Steel and Composite Structures, *Vol. 32, No. 5 (2019) 611-632*
DOI: https://doi.org/10.12989/scs.2019.32.5.611

Thermomechanical bending investigation of FGM sandwich plates using four shear deformation plate theory

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(*Received April 4, 2019, Revised June 9, 2019, Accepted June 24, 2019*)

Abstract. In this work, a four-variable refined plate model is applied to study the thermomechanical bending of two kinds of functionally graded material (FGM) sandwich plates. The sandwich core of one kind is isotropic with the FGM face sheets whereas in the second kind, the sandwich core is FGM with the isotropic and homogeneous face sheets. By considering only four unknown variables, the governing equations are written based on the principle of virtual work and then Navier method is employed to solve these equations. Deflections and stresses of two kinds of FGM sandwich structures are analyzed and discussed. The validity and efficiency of the proposed model is checked by comparing it with various available solutions in the literature. The effects of volume fraction distribution, geometric ratio and thermal load on thermomechanical bending properties of FGM sandwich plate are investigated in detail.

Keywords: sandwich plate; thermomechanical; HSDT; functionally graded material

1. Introduction

There is long time that sandwich structures have been widely used in the aeronautical, aerospace, marine / marine, construction, transportation and wind energy sectors due to their outstanding properties such as high rigidity and low weight (Vinson 2001, 2005, Ahmed 2014, Meziane *et al*. 2014, Nguyen *et al*. 2015, Yahia *et al*. 2015, Tian *et al*. 2016, Kolahchi *et al*. 2017a, Daouadji and Adim 2017, Mehar and Panda 2018a, Tahouneh 2018, Ebrahimi and Farazmandnia 2018, Abazid *et al*. 2018, Dash *et al*. 2019, Draoui *et al*. 2019, Meksi *et al*. 2019). Although sandwich structures provide benefits over other kinds of structures, abrupt changes in material characteristics at face-to-core interfaces can result in high interlaminar stresses, often inducing to delamination, which is an important problem in conventional sandwich structures. In addition, the difference in thermal coefficients of materials can lead to residual stresses. One way to overcome this problem is to introduce functionally graded material (FGM). FGM refers to heterogeneous composite materials whose properties vary progressively from one surface to the other, resulting in a continuous variation in the properties of the materials, thus eliminating the abrupt changes in thermo-mechanical properties mentioned above (Koizumi 1997, Shaw 1998, Birman *et al*. 2013, Swaminathan *et al*. 2015, Belkorissat *et al*. 2015, Zemri *et al*. 2015, Benferhat *et al*. 2016, Bellifa *et al*. 2016, Bounouara *et al*. 2016, Houari *et al*. 2016, Panyatong *et al*. 2016, Ahouel *et al*. 2016, Ebrahimi and Daman 2017, Chen *et al*. 2017, Besseghier *et al*. 2017, Benadouda *et al*. 2017, Zidi *et al*. 2017, Akbas 2017, Hachemi *et al*. 2017, Sekkal *et al*. 2017a, Shahsavari *et al*. 2018, Selmi and Bisharat 2018, Mehar *et al*. 2018, Fourn *et al*. 2018, Eltaher *et al*. 2018, Karami *et al*. 2018a, b, Zine *et al*. 2018, Bakhadda *et al*. 2018, Belabed *et al*. 2018, Mehar and Panda 2018b, Faleh *et al*. 2018, Karami *et al*. 2019a, b, Avcar 2019, Chaabane *et al*. 2019, Bourada *et al*. 2019).

A number of works have been carried out to investigate the bending response of FGM plates subjected to thermal or thermo-mechanical loads. Cheng and Batra (2003) investigated thermo-mechanical bending of a linear elastic FG elliptic plate. Reddy and Cheng (2001) analyzed 3D thermo-mechanical bending of simply supported FG rectangular plates by employing an asymptotic method. Vel and Batra (2002) proposed an exact solution for 3D deformations of simply supported FG thick plates under mechanical and thermal loads. Shen (2002) investigated

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http://www.techno-press.org/?journal=scs&subpage=6
ISSN: 1229-9367 (Print), 1598-6233 (Online)

