}^s(k_2B')^2d_{22}\theta\\ & +A_{55}^s(k_1A')^2d_{11}\theta-k_1Y_{13}^s\phi_z-k_2Y_{23}^s\phi_z+A_{44}^s(k_2B')d_{22}\phi_z\\ & +A_{55}^s(k_1A')d_{11}\phi_z=p_4\end{aligned} \tag{22d}$$

$$\begin{aligned}& -X_{13}d_1u_0-X_{23}d_2v_0+Y_{13}d_{11}w_0+Y_{23}d_{22}w_0+\\ & (A_{44}^s-Y_{23}^s)(k_2B')d_{22}\theta+(A_{55}^s-Y_{13}^s)(k_1A')d_{11}\theta\\ & -Z_{33}\phi_z+A_{44}^s d_{22}\phi_z+A_{55}^s d_{11}\phi_z=p_5\end{aligned} \tag{22e}$$

where d_{ij}, d_{ijl} and d_{ijlm} are the following differential operators

$$\begin{aligned}& d_{ij}=\frac{\partial^2}{\partial x_i\partial x_j}, \qquad d_{ijl}=\frac{\partial^3}{\partial x_i\partial x_j\partial x_l},\\ & d_{ijlm}=\frac{\partial^4}{\partial x_i\partial x_j\partial x_l\partial x_m}, \qquad d_i=\frac{\partial}{\partial x_i}, \qquad (i,j,l,m=1,2)\end{aligned} \tag{22f}$$

The components of the generalized force vector $\{p\}$ are given by

$$\begin{aligned}& p_1=\frac{\partial N_x^T}{\partial x}, \quad p_2=\frac{\partial N_y^T}{\partial y}, \quad p_3=q-\frac{\partial^2 M_x^{bT}}{\partial x^2}-\frac{\partial^2 M_y^{bT}}{\partial y^2},\\ & p_4=-\frac{\partial^2 M_x^{sT}}{\partial x^2}-\frac{\partial^2 M_y^{sT}}{\partial y^2}, \quad p_5=N_z^T\end{aligned} \tag{23}$$

3. Solution procedure

The Navier method (for simply supported FG sandwich plate) is used to solve the present five governing equations, the Navier solution can be written in the following form

$$\begin{Bmatrix} u_0\\ v_0\\ w_0\\ \theta\\ \varphi_z\end{Bmatrix}=\begin{Bmatrix} U\cos(\alpha\, x)\sin(\beta\, y)\\ V\sin(\alpha\, x)\cos(\beta\, y)\\ W\sin(\alpha\, x)\sin(\beta\, y)\\ X\sin(\alpha\, x)\sin(\beta\, y)\\ \Phi\sin(\alpha\, x)\sin(\beta\, y)\end{Bmatrix} \tag{24}$$

The transverse mechanical load (q) and temperature loads (T_1, T_2, and T_3) are given in the form of a double trigonometric series as

$$\begin{Bmatrix} q\\ T_1\\ T_2\\ T_3\end{Bmatrix}=\begin{Bmatrix} q_0\\ t_1\\ t_2\\ t_3\end{Bmatrix}\sin(\alpha x)\sin(\beta y) \tag{25}$$

where the terms (q_0, t_1, t_2, and t_3) are constants and the coefficients α and β are given by

$$\alpha=m\pi/a \qquad \text{and} \qquad \beta=n\pi/b \tag{26}$$

By replacing Eqs. (24) and (25) into Eq. (22), one gets the following matrix system

$$\begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{14} & S_{15}\\ S_{12} & S_{22} & S_{23} & S_{24} & S_{25}\\ S_{13} & S_{23} & S_{33} & S_{34} & S_{35}\\ S_{14} & S_{24} & S_{34} & S_{44} & S_{45}\\ S_{15} & S_{25} & S_{35} & S_{45} & S_{55}\end{bmatrix}\begin{Bmatrix} U\\ V\\ W\\ X\\ \Phi\end{Bmatrix}=\begin{Bmatrix} P_1\\ P_2\\ P_3\\ P_4\\ P_5\end{Bmatrix} \tag{27}$$

With

$$
\begin{aligned}
S_{11} &= -(A_{11}\alpha^2 + A_{66}\beta^2), \\
S_{12} &= -(A_{12} + A_{66})\alpha\beta \\
S_{13} &= B_{11}\alpha^3 + (B_{12} + 2B_{66})\alpha\beta^2 \\
S_{14} &= (k_1 B_{11}^s + B_{12}^s k_2)\alpha - (k_1 A_1 + k_2 B_2) B_{66}^s \alpha\beta^2 \\
S_{15} &= \alpha X_{13}, \\
S_{22} &= -(A_{66}\alpha^2 + A_{22}\beta^2) \\
S_{23} &= B_{22}\beta^3 + (B_{12} + 2B_{66})\alpha^2\beta \\
S_{24} &= -(k_1 A' + k_2 B') B_{66}^s \alpha^2\beta + (k_1 B_{12}^s + k_2 B_{22}^s)\beta \\
S_{25} &= X_{23}\beta, \\
S_{33} &= -(D_{11}\alpha^4 + 2(D_{12} + 2D_{66})\alpha^2\beta^2 + D_{22}\beta^4) \\
S_{34} &= -((k_1 D_{11}^s + k_2 D_{12}^s)\alpha^2 - 2D_{66}^s (k_1 A' + k_2 B')\alpha^2\beta^2 \\
&\quad + (k_1 D_{12}^s + k_2 D_{22}^s)\beta^2) \\
S_{35} &= -(Y_{13}\alpha^2 + Y_{23}\beta^2) \\
S_{44} &= -((k_1)^2 H_{11}^s + 2k_1 k_2 H_{12}^s + (k_2)^2 H_{22}^s \\
&\quad + (k_1 A' + k_2 B')^2 H_{66}^s \alpha^2\beta^2 + (k_1 A')^2 A_{55}^s \alpha^2 \\
&\quad + (k_2 B')^2 A_{44}^s \beta^2) \\
S_{45} &= -(k_1 Y_{13}^s + k_2 Y_{23}^s + k_1 A' \alpha^2 A_{55}^s + k_2 B' \beta^2 A_{44}^s) \\
S_{55} &= -(Z_{33} + \alpha^2 A_{55}^s + \beta^2 A_{44}^s)
\end{aligned}
\tag{28}
$$

The components of force vector $\{P\} = \{P_1, P_2, P_3, P_4, P_5\}^t$ are expressed by

$$
\begin{aligned}
p_1 &= \alpha(A^T t_1 + B^T t_2 + {}^aB^T t_3) \\
p_2 &= \beta(A^T t_1 + B^T t_2 + {}^aB^T t_3) \\
p_3 &= -q - h(\alpha^2 + \beta^2)(B^T t_1 + D^T t_2 + {}^aD^T t_3) \\
p_4 &= -h(\alpha^2 + \beta^2)({}^sB^T t_1 + {}^sD^T t_2 + {}^sF^T t_3) \\
p_5 &= -h(L^T t_1 + {}^aL^T t_2 + R^T t_3)
\end{aligned}
\tag{29}
$$

