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A simple nth-order shear deformation theory for thermomechanical bending analysis of different configurations of FG sandwich plates

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Abstract. In this work, thermomechanical flexural analysis of functionally graded material sandwich plates with P-FGM face sheets and E-FGM and symmetric S-FGM core is performed by employing a nth-order shear deformation theory. A novel type of S-FGM sandwich plates, namely, both P-FGM face sheets and a symmetric S-FGM hard core are considered. By employing only four unknown variables, the governing equations are obtained based on the principle of virtual work and then Navier method is used to solve these equations. Analytical solutions are deduced to compute the stresses and deflections of simply supported S-FGM sandwich plates. The effects of volume fraction variation, geometrical parameters and thermal load on thermomechanical flexural behavior of the symmetric FGM sandwich plates are investigated.

Keywords: sandwich plate; thermomechanical; analytical modeling; functionally graded material

1. Introduction

Sandwich structures, because of their low weight and high rigidity as well as their capability of energy absorption, have been widely employed in industries of aircraft, aerospace, construction, naval/marine, transportation, and wind energy systems (Vinson 2001, 2005, Lindström and Hallström 2010, Dean *et al*. 2011, Sekkal *et al*. 2017a). We can find several kinds of sandwich structures. The most often utilized one is the sandwich structure with homogeneous core and homogeneous face sheets (Librescu and Hause 2000). With the discovery of new advanced materials, functionally graded material (FGM) is currently being employed in design of structures (Benferhat *et al*. 2016, Aldousari 2017, Ebrahimi and Daman 2017, Zidi *et al*. 2017, Hachemi *et al*. 2017, Lal *et al*. 2017, Avcar and Mohammed 2018, Attia *et al*. 2018, Rezaiee-Pajand *et al*. 2018, Selmi and Bisharat 2018, Belabed *et al*. 2018, Bensaid *et al*. 2018, Soliman *et al*. 2018, Fourn *et al*. 2018, Akbas 2018, Faleh *et al*. 2018, Avcar 2019, Addou *et al*. 2019, Hellal *et al*. 2019, Karami and Shahsavari 2019). Two novel kinds of sandwich structures with FGM face sheets and homogeneous core (Shen and Li 2008, Sobhy 2013, Ahmed 2014, Taibi *et al*. 2015, Mahi *et al*. 2015, Fazzolari 2015, Bouderba *et al*. 2016, Menasria *et al*. 2017, El-Haina *et al*. 2017) or with homogeneous face sheets and FGM core (Kashtalyan and Menshykova 2009, Alibeigloo and Liew 2014, Swaminathan *et al*. 2015, Liu *et al*. 2016) have been considered and studied. Thus, the thermal, mechanical, and thermo-mechanical responses of functionally graded (FG) sandwich structures have gained considerable attention by many scientists.

For the mechanical flexural and dynamic behaviors of FG sandwich plates, Bessaim *et al*. (2013) utilized a hyperbolic shear deformation model to investigate the dynamic and bending of a simply supported sandwich plate with homogeneous ceramic core and FG face sheets. By using a two-step perturbation method, Wang and Shen (2011) presented a nonlinear static investigation of a sandwich plate containing FGM face sheets. Neves *et al*. (2012) developed a distribution of Murakami's Zig-Zag model to present the bending study of two kinds of FG sandwich plates, including the thickness stretching influence. Natarajan and Manickam (2012) proposed a QUAD-8 shear flexible element based on higher order theory to investigate the bending and dynamic of two kinds of FG sandwich plates. By developing a thickness-stretching higher-order shear deformation model, Neves *et al*. (2013) studied the bending, dynamic, and stability analysis of two kinds of FG sandwich plates. Li *et al*. (2016) discussed the thermo-mechanical bending responses of two kinds of FG sandwich plates via four-variable refined plate theory. Li *et al*. (2017) examined also the thermo-mechanical bending behavior of sandwich plates with both FG face sheets and FG core. Nguyen *et al*. (2016) investigated the flexural and dynamic response of two kinds

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of isotropic FG sandwich plates by employing an edge-based MITC3 finite element. Akavci (2016) utilized a novel hyperbolic normal and shear deformation plate model to examine the bending, dynamic and stability responses of FG sandwich plates supported by elastic foundation. Akavci and Tanrikulu (2015) presented bending and free vibration analysis of FG plates based on a new quasi-3D and 2D shear deformation theories. Meziane *et al*. (2014) presented an efficient and simple plate theory to investigate the stability and dynamic behavior of exponentially graded sandwich plates under various boundary conditions. By developing a simple four variable refined plate model, Bellifa *et al*. (2017a) examined the buckling response of FG plates. It should be indicated that in the open literature, we can find a number of advanced structural theories to investigate bending, buckling and dynamic behavior of FG structures (Bouderba *et al*. 2013, Zidi *et al*. 2014, Zemri *et al*. 2015, Belkorissat *et al*. 2015, Yahia *et al*. 2015, Attia *et al*. 2015, Al-Basyouni *et al*. 2015, Houari *et al*. 2016, Bellifa *et al*. 2016, Bounouara *et al*. 2016, Boukhari *et al*. 2016, Saidi *et al*. 2016, Beldjelili *et al*. 2016, Kar *et al*. 2017, Abdelaziz *et al*. 2017, Benadouda *et al*. 2017, Kolahchi *et al*. 2017, Meftah *et al*. 2017, Chaabane *et al*. 2019, Bourada *et al*. 2019). The thermoelastic and mechanical bending responses of FG sandwich plates has been studied mathematically by a number of scientists. Tounsi *et al*. (2013) investigated the thermoelastic bending response of sandwich plates with FG core and isotropic homogeneous face sheets using a refined trigonometric shear deformation model. By employing a novel plate theory, Houari *et al*. (2013) studied the thermoelastic static of sandwich plates with isotropic homogeneous core and FG face sheets. Mehar and Panda (2017) examined the thermoelastic nonlinear frequency analysis of CNT reinforced functionally graded sandwich structure. Taibi *et al*. (2015) discussed the thermo-mechanical deformation response of FG sandwich plates resting on a two-parameter elastic foundation. Li *et al*. (2016) studied the thermo-mechanical bending of two kinds of FG sandwich plates using a four-variable refined plate theory.

From the literature review, it is observed that most of the studied FG sandwich plates didn't take both FG core and FG face sheets. Generally in practice, the core and the face sheets of a sandwich plate may all present functionally graded material characteristics. Thus, this type of FG sandwich structure needs to be further studied.

The aim of this article is to extend a refined nth-order shear deformation theory to examine the thermo-mechanical flexural behavior of a novel kind of FG sandwich plate which consists of FG face sheets and E-FGM and symmetric S-FG core. By considering both the principle of virtual work and Navier procedure, the governing equations of the present formulation are obtained. The unknown variables used in the equilibrium equations are only in number of four. Comparative discussions are conducted to check the efficiency and precision of the present model. The stresses and deformations of sandwich plates with FG core and FG face sheets or with FG core and homogeneous face sheets are examined and presented with considering also the case of FG face sheets and S-FG core. The influences of thermal force and other type of parameters on the thermo-mechanical flexural response of the FG sandwich plates are investigated.

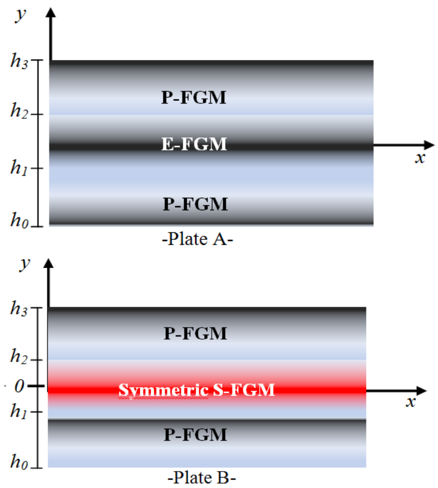

Fig. 1 Sandwich plate with FGM face sheets and FGM core

2. Theoretical formulation

2.1 Kinematics and strains

In this work, a rectangular FG sandwich plate has dimensions $(axbxh)$ such as "a" is length, "b" width and "h" thickness is considered. two types of the plates are proposed, "plate A" has P-FGM face sheets and E-FGM core and "plate B" has P-FGM face sheets and symmetric S-FGM core as shown in Fig. 1, The mid-plane of the FGM sandwich plate is defined by z = 0 and its free surfaces being defined by (the bottom surface, $h_0 = -h/2$) and (the top surface, $h_3 = +h/2$), the two interfaces between the core and faces sheets (h_1, h_2) vary according to the configuration of the plate as:

- The (1-0-1) FGM sandwich plate: $h_1 = 0, h_2 = 0$.
- The (1-2-1) FGM sandwich plate: $h_1 = -h/4$, $h_2 = h/4$.
- The (1-1-1) FGM sandwich plate: $h_1 = -h/6$, $h_2 = h/6$.
- The (1-3-1) FGM sandwich plate: $h_1 = -3h/10$, $h_2 = 3h/10$.
- The (2-1-2) FGM sandwich plate: $h_1 = -h/10$, $h_2 = h/10$.
- The (3-1-3) FGM sandwich plate: $h_1 = -h/14$, $h_2 = h/14$.

In this current investigation, the studied plate is under a thermal load varying through the thickness and a transverse mechanical load applied at the top surface.

2.2 Material properties of the FG face sheets

In the two type of plate the top face sheet varies from alumine-rich surface$(z = h_2)$ to a metal-rich surface $(z =$

h_3) and the bottom face sheet varies from a metal-rich surface ($z = h_0$) to a ceramic-rich surface ($z = h_1$). The volume fraction of the top and the bottom face sheets is varies as Power-law function (Bourada *et al*. 2012, Houari *et al*. 2013, Kettaf *et al*. 2013, Mantari and Monge 2016) can be given as

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

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

Where $V^{(1)}, V^{(3)}$ the volume fractions of bottom and top layers are, respectively, p is a material index of the faces sheets with ($p \geq 0$).

The effective material properties for top and bottom layers, like Young's modulus $E^{(n)}$, Poisson's ratio $\mu^{(n)}$and thermal expansion coefficient $\alpha^{(n)}$, given by (Zenkour and Alghamdi 2010a, Houari *et al*. 2011, Bessaim *et al*. 2013, Bennoun *et al*. 2016) can be expressed as

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

Where index m and c represent metal and ceramic respectively.

2.3 Material properties of the sandwich core

The volume fraction of the sandwich core (plate A) is given as

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

($k \geq 0$) is a material index of the sandwich core (plate A).The FGM core of plate "A" has the effective material properties vary exponentially along the thickness of the layer (Asnafi and Abedi 2015, Li *et al*. 2017)

$$P^{(2)}(z) = P_m\, exp\ (\beta V^{(2)}) \quad (4a)$$

With

$$\beta = ln \frac{P_c}{P_m} \quad (4b)$$

The volume fraction of the Symmetric S-FGM sandwich core (plate B) is given as

$$V_m(z) = \begin{cases} \left(\dfrac{2z + h_1}{h_1}\right)^k & \text{for} \quad z \in [h_1, 0] \\ \left(\dfrac{-2z + h_2}{h_2}\right)^k & \text{for} \quad z \in [0, h_2] \end{cases} : V_c(z) = 1 - V_m(z) \quad (5)$$

($k \geq 0$) is a material index of the symmetric S-FGM sandwich core (plate B).