nonlinear bending behavior of simply supported FG plates under transverse loads in thermal environments utilizing a mixed Galerkin-perturbation method. Yang and Shen (2003) used a semi-numerical formulation to study nonlinear thermo-mechanical bending of FG thick plates by considering various boundary conditions. Na and Kim (2006) investigated nonlinear static of FG plates under an uniform pressure and thermal loads employing a 3-Dfinite element method. Brischetto *et al*. (2008) employed the Carrera's unified approach (Carrera and Brischetto 2009, Carrera and Petrolo 2010, Carrera *et al*. 2013, Fazzolari and Carrera 2013, Petrolo *et al*. 2015) to study thermo-mechanical bending of a simply supported FG rectangular plate. Zhao and Liew (2009) analyzed the nonlinear behavior of FG ceramic-metal plates subjected to mechanical and thermal loads employing the mesh-free kp-Ritz procedure. Sepahi *et al*. (2010) presented a nonlinear bending analysis of annular FGM plates under the effects of three-parameter elastic foundations and thermo-mechanical loadings using DQM. Bouderba *et al*. (2013) studied thermo-mechanical bending behavior of FG thick plates resting on Winkler-Pasternak elastic foundations based on a refined trigonometric shear deformation theory. Tounsi *et al*. (2013) performed a thermoelastic bending investigation of FG sandwich plates using a refined trigonometric shear deformation model. In their work, the core layer is considered as FGM and two face sheets with different material characteristics. Zhu *et al*. (2014) carried out a geometrically nonlinear thermo-mechanical investigation of moderately thick FGM plates employing a local meshless technique with Kriging interpolation method. Tung and Duc (2014) analyzed the nonlinear behavior of thick FG doubly curved shallow panels resting on elastic foundations and subjected to thermo-mechanical loads. Kar and Panda (2015) presented a thermoelastic analysis of FG doubly curved shell panels using nonlinear finite element method. Mantari and Granados (2015a, b) presented a thermoelastic bending study of two kinds of FG sandwich plates by employing a novel quasi-3D hybrid type HSDT with 5 unknowns. Li *et al*. (2016) developed a four-variable refined plate theory to investigate the thermo-mechanical bending of two types of FG sandwich plates.

Recently, new plate/beams theories were developed to study the mechanical behaviors of structures made of different types of materials (Zidi *et al*. 2014, Al-Basyouni *et al*. 2015, Kolahchi and Moniri Bidgoli 2016, Madani *et al*. 2016, Kolahchi *et al*. 2016a, b, Bilouei *et al*. 2016, Boukhari *et al*. 2016, Arani and Kolahchi 2016, Mahapatra *et al*. 2016, Kolahchi *et al*. 2017b, c, Zamanian *et al*. 2017, Kolahchi and Cheraghbak 2017, Avcar and Alwan 2017, Sahoo *et al*. 2017, Bellifa *et al*. 2017a, Hajmohammad *et al*. 2017, Kolahchi 2017, Suman *et al*. 2017, Klouche *et al*. 2017, Karami *et al*. 2017, Lal *et al*. 2017, Hajmohammad *et al*. 2018a, b, c, Amnieh *et al*. 2018, Sharma *et al*. 2018, Katariya *et al*. 2018, Karami *et al*. 2018c, Avcar and Mohammed 2018, Yazid *et al*. 2018, Fakhar and Kolahchi 2018, Hirwani and Panda 2018, 2019, Golabchi *et al*. 2018, Bouadi *et al*. 2018, Behera and Kumari 2018, Mokhtar *et al*. 2018, Hirwani *et al*. 2018a, b, Hosseini and Kolahchi 2018, Kadari *et al*. 2018, Kaci *et al*. 2018, Karami *et al*. 2019c, Bouanati *et al*. 2019, Katariya and Panda 2019, Adda Bedia *et al*. 2019, Mehar and Panda 2019) and it is an interesting topic for scientific community.

The purpose of this work is to study the thermo-mechanical bending response of FG sandwich plates employing a refined 4-variable plate model. The use of the integral term in the displacement field led to a reduction in the number of unknowns and governing equations. Two kinds of FG sandwich plates are considered in this study. In the first kind the sandwich core is isotropic and homogeneous with the FGM face sheets while in the second kind the sandwich core is FGM with the face sheets isotropic and homogeneous. Some examples are considered to check the validity and efficiency of the proposed theory. The influences of material index, aspect ratio and thermal load on the non-dimensional displacements and stresses of the FG sandwich plates are examined.

2. Theoretical formulation

In this research, two types of FG sandwich plates are examined (see Fig. 1). The first type of sandwich plate (FG sandwich plate "A") has FGM face sheets and ceramic core and the second type has metal bottom face sheet, ceramic top face sheet and FGM core (FG sandwich plate "B"). The core of each FG sandwich plate is between h_1 and h_2, the bottom and the top face sheets are between (h_0, h_1) and (h_2, h_3), respectively.

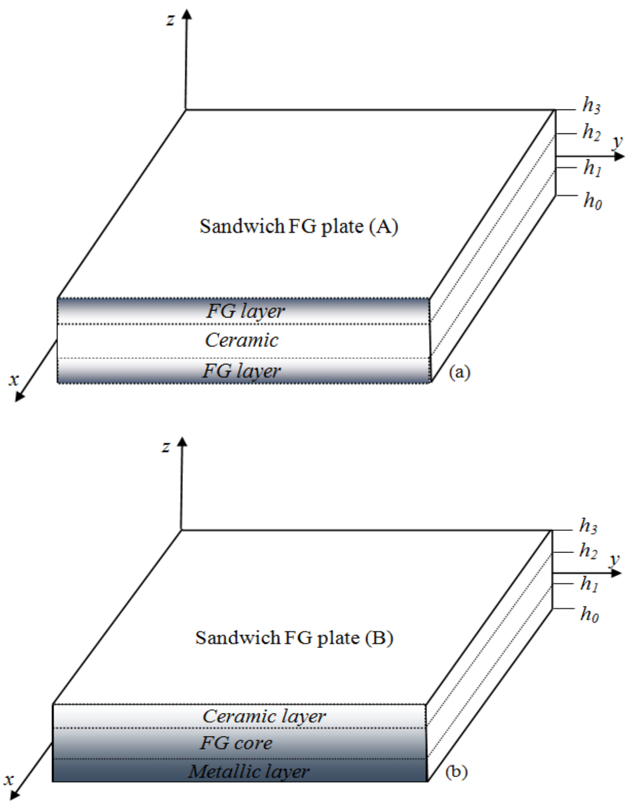

Fig. 1 Two different types of FG sandwich plates: (a) FGM face sheets and homogeneous core; (b) Homogeneous face sheets and FGM core