Where the coefficients A^T, B^T, ${}^aB^T$, D^T, ${}^aD^T$, ${}^sB^T$, ${}^sD^T$, ${}^aF^T$, L^T, ${}^aL^T$ and R^T appear in the above equations (Eq. (29)) are given as

$$
(A^T, B^T, D^T) = \sum_{n=1}^{3} \int_{h_{n-1}}^{h_n} \frac{E^{(n)}(z)}{1-(\nu^{(n)})^2}(1+2\nu^{(n)})\alpha^{(n)}(1, \bar{z}, \bar{z}^2)dz \tag{30a}
$$

$$
({}^aB^T, {}^aD^T) = \sum_{n=1}^{3} \int_{h_{n-1}}^{h_n} \frac{E^{(n)}(z)}{1-(\nu^{(n)})^2}(1+2\nu^{(n)})\alpha^{(n)}\bar{f}(z)(1, \bar{f})dz \tag{30b}
$$

$$
({}^sB^T, {}^sD^T, {}^sF^T) = \sum_{n=1}^{3} \int_{h_{n-1}}^{h_n} \frac{E^{(n)}(z)}{1-(\nu^{(n)})^2}(1+2\nu^{(n)})\alpha^{(n)}\bar{f}(z)(1, \bar{z}, \bar{f}(z))dz \tag{30c}
$$

$$
(L^T, L_a^T, R^T) = \sum_{n=1}^{3} \int_{h_{n-1}}^{h_n} \frac{E^{(n)}(z)}{1-(\nu^{(n)})^2}(1+2\nu^{(n)})\alpha^{(n)}\bar{g}'(z)(1, \bar{z}, \bar{f}(z))dz \tag{30d}
$$

with $\bar{z} = z/h$ and $\bar{f}(z) = f(z)/h$.

4. Numerical results and discussion

In this research investigation, a simple quasi-3D shear deformation theory for thermo-mechanical bending analysis of simply supported FG-sandwich plate is presented. To illustrate the effect of shear deformation and normal stress on the deflection and stresses of FG-sandwich plates, several results are presented and compared with others theories found in the literature in three sections of results in this investigation.

The deflection and stresses of thermo-mechanical bending problem are computed with following dimensionless relations

Deflection :

$$
\bar{w} = \frac{10^3}{q_0 a^4/(E_0 h^3) + 10^3 \alpha_0 t_2 a^4/h} w\left(\frac{a}{2}, \frac{b}{2}\right) \tag{31}
$$

Normal stress :

$$
\bar{\sigma}_x = \frac{10}{q_0 a^2/h^2 + 10\,\alpha_0 t_2 a^2/h^2} \sigma_x\left(\frac{a}{2}, \frac{b}{2}, z\right) \tag{32}
$$

Shear stress :

$$
\bar{\tau}_{xz} = \frac{1}{q_0 a/h + E_0 \alpha_0 t_2 a/(10h)} \tau_{xz}\left(0, \frac{b}{2}, z\right) \tag{33}
$$

with E_0 = 1 GPa, $\alpha_0 = 10^{-6}/K$.

A-Thermo-mechanical bending analysis of FG-sandwich plate type "A" with P-FG faces sheets and homogeneous core.

The first examples present the thermo-mechanical bending analysis of FG-sandwich plate type "A" with Power-law FG-face sheets and homogeneous core "k = 0". The actual results are compared with those obtained by shear deformation theories such as FSDT (first shear deformation theory) and HSDT (high shear deformation theory with five variables) developed by Zenkour and Alghamdi (2010) and RPT proposed by Li *et al.* (2017).

The variation of the non-dimensional deflection "$\bar{w}(a/2, b/2)$" of the FG-sandwich plate type "A" versus the face sheets power index "p" is presented in Table 3, the present results obtained using a quasi-3D shear deformation theory are compared with those given by the first shear deformation theory (Li *et al.* 2017) and those obtained by high order shear deformation theory (Zenkour *et al.* 2010) and those computed by refined shear deformation plate theory (Li *et al.* 2017) without including the stretching effect. Through this table, it can be observed that the

Table 3 Comparison of the non-dimensional deflection “$\overline{w}$”of FG-sandwich plate type “A” versus power index of the face sheets “p” with “a/h = 10”

p	Theory	$\overline{w}(a/2, b/2)$			
		1-0-1	3-1-3	2-1-2	1-1-1
0	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.806085	0.806085	0.806085	0.806085
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	0.808168	0.808168	0.808168	0.808168
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	0.895735	0.895735	0.895735	0.895735
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.864140	0.864140	0.864140	0.864140
1	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.072202	1.054599	1.045864	1.021066
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	1.077690	1.059613	1.050672	1.025367
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	1.190728	1.170533	1.160568	1.132449
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.149038	1.130125	1.120741	1.094113
2	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.129683	1.113609	1.104673	1.076998
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	1.137297	1.120582	1.111353	1.082911
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	1.257304	1.238234	1.227765	1.195703
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.210756	1.193444	1.183826	1.154061
3	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.149112	1.135925	1.127799	1.100705
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	1.157693	1.143856	1.135420	1.107475
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	1.280741	1.264724	1.255041	1.223232
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.231675	1.217447	1.208690	1.179518
4	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.157329	1.146452	1.139118	1.113133
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	1.166403	1.154902	1.147260	1.120403
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	1.290961	1.277527	1.268689	1.237931
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.240542	1.228791	1.220879	1.192880
5	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.161364	1.152187	1.145491	1.120562
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	1.170720	1.160948	1.153952	1.128152
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	1.296101	1.284626	1.276497	1.246833
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.244905	1.234980	1.227750	1.200876

Table 4 Effect of aspect ratio “a/b” on the non-dimensional deflection “$\overline{w}$” of FG-sandwich plate type “A” under thermo-mechanical load with “a/h = 10” and “p = 3”

p	Theory	$\overline{w}(a/2, b/2)$				
		$a/b = 1$	$a/b = 2$	$a/b = 3$	$a/b = 4$	$a/b = 5$
1-0-1	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.149112	0.456181	0.225191	0.130053	0.082979
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	1.157693	0.454308	0.225639	0.132324	0.086360
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	1.280741	0.503607	0.250355	0.146917	0.095948
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.231675	0.492573	0.246212	0.144771	0.094608
3-1-3	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.135925	0.451063	0.222763	0.128734	0.082209
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	1.143856	0.449019	0.223077	0.130867	0.085446
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	1.264724	0.497383	0.247274	0.145112	0.094770
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.217447	0.486952	0.243459	0.143199	0.093619
2-1-2	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.127799	0.447899	0.221252	0.127903	0.081716
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	1.135420	0.445781	0.221504	0.129968	0.084879
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	1.255041	0.493613	0.245406	0.144017	0.094055
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.208690	0.483486	0.241757	0.142222	0.093002
1-1-1	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.100705	0.437311	0.216165	0.125080	0.080011
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	1.107475	0.435020	0.216255	0.126958	0.082969
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	1.223232	0.481212	0.239259	0.140414	0.091704
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.179518	0.471920	0.236060	0.138942	0.090916

present results are slightly lower than the results obtained by Zenkour *et al*. (2010) and this is due to the introduction of the transverse deformation ($\varepsilon_z \neq 0$). It can also be noted that the non-dimensional deflection "$\bar{w}(a/2,\ b/2)$" is in direct correlation relation with the face sheets power index "p" and this for the different layer thickness ratios.

Table 4 shows the effect of aspect ratio "a/b" on the non-dimensional deflection "$\bar{w}(a/2,\ b/2)$" for FG-sandwich plate type "A" under combined loads (thermal and mechanical) using a quasi-3D shear deformation theory. From the presented results, it can be seen that the results obtained using quasi-3D theory are lower than the results obtained by refined shear deformation plate theory (Li *et al*. 2017), we can notice that the deflection "$\bar{w}(a/2,\ b/2)$" is in inverse relation with the aspect ratio "a/b" and the stretching effect always leads to a reduction of non-dimensional deflection "$\bar{w}(a/2,\ b/2)$".