The FGM core of plate "B" has the effective material properties vary symmetrically along the thickness of the layer

Table 1 Material properties of Metal and Ceramic

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

$$P^{(2)}(z) = P_c V_C(z) + P_m V_M(z) \quad (6)$$

The material properties used in this research are presented in Table 1.

2.4 Conventional higher-order plate theory

The displacements field of classical higher order shear deformation theory can be expressed as

$$u(x, y, z) = u_0(x, y) - z\frac{\partial w_0(x, y)}{\partial x} + \psi(z)\theta_x(x, y) \quad (7a)$$

$$v(x, y, z) = v_0(x, y) - z\frac{\partial w_0(x, y)}{\partial y} + \psi(z)\theta_y(x, y) \quad (7b)$$

$$w(x, y, z) = w_0(x, y) \quad (7c)$$

where u_0 ; v_0 ; w_0 , ϕ_x , ϕ_y are five unknown displacements of the mid-plane of the plate, $\psi(z)$ denotes warping function.

2.5 A novel four-variables refined plate theory

By supposing that 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 kinematic of the present four variables refined theory can be found in a simpler form (Bourada *et al*. 2016, Chikh *et al*. 2017, Ait Sidhoum *et al*. 2017, Fahsi *et al*. 2017, Khetir *et al*. 2017, Elmossouess *et al*. 2017) as

$$u(x, y, z) = u_0(x, y) - z\frac{\partial w_0}{\partial x} + k_1 f(z)\int \theta(x, y)\, dx \quad (8a)$$

$$v(x, y, z) = v_0(x, y) - z\frac{\partial w_0}{\partial y} + k_2 f(z)\int \theta(x, y)\, dy \quad (8b)$$

$$w(x, y, z) = w_0(x, y) \quad (8c)$$

In this study, the proposed n-order shear deformation plate theory is determined by considering the shape function as

$$f(z) = z - \frac{1}{n}\left(\frac{2}{h}\right)^{n-1} z^n, \quad n = (3{,}5{,}7{,}9\ldots\ldots) \quad (9)$$

The non-zero strain expressions derived from Eq. (8) are as follows

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + z\begin{Bmatrix} k_x^b \\ k_y^b \\ k_{xy}^b \end{Bmatrix} + f(z)\begin{Bmatrix} k_x^s \\ k_y^s \\ k_{xy}^s \end{Bmatrix}, \quad (10)$$

$$\begin{Bmatrix}\gamma_{yz}\\ \gamma_{xz}\end{Bmatrix} = g(z)\begin{Bmatrix}\gamma_{yz}^0\\ \gamma_{xz}^0\end{Bmatrix},\quad \varepsilon_z = 0 \tag{10}$$

where

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

$$\begin{Bmatrix}k_x^s\\ k_y^s\\ k_{xy}^s\end{Bmatrix} = \begin{Bmatrix}k_1\theta\\ k_2\theta\\ k_1\dfrac{\partial}{\partial y}\int\theta\, dx + k_2\dfrac{\partial}{\partial x}\int\theta\, dy\end{Bmatrix}, \tag{11}$$

$$\begin{Bmatrix}\gamma_{yz}^0\\ \gamma_{xz}^0\end{Bmatrix} = \begin{Bmatrix}k_2\int\theta\, dy\\ k_1\int\theta\, dx\end{Bmatrix}$$

and

$$g(z) = \frac{df(z)}{dz} \tag{12}$$

The integrals used in the expressions of Eqs. (8), (11) shall be resolved by a Navier procedure method and can be obtained as follows

$$\frac{\partial}{\partial y}\int\theta dx = A'\frac{\partial^2\theta}{\partial x\partial y},\quad \frac{\partial}{\partial x}\int\theta dy = B'\frac{\partial^2\theta}{\partial x\partial y},$$
$$\int\theta dx = A'\frac{\partial\theta}{\partial x},\qquad \int\theta dy = B'\frac{\partial\theta}{\partial y} \tag{13}$$

Where the coefficients A' and B' are defined using the Navier method and can be expressed as follows

$$A' = -\frac{1}{\lambda^2},\quad B' = -\frac{1}{\mu^2},\quad k_1 = \lambda^2,\quad k_2 = \mu^2 \tag{14}$$

Where λ and μ are defined in expression (30).

2.6 Constitutive equations

The stress-strain relation of the n^{th} layer of the functionally graded sandwich plate can be expressed as

$$\begin{Bmatrix}\sigma_x\\ \sigma_y\\ \tau_{xy}\\ \tau_{yz}\\ \tau_{xz}\end{Bmatrix}^{(n)} = \begin{bmatrix}c_{11} & c_{12} & 0 & 0 & 0\\ c_{12} & c_{22} & 0 & 0 & 0\\ 0 & 0 & c_{66} & 0 & 0\\ 0 & 0 & 0 & c_{44} & 0\\ 0 & 0 & 0 & 0 & c_{55}\end{bmatrix}^{(n)}\begin{Bmatrix}\varepsilon_x-\alpha T\\ \varepsilon_y-\alpha T\\ \gamma_{xy}\\ \gamma_{yz}\\ \gamma_{xz}\end{Bmatrix}^{(n)}, \tag{15}$$
$$(n = 1,2,3.....)$$

Where $(\sigma_x,\sigma_y,\tau_{xy},\tau_{yz},\tau_{xz})$ are the stresses and $(\varepsilon_x,\varepsilon_y,\gamma_{xy},\gamma_{yz},\gamma_{xz})$ are the strains components.

The stiffness coefficients $c_{ij}^{(n)}$ are given by the expressions

$$c_{11}^{(n)} = c_{22}^{(n)} = \frac{E^{(n)}(z)}{1-(\mu^{(n)})^2},\, c_{12}^{(n)} = \mu^{(n)}c_{11}^{(n)} \tag{16a}$$

$$c_{44}^{(n)} = c_{55}^{(n)} = c_{66}^{(n)} = \frac{E^{(n)}(z)}{2(1+\mu^{(n)})} \tag{16b}$$

2.7 Governing equations

The total potential energy of the functionally graded sandwich plate for the thermo mechanical bending problem is obtained using the Virtual Work principle as follows (Bousahla *et al*. 2016, Klouche *et al*. 2017, Bourada *et al*. 2018, Zine *et al*. 2018, Mokhtar *et al*. 2018, Yazid *et al*. 2018, Tounsi *et al*. 2019, Draiche *et al*. 2019, Meksi *et al*. 2019)

$$U = \frac{1}{2}\int_V\begin{bmatrix}\sigma_x^{(n)}(\varepsilon_x-\alpha T)^{(n)} + \sigma_y^{(n)}(\varepsilon_y-\alpha T)^{(n)} +\\ \tau_{xy}^{(n)}\gamma_{xy}^{(n)} + \tau_{yz}^{(n)}\gamma_{yz}^{(n)} + \tau_{xz}^{(n)}\gamma_{xz}^{(n)}\end{bmatrix}dV \tag{17}$$

The principle of virtual work can be rewritten as

$$\int_\Omega\begin{bmatrix}N_x\delta\,\varepsilon_x^0 + N_y\delta\,\varepsilon_y^0 + N_{xy}\delta\,\gamma_{xy}^0 + M_x^b\delta\,k_x^b +\\ M_y^b\delta\,k_y^b + M_{xy}^b\delta\,k_{xy}^b + M_x^s\delta\,k_x^s + M_y^s\delta\,k_y^s +\\ M_{xy}^s\delta\,k_{xy}^s + Q_{yz}^s\delta\,\gamma_{yz}^s + Q_{xz}^s\delta\,\gamma_{xz}^s\end{bmatrix}d\Omega$$
$$-\int_\Omega q\delta w_0 d\Omega = 0 \tag{18}$$

with

$$\left(N_i, M_i^b, M_i^s\right) = \sum_{n=1}^{3}\int_{h_{n-1}}^{h_n}\left(1,z,f(z)\right)\sigma_i^{(n)}dz,$$
$$(i = x,y,xy)\quad \textbf{and} \tag{19}$$
$$\left(Q_{xz}^s, Q_{yz}^s\right) = \sum_{n=1}^{3}\int_{h_{n-1}}^{h_n}g(z)\left(\tau_{yz},\tau_{xz}\right)^{(n)}dz$$

where N, M and Q are the stress resultants, h_n and h_{n-1} are the top and bottom z-coordinates of the n^{th} layer.

By substituting Eq. (11) into Eq. (18).Integrating the resulting equation by parts and then collecting the coefficients (δu_0, δv_0, δw_0, $\delta\theta$), the following governing equations can be derived

$$\delta\, u_0:\quad \frac{\partial N_x}{\partial x} + \frac{\partial N_{xy}}{\partial y} = 0$$
$$\delta\, v_0:\quad \frac{\partial N_{xy}}{\partial x} + \frac{\partial N_y}{\partial y} = 0$$
$$\delta\, w_0:\quad \frac{\partial^2 M_x^b}{\partial x^2} + 2\frac{\partial^2 M_{xy}^b}{\partial x\partial y} + \frac{\partial^2 M_y^b}{\partial y^2} + q = 0 \tag{20}$$
$$\delta\,\theta:\quad -k_1 M_x^s - k_2 M_y^s - (k_1A' + k_2B')\frac{\partial^2 M_{xy}^s}{\partial x\partial y}$$
$$+k_1A'\frac{\partial S_{xz}^s}{\partial x} + k_2B'\frac{\partial S_{yz}^s}{\partial y} = 0$$

Replacing the Eqs. (10) and (15) int Eq. (19), the moment M and stress N resultants can be obtained as

$$\begin{Bmatrix}\{N\}\\\{M^b\}\\\{M^s\}\end{Bmatrix}=\begin{bmatrix}[A] & [B] & [C]\\ [B] & [D] & [F]\\ [C] & [F] & [H]\end{bmatrix}\begin{Bmatrix}\{\varepsilon^0\}\\\{k^b\}\\\{k^s\}\end{Bmatrix}-\begin{Bmatrix}\{N^T\}\\\{M^{bT}\}\\\{M^{sT}\}\end{Bmatrix}, \quad (21)$$
$$\begin{Bmatrix}Q^s_{yz}\\Q^s_{xz}\end{Bmatrix}=\begin{bmatrix}J_{44} & 0\\ 0 & J_{55}\end{bmatrix}\begin{Bmatrix}\gamma_{yz}\\\gamma_{xz}\end{Bmatrix}$$