2.1 FG sandwich plates "A": sandwich plates with FGM face sheets and homogeneous core

In the FG sandwich plates "A", the middle layer "core" is isotropic $p = 0$ (fully ceramic), the bottom face sheet "layer 1" varies from a metal-rich surface "h_0" to a ceramic-rich surface "h_1" and the top face sheet "layer 3" varies from a ceramic-rich surface "h_2" to a metal-rich surface "h_3" (as illustrated in Fig. 1). In this type of sandwich plate does not exist the interface at ($z = h_1$ and $z = h_2$), the volume fraction $V^{(n)}$ of the FG sandwich plates "A", is obtained as (Belalia 2017, Mantari and Monge 2016, Elmossouess *et al*. 2017, Abdelaziz *et al*. 2017, Menasria *et al*. 2017, El-Haina *et al*. 2017)

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

$$V^{(2)} = 1 \qquad \text{for } z \in [h_1, h_2] \tag{1b}$$

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

where 1, 2 and 3 represent are the number of layers from bottom to top, respectively. $V^{(n)}$ is the volume fraction of nth layer of the plate and p is the material index with ($p \geq 0$).

2.2 FG sandwich plates "B": sandwich plates with homogeneous face sheets and FGM core

The middle layer in the FG sandwich plates "B" is with functionally graded material and varies from a metal-rich surface "h_1" to a ceramic-rich surface "h_2", the bottom face sheet is fully metallic and the top face sheet is fully ceramic, The volume fraction $V^{(n)}$ of the FG sandwich plates "B", is expressed as (Li *et al*. 2016)

$$V^{(1)} = 0 \qquad \text{for } z \in [h_0, h_1] \tag{2a}$$

$$V^{(2)} = \left(\frac{z-h_1}{h_2-h_1}\right)^p \qquad \text{for } z \in [h_1, h_2] \tag{2b}$$

$$V^{(3)} = 1 \qquad \text{for } z \in [h_2, h_3] \tag{2c}$$

2.3 Material properties

The effective material properties: Young's modulus $E^{(n)}$, Poisson's ratio $\mu^{(n)}$ and thermal expansion coefficient $\alpha^{(n)}$ can be expressed as follows (Marur 1999)

$$E^{(n)}(z) = E_m + (E_c - E_m)V^{(n)} \tag{3a}$$

$$\mu^{(n)}(z) = \mu_m + (\mu_c - \mu_m)V^{(n)} \tag{3b}$$

$$\alpha^{(n)}(z) = \alpha_m + (\alpha_c - \alpha_m)V^{(n)} \tag{3c}$$

Where index m and c represent metal and ceramic respectively.

2.4 Higher-order plate theory

In order to reduce the number of unknown variables of the classical HSDT, the rotations ϕ_x and ϕ_y caused by shear are replaced by $\int \theta(x,y)dx$ and $\int \theta(x,y)dy$, respectively. The expression of the classical HSDT with five variables is given as

$$u(x,y,z) = u_0(x,y) - z\frac{\partial w_0(x,y)}{\partial x} + \psi(z)\theta_x(x,y) \tag{4a}$$

$$v(x,y,z) = v_0(x,y) - z\frac{\partial w_0(x,y)}{\partial y} + \psi(z)\theta_y(x,y) \tag{4b}$$

$$w(x,y,z) = w_0(x,y) \tag{4c}$$

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.

Taking into account the simplification cited above, the present refined plate theory with four variables can be expressed in the simplest way as following form (Bourada *et al*. 2016, 2018, Ait Sidhoum *et al*. 2017, Fahsi *et al*. 2017, Chikh *et al*. 2017, Bellifa *et al*. 2017b, Berghouti *et al*. 2019)

$$u(x,y,z) = u_0(x,y) - z\frac{\partial w_0}{\partial x} + k_1 f(z)\int \theta(x,y)\,dx \tag{5a}$$

$$v(x,y,z) = v_0(x,y) - z\frac{\partial w_0}{\partial y} + k_2 f(z)\int \theta(x,y)\,dy \tag{5b}$$

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

In this investigation, the proposed theory has a cosines function in the form

$$f(z) = \frac{z\left(\pi + 2\cos\left(\frac{\pi z}{h}\right)\right)}{(2+\pi)} \tag{5d}$$

The strain associated to the above displacement field Eq. (5) can be obtained as follows

$$\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} = \begin{Bmatrix} \varepsilon_x^{(0)} \\ \varepsilon_y^{(0)} \\ \gamma_{xy}^{(0)} \end{Bmatrix} + z\begin{Bmatrix} k_x^b \\ k_y^b \\ k_{xy}^b \end{Bmatrix} + f(z)\begin{Bmatrix} k_x^s \\ k_y^s \\ k_{xy}^s \end{Bmatrix}, \qquad \varepsilon_z = 0, \begin{Bmatrix} \gamma_{yz} \\ \gamma_{xz} \end{Bmatrix} = f'(z)\begin{Bmatrix} \gamma_{yz}^{(0)} \\ \gamma_{xz}^{(0)} \end{Bmatrix} \tag{6a}$$