Table 5 illustrate the variation of the dimensionless normal stress "$\bar{\sigma}_x(a/2,\ b/2,\ h/2)$" as function of the layer thicknesses (1-2-1, 2-1-2, 1-1-1 and 1-3-1) and the face sheets power index "p" for simply supported FG-sandwich plate type "A" . According to the obtained results (Table 4), it is remarkable that the face sheets power index effects on the non-dimensional normal stress "$\bar{\sigma}_x$" via inverse relation and this for the different value of thickness ratio.

B-Thermo-mechanical bending analysis of FG-sandwich plate type "B" with homogeneous face sheets "p = 0" and E-FGM core "$k \geq 0$".

The second example, show the thermo-mechanical bending analysis of FG-sandwich plate type "B" with E-FGM core "$k \geq 0$" and homogeneous face sheets "$p = 0$". A comparison is made between the current results and those obtained by FSDT and RPT developed by Li *et al*. (2017).

Table 6 illustrate the variation of the non-dimensional deflection "$\bar{w}(a/2,\ b/2)$" of FG-sandwich plate type "B" versus material index of E-FG core. The plate is under thermo mechanical load. The current results are compared with those obtained by FSDT and RPT (Li *et al*. 2017). From the table, it can be seen that the non-dimensional deflection values "$\bar{w}$" computed by the actual quasi-3Dtheory "$\varepsilon_z \neq 0$" are smaller than those published by Li *et al*. (2017) utilizing a five variables FSDT and RPT (with ε_z = 0) and this is due to the non-zero shear stress at the top and the bottom faces of the sandwich plate assumed by FSDT and the neglect of stretching effect by the RPT .it can also be noted that the bigger values of the non-dimensional deflection "$\bar{w}(a/2,\ b/2)$" are obtained for thickness ratio "1-3-1".

Table 5 Comparison of the non-dimensional normal stress "$\bar{\sigma}_x$" as function of layer thicknesses ratio and the face sheets power index "p" of FG-sandwich plate type "A" with "a/h = 10"

p	Theory	$\bar{\sigma}_x(a/2, b/2, h/2)$			
		1-0-1	3-1-3	2-1-2	1-1-1
0	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.446783	-2.446783	-2.446783	-2.446783
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	–2.461177	–2.461177	–2.461177	–2.461177
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	-3,597007	-3,597007	-3,597007	-3,597007
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2,911440	-2,911440	-2,911440	-2,911440
1	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.716951	-2.847778	-2.912696	-3.096888
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	–2.473903	–2.562491	–2.606343	–2.730494
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	-3,471099	-3,569762	-3,618476	-3,756017
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2,892290	-2,985255	-3,031378	-3,162208
2	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.290281	-2.410084	-2.476636	-2.682569
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	–2.181780	–2.263627	–2.308903	–2.448528
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	-3,145662	-3,238636	-3,289757	-3,446485
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2,589234	-2,674492	-2,721838	-2,868271
3	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.145598	-2.244126	-2.304740	-2.506605
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	–2.081815	–2.149449	–2.190823	–2.328042
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	-3,031284	-3,109180	-3,156414	-3,311823
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2,486287	-2,556476	-2,599635	-2,743281
4	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.084230	-2.165678	-2.220469	-2.414237
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	–2.039172	–2.095247	–2.132710	–2.264592
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	-2,981507	-3,046666	-3,089733	-3,239941
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2,442566	-2,500626	-2,539661	-2,677611
5	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.054012	-2.122872	-2.172951	-2.358964
	Zenkour and Alghamdi 2010 (TSDPT, $\varepsilon_z = 0$)	–2.018086	–2.065589	–2.099863	–2.226550
	Zenkour and Alghamdi 2010 (FSDPT, $\varepsilon_z = 0$)	-2,956534	-3,012040	-3,051612	-3,196423
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2,421017	-2,470126	-2,505817	-2,638388

Table 6 Variation of the non-dimensional deflection $\bar{w}$ of FG-sandwich plate type "B" versus material index of E-FG core "k" with "a/h = 10"

k	Theory	$\bar{w}(a/2, b/2)$			
		2-1-2	1-1-1	1-2-1	1-3-1
0	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	0.960453	0.960453	0.960453	0.960453
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.864140	0.864140	0.864140	0.864140
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.806085	0.806085	0.806085	0.806085
1	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	0.961067	0.963305	0.970187	0.977474
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.864623	0.866466	0.872221	0.878396
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.806521	0.808215	0.813523	0.819230
2	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	0.961375	0.964745	0.975191	0.986392
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.864867	0.867635	0.876353	0.885834
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.806743	0.809287	0.817325	0.826088
3	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	0.961565	0.965637	0.978325	0.992040
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.865018	0.868359	0.878938	0.890547
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.806880	0.809951	0.819705	0.830434
4	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	0.961696	0.966250	0.980491	0.995971
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.865121	0.868855	0.880725	0.893831
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.806975	0.810406	0.821350	0.833464
5	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	0.961791	0.966697	0.982082	0.998875
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.865197	0.869218	0.882038	0.896261
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.807043	0.810739	0.822560	0.835706

Table 7 present the effect of aspect ratio "a/b" on the non-dimensional central deflection "$\bar{w}(a/2,\ b/2)$" of FG-sandwich plate type "B" under thermo mechanical load. The present results are compared with those obtained by FSDT and RPT developed by Li *et al*. (2017). From the table, it can be observed that the present results are smaller than obtained by Li *et al*. (2017) using RPT and FSDT, it can be concluded that the non-dimensional deflection "$\bar{w}$" is in inverse relation with aspect ratio "a/b" and this whatever the thickness ratio.

Table 8 illustrate the variation of the axial stress "$\bar{\sigma}_x(a/2,\ b/2,\ h/2)$" of the FG-sandwich plate type "B" versus the core material index "k" for the various values of layer thickness ratio .The obtained result are compared with those published by Li *et al*. (2017) (without stretching effect). According to the comparison in the Table 7, it can be seen that the stretching effect leads to a reduction of the non-dimensional axial stress "$\bar{\sigma}_x$". It can also be noted that the increasing of the material index "k" leads to a decreasing of the values of normal stress "$\bar{\sigma}_x$".

Table 7 Effect of aspect ratio "a/b" on the non-dimensional deflection "$\bar{w}(a/2, b/2)$" of FG-sandwich plate type "B" under thermo-mechanical load with "a/h = 10" and "k = 1"

Scheme	Theory	$\bar{w}(a/2, b/2)$				
		$a/b = 1$	$a/b = 2$	$a/b = 3$	$a/b = 4$	$a/b = 5$
2-1-2	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	0.961067	0.384421	0.192210	0.113064	0.073927
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.864623	0.345661	0.172678	0.101451	0.066229
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.806521	0.319975	0.157778	0.090968	0.057905
1-1-1	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	0.963305	0.385316	0.192657	0.113328	0.074099
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.866466	0.346369	0.173008	0.101625	0.066327
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.808215	0.320604	0.158051	0.091094	0.057905
1-2-1	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	0.970187	0.388069	0.194034	0.114137	0.074628
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.872221	0.348604	0.174070	0.102204	0.066667
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.813523	0.322612	0.158958	0.091547	0.058184
1-3-1	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	0.977474	0.390984	0.195491	0.114994	0.075189
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.878396	0.351016	0.175228	0.102846	0.067055
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.806232	0.319872	0.157737	0.090954	0.057904