Where

$$\{N\}=\{N_xN_yN_{xy}\}^T,\quad \{M^b\}=\{M^b_xM^b_yM^b_{xy}\}^T,\quad \{M^s\}=\{M^s_xM^s_yM^s_{xy}\}^T, \quad (22a)$$

$$N=\{N^T_xN^T_y0\}^T,\quad \{M^{bT}\}=\{M^{bT}_xM^{bT}_y0\}^T,\quad \{M^{sT}\}=\{M^{sT}_xM^{sT}_y0\}^T, \quad (22b)$$

$$\varepsilon=\{\varepsilon^0_x\varepsilon^0_y\gamma^0_{xy}\}^T,\quad k^b=\{k^b_xk^b_yk^b_{xy}\}^T,\quad k^s=\{k^s_xk^s_yk^s_{xy}\}^T, \quad (22c)$$

A_{ij}, D_{ij} and B_{ij} are the extensional, bending and the extensional-bending coupling stiffness, respectively. C_{ij}, F_{ij}, H_{ij} are the stiffness components associated with the transverse shear effects. They are expressed as follows

$$\{A_{ij},B_{ij},D_{ij},C_{ij},F_{ij},H_{ij}\}=\sum_{n=1}^{3}\int_{h_{n-1}}^{h_n}c^{(n)}_{ij}\{1,z,z^2,f(z),z\,f(z),f^2(z)\}dz,\quad (i,j=1,2,6) \quad (23)$$

and

$$J_{ii}=\sum_{n=1}^{3}\int_{h_{n-1}}^{h_n}c^{(n)}_{ii}[g(z)]^2dz,\quad (i=4,5) \quad (24)$$

The stress and moment resultants due to thermal loading (N^T_x ,N^T_y, M^{bT}_x, M^{bT}_y, M^{sT}_x and M^{sT}_y) are defined by

$$\begin{Bmatrix}N^T_x\\N^T_y\end{Bmatrix}=\sum_{n=1}^{3}\int_{h_{n-1}}^{h_n}\begin{Bmatrix}(c_{11}+c_{12})\alpha T\\(c_{12}+c_{22})\alpha T\end{Bmatrix}^{(n)}dz \quad (25a)$$

$$\begin{Bmatrix}M^{bT}_x\\M^{bT}_y\end{Bmatrix}=\sum_{n=1}^{3}\int_{h_{n-1}}^{h_n}\begin{Bmatrix}(c_{11}+c_{12})\alpha T\\(c_{12}+c_{22})\alpha T\end{Bmatrix}^{(n)}zdz \quad (25b)$$

$$\begin{Bmatrix}M^{sT}_x\\M^{sT}_y\end{Bmatrix}=\sum_{n=1}^{3}\int_{h_{n-1}}^{h_n}\begin{Bmatrix}(c_{11}+c_{12})\alpha T\\(c_{12}+c_{22})\alpha T\end{Bmatrix}^{(n)}f(z)dz \quad (25c)$$

The mechanical and temperature loads variation through the thickness of the FG sandwich plate is assumed to be (Zenkour and Alghamdi 2010a, b, Zenkour 2012, 2015, Houari *et al*. 2013, Mantari and Granados 2015a, b, Taibi *et al*. 2015, Li *et al*. 2016)

$$q(x,y)=q_0\sin(\lambda x)\sin(\mu y) \quad (26a)$$

$$T(x,y,z)=T_1(x,y)+\frac{z}{h}T_2(x,y)+\frac{f(z)}{h}T_3(x,y) \quad (26b)$$

Where T_1, T_2 and T_3 are the uniform linearly and nonlinearly thermal loads along the thickness of the sandwich plate, respectively

3. Close-form solutions

In this investigation the plate is simply supported whose conditions at the four edges are

$$x=0,\quad a: v_0=w_0=\theta=0,\quad \frac{\partial w_0}{\partial y}=\frac{\partial\theta}{\partial y}=0,\quad N_x=0, M^b_x=M^s_x=0, \quad (27a)$$

$$y=0,\quad b: u_0=w_0=\theta=0,\quad \frac{\partial w_0}{\partial x}=\frac{\partial\theta}{\partial x}=0,\quad N_y=0, M^b_y=M^s_y=0, \quad (27b)$$

In this case the Navier procedure is used to solve Eq. (16), the solution can be expressed in the following form

$$\begin{Bmatrix}u_0\\v_0\\w_0\\\theta\end{Bmatrix}=\begin{Bmatrix}U_{mn}\cos(\lambda x)\sin(\mu y)\\V_{mn}\sin(\lambda x)\cos(\mu y)\\W_{mn}\sin(\lambda x)\sin(\mu y)\\\theta_{mn}\sin(\lambda x)\sin(\mu y)\end{Bmatrix} \quad (28)$$

where U_{mn}, V_{mn}, W_{mn} and θ_{mn} are arbitrary parameters.

The temperature loads T_1 , T_2 and T_3 are also presented in the form of a double trigonometric series

$$\begin{Bmatrix}T_1\\T_2\\T_3\end{Bmatrix}=\begin{Bmatrix}t_1\\t_2\\t_3\end{Bmatrix}\sin(\lambda x)\sin(\mu y) \quad (29)$$

where t_1, t_2 and t_3 are constants, with

$$\lambda=\pi/a,\quad \mu=\pi/b \quad (30)$$

By replacing Eqs. (28) and (29) into Eq. (21) and the consequent outcomes into Eq. (20), one gets the following matrix system

$$\begin{bmatrix}K_{11} & K_{12} & K_{13} & K_{14}\\ K_{12} & K_{22} & K_{23} & K_{24}\\ K_{13} & K_{23} & K_{33} & K_{34}\\ K_{13} & K_{24} & K_{34} & K_{44}\end{bmatrix}\begin{Bmatrix}U_{mn}\\V_{mn}\\W_{mn}\\\theta_{mn}\end{Bmatrix}=\begin{Bmatrix}P_1\\P_2\\P_3\\P_4\end{Bmatrix} \quad (31)$$

Where

$$\begin{aligned}
K_{11}&=A_{11}\lambda^2+A_{66}\mu^2\\
K_{12}&=\lambda\mu(A_{12}+A_{66})\\
K_{13}&=-\lambda[B_{11}\lambda^2+(B_{12}+2B_{66})\mu^2]\\
K_{14}&=\lambda[k_1A'C_{11}\lambda^2+(k_2B'C_{12}+(k_1A'+k_2B')C_{66})\mu^2]\\
K_{22}&=A_{66}\lambda^2+A_{22}\mu^2\\
K_{23}&=-\mu[B_{22}\mu^2+(B_{12}+2B_{66})\lambda^2]\\
K_{24}&=\mu[k_2B'C_{22}\mu^2+(k_1A'C_{12}+(k_1A'+k_2B')C_{66})\lambda^2]\\
K_{33}&=D_{11}\lambda^4+2(D_{12}+2D_{66})\lambda^2\mu^2+D_{22}\mu^4\\
K_{34}&=-k_1A'F_{11}\lambda^4-\begin{bmatrix}(k_1A'+k_2B')F_{12}\\+2(k_1A'+k_2B')F_{66}\end{bmatrix}\lambda^2\mu^2\\
&\quad -k_2B'F_{22}\mu^4
\end{aligned} \quad (32)$$

$$K_{44}=k_1^2A'^2H_{11}\lambda^4+[2k_1k_2A'B'H_{12}+(k_1A'+k_2B')^2H_{66}]\lambda^2\mu^2+k_2^2B'^2H_{22}\mu^4+k_1^2A'^2J_{55}\lambda^2+k_2^2B'^2H_{22}\mu^2 \tag{32}$$

The components of the generalized force vector $\{P\}=\{P_1,P_2,P_3,P_4\}^T$ are obtained as follows

$$\begin{aligned}P_1&=-\lambda(A^Tt_1+B^Tt_2+C^Tt_3),\\P_2&=-\mu(A^Tt_1+B^Tt_2+C^Tt_3),\\P_3&=q_0+h(\lambda^2+\mu^2)(B^Tt_1+D^Tt_2+F^Tt_3),\\P_4&=h(\lambda^2+\mu^2)(C^Tt_1+F^Tt_2+G^Tt_3),\end{aligned} \tag{33}$$

which

$$\{A^T,B^T,D^T\}=\sum_{n-1}^{3}\int_{h_{n-1}}^{h_n}\frac{E^{(n)}(z)}{1-(\mu^{(n)})^2}(1+\mu^{(n)})\alpha^{(n)}\{1,\bar{z},\bar{z}^2\}\,\mathrm{d}z \tag{34a}$$

$$\{C^T,F^T,G^T\}=\sum_{n-1}^{3}\int_{h_{n-1}}^{h_n}\frac{E^{(n)}(z)}{1-(\mu^{(n)})^2}(1+\mu^{(n)})\alpha^{(n)}\bar{f}(z)\{1,\bar{z},\bar{f}(z)\}\,\mathrm{d}z \tag{34b}$$

Where $\bar{z}=\frac{z}{h}$, $\bar{f}(z)=\frac{f(z)}{h}$.

4. Numerical results

In this section, thermomechanical flexural analysis of simply supported functionally graded sandwich plate is performed by utilizing a novel nth–order shear deformation theory. Several numerical results are examined and compared with the existing method for checking the accuracy of the proposed theory in computing the deflections and stresses of a sandwich plate under thermo-

Table 2 Comparison of the non-dimensional deflection $(\overline{w})$ of square sandwich plate (Type A) with FGM face sheets and homogeneous core ($k=0$) under thermo-mechanical load ($a/h=10$)

p	Theory	$\overline{w}(a/2,b/2)$			
		1-0-1	3-1-3	2-1-2	1-1-1
0	FSDPT (Zenkour and Alghamdi 2010a)	0.895735	0.895735	0.895735	0.895735
	RPT (Li *et al*. 2017)	0.864140	0.864140	0.864140	0.864140
	present (n = 3)	0.864140	0.864140	0.864140	0.864140
	present (n = 5)	0.919184	0.919184	0.919184	0.919184
	present (n = 7)	0.937534	0.937534	0.937534	0.937534
1	FSDPT (Zenkour and Alghamdi 2010a)	1.190728	1.170533	1.160568	1.132449
	RPT (Li *et al*. 2017)	1.149038	1.130125	1.120741	1.094113
	present (n = 3)	1.149038	1.130125	1.120741	1.094113
	present (n = 5)	1.220801	1.200618	1.190618	1.162286
	present (n = 7)	1.244390	1.223761	1.213547	1.184630
2	FSDPT (Zenkour and Alghamdi 2010a)	1.257304	1.238234	1.227765	1.195703
	RPT (Li *et al*. 2017)	1.210756	1.193444	1.183826	1.154061
	present (n = 3)	1.210756	1.193444	1.183826	1.154061
	present (n = 5)	1.286561	1.267886	1.257549	1.225680
	present (n = 7)	1.311590	1.292411	1.281807	1.249166
3	FSDPT (Zenkour and Alghamdi 2010a)	1.280741	1.264724	1.255041	1.223232
	RPT (Li *et al*. 2017)	1.231675	1.217447	1.208690	1.179518
	present (n = 3)	1.231675	1.217447	1.208690	1.179518
	present (n = 5)	1.309161	1.293664	1.284186	1.252786
	present (n = 7)	1.334860	1.318878	1.309126	1.276887
4	FSDPT (Zenkour and Alghamdi 2010a)	1.290961	1.277527	1.268689	1.237931
	RPT (Li *et al*. 2017)	1.240542	1.228791	1.220879	1.192880
	present (n = 3)	1.240542	1.228791	1.220879	1.192880
	present (n = 5)	1.318866	1.305971	1.297361	1.267109
	present (n = 7)	1.344903	1.331572	1.322698	1.291590
5	FSDPT (Zenkour and Alghamdi 2010a)	1.296101	1.284626	1.276497	1.246833
	RPT (Li *et al*. 2017)	1.244905	1.234980	1.227750	1.200876
	present (n = 3)	1.244905	1.234980	1.227750	1.200876
	present (n = 5)	1.323695	1.312741	1.304845	1.275727
	present (n = 7)	1.349918	1.338577	1.330429	1.300461