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

$$\begin{Bmatrix} k_x^s \\ k_y^s \\ k_{xy}^s \end{Bmatrix} = \begin{Bmatrix} k_1\theta \\ k_2\theta \\ k_1 \dfrac{\partial}{\partial y}\int \theta\, dx + k_2 \dfrac{\partial}{\partial x}\int \theta\, dy \end{Bmatrix}, \begin{Bmatrix} \gamma_{yz}^{(0)} \\ \gamma_{xz}^{(0)} \end{Bmatrix} = \begin{Bmatrix} k_2 \int \theta\, dy \\ k_1 \int \theta\, dx \end{Bmatrix}$$

and

$$f'(z) = \frac{\pi + 2\cos\left(\dfrac{\pi z}{h}\right)}{(2+\pi)} - \frac{2z\sin\left(\dfrac{\pi z}{h}\right)\pi}{h(2+\pi)} \tag{6c}$$

The indeterminate integrals used in the above Eqs. (4) and (6) shall be resolved by a Navier type solution and can be expressed as follows

$$\begin{aligned} &\frac{\partial}{\partial y}\int \theta\, dx = A'\frac{\partial^2\theta}{\partial x \partial y}, \qquad \frac{\partial}{\partial x}\int \theta\, dy = B'\frac{\partial^2\theta}{\partial x \partial y}, \\ &\int \theta\, dx = A'\frac{\partial \theta}{\partial x}, \qquad \int \theta\, dy = B'\frac{\partial \theta}{\partial y} \end{aligned} \tag{7}$$

where the coefficients A' and B' depend on the type of solution (in this case Navier method). Hence, A' and $B'$are obtained as follows

$$A' = -\frac{1}{\lambda^2}, \quad B' = -\frac{1}{\mu^2}, \quad k_1 = \lambda^2, \quad k_2 = \mu^2 \tag{8}$$

where λ and μ are used in expression (25).

2.5 Constitutive equations

By introducing the thermal effect, the stress-strain relationships for the nth layer can be written as (Li *et al*. 2016, Elmossouess *et al*. 2017)

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{Bmatrix}^{(n)} = \begin{bmatrix} c_{11} & c_{12} & 0 & 0 & 0 \\ c_{12} & c_{22} & 0 & 0 & 0 \\ 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & c_{66} \end{bmatrix}^{(n)} \begin{Bmatrix} \varepsilon_x - \alpha T \\ \varepsilon_y - \alpha T \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{Bmatrix}^{(n)}, \tag{9}$$

$$\mathrm{n} = (1,2,3)$$

Where (σ_x, σ_y, τ_{xy}, τ_{yz}, τ_{xz}) are the stresses and (ε_x, ε_y, γ_{xy}, γ_{yz}, γ_{xz}) are the strains components.

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

$$\begin{aligned} &c_{11}^{(n)} = c_{22}^{(n)} = \frac{E^{(n)}(z)}{1-(\mu^{(n)})^2}, c_{12}^{(n)} = \mu^{(n)} c_{11}^{(n)}, \\ &c_{44}^{(n)} = c_{55}^{(n)} = c_{66}^{(n)} = \frac{E^{(n)}(z)}{2(1+\mu^{(n)})} \end{aligned} \tag{10}$$

2.6 Governing equations

By utilization of the Virtual Work principle, the total potential energy of the FG sandwich plate for the present problem is obtained as follows (Attia *et al*. 2015, Beldjelili *et al*. 2016, Bousahla *et al*. 2016, Bouderba *et al*. 2016, Khetir *et al*. 2017, Mouffoki *et al*. 2017, Youcef *et al*. 2018, Cherif *et al*. 2018, Semmah *et al*. 2019)

$$\begin{aligned} U = \frac{1}{2}\int_V &\begin{bmatrix} \sigma_x^{(n)}(\varepsilon_x - \alpha T)^{(n)} + \sigma_y^{(n)}(\varepsilon_y - \alpha T)^{(n)} + \\ \tau_{xy}^{(n)}\gamma_{xy}^{(n)} + \tau_{yz}^{(n)}\gamma_{yz}^{(n)} + \tau_{xz}^{(n)}\gamma_{xz}^{(n)} \end{bmatrix} \mathrm{d}V \\ &- \int_\Omega q w \mathrm{d}\Omega \end{aligned} \tag{11}$$