Table 8 Variation of the axial stress "$\bar{\sigma}_x$" of FG-sandwich plate type "B" versus the core material index "k" with "a/h = 10"

k	Theory	$\bar{\sigma}_x(a/2, b/2, h/2)$			
		2-1-2	1-1-1	1-2-1	1-3-1
0	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-4.158732	-4.158732	-4.158732	-4.158732
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2.911440	-2.911440	-2.911440	-2.911440
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.446783	-2.446783	-2.446783	-2.446783
1	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-4.153417	-4.134036	- 4.074434	-4.011326
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2.907015	-2.890699	-2.840040	-2.785860
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.440581	-2.417713	-2.346661	-2.270612
2	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-4.150749	-4.121567	-4.031095	-3.934090
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2.904809	-2.880305	-2.803535	-2.720298
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.437490	-2.403148	-2.295477	-2.178638
3	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-4.149101	-4.113838	-4.003951	-3.885176
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2.903451	-2.873883	-2.780706	-2.678783
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.435588	-2.394150	-2.263468	-2.120395
4	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-4.147973	-4.108535	-3.985199	-3.851130
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2.902523	-2.869484	-2.764940	-2.649867
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.434288	-2.387987	-2.241361	-2.079825
5	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-4.147150	-4.104658	-3.971420	-3.825981
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2.901847	-2.866270	-2.753353	-2.628487
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.433341	-2.383485	-2.225115	-2.049826

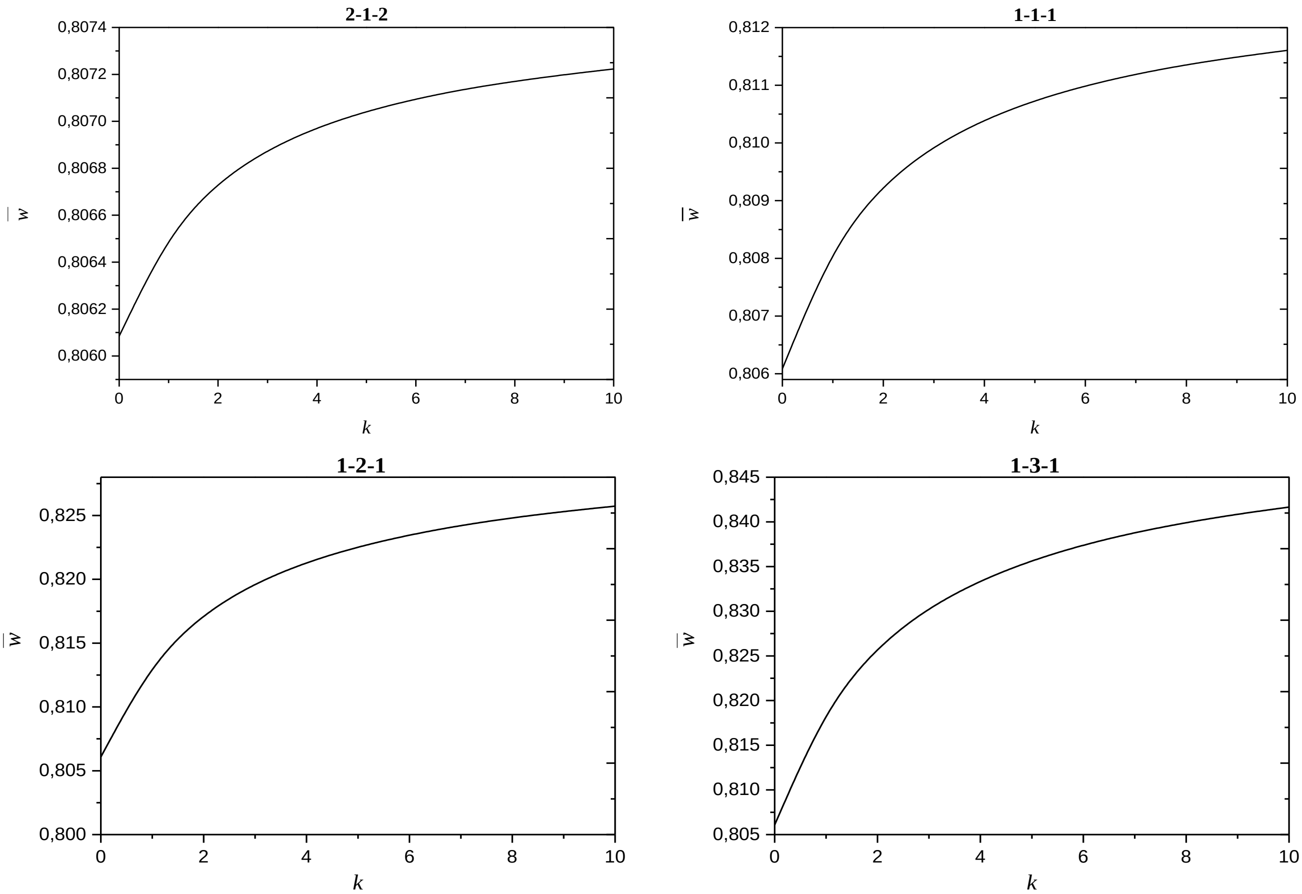

Fig. 2 The variation of the non-dimensional deflection "$\bar{w}$" of symmetric FG-sandwich plate type "B" versus the core material index "k"

The variation of the non-dimensional deflection "$\bar{w}(a/2, b/2)$" of symmetric FG-sandwich plate type "B" versus the core material index "k" is illustrated in Fig. 2.

According to the results, we can see that the increasing of the core material index "k" leads to the increasing of the non-dimensional deflection "$\bar{w}$".

The effects of the thermal loading and the aspect ratio "a/b" on the deflection "$\bar{w}(a/2, b/2)$" are presented in the Fig. 3. The results are for symmetric "1–2–1" and anti-symmetric "2–1–1" FG-sandwich plate type "B" with core material index "$k = 1$". From the plotted graphs, it can be concluded that the deflection "$\bar{w}(a/2, b/2)$" is in inverse relation with the aspect ratio "a/b". For the different thickness ratio "1–2–1" and "2–1–1", the smaller value of deflection "$\bar{w}$" is obtained with zero thermal loads "$t_2 = t_3 = 0$".

The influences of the thermal loading "t_2 and t_3" and side to thickness ratio "a/h" on the central deflection "$\bar{w}(a/2, b/2)$" for symmetric "1–2–1" and anti-symmetric "2–2–1" FG-sandwich plate type "B" are illustrated in the Fig. 4. From the graphs, it can be noted that the deflection "$\bar{w}$" is in direct correlation relation with the side to thickness ratio "a/h" except for only mechanical load q_0 = 100 Pa the relation is inversed , also the increasing of the value of "t_3" leads to the increasing of the deflection "$\bar{w}$".

The distribution of the normal stress "$\bar{\sigma}_x(a/2, b/2, h/2)$" across the thickness "$\bar{z}$" of the symmetric "2–1–2 and 1–2–1" and anti-symmetric "2–2–1 and 2–1–1" FG-sandwich plate type "B" is presented in Fig. 5, the normal stress "$\bar{\sigma}_x$" is plotted for the various values of core material index k = 0, 1, 2, 3 and 4". From the graphs of Fig. 5, it can be concluded that the axial stress "$\bar{\sigma}_x$" is symmetrical about the mean axis "$\bar{z}$" for the "2–1–2 and 1–2–1" FG-sandwich plate and non-symmetrical for the "2–2–1 and 2–1–1" FG-sandwich plate.

C-Thermo-mechanical bending analysis of FG-sandwich plate type "C" with P-FGM face sheets "p ≥ 0" and E-FGM core "k ≥ 0"

The third example, illustrate the thermo-mechanical bending analysis of FG-sandwich plate type "C" with E-FGM core "$k \geq 0$" and P-FGM face sheets "$p \geq 0$". A comparison is made between the current results "$\varepsilon_z \neq 0$" and those obtained with FSDT (five variables, $\varepsilon_z = 0$) and RPT (four variables $\varepsilon_z = 0$) published by Li *et al*. (2017).