Table 3 Effect of dimension ratio (a/b) on dimensionless center deflection $\overline{w}(a/2, b/2)$ of sandwich plate (Type A) with FGM face sheets and homogeneous core ($k = 0$) under thermo-mechanical load $(a/h = 10,\ p = 3)$

Scheme	Theory	$\overline{w}(a/2, b/2)$				
		$a/b = 1$	$a/b = 2$	$a/b = 3$	$a/b = 4$	$a/b = 5$
1-0-1	FSDPT (Zenkour and Alghamdi 2010a)	1.280741	0.503607	0.250355	0.146917	0.095948
	RPT (Li *et al*. 2017)	1.231675	0.492573	0.246212	0.144771	0.094608
	present (n = 3)	1.231675	0.492573	0.246212	0.144771	0.094608
	present (n = 5)	1.309161	0.523630	0.261792	0.153978	0.100663
	present (n = 7)	1.334860	0.533928	0.266957	0.157028	0.102668
3-1-3	FSDPT (Zenkour and Alghamdi 2010a)	1.264724	0.497383	0.247274	0.145112	0.094770
	RPT (Li *et al*. 2017)	1.217447	0.486952	0.243459	0.143199	0.093619
	present (n = 3)	1.217447	0.486952	0.243459	0.143199	0.093619
	present (n = 5)	1.293664	0.517466	0.258739	0.152205	0.099523
	present (n = 7)	1.318878	0.527555	0.263786	0.155177	0.101469
2-1-2	FSDPT (Zenkour and Alghamdi 2010a)	1.255041	0.493613	0.245406	0.144017	0.094055
	RPT (Li *et al*. 2017)	1.208690	0.483486	0.241757	0.142222	0.093002
	present (n = 3)	1.208690	0.483486	0.241757	0.142222	0.093002
	present (n = 5)	1.284186	0.513693	0.256868	0.151118	0.098824
	present (n = 7)	1.309126	0.523665	0.261850	0.154045	0.100735
1-1-1	FSDPT (Zenkour and Alghamdi 2010a)	1.223232	0.481212	0.239259	0.140414	0.091704
	RPT (Li *et al*. 2017)	1.179518	0.471920	0.236060	0.138942	0.090916
	present (n = 3)	1.179518	0.471920	0.236060	0.138942	0.090916
	present (n = 5)	1.252786	0.501189	0.250663	0.147506	0.096494
	present (n = 7)	1.276887	0.510802	0.255447	0.150301	0.098306

mechanical loads. The results are divided into three parts:

A - Flexural analysis of sandwich plate with FGM face sheets and homogeneous core $(k = 0)$ *under thermo-mechanical loads*

In this part, thermo-mechanical bending analysis of sandwich plate (Type A) with FGM face sheets and homogeneous core are presented in explicit tables. Numerical results (Tables 2-4) are compared with those given by the first shear deformation theory (FSDT) developed by Zenkour and Alghamdi (2010a) and Refined plate theory presented by Li *et al*. (2017).

Table 2 present a comparison of the non-dimensional deflection $(\overline{w})$ of simply supported square sandwich plate ($a/b = 1$, Type A) with FGM face sheets and homogeneous core under thermo-mechanical load for several values of power index (p) and different layer thickness ratios (1-0-1, 3-1-3, 2-1-2 and 1-1-1). According to the obtained results, it can be seen that the present theory are with excellent accord with those developed by Li *et al*. (2017) for an order number $(n = 3)$, and for $(n \succ 3)$ the result converge towards the results obtained by the FSDT, it can be observed also that the increase of material index Table 2 present a comparison of the non-dimensional deflection $(\overline{w})$ of simply supported square sandwich plate ($a/b = 1$, Type A) with FGM face sheets and homogeneous core under thermo-mechanical load for several values of power index (p) and different layer thickness ratios (1-0-1, 3-1-3, 2-1-2 and 1-1-1). According to the obtained results, it can be seen that the present theory are with excellent accord with those developed by Li *et al*. (2017) for an order number $(n = 3)$, and for $(n \succ 3)$ the result converge towards the results obtained by the FSDT, it can be observed also that the increase of material index leads to an increase of the center deflection $(\overline{w})$.

The variation of the dimensionless center deflection $(\overline{w})$ of the FGM sandwich plate (Type A) under a thermo-mechanical loading as a function of the aspect ratio (a/b) and the layer thicknesses ratios is illustrated in Table 3, the results obtained are for a material index $p = 3$ and a geometry ratio $a/h = 10$, it can be noted that the central deflection $(\overline{w})$ decreases with the increase of the dimension ratio a/b, and the lowest values of the non-dimensional deflection are obtained for layer thickness ratio (1-1-1).

Table 4 demonstrates the index material and layer thicknesses effects on the dimensionless normal stress $(\overline{\sigma}_x)$ of the sandwich plate ($a/h = 10$, Type A). It can be seen that the dimensionless normal stress diminishes with increases of the power low index of FGM face sheets and this is due that the plate becomes flexible. It is also noteworthy that the greatest dimensionless normal stress $(\overline{\sigma}_x)$ values are obtained for layer thickness ratio (1-1-1).

Table 4 Comparison of dimensionless normal stress $(\overline{\sigma}_x)$ of square sandwich plate ($a/b = 1$, Type A) with FGM face sheets and homogeneous core $(k = 0)$ under thermomechanical load $(a/h = 10)$

p	Theory	$\overline{w}(a/2, b/2, h/2)$			
		1-0-1	3-1-3	2-1-2	1-1-1
0	FSDPT (Zenkour and Alghamdi 2010a)	-3,597007	-3,597007	-3,597007	-3,597007
	RPT (Li *et al*. 2017)	-2,911440	-2,911440	-2,911440	-2,911440
	present (n = 3)	-2.911439	-2.911440	-2.911440	-2.911440
	present (n = 5)	-3.267647	-3.267647	-3.267647	-3.267647
	present (n = 7)	-3.465619	-3.465619	-3.465619	-3.465619
1	FSDPT (Zenkour and Alghamdi 2010a)	-3,471099	-3,569762	-3,618476	-3,756017
	RPT (Li *et al*. 2017)	-2,892290	-2,985255	-3,031378	-3,162208
	present (n = 3)	-2.892290	-2,985255	-3,031378	-3,162208
	present (n = 5)	-3.222468	-3.321533	-3.370618	-3.509663
	present (n = 7)	-3.398971	-3.500162	-3.550267	-3.692106
2	FSDPT (Zenkour and Alghamdi 2010a)	-3,145662	-3,238636	-3,289757	-3,446485
	RPT (Li *et al*. 2017)	-2,589234	-2,674492	-2,721838	-2,868271
	present (n = 3)	-2.589234	-2,674492	-2,721838	-2,868271
	present (n = 5)	-2.899800	-2.991550	-3.042321	-3.198827
	present (n = 7)	-3.069336	-3.1635092	-3.215542	-3.375706
3	FSDPT (Zenkour and Alghamdi 2010a)	-3,031284	-3,109180	-3,156414	-3,311823
	RPT (Li *et al*. 2017)	-2,486287	-2,556476	-2,599635	-2,743281
	present (n = 3)	-2.486287	-2,556476	-2,599635	-2,743281
	present (n = 5)	-2.788790	-2.864971	-2.911552	-3.065816
	present (n = 7)	-2.955183	-3.033641	-3.081508	-3.239727
4	FSDPT (Zenkour and Alghamdi 2010a)	-2,981507	-3,046666	-3,089733	-3,239941
	RPT (Li *et al*. 2017)	-2,442566	-2,500626	-2,539661	-2,677611
	present (n = 3)	-2.442566	-2,500626	-2,539661	-2,677611
	present (n = 5)	-2.741079	-2.804506	-2.846834	-2.995497
	present (n = 7)	-2.905879	-2.971338	-3.014905	-3.167589
5	FSDPT (Zenkour and Alghamdi 2010a)	-2,956534	-3,012040	-3,051612	-3,196423
	RPT (Li *et al*. 2017)	-2,421017	-2,470126	-2,505817	-2,638388
	present (n = 3)	-2.421017	-2,470126	-2,505817	-2,638388
	present (n = 5)	-2.717327	-2.771229	-2.846834	-2.953172
	present (n = 7)	-2.881248	-2.936947	-3.014905	-3.124059

B - Flexural analysis of sandwich plate with homogeneous face sheets $(p = 0)$ and FGM core under thermo-mechanical loads

As a second example of the present examination, the sandwich plate has a FGM core $(k \geq 0)$ and homogeneous face sheets $(p = 0)$.

Table 5 present the non-dimensional deflection values $\overline{w}(a/2, b/2)$ of simply supported sandwich plate (Type A) under mechanical and thermal loads. Several layer thickness ratios are considered such as 2-1-2, 1-1-1, 1-2-1 and 1-3-1 for different values of core material index$(k = 0, 1, 2, 3, 4 and 5)$. The present results are in good agreement with those given by Li *et al*. (2017), it should be noted that the non-dimensional deflection $\overline{w}$ increases slightly with the increase of the material index of the core (k).

The same results of the non-dimensional deflection are obtained for the different layer thickness ratios (2-1-2, 1-1-1, 1-2-1 and 1-3-1) in the case $k = 0$ because the plate is entirely ceramic.

The comparison of the non-dimensional deflection $\overline{w}$ $(a/2, b/2)$ of simply supported sandwich plate (Type A) with homogeneous face sheets $p = 0$ and FGM core is presented in the Table 6. The sandwich plate is under thermo mechanical loading with ($q_0 = 100Pa, t_1 = 0, t_2 = t_3 = 100K$). According to the table, it can be seen that the deflection $\overline{w}$decreases with the increase of the dimension ratio a/b, also it should be noted that the highest values of the dimensionless deflection are obtained for a thickness ratio (1-3-1).