The virtual work principle can be rewritten as

$$\begin{aligned} &\int_\Omega (N_x \delta\varepsilon_{\mathrm{x}}^{(0)} + N_y \delta\varepsilon_{\mathrm{y}}^{(0)} + N_{xy}\delta\gamma_{\mathrm{xy}}^{(0)} + M_x^b \delta k_x^b + M_y^b \delta k_y^b + \\ &M_{xy}^b \delta k_{xy}^b + M_x^s \delta k_x^s + M_y^s \delta k_y^s + M_{xy}^s \delta k_{xy}^s + Q_{yz}^s \delta\gamma_{yz}^{(0)} + \\ &Q_{yz}^s \delta\gamma_{yz}^{(0)}) \mathrm{d}\Omega - \int_\Omega q w \mathrm{d}\Omega \end{aligned} \tag{12}$$

where the stress resultants N, M and Q are defined as

$$\begin{aligned} &\begin{bmatrix} N_x & N_y & N_{xy} \\ M_x^b & M_y^b & M_{xy}^b \\ M_x^s & M_y^s & M_{xy}^s \end{bmatrix} = \sum_{n=1}^{3}\int_{h_{n-1}}^{h_n} \begin{Bmatrix} 1 \\ z \\ f(z) \end{Bmatrix} (\sigma_x, \sigma_y, \tau_{xy})^{(n)} \mathrm{dz}, \\ &(Q_{yz}^s, Q_{yz}^s) = \sum_{n=1}^{3}\int_{h_{n-1}}^{h_n} (\tau_{yz}, \tau_{xz})^{(n)} f'(\mathrm{z})\mathrm{dz} \end{aligned} \tag{13}$$

Where h_{n-1} and h_n are the bottom and top z-coordinates of the n^{th} layer, respectively.

The governing equations of equilibrium can be obtained by substituting Eq. (6) into Eq. (12). Integrating the resulting equation by parts and then collecting the coefficients of displacement (δu_0, δv_0, δw_0, $\delta\theta$), the governing equations are as follow

$$\delta u_0 : \frac{\partial N_x}{\partial x} + \frac{\partial N_{xy}}{\partial y} = 0 \tag{14a}$$

$$\delta v_0 : \frac{\partial N_{xy}}{\partial x} + \frac{\partial N_y}{\partial y} = 0 \tag{14b}$$

$$\delta w_0 : \frac{\partial^2 M_x^b}{\partial x^2} + 2\frac{\partial^2 M_{xy}^b}{\partial x \partial y} + \frac{\partial^2 M_y^b}{\partial y^2} + q = 0 \tag{14c}$$

$$\delta\theta: \; -k_1 M_x^s - k_2 M_y^s \; -\left(k_1 A' + k_2 B'\right)\frac{\partial^2 M_{xy}^s}{\partial x \partial y} + k_1 A' \frac{\partial Q_{xy}^s}{\partial x} + k_2 B' \frac{\partial Q_{xy}^s}{\partial x} = 0 \tag{14d}$$

The stress and moment resultants are obtained by replacing Eqs. (6) and (9) into Eq. (13), the stress and moment resultants can be written as

$$\begin{Bmatrix} \{N\} \\ \{M^b\} \\ \{M^s\} \end{Bmatrix} = \begin{bmatrix} [A] & [B] & [C] \\ [B] & [D] & [F] \\ [C] & [F] & [H] \end{bmatrix} \begin{Bmatrix} \{\varepsilon^{(0)}\} \\ \{k^b\} \\ \{k^s\} \end{Bmatrix} - \begin{Bmatrix} \{N^T\} \\ \{M^{bT}\} \\ \{M^{sT}\} \end{Bmatrix}, \quad \begin{Bmatrix} Q_{yz} \\ Q_{xz} \end{Bmatrix} = \begin{bmatrix} J_{44} & 0 \\ 0 & J_{55} \end{bmatrix} \begin{Bmatrix} \gamma_{yz}^{(0)} \\ \gamma_{xz}^{(0)} \end{Bmatrix} \tag{15}$$

Where

$$\begin{gathered} \{N\} = \{N_x \; N_y \; N_{xy}\}^T, \{M^b\} = \{M_x^b \; M_y^b \; M_{xy}^b\}^T, \\ \{M^s\} = \{M_x^s \; M_y^s \; M_{xy}^s\}^T \\ \{N^T\} = \{N_x^T \; N_y^T \; 0\}^T, \{M^{bT}\} = \{M_x^{bT} \; M_y^{bT} \; 0\}^T, \\ \{M^s\} = \{M_x^{sT} \; M_y^{sT} \; 0\}^T \\ \{\varepsilon^{(0)}\} = \{\varepsilon_x^{(0)} \; \varepsilon_y^{(0)} \; \gamma_{xy}^{(0)}\}^T, \{k^b\} = \{k_x^b \; k_y^b \; k_{xy}^b\}^T, \\ \{k^s\} = \{k_x^s \; k_y^s \; k_{xy}^s\}^T \end{gathered} \tag{16}$$

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

$$\{A_{ij}, B_{ij}, D_{ij}, C_{ij}, F_{ij}, H_{ij}\} = \sum_{n=1}^{3} \int_{h_{n-1}}^{h_n} c_{ij}^{(n)} \{1, z, z^2, f(z), zf(z), f^2(z)\} \; \mathrm{dz}, (i, j = 1, \; 2, 6) \tag{17}$$

and

$$j_{ii} = \sum_{n=1}^{3} \int_{h_{n-1}}^{h_n} c_{ii}^{(n)} f'(z)^2 \; \mathrm{dz}, (i = 4, \; 5) \tag{18}$$