The variation of the non-dimensional central deflection "$\bar{w}(a/2, b/2)$" versus face sheets power index "p" is presented in the Table 9. The FG-sandwich plate type "C" is subjected to thermo-mechanical load with side to thickness

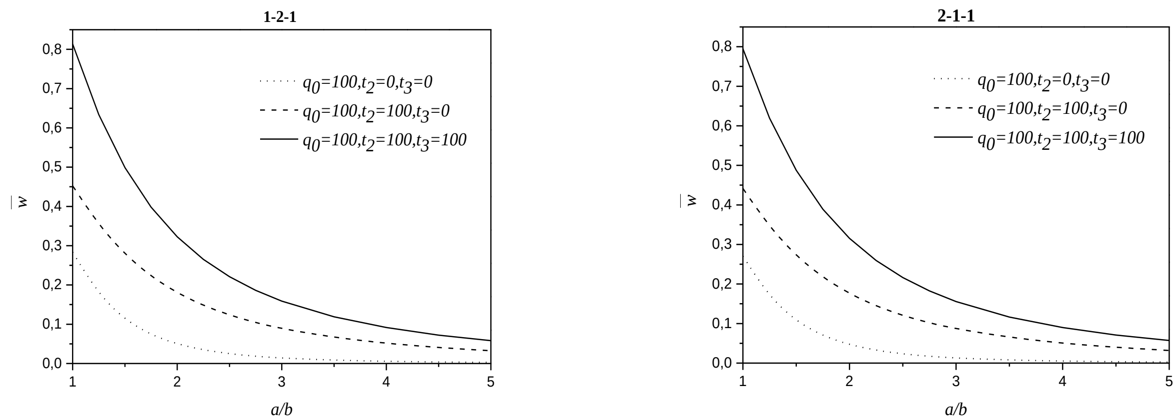

Fig. 3 The effects of the thermal loading and the aspect ratio on the non-dimensional deflection "$\bar{w}(a/2, b/2)$" of the symmetric and anti-symmetric FG-sandwich plate Type "B" with "$p = 0$" and "$k = 1$"

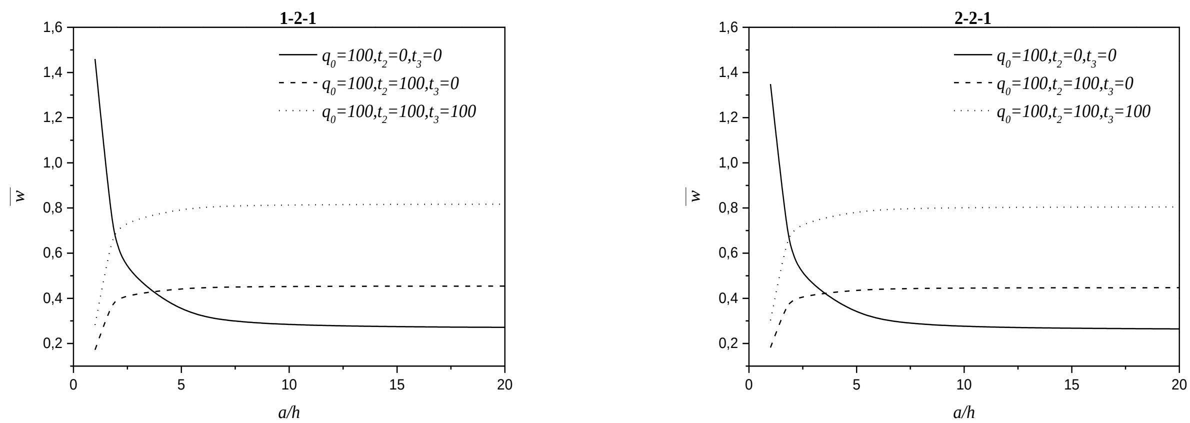

Fig. 4 Effect of the thermal loading "t_2, t_3" and the geometric ratio "a/h" on the center deflection "$\bar{w}(a/2, b/2)$" with "$p = 0$" and "$k = 1$"

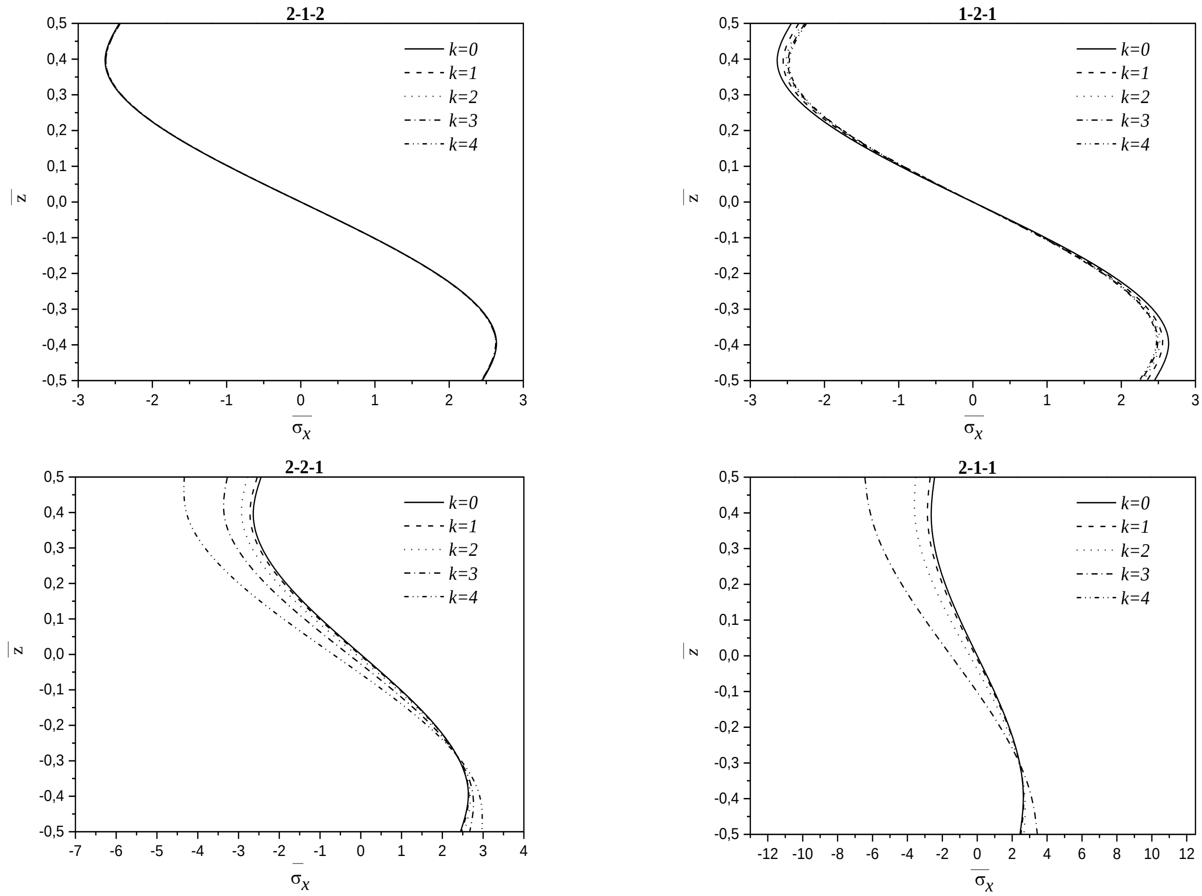

Fig. 5 The distribution of the normal stress "$\bar{\sigma}_x$" across the thickness "$\bar{z}$" of the FG-sandwich plate "B" with " p = 0"