Table 5 Dimensionless center deflection $\overline{w}(a/2, b/2)$ of square sandwich plate ($a/b = 1$, Type A) with homogeneous face sheets ($p = 0$) and FGM core under thermomechanical load ($a/h = 10$)

k	Theory	$\overline{w}(a/2, b/2)$			
		2-1-2	1-1-1	1-2-1	1-3-1
0	FSDPT (Li *et al*. 2017)	0.960453	0.960453	0.960453	0.960453
	RPT (Li *et al*. 2017)	0.864140	0.864140	0.864140	0.864140
	present (n = 3)	0.864140	0.864140	0.864140	0.864140
	present (n = 5)	0.919184	0.919184	0.919184	0.919184
	present (n = 7)	0.937534	0.937534	0.937534	0.937534
1	FSDPT (Li *et al*. 2017)	0.961067	0.963305	0.970187	0.977474
	RPT (Li *et al*. 2017)	0.864623	0.866466	0.872221	0.878396
	present (n = 3)	0.864623	0.866466	0.872221	0.878396
	present (n = 5)	0.919744	0.921811	0.928180	0.934941
	present (n = 7)	0.938205	0.940263	0.946858	0.953845
2	FSDPT (Li *et al*. 2017)	0.961375	0.964745	0.975191	0.986392
	RPT (Li *et al*. 2017)	0.864867	0.867635	0.876353	0.885834
	present (n = 3)	0.864867	0.867635	0.876353	0.885834
	present (n = 5)	0.920026	0.923134	0.932788	0.943167
	present (n = 7)	0.938413	0.941639	0.951641	0.962371
3	FSDPT (Li *et al*. 2017)	0.961565	0.965637	0.978325	0.992040
	RPT (Li *et al*. 2017)	0.865018	0.868359	0.878938	0.890547
	present (n = 3)	0.865018	0.868359	0.878938	0.890547
	present (n = 5)	0.920199	0.923952	0.935669	0.948370
	present (n = 7)	0.938595	0.942490	0.954634	0.967766
4	FSDPT (Li *et al*. 2017)	0.961696	0.966250	0.980491	0.995971
	RPT (Li *et al*. 2017)	0.865121	0.868855	0.880725	0.893831
	present (n = 3)	0.865121	0.868855	0.880725	0.893831
	present (n = 5)	0.920319	0.924514	0.937658	0.951990
	present (n = 7)	0.938719	0.943075	0.956700	0.971519
5	FSDPT (Li *et al*. 2017)	0.961791	0.966697	0.982082	0.998875
	RPT (Li *et al*. 2017)	0.865197	0.869218	0.882038	0.896261
	present (n = 3)	0.865197	0.869218	0.882038	0.896261
	present (n = 5)	0.920406	0.924924	0.939119	0.954664
	present (n = 7)	0.938810	0.943501	0.958218	0.974291

Table 6 Effect of aspect ratio a/b on dimensionless center deflection $\overline{w}(a/2, b/2)$ of sandwich plate (Type A) with homogeneous face sheets ($p = 0$) and FGM core under thermomechanical load ($a/h = 10, k = 1$)

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	FSDPT (Li *et al*. 2017)	0.961067	0.384421	0.192210	0.113064	0.073927
	RPT (Li *et al*. 2017)	0.864623	0.345661	0.172678	0.101451	0.066229
	present (n = 3)	0.864623	0.345661	0.172678	0.101451	0.066229
	present (n = 5)	0.919744	0.367820	0.183850	0.108098	0.070638
	present (n = 7)	0.938205	0.375293	0.187660	0.110399	0.072194

Table 6 Continued

Scheme	Theory	$\overline{w}(a/2, b/2)$				
		$a/b = 1$	$a/b = 2$	$a/b = 3$	$a/b = 4$	$a/b = 5$
1-1-1	FSDPT (Li *et al*. 2017)	0.963305	0.385316	0.192657	0.113328	0.074099
	RPT (Li *et al*. 2017)	0.866466	0.346369	0.173008	0.101625	0.066327
	present (n = 3)	0.866466	0.346369	0.173008	0.101625	0.066327
	present (n = 5)	0.921811	0.368636	0.184248	0.108324	0.070780
	present (n = 7)	0.941380	0.377177	0.189113	0.111675	0.073381
1-2-1	FSDPT (Li *et al*. 2017)	0.970187	0.388069	0.194034	0.114137	0.074628
	RPT (Li *et al*. 2017)	0.872221	0.348604	0.174070	0.102204	0.066667
	present (n = 3)	0.872221	0.348604	0.174070	0.102204	0.066667
	present (n = 5)	0.928299	0.371274	0.185602	0.109150	0.071344
	present (n = 7)	0.946858	0.378683	0.189296	0.111312	0.072749
1-3-1	FSDPT (Li *et al*. 2017)	0.977474	0.390984	0.195491	0.114994	0.075189
	RPT (Li *et al*. 2017)	0.878396	0.351016	0.175228	0.102846	0.067055
	present (n = 3)	0.878396	0.351016	0.175228	0.102846	0.067055
	present (n = 5)	0.934941	0.373830	0.186797	0.109784	0.071701
	present (n = 7)	0.953845	0.381461	0.190671	0.112110	0.073262

Table 7 Dimensionless normal stress $(\overline{\sigma}_x)$ of square sandwich plate ($a/b = 1$, Type A) with homogeneous face sheets $(p = 0)$ and FGM core under thermomechanical load $(a/h = 10)$

k	Theory	$\overline{w}(a/2, b/2, h/2)$			
		2-1-2	1-1-1	1-2-1	1-3-1
0	FSDPT (Li *et al*. 2017)	-4.158732	-4.158732	-4.158732	-4.158732
	RPT (Li *et al*. 2017)	-2.911440	-2.911440	-2.911440	-2.911440
	present (n = 3)	-2.911440	-2.911440	-2.911440	-2.911440
	present (n = 5)	-3.267647	-3.267647	-3.267647	-3.267647
	present (n = 7)	-3.465619	-3.465619	-3.465619	-3.465619
1	FSDPT (Li *et al*. 2017)	-4.153417	-4.134036	-4.074434	-4.011326
	RPT (Li *et al*. 2017)	-2.907015	-2.890699	-2.840040	-2.785860
	present (n = 3)	-2.907015	-2.890699	-2.840040	-2.785860
	present (n = 5)	-3.262709	-3.244672	-3.189141	-3.130226
	present (n = 7)	-3.460438	-3.441876	-3.384558	-3.323842
2	FSDPT (Li *et al*. 2017)	-4.150749	-4.121567	-4.031095	-3.934090
	RPT (Li *et al*. 2017)	-2.904809	-2.880305	-2.803535	-2.720298
	present (n = 3)	-2.904809	-2.880305	-2.803535	-2.720298
	present (n = 5)	-3.260238	-3.233114	-3.148920	-3.058439
	present (n = 7)	-3.457953	-3.429913	-3.342968	-3.249700
3	FSDPT (Li *et al*. 2017)	-4.149101	-4.113838	-4.003951	-3.885176
	RPT (Li *et al*. 2017)	-2.903451	-2.873883	-2.780706	-2.678783
	present (n = 3)	-2.903451	-2.873883	-2.780706	-2.678783
	present (n = 5)	-3.258715	-3.225963	-3.123767	-3.013026
	present (n = 7)	-3.456373	-3.422504	-3.316945	-3.202784
4	FSDPT (Li *et al*. 2017)	-4.147973	-4.108535	-3.985199	-3.851130
	RPT (Li *et al*. 2017)	-2.902523	-2.869484	-2.764940	-2.649867
	present (n = 3)	-2.902523	-2.869484	-2.764940	-2.649867
	present (n = 5)	-3.257673	-3.221061	-3.106403	-2.981431
	present (n = 7)	-3.455293	-3.417425	-3.298976	-3.170145

Table 7 Continued

k	Theory	$\overline{w}(a/2, b/2, h/2)$			
		2-1-2	1-1-1	1-2-1	1-3-1
	FSDPT (Li *et al*. 2017)	-4.147150	-4.104658	-3.971420	-3.825981
	RPT (Li *et al*. 2017)	-2.901847	-2.866270	-2.753353	-2.628487
5	present (n = 3)	-2.901847	-2.866270	-2.753353	-2.628487
	present (n = 5)	-3.256912	-3.217480	-3.093650	-2.958096
	present (n = 7)	-3.454504	-3.413712	-3.285778	-3.146040

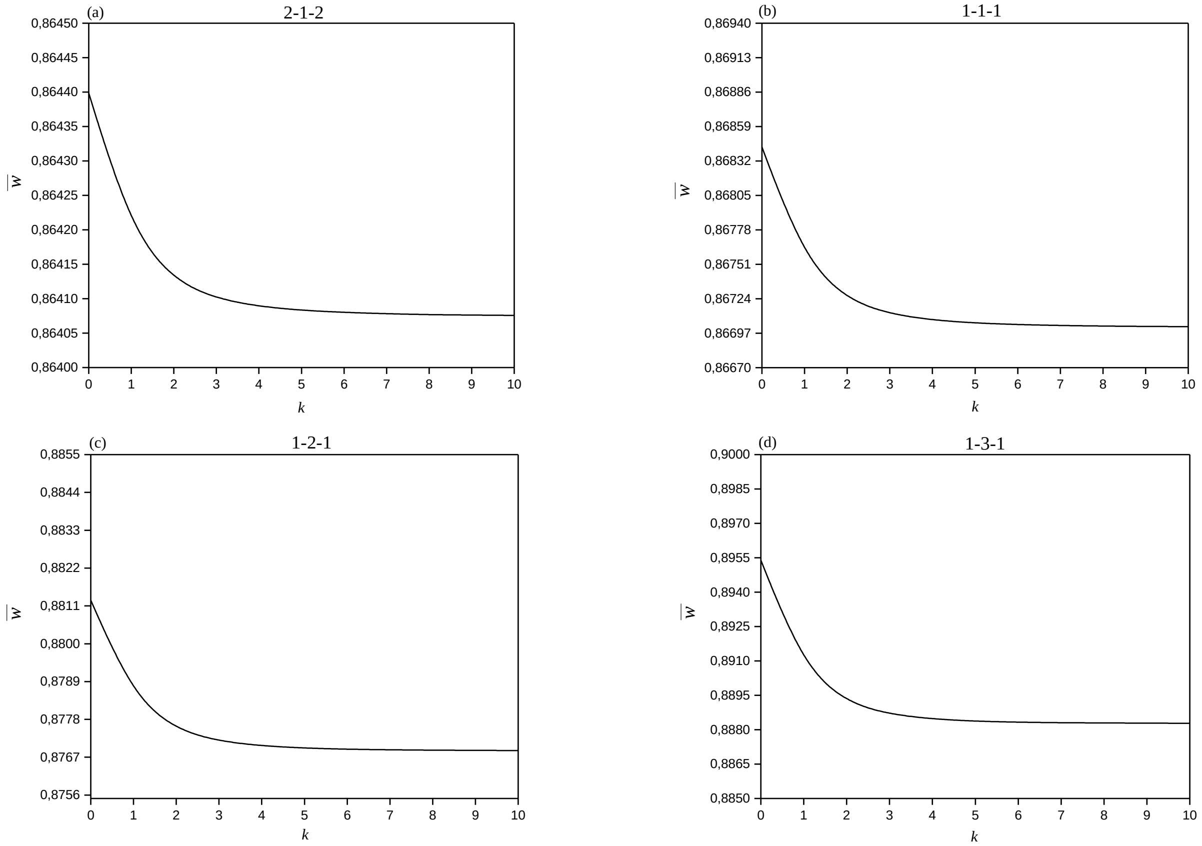

Fig. 2 Effect of the gradient index of the core (k) on the dimensionless central deflection$(\overline{w})$ of sandwich plates (Type B) with homogeneous face sheets $(p = 0)$ and symmetric S-FGM core: (a) the (2-1-2) sandwich plate; (b) the (1-1-1) sandwich plate; (c) the (1-2-1) sandwich plate; (d) the (1-3-1) sandwich plate