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

$$\begin{Bmatrix} N_x^T \\ N_y^T \end{Bmatrix} = \sum_{n=1}^{3} \int_{h_{n-1}}^{h_n} \begin{Bmatrix} (c_{11} + c_{12})\alpha T \\ (c_{12} + c_{22})\alpha T \end{Bmatrix}^{(n)} \mathrm{dz} \tag{19a}$$

$$\begin{Bmatrix} M_x^{bT} \\ M_y^{bT} \end{Bmatrix} = \sum_{n=1}^{3} \int_{h_{n-1}}^{h_n} \begin{Bmatrix} (c_{11} + c_{12})\alpha T \\ (c_{12} + c_{22})\alpha T \end{Bmatrix}^{(n)} \mathrm{dz} \tag{19b}$$

$$\begin{Bmatrix} M_x^{sT} \\ M_y^{sT} \end{Bmatrix} = \sum_{n=1}^{3} \int_{h_{n-1}}^{h_n} \begin{Bmatrix} (c_{11} + c_{12})\alpha T \\ (c_{12} + c_{22})\alpha T \end{Bmatrix}^{(n)} \mathrm{dz} \tag{19c}$$

The temperature field variation $T(x, y, z)$ through the FG sandwich plate thickness is assumed to be (Houari *et al*. 2013, Taibi *et al*. 2015, Attia *et al*. 2018)

$$T(x, y, z) = T_1(x, y) + \frac{z}{h} T_2(x, y) + \frac{f(z)}{h} T_3(x, y) \tag{20}$$

Where T_1 is the uniform thermal load, T_2 is the linear thermal load and T_3 is the nonlinear thermal load.

3. Closed from solutions

In this study, the simply supported FG sandwich plate is subjected to a bi-sinusoidal load whose conditions at the four edges are

$$\begin{gathered} x = 0, a : v_0 = w_0 = \theta = 0, \frac{\partial w_0}{\partial y} = \frac{\partial \theta}{\partial y} = 0, \\ N_x = 0, M_x^b = M_x^s = 0, \end{gathered} \tag{21a}$$

$$\begin{gathered} y = 0, b : u_0 = w_0 = \theta = 0, \frac{\partial w_0}{\partial x} = \frac{\partial \theta}{\partial x} = 0, \\ N_y = 0, M_y^b = M_y^s = 0, \end{gathered} \tag{21b}$$

The bi-sinusoidal load can be expressed as

$$q(x, y) = q_0 \sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{\pi x}{b}\right) \tag{22}$$

Where a and b are length and width of the sandwich FG plate, respectively.

The Navier procedure is used herein to solve the problem of the thermo mechanical bending of sandwich FG plate, The following displacement functions of Navier are chosen to automatically satisfy the boundary conditions of Eq. (21)

$$\begin{Bmatrix} u_0 \\ v_0 \\ w_0 \\ \theta \end{Bmatrix} = \begin{Bmatrix} U_{mn} \; \cos(\lambda x) \; \sin(\mu y) \\ V_{mn} \; \sin(\lambda x) \; \cos(\mu y) \\ W_{mn} \; \sin(\lambda x) \; \sin(\mu y) \\ \theta_{mn} \; \sin(\lambda x) \; \sin(\mu y) \end{Bmatrix} \tag{23}$$

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

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

$$\begin{Bmatrix} T_1 \\ T_2 \\ T_3 \end{Bmatrix} = \begin{Bmatrix} t_1 \\ t_2 \\ t_3 \end{Bmatrix} \sin(\lambda x)\sin(\mu y) \tag{24}$$

t_1, t_2 and t_3 are constants.

With

$$\lambda = \pi / a, \quad \mu = \pi / b \tag{25}$$

By substituting Eqs. (22), (23) and (24) into Eq. (15) and the subsequent results into Eq. (14), one gets the following operator equation

$$[K]\{\Delta\} = \{P\} \tag{26}$$

where $\{\Delta\} = \{U\ V\ W\ \theta\}^T$ and the elements K_{ij} of the symmetric matrix $[K]$ are given by

$$\begin{aligned}
K_{11} &= A_{11}\lambda^2 + A_{66}\mu^2 \\
K_{12} &= \lambda\mu(A_{12} + A_{66}) \\
K_{13} &= -\lambda[B_{11}\lambda^2 + (B_{12} + 2B_{66})\mu^2] \\
K_{14} &= \lambda[k_1A'C_{11}\lambda^2 + (k_2B'C_{12} + (k_1A' + k_2B')C_{66})\mu^2] \\
K_{22} &= A_{66}\lambda^2 + A_{22}\mu^2 \\
K_{23} &= -\mu[B_{11}\mu^2 + (B_{12} + 2B_{66})\lambda^2] \\
K_{24} &= \mu[k_2B'C_{22}\mu^2 + (k_1A'C_{12} + (k_1A' + k_2B')C_{66})\lambda^2] \\
K_{33} &= D_{11}\lambda^4 + \mu^2 2(D_{12} + 2D_{66})\lambda^2\mu^2 + D_{22}\mu^4 \\
K_{34} &= -k_1A'F_{11}\lambda^4 - [(k_1A' + k_2B')F_{12} + 2(k_1A' + k_2B')F_{66}]\lambda^2\mu^2 \\
&\quad - k_2B'F_{22}\mu^4 \\
K_{44} &= k_1^2A'^2H_{11}\lambda^4 + [2k_1k_2A'B'H_{12} + (k_1A' + k_2B')^2H_{66}]\lambda^2\mu^2 \\
&\quad + k_2^2B'^2H_{22}\mu^4 + k_1^2A'^2J_{55}\lambda^2 + k_2^2B'^2H_{22}\mu^2
\end{aligned} \tag{27}$$