Table 9 Variation of the non-dimensional central deflection "$\bar{w}(a/2, b/2)$" of the FG-sandwich plate type "C" versus the power index "p" with "a/h = 10" and "k = 1"

p	Theory	$\bar{w}(a/2, b/2)$			
		2-1-2	1-1-1	1-2-1	1-3-1
0	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	0.961067	0.963305	0.970187	0.977474
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	0.864623	0.866466	0.872221	0.878396
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	0.806521	0.808215	0.813523	0.819230
1	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	1.242779	1.217361	1.180797	1.156699
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.121862	1.098934	1.065520	1.043229
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.046907	1.025543	0.994357	0.973513
2	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	1.313230	1.284594	1.238612	1.206011
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.185157	1.159800	1.118459	1.088746
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.105907	1.082325	1.043808	1.016073
3	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	1.341711	1.313791	1.265222	1.229142
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.210108	1.185685	1.142459	1.109859
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.129112	1.106426	1.066195	1.035791
4	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	1.355934	1.329367	1.280204	1.242418
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.222339	1.199282	1.155813	1.121864
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.140467	1.119067	1.078638	1.046995
5	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	1.364062	1.338795	1.289699	1.250973
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.229235	1.207420	1.164203	1.129545
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.146860	1.126626	1.086449	1.054159

Table 10 Effect of aspect ratio "a/b"on dimensionless center deflection "$\overline{w}(a/2, b/2)$" of the FG-sandwich plate type "C" under thermo-mechanical load (a/h = 10, k = 1 and p = 3)

Scheme	Theory	$\overline{w}(a/2, b/2)$				
		a/b = 1	a/b = 2	a/b = 3	a/b = 4	a/b = 5
2-1-2	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	1.341711	0.536675	0.268336	0.157844	0.103206
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.210108	0.484045	0.242031	0.142378	0.093100
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.129112	0.448404	0.221486	0.128022	0.081774
1-1-1	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	1.313791	0.525507	0.262752	0.154560	0.101058
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.185685	0.474370	0.237271	0.139642	0.091364
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.106426	0.439544	0.217231	0.125662	0.080349
1-2-1	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	1.265222	0.506080	0.253039	0.148846	0.097322
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.142459	0.457190	0.228773	0.134719	0.088208
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.066195	0.423731	0.209556	0.121336	0.077676
1-3-1	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	1.229142	0.491649	0.245823	0.144601	0.094547
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	1.109859	0.444182	0.222295	0.130929	0.085748
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	1.035791	0.411695	0.203643	0.117944	0.075531

Table 11 Variation of the normal stress "$\bar{\sigma}_x$"of the FG-sandwich plate type "C" versus the core material index "k" under thermo-mechanical load with "a/h = 10"

p	Theory	$\bar{\sigma}_x(a/2, b/2, h/2)$			
		1-0-1	3-1-3	2-1-2	1-1-1
0	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-4.153417	-4.134036	-4.074434	-4.011326
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2.907015	-2.890699	-2.840040	-2.785860
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.446783	-2.444543	-2.440581	-2.417712
1	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-4.136946	-4.261501	-4.440672	-4.558762
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-3.025929	-3.138583	-3.302462	-3.411521
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.716951	-2.844923	-2.905056	-3.063748
2	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-3.791718	-3.932040	-4.157364	-4.317119
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2.715313	-2.840096	-3.043204	-3.188866
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.290281	-2.406671	-2.467487	-2.643040
3	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-3.652156	-3.788971	-4.026970	-4.203773
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2.592638	-2.712947	-2.925506	-3.085463
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.145598	-2.240479	-2.294927	-2.464046
4	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-3.582456	-3.712645	-3.953554	-4.138716
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2.532421	-2.646085	-2.859957	-3.026620
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.084230	-2.161916	-2.210316	-2.370007
5	Li *et al*. 2017 (FSDOT, $\varepsilon_z = 0$)	-3.542632	-3.666444	-3.907027	-4.096793
	Li *et al*. 2017 (RPT, $\varepsilon_z = 0$)	-2.498436	-2.606029	-2.818750	-2.988949
	Present (Quasi-3D, $\varepsilon_z \neq 0$)	-2.054012	-2.119047	-2.162601	-2.313708

ratio "a/h = 10" and the core material index "k = 1". The computed results using a quasi-3D shear deformation theory are compared with those obtained by Li *et al*. (2017) using FSDT and RPT with "ε_z = 0". From the table, it can be remarked that the central deflection "$\overline{w}$" of The FG-sandwich plate type "C" increase with increasing of the face sheets power index "p". It can also be concluded that the most rigid plate has a layer thickness ratio "1– 3–1".

Table 10 show the effect of aspect ratio "a/b" on dimensionless central deflection "$\overline{w}(a/2, b/2)$" of FG-sandwich plate type "C" under combined load (thermal and mechanical) with geometry ratio "a/h = 10", core material index "k = 1" and face sheet power index "p = 3". According to the table, it can be noted that the present results is smaller than those obtained using FSDT and RPT (Li *et al*. 2017) and this is due to the stretching effect. It can also be observed that the increasing of the aspect ratio "a/b"