The effects of the material index of the core (k) and the layer thickness ratios on the axial stress along the x axis $(\overline{\sigma}_x)$ are presented in Table 7. The results are for the layer thickness ratios (2-1-2, 1-1-1, 1-2-1 and 1-3-1). From the obtained results, it can be observed that the current model gives almost the same values of the normal stress $(\overline{\sigma}_x)$ as those of Li *et al*. (2017) and the results found by the FSDT are bigger compared to the other models. It can also be seen that the normal stress $(\overline{\sigma}_x)$ decreases slightly with the increase of the power index k. Fig. 2 plots the dimensionless central deflection $\overline{w}$ of a sandwich plates (2-1-2, 1-1-1, 1-2-1 and 1-3-1) as a function of the material index of the core (k) (symmetric S-FGM core) with a ratio of geometry $a/h = 5$. From these obtained graphs, it can be noted that the central deflection $(\overline{w})$ is in inverse relation with the power index k and that for the different layer thickness ratios.

Fig. 3 shows the variation of the non-dimensional central deflection $\overline{w}(a/2, b/2, h/2)$ of the sandwich plate (with homogeneous face sheets $p = 0$ and a symmetric S-FGM core $k = 2$) as a function of aspect ratio (a/b) and thermal loading $\{(q_0 = 100Pa,\ t_2 = t_3 = 0),\ (q_0 = 100Pa,\ t_2 = 100K, t_3 = 0)$ and $(q_0 = 100Pa,\ t_2 = t_3 = 100K)\}$. It should be noted that the increase in the a/b ratio leads to a decrease in the central deflection $\overline{w}$and this for the three types of loading, it can also be concluded that the effect of thermal loading is significant on the central deflection $\overline{w}$. and the largest values of this last are obtained for $(q_0 = 100Pa,\ t_2 = t_3 = 100K)$.

Fig. 4 illustrates the variation of the non-dimensional central deflection $\overline{w}$ as a function of the thermal effect and the geometry ratio of a sandwich plate (1-2-1) with

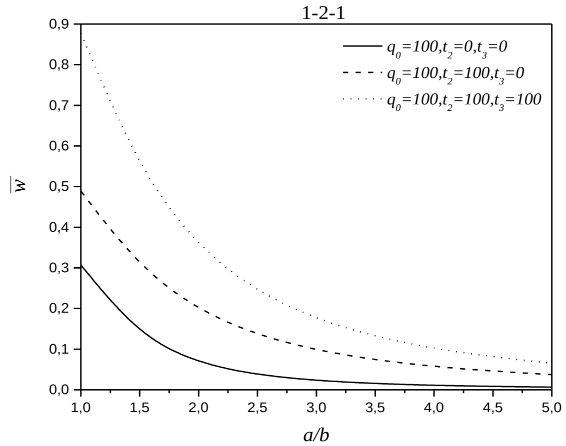

Fig. 3 Effect of the thermal loads on the non-dimensional central deflection $\overline{w}(a/2, b/2, h/2)$ of the (1-2-1) sandwich plate (Type B) with homogeneous face sheets and symmetric S-FGM core $(k = 2)$ versus (a/b)

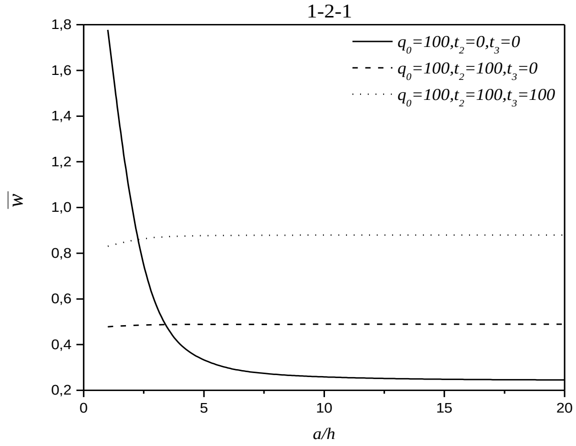

Fig. 4 Effect of the thermal loads on the non-dimensional central deflection $\overline{w}$ of the (1-2-1) sandwich plate (Type B) with homogeneous face sheets and symmetric S-FGM core $(k = 2)$ versus (a/h)

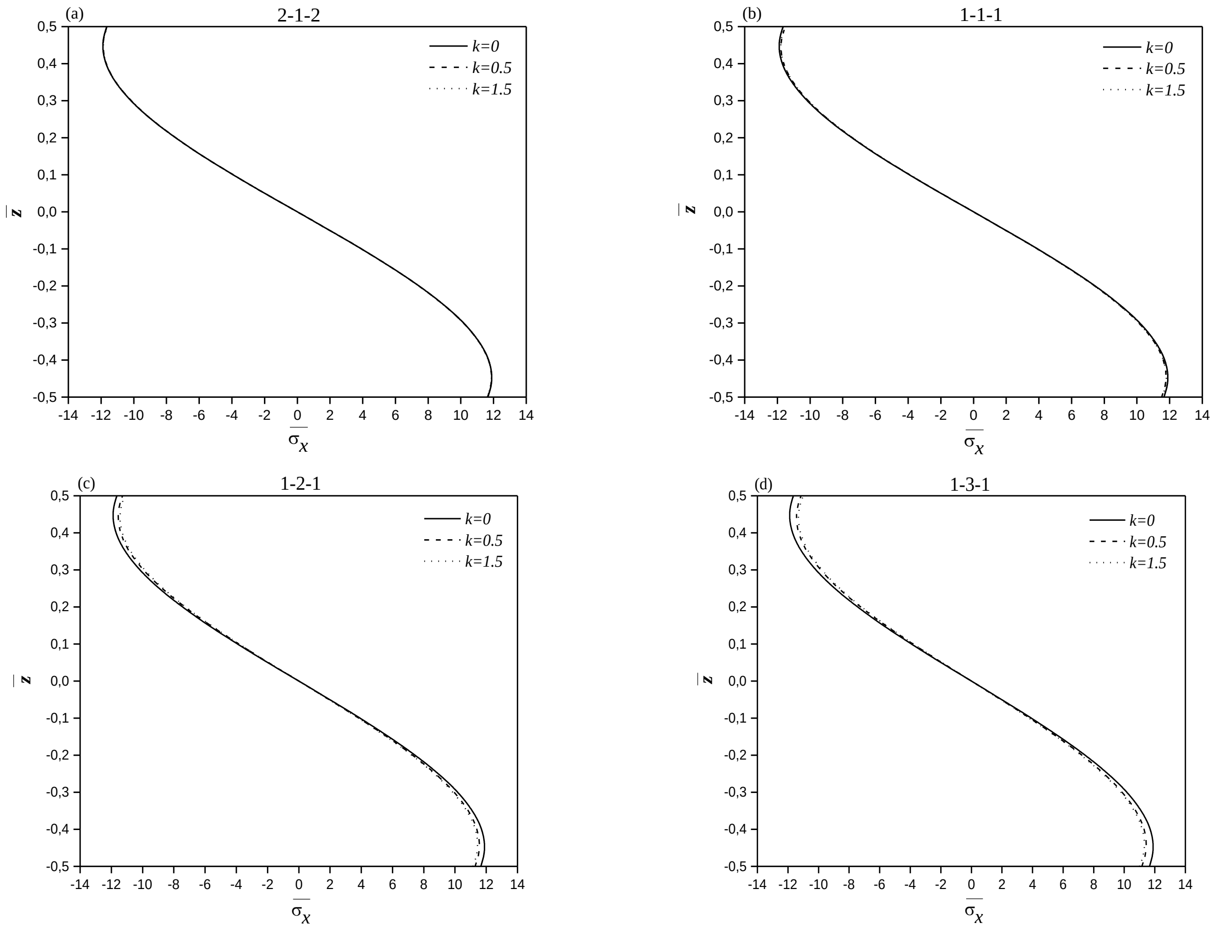

Fig. 5 Variation of normal stress $\overline{\sigma_x}$ through the thickness of sandwich plates ($a/h = 5$, Type B) with homogeneous face sheets $(p = 0)$ and symmetric S-FGM core: (a) the (2-1-2) sandwich plate; (b) the (1-1-1) sandwich plate; (c) the (1-2-1) sandwich plate; (d) the (1-3-1) sandwich plate

homogeneous face sheets $(p = 0)$ and Symmetric S-FGM core $k = 2$. From the graphs obtained it can be noticed that the ratio (a/h) has a slight influence on the central deflection $\overline{w}$, one can also note that for $(t_2 = 200)$ the thermal loading (t_3) is significant on the central deflection $(\overline{w})$.