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

$$\begin{aligned}
P_1 &= -\lambda(A^Tt_1 + B^Tt_2 + {}^aB_Tt_3) \\
P_2 &= -\mu(A^Tt_1 + B^Tt_2 + {}^aB_Tt_3) \\
P_3 &= q_0 + h(\lambda^2 + \mu^2)(B^Tt_1 + D^Tt_2 + {}^aD_Tt_3) \\
P_4 &= -h(k_1A'\lambda^2 + k_2B'\mu^2)({}^aB_Tt_1 + {}^aD_Tt_2 + {}^aF_Tt_3)
\end{aligned} \tag{28}$$

in which

$$\left\{A^T, B^T, D^T\right\} = \sum_{n-1}^{3} \int_{h_{n-1}}^{h_n} \frac{E^{(n)}(z)}{1-(\mu^{(n)})^2}(1+\mu^{(n)})\alpha^{(n)} \left\{1, \bar{z}, \bar{z}^2\right\} \mathrm{d}z \tag{29a}$$

$$\left\{{}^aB_T, {}^aD_T, {}^aF_T\right\} = \sum_{n-1}^{3} \int_{h_{n-1}}^{h_n} \frac{E^{(n)}(z)}{1-(\mu^{(n)})^2}(1+\mu^{(n)})\alpha^{(n)} \bar{f}(z) \left\{1, \bar{z}, \bar{f}(z)\right\} \mathrm{d}z \tag{29b}$$

Where

$$\bar{z} = z/h, \ \bar{f}(z) = f(z)/h \tag{30}$$

4. Numerical results

In this section, various numerical examples are presented and discussed to verify the accuracy of the present refined plate theory with four variables which has a displacement field containing four unknowns to investigate the bending responses of two types of functionally graded material (FGM) sandwich plates under mechanical, thermal and thermomechanical loads.

4.1 Bending analysis of sandwich plate "A" under mechanical load

This example aims to verify the accuracy of the present theory in predicting the bending responses of functionally graded sandwich plates type "A". It is assumed that the FG sandwich plate type "A" is made from aluminum and zirconia. The following material properties are:

metal (aluminum): E_m = 70 GPa, μ_m = 0.3
ceramic (zirconia): E_c = 151 GPa, μ_c = 0.3

The following non-dimensional deflection is used

$$\hat{w} = \frac{10E_0h}{q_0a^2} w \left(\frac{a}{2}, \frac{b}{2}\right) \tag{31}$$

Table 1 contains the non-dimensional transverse displacement $\hat{w}$ of the mid-plane under sinusoidal loads only for various values of layer thickness ratio and material parameter p (a/h = 10). The obtained results are compared with the 2D and quasi-3D obtained by Zenkour (2005) and Zenkour (2013) respectively, the first-order shear deformation theory (FSDT) of Thai *et al*. (2014), also, the first-order shear deformation theory (FSDT), the third order shear deformation (TSDT) and sinusoidal shear deformation theory (SSDT) solution obtained by Li *et al*. (2016). It should be noted that the 2D solutions of Zenkour (2005) are derived based on a sinusoidal variation of both in-plane and transverse displacements. In general, a good agreement between the results is found, particularly with those reported by Zenkour (2005). From Table 1, it can be observed that as the core thickness increases, the dimensionless deflection decreases. The maximum dimensionless deflection occurs for the (1-0-1) FGM plate irrespective of the value of index p.

4.2 Bending analysis of sandwich plate "B" under mechanical load

In this example, a simply supported square sandwich plate "B" subjected to a sinusoidal mechanical load is considered and analyzed. The bottom skin is aluminum and

Table 1 Dimensionless deflection $\hat{w}$ of square sandwich plate “A” under sinusoidal mechanical load only (a/h = 10)