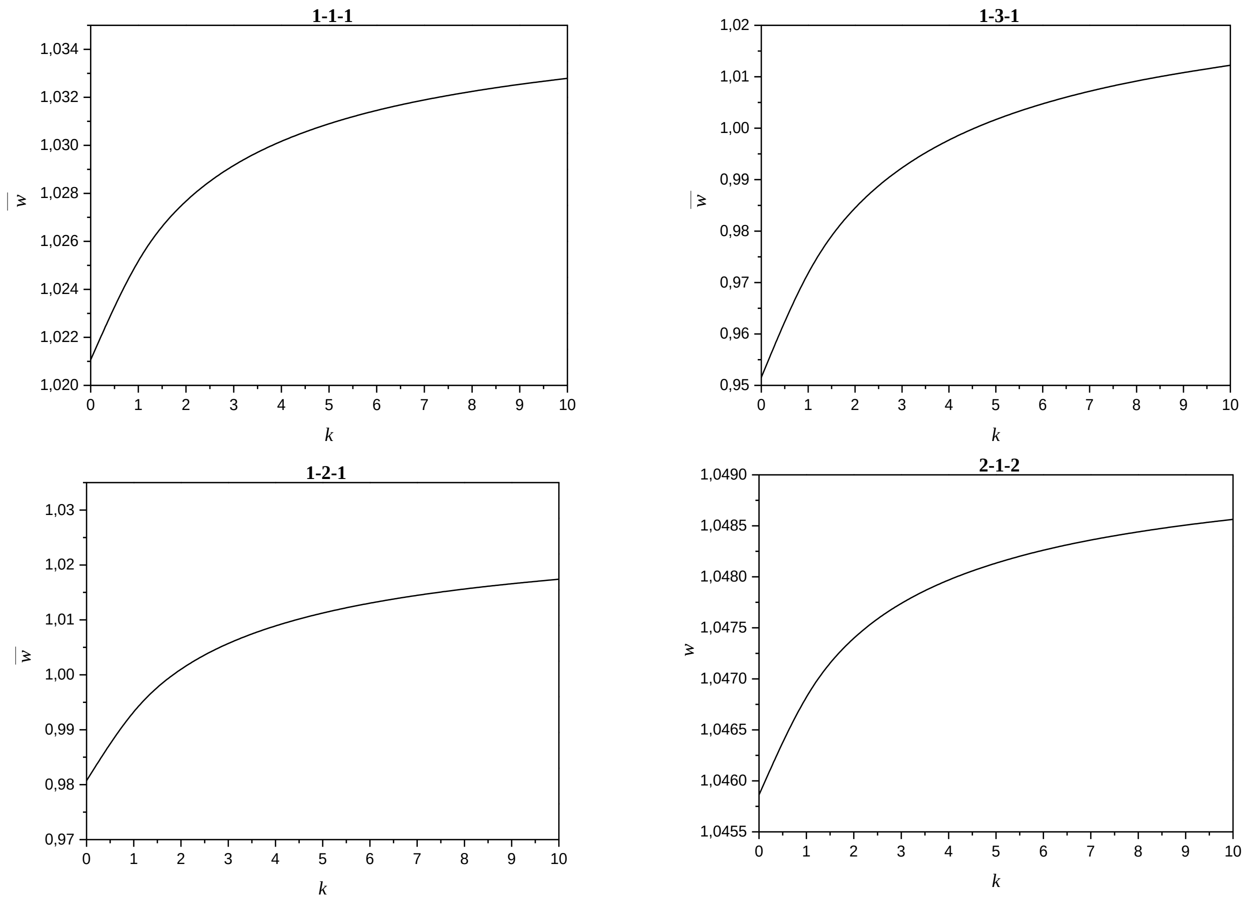

Fig. 6 Effect of the core power index "k"on the dimensionless central deflection "$\overline{w}$"of FG- sandwich plates "Type C" with "p = 1"

leads to the decreasing of the dimensionless central deflection "$\overline{w}(a/2,\ b/2)$" of the FG-sandwich plate.

Table 11 shows the values of the dimensionless normal stress "$\bar{\sigma}_x(a/2,\ b/2,\ h/2)$" of FG-sandwich plate type "C" versus power index "p". For the different layers thickness ratio, it can be seen that the dimensionless normal stress "$\bar{\sigma}_x$" is in inverse relation with power index "p" for "$p \geq 1$". The same conclusions are noted for the different layers thickness ratio "1–0–1, 3–1–3, 2–1–2 and 1–1–1".

Fig. 6 present the effect of the core power index "k" on the dimensionless central deflection "$\overline{w}(a/2,\ b/2)$" of the FG-sandwich plate type "C". The deflection "$\overline{w}$" is computed by for the different layers thickness ratio using the present quasi-3D shear deformation theory. From the plotted graphs, it can be noted that the increasing of the core material index "k" leads to the increasing of dimensionless central deflection "$\overline{w}$" and that for the different layer thickness ratios.

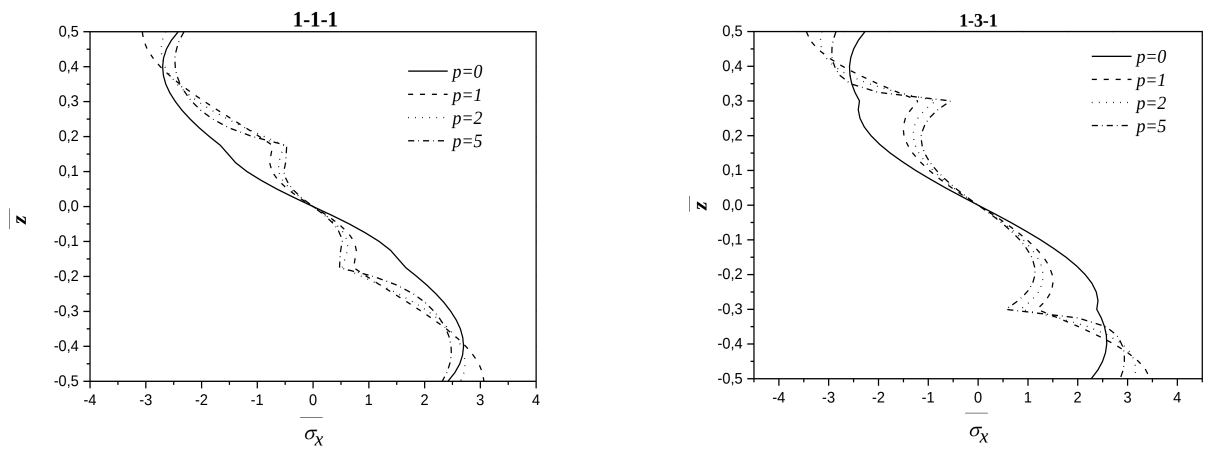

Fig. 7 The distribution of the normal stress "$\bar{\sigma}_x$"across the thickness "$\bar{z}$"of the FG-sandwich plate type "C" as function of the face sheet power index "p" with core material index "k = 1"