Fig. 5 shows the dimensionless normal stress distribution $\overline{\sigma}_x$ across the thickness h of a simply supported

Table 8 Dimensionless center deflection $(\overline{w})$ of square sandwich plate (Type A) with P-FGM face sheets and E-FGM core under thermomechanical load $(a/h = 10)$

p	Theory	$\overline{w}(a/2, b/2)$			
		2-1-2	1-1-1	1-2-1	1-3-1
0	FSDPT (Li *et al*. 2017)	0.961067	0.963305	0.970187	0.977474
	RPT (Li *et al*. 2017)	0.864623	0.866466	0.872221	0.878396
	present (n = 3)	0.864623	0.866466	0.872221	0.878396
	present (n = 5)	0.919744	0.921811	0.928180	0.934941
	present (n = 7)	0.938120	0.940263	0.946858	0.953845
1	FSDPT (Li *et al*. 2017)	1.242779	1.217361	1.180797	1.156699
	RPT (Li *et al*. 2017)	1.121862	1.098934	1.065520	1.043229
	present (n = 3)	1.121862	1.098934	1.065520	1.043229
	present (n = 5)	1.191838	1.167546	1.132364	1.108998
	present (n = 7)	1.214798	1.190035	1.154277	1.130599
2	FSDPT (Li *et al*. 2017)	1.313230	1.284594	1.238612	1.206011
	RPT (Li *et al*. 2017)	1.185157	1.159800	1.118459	1.088746
	present (n = 3)	1.185157	1.159800	1.118459	1.088746
	present (n = 5)	1.259002	1.231932	1.188143	1.156852
	present (n = 7)	1.283299	1.255589	1.210921	1.179111
3	FSDPT (Li *et al*. 2017)	1.341711	1.313791	1.265222	1.229142
	RPT (Li *et al*. 2017)	1.210108	1.185685	1.142459	1.109859
	present (n = 3)	1.210108	1.185685	1.142459	1.109859
	present (n = 5)	1.285739	1.259507	1.213521	1.179084
	present (n = 7)	1.310724	1.283795	1.236773	1.201694
4	FSDPT (Li *et al*. 2017)	1.355934	1.329367	1.280204	1.242418
	RPT (Li *et al*. 2017)	1.222339	1.199282	1.155813	1.121864
	present (n = 3)	1.222339	1.199282	1.155813	1.121864
	present (n = 5)	1.298966	1.274089	1.227696	1.191755
	present (n = 7)	1.324349	1.298766	1.251253	1.214590
5	FSDPT (Li *et al*. 2017)	1.364062	1.338795	1.289699	1.250973
	RPT (Li *et al*. 2017)	1.229235	1.207420	1.164203	1.129545
	present (n = 3)	1.229235	1.207420	1.164203	1.129545
	present (n = 5)	1.306479	1.282866	1.236632	1.199879
	present (n = 7)	1.332113	1.307802	1.260399	1.222873

square plate (type B) according to the material index of the core ($k = 0, 0.5, 1.5$) for the different layer thickness ratios (2-1-2, 1-1-1, 1-2-1 and 1-3-1) .From these graphs, it is clear that the normal stress $(\overline{\sigma}_x)$ has a nonlinear variation through the thickness $z$of the plate. It can also be seen that for a thickness ratio of the larger layer (1-3-1), the influence of the power index (k) becomes greater, for all layer thickness ratios (2-1-2, 1-1-1, 1-2-1 and 1-3-1) the compressive stresses occur in the lower layer and the tensile in the upper layer.

C - Flexural analysis of sandwich plate with FGM face sheets and FGM core $(k \neq 0)$ under thermo-mechanical loads

In this third example, the sandwich plate with FGM face sheets and FGM core is considered. Two types of FG materials core are used here such as E-FGM and the novel symmetric S-FGM.

Table 8 shows the effects of the face sheets power index$p$, and the different layer thicknesses ratios on the variation of the center non-dimensional deflection $(\overline{w})$of the sandwich plate (Type A) with $(a/h = 10$ and $k = 1)$ under a combined thermal and mechanical loading. The results are calculated for the layer thickness ratios (2-1-2, 1-1-1, 1-2-1 and 1-3-1) and this for $(p = 0, 1, 2, 3, 4 and 5)$. It can be concluded from the results of the Table 8 that the non-dimensional deflection $\overline{w}$ is in direct correlation relation with the material index p. It is also clear that the largest values of the non-dimensional deflection are given by a layer thickness ratio 2-1-2.

Table 9 present the variation of the non-dimensional

Table 9 Effect of aspect ratio (a/b) on dimensionless center deflection $(\overline{w})$ of sandwich plate (Type A) with P-FGM face sheets and E-FGM core under thermomechanical load ($a/h = 10$,$p = 3$,$k = 1$)

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	FSDPT (Li *et al*. 2017)	1.341711	0.536675	0.268336	0.157844	0.103206
	RPT (Li *et al*. 2017)	1.210108	0.484045	0.242031	0.142378	0.093100
	present (n = 3)	1.210108	0.484045	0.242031	0.142378	0.093100
	present (n = 5)	1.285739	0.514313	0.257177	0.151298	0.098941
	present (n = 7)	1.310724	0.524303	0.262170	0.154233	0.100858
1-1-1	FSDPT (Li *et al*. 2017)	1.313791	0.525507	0.262752	0.154560	0.101058
	RPT (Li *et al*. 2017)	1.185685	0.474370	0.237271	0.139642	0.091364
	present (n = 3)	1.185685	0.474370	0.237271	0.139642	0.091364
	present (n = 5)	1.259507	0.503873	0.252001	0.148290	0.097004
	present (n = 7)	1.283795	0.513564	0.256826	0.151111	0.098835
1-2-1	FSDPT (Li *et al*. 2017)	1.265222	0.506080	0.253039	0.148846	0.097322
	RPT (Li *et al*. 2017)	1.142459	0.457190	0.228773	0.134719	0.088208
	present (n = 3)	1.142459	0.457190	0.228773	0.134719	0.088208
	present (n = 5)	1.213521	0.485554	0.242904	0.142989	0.093581
	present (n = 7)	1.236773	0.494804	0.247487	0.145651	0.095293
1-3-1	FSDPT (Li *et al*. 2017)	1.229142	0.491649	0.245823	0.144601	0.094547
	RPT (Li *et al*. 2017)	1.109859	0.444182	0.222295	0.130929	0.085748
	present (n = 3)	1.109859	0.444182	0.222295	0.130929	0.085748
	present (n = 5)	1.179084	0.471815	0.236063	0.138990	0.090986
	present (n = 7)	1.201694	0.480801	0.240508	0.141565	0.092637

Table 10 Dimensionless normal stress $(\overline{\sigma}_x)$ of square sandwich plate (Type A) with P-FGM face sheets and E-FGM core under thermomechanical load ($a/h = 10$)

p	Theory	$\overline{w}(a/2,b/2,h/2)$			
		2-1-2	1-1-1	1-2-1	1-3-1
0	FSDPT (Li *et al*. 2017)	-4.153417	-4.134036	-4.074434	-4.011326
	RPT (Li *et al*. 2017)	-2.907015	-2.890699	-2.840040	-2.785860
	present (n = 3)	-2.907015	-2.890699	-2.840040	-2.785860
	present (n = 5)	-3.262709	-3.244672	-3.189012	-3.130226
	present (n = 7)	-3.460438	-3.440911	-3.384558	-3.323842
1	FSDPT (Li *et al*. 2017)	-4.136946	-4.261501	-4.440672	-4.558762
	RPT (Li *et al*. 2017)	-3.025929	-3.138583	-3.302462	-3.411521
	present (n = 3)	-3.025929	-3.138583	-3.302462	-3.411521
	present (n = 5)	-3.364680	-3.483925	-3.656521	-3.771021
	present (n = 7)	-3.544116	-3.665003	-3.841035	-3.957110
2	FSDPT (Li *et al*. 2017)	-3.791718	-3.932040	-4.157364	-4.317119
	RPT (Li *et al*. 2017)	-2.715313	-2.840096	-3.043204	-3.188866
	present (n = 3)	-2.715313	-2.840096	-3.043204	-3.188866
	present (n = 5)	-3.035217	-3.168193	-3.383187	-3.536675
	present (n = 7)	-3.208193	-3.343558	-3.563416	-3.719438

Table 10 Continued

p	Theory	$\overline{w}(a/2, b/2, h/2)$			
		2-1-2	1-1-1	1-2-1	1-3-1
3	FSDPT (Li *et al*. 2017)	-3.652156	-3.788971	-4.026970	-4.203773
	RPT (Li *et al*. 2017)	-2.592638	-2.712947	-2.925506	-3.085463
	present (n = 3)	-2.592638	-2.712947	-2.925506	-3.085463
	present (n = 5)	-2.903931	-3.032848	-3.258721	-3.427715
	present (n = 7)	-3.073624	-3.205169	-3.436644	-3.608739
4	FSDPT (Li *et al*. 2017)	-3.582456	-3.712645	-3.953554	-4.138716
	RPT (Li *et al*. 2017)	-2.532421	-2.646085	-2.859957	-3.026620
	present (n = 3)	-2.532421	-2.646085	-2.859957	-3.026620
	present (n = 5)	-2.838945	-2.961237	-3.189162	-3.365586
	present (n = 7)	-3.006743	-3.131691	-3.365615	-3.545504

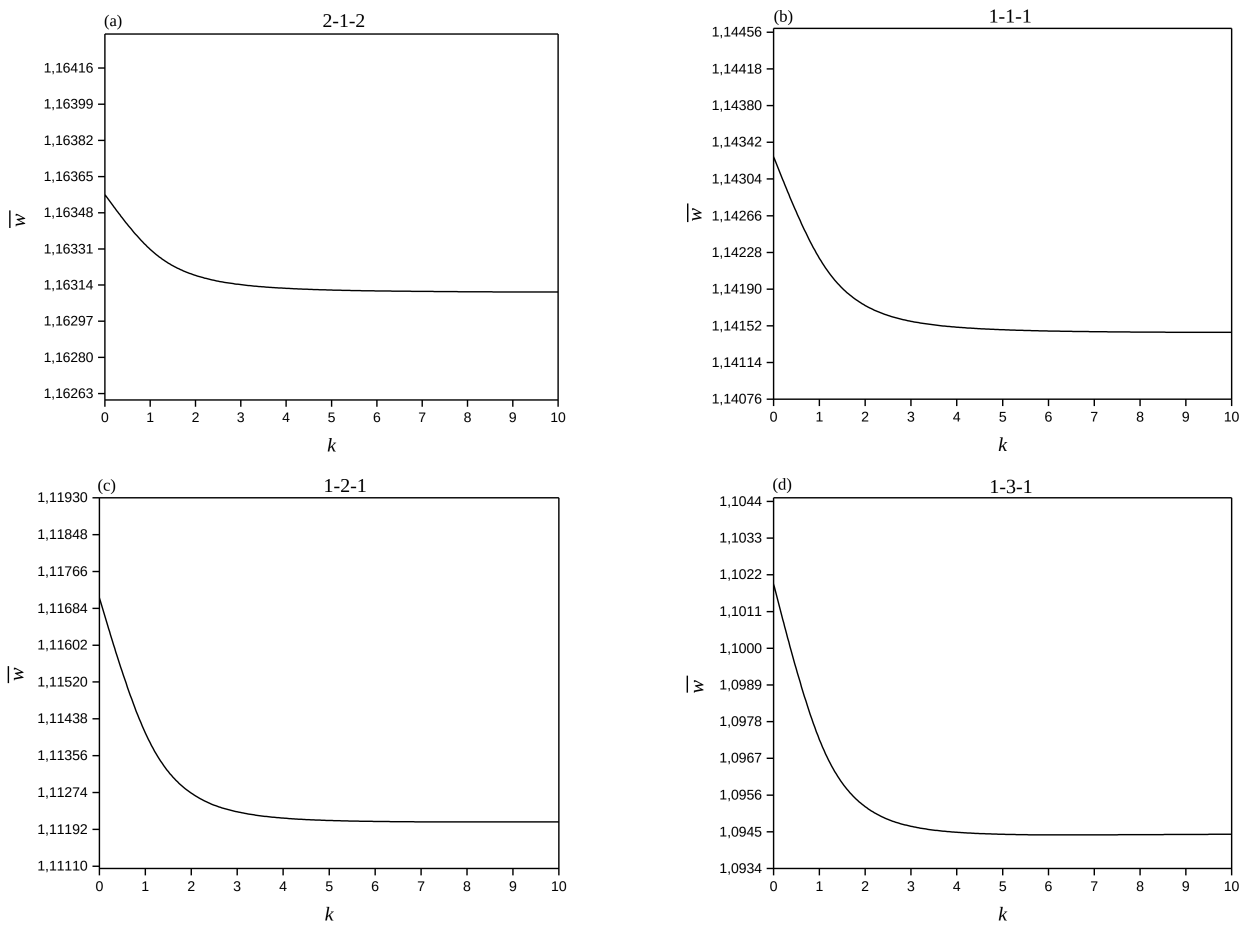

Fig. 6 Effect of the power index (k) on the dimensionless center deflection $(\overline{w})$ of sandwich plates (Type B) with FGM face sheets and symmetric S-FGM core: (a) the (2-1-2) sandwich plate; (b) the (1-1-1) sandwich plate; (c) the (1-2-1) sandwich plate; (d) the (1-3-1) sandwich plate

deflection $\overline{w}$ of a sandwich plate (Type A) with P-FGM face sheet $(p = 3)$ and E-FGM core $(k = 1)$ under a thermo-mechanical loading as a function of the dimension ratio (a/b) and the layer thickness ratios. It can be seen that the non-dimensional central deflection is in inverse relation with the aspect ratio (a/b) and the thickness of the core of the plate.

The variation of the non-dimensional normal stress $(\overline{\sigma}_x)$ as a function of the material index of the face sheets (p) and the layer thickness ratios is presented in Table 10, from the obtained results, it can be noted that the values of the non-dimensional normal stress $\overline{\sigma}_x$ decreases with increasing of the power index p in the case of $p \geq 1$. It can be also concluded that the lowest values of $\overline{\sigma}_x$ are found for

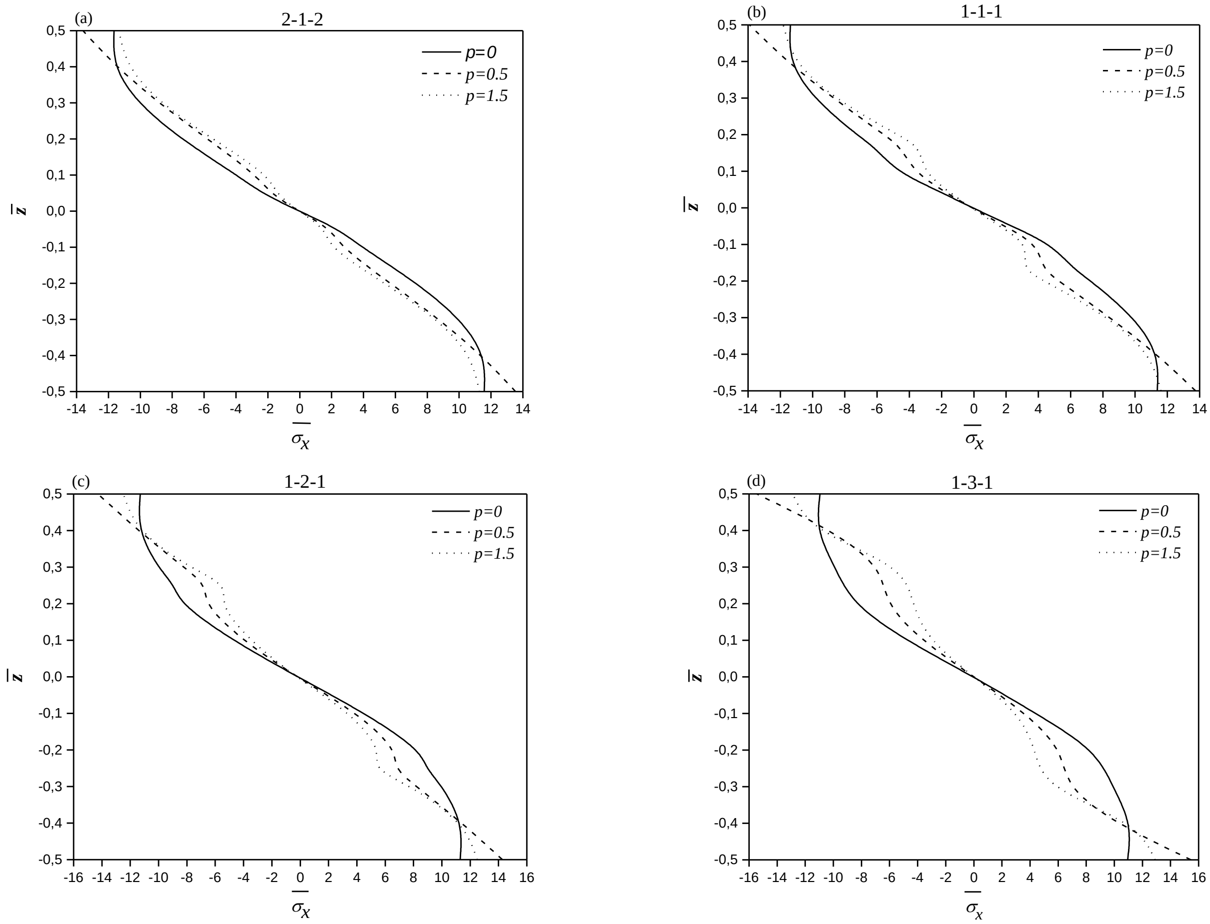

Fig. 7 Variation of the normal stress $\overline{\sigma_x}$ across the thickness of sandwich plates ($a/h = 5$, Type B) with FGM face sheets and symmetric S-FGM core($k = 0.5$): (a) the (2-1-2) sandwich plate; (b) the (1-1-1) sandwich plate; (c) the (1-2-1) sandwich plate; (d) the (1-3-1) sandwich plate

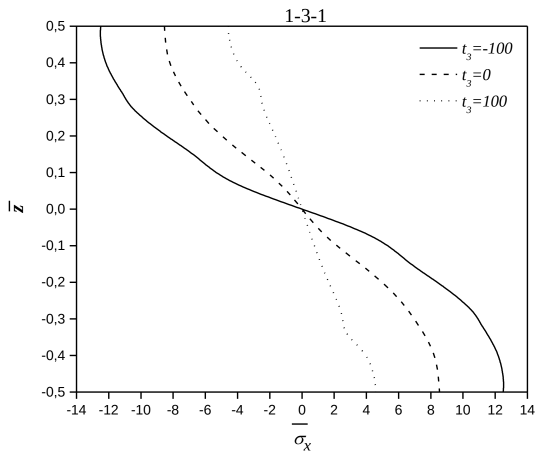

Fig. 8 Effect of the thermal load t_3 on the normal stress $\overline{\sigma}_x$ of the square (1-3-1) sandwich plate (Type B) with FGM face sheets $(p = 1.5)$ and symmetric S-FGM core $(k = 1.5)$

a layer thickness ratio 2- 1-2.

Fig. 6 depicts plots of the non-dimensional central deflection $\overline{w}$ of the sandwich plate ($a/h = 5$, Type B) with FGM face sheet ($p = 1.5$) and symmetric S-FGM core as a function of the power index (k) for the various layer thickness ratios such as (2-1-2, 1-1-1, 1-2-1 and 1-3-1).

From the curves obtained, it can be concluded that the central deflection $(\overline{w})$ is in inverse relation with the power parameter k and that for the different layer thickness ratios.

Fig. 7 illustrates the variation of the normal stress $(\overline{\sigma}_x)$ across the thickness h of the square plate (Type B) with P-FGM face sheet and symmetric S-FGM core with ($k = 0.5$) as a function of the power index ($p = 0, 0.5, 1.5$). According to the obtained results, we can note that the variation of the stress $\overline{\sigma}_x$ is continuous and nonlinear through the thickness, it can be also seen that the stress $\overline{\sigma}_x$ is not smooth at the interfaces and depends the thickness of the core of the plate. It is found that in the lower part it is a tensile stress and in the upper part it is a compression stress.

Fig. 8 shows the effect of the thermal load t_3 on the distribution of the normal stress $\overline{\sigma}_x$ of the square (1-3-1) plate (Type B) with P-FGM face sheet $(p = 1.5)$ and symmetric S-FGM core ($k = 1.5$). It can be concluded from these graphs that the thermal load (t_3) has a significant effect on the normal stress $(\overline{\sigma}_x)$.

5. Conclusions

In this research, the thermo-mechanical flexural response of the sandwich plate with P-FGM face sheets and E-FGM and symmetric S-FGM core is studied by utilizing a novel n^{th} order shear deformation theory. The virtual work principle is employed to determine the governing equations and this last are solved by using the Navier method. The obtained results are in good agreement with those given by the RPT, which shows the efficiency and accuracy of the current theory. From the results, it can be concluded that the material index of the volume fractions (E-FGM, P-FGM and symmetric S-FGM) have a significant effect on the dimensionless deflection and stresses of simply supported sandwich plates. An improvement of the present study will be considered in the future work to consider other types of materials and structures (Panjehpour *et al*. 2013, 2018, Panjehpour 2014, Ahouel *et al*. 2016, Besseghier *et al*. 2017, Bellifa *et al*. 2017b, Daouadji 2017, Karami *et al*. 2017, 2018a, b, c, d, 2019a, b, c, Yeghnem *et al*. 2017, Mouffoki *et al*. 2017, Bouadi *et al*. 2018, Narwariya *et al*. 2018, Bakhadda *et al*. 2018, Ayat *et al*. 2018, Cherif *et al*. 2018, Kaci *et al*. 2018, Kadari *et al*. 2018, Behera and Kumari 2018, Youcef *et al*. 2018, Adda Bedia *et al*. 2019, Berghouti *et al*. 2019, Hussain *et al*. 2019, Medani *et al*. 2019, Boutaleb *et al*. 2019, Bensattalah *et al*. 2019, Draoui *et al*. 2019) and also to take into account the stretching effect (Bessaim *et al*. 2013, Belabed *et al*. 2014, Hebali *et al*. 2014, Bousahla *et al*. 2014, Larbi Chaht *et al*. 2015, Bourada *et al*. 2015, Hamidi *et al*. 2015, Draiche *et al*. 2016, Bennoun *et al*. 2016, Sekkal *et al*. 2017b, Ait Atmane *et al*. 2017, Bouafia *et al*. 2017, Benchohra *et al*. 2018, Younsi *et al*. 2018, Bouhadra *et al*. 2018, Abualnour *et al*. 2018, Boukhlif *et al*. 2019, Boulefrakh *et al*. 2019, Zaoui *et al*. 2019, Zarga *et al*. 2019, Bendaho *et al*. 2019, Benmansour *et al*. 2019, Bouanati *et al*. 2019, Khiloun *et al*. 2019).

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