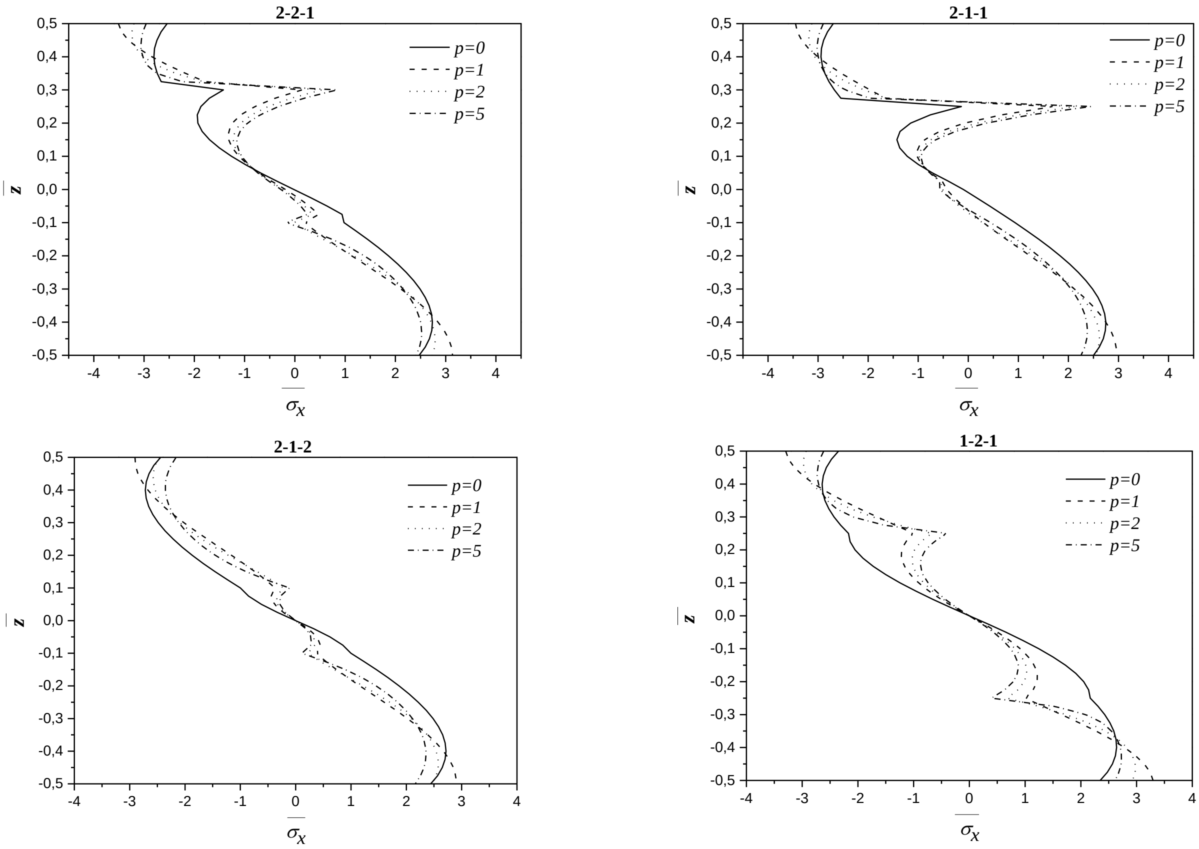

Fig. 7 Continued

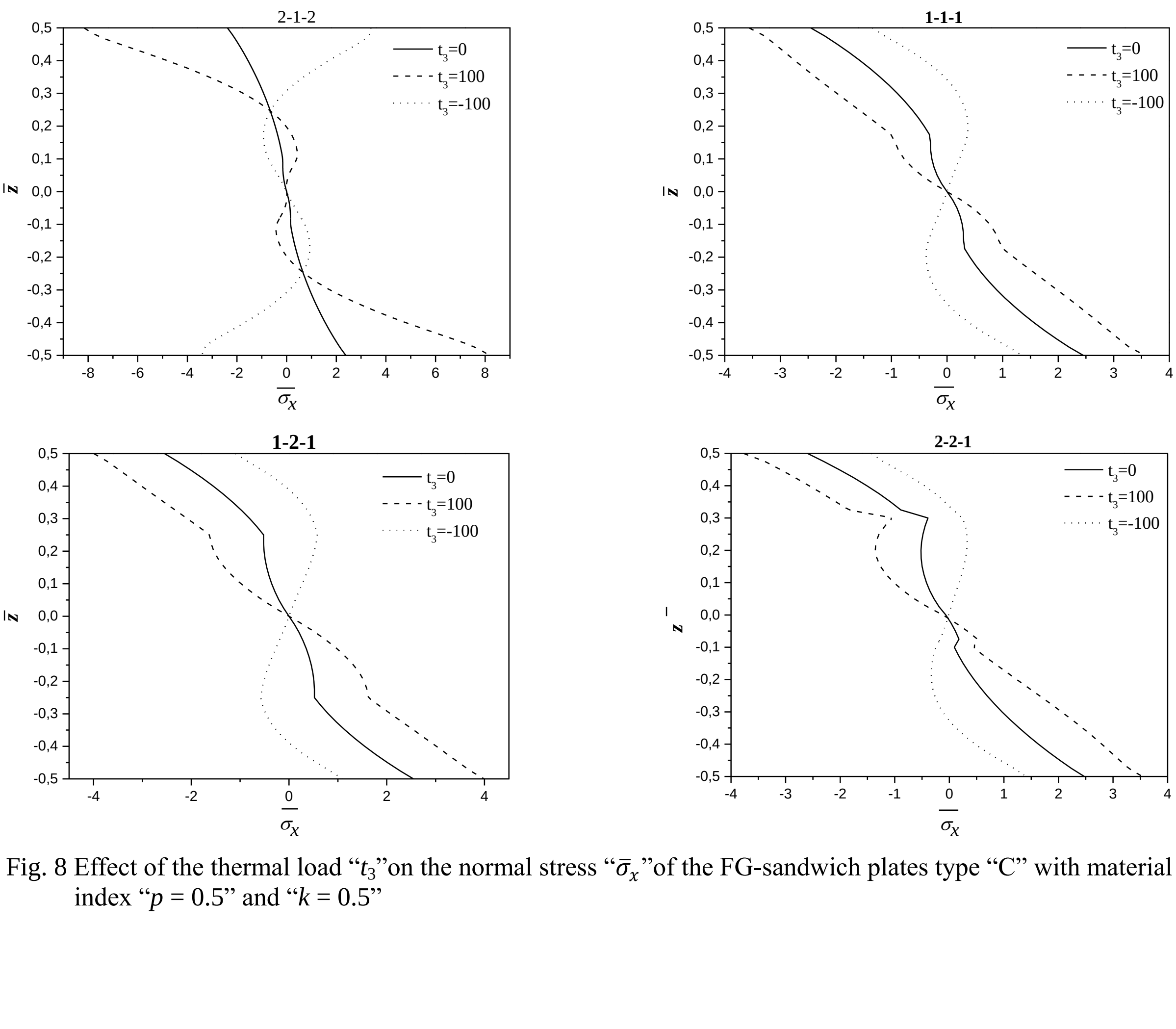

Fig. 8 Effect of the thermal load “t_3”on the normal stress “$\bar{\sigma}_x$”of the FG-sandwich plates type “C” with material index “p = 0.5” and “k = 0.5”

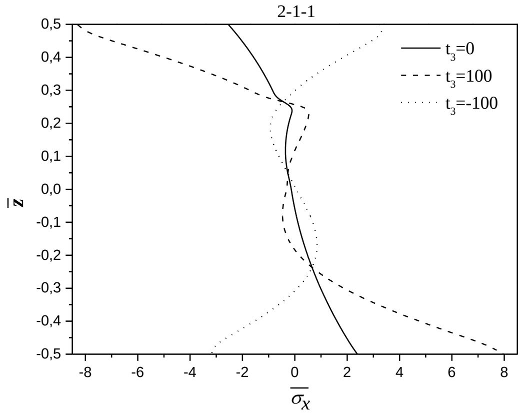

Fig. 8 Continued

Fig. 7 plots the distribution of the normal stress “$\bar{\sigma}_x$” through the thickness “$\bar{z}$” of the symmetric and anti-symmetric FG-sandwich plate type “C” as function of the face sheet power index “p” with core material index “k = 1”, From the plotted graphs, it can be seen that the distribution of the normal stress “$\bar{\sigma}_x$” is nonlinear across the thickness of the FG-sandwich plate, it can also be observed that the normal stress “$\bar{\sigma}_x$” is symmetrical about the mean axis “z = 0” for the symmetric FG-sandwich plate “1–1–1, 1–3–1 and 2–1–2” and non-symmetrical for the plate “2–2–1 and 2–1–1”.

Fig. 8 plots the distribution of the normal stress “$\bar{\sigma}_x$” across the thickness of the symmetric and anti-symmetric FG-sandwich plate type “C” as function of thermal load “t_3” with material index “p = 0.5” and “k = 0.5”. From this results, it can be noted that the thermal load “t_3” has a significant influence on the axial stress “$\bar{\sigma}_x$”. It can also be concluded that the distribution of sigma has a symmetric variation about the mean axis only for symmetric plate “2–1–2, 1–1–1 and 1–2–1 “.

5. Conclusions

In this research, the thermo-mechanical bending analysis of FG-sandwich plate is investigated using a simple quasi-3D shear deformation theory. The displacement field defined by introducing the stretching effect using only five variables as the FSDT (first shear deformation theory. The governing equations were derived by utilizing the virtual work principle and solved via Navier solution. A variety of results are presented to show the accuracy and the efficiency of the present theory. From the results, it can be concluded that the stretching effect, geometry ratio “a/h”, aspect ratio “a/b”, layer thickness ratio and core and faces sheets material index “p and k” have a significant effect on the non-dimensional and normal stress of FG-sandwich plate. An improvement of present formulation will be considered in the future work to consider other type of materials (Panjehpour *et al*. 2013, Panjehpour 2014, Mahi *et al*. 2015, Larbi Chaht *et al*. 2015, Draiche *et al*. 2016, Bouafia *et al*. 2017, Klouche *et al*. 2017, Mouffoki *et al*. 2017, Chikh *et al*. 2017, Karami *et al*. 2017, Bakhadda *et al*. 2018, Kaci *et al*. 2018, Mokhtar *et al*. 2018, Yazid *et al*. 2018, Panjehpour *et al*. 2018, Karami *et al*. 2018b, c, d, e, 2019a, b, c, Youcef *et al*. 2018, Zine *et al*. 2018, Bouadi *et al*. 2018, Kadari *et al*. 2018, Draoui *et al*. 2019, Semmah *et al*. 2019).

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