p	Theory	$\bar{w}(a/2, b/2)$				
		1-0-1	2-1-2	1-1-1	2-2-1	1-2-1
0	Zenkour (2005)	0.1961	0.1961	0.1961	0.1961	0.1961
	Thai *et al.* (2014)	0.1961	0.1961	0.1961	0.1961	0.1961
	Li *et al.* (2016) (Reissner)	0.1961	0.1961	0.1961	0.1961	0.1961
	Li *et al.* (2016) (Reddy)	0.1961	0.1961	0.1961	0.1961	0.1961
	Li *et al.* (2016) (Touratier)	0.1960	0.1960	0.1960	0.1960	0.1960
	Present	0.1960	0.1960	0.1960	0.1960	0.1960
1	Zenkour (2013)	0.3200	0.3028	0.2887	0.2776	0.2682
	Mahi *et al.* (2015)	0.3234	0.3062	0.2919	0.2808	0.2709
	Zenkour (2005)	0.3235	0.3062	0.2919	0.2808	0.2709
	Thai *et al.* (2014)	0.3237	0.3064	0.2920	0.2809	0.2710
	Li *et al.* (2016) (Reissner)	0.3236	0.3063	0.2920	0.2809	0.2709
	Li *et al.* (2016) (Reddy)	0.3236	0.3063	0.2920	0.2809	0.2709
	Li *et al.* (2016) (Touratier)	0.3235	0.3062	0.2919	0.2809	0.2709
	Present	0.3234	0.3062	0.2919	0.2808	0.2709
2	Zenkour (2013)	0.3689	0.3474	0.3282	0.3115	0.2987
	Mahi *et al.* (2015)	0.3731	0.3521	0.3328	0.3161	0.3026
	Zenkour (2005)	0.3732	0.3522	0.3328	0.3161	0.3026
	Thai *et al.* (2014)	0.3737	0.3526	0.3330	0.3163	0.3027
	Li *et al.* (2016) (Reissner)	0.3733	0.3523	0.3329	0.3162	0.3026
	Li *et al.* (2016) (Reddy)	0.3733	0.3523	0.3329	0.3162	0.3026
	Li *et al.* (2016) (Touratier)	0.3732	0.3522	0.3328	0.3161	0.3026
	Present	0.3730	0.3520	0.3327	0.3160	0.3026
5	Zenkour (2013)	0.4053	0.3861	0.3655	0.3436	0.3297
	Mahi *et al.* (2015)	0.4089	0.3915	0.3712	0.3494	0.3347
	Zenkour (2005)	0.4091	0.3916	0.3713	0.3495	0.3347
	Thai *et al.* (2014)	0.4101	0.3927	0.3720	0.3501	0.3350
	Li *et al.* (2016) (Reissner)	0.4093	0.3918	0.3714	0.3496	0.3348
	Li *et al.* (2016) (Reddy)	0.4093	0.3918	0.3714	0.3496	0.3348
	Li *et al.* (2016) (Touratier)	0.4090	0.3916	0.3713	0.3495	0.3347
	Present	0.4088	0.3914	0.3711	0.3494	0.3347
10	Zenkour (2013)	0.4145	0.3986	0.3792	0.3558	0.3426
	Mahi *et al.* (2015)	0.4174	0.4037	0.3852	0.3619	0.3481
	Zenkour (2005)	0.4175	0.4037	0.3849	0.3492	0.3412
	Thai *et al.* (2014)	0.3988	0.3894	0.3724	0.3492	0.3361
	Li *et al.* (2016) (Reissner)	0.4177	0.4041	0.3855	0.3621	0.3482
	Li *et al.* (2016) (Reddy)	0.4177	0.4041	0.3855	0.3621	0.3482
	Li *et al.* (2016) (Touratier)	0.4175	0.4036	0.3865	0.3620	0.3480
	Present	0.4173	0.4035	0.3851	0.3619	0.3480

the top skin is alumina, while the sandwich core is assumed to be aluminum-alumina FGM. The following material properties are:

metal (aluminum): E_m = 70 GPa, μ_m = 0.3
ceramic (alumina): E_c = 380 GPa, μ_c = 0.3

The following non-dimensional deflection and non-dimensional shear stress are employed

$$\bar{w} = \frac{10E_c h^3}{q_0 a^4} w\left(\frac{a}{2}, \frac{b}{2}, z\right) \tag{32}$$

Table 2 Dimensionless shear stress $\bar{\tau}_{xz}$ and deflection $\bar{w}$ of square sandwich plate “B” under sinusoidal mechanical load only

p	Theory	$\bar{\tau}_{xz}$ (0, b/2, h/6)			$\bar{w}$ (a/2, b/2, 0)		
		a/h = 4	a/h = 10	a/h = 100	a/h = 4	a/h = 10	a/h = 100
0	Neves *et al*. (2013)	0.2208	0.2227	0.2228	0.4447	0.3711	0.3568
	Mantari and Granados (2015)	0.2080	0.2080	0.2080	0.4653	0.3750	0.3579
	Li *et al*. (2016)	0.2185	0.2191	0.2192	0.4621	0.3745	0.3579
	Present	0.2203	0.2212	0.2213	0.4622	0.3745	0.3579
0.5	Neves *et al*. (2013)	0.2546	0.2581	0.2585	0.6168	0.5238	0.5058
	Mantari and Granados (2015)	0.2373	0.2373	0.2374	0.6446	0.5268	0.5045
	Li *et al*. (2016)	0.2518	0.2525	0.2527	0.6382	0.5239	0.5023
	Present	0.2526	0.2537	0.2540	0.6373	0.5238	0.5023
1	Brischetto (2009)	0.2613	0.2605	0.2603	0.7628	0.6324	0.6072
	Neves *et al*. (2012)	0.2742	0.2788	0.2793	0.7416	0.6305	0.6092
	Neves *et al*. (2013)	0.2745	0.2789	0.2795	0.7417	0.6305	0.6092
	Mantari and Granados (2015)	0.2458	0.2458	0.2458	0.7739	0.6337	0.6073
	Li *et al*. (2016)	0.2715	0.2725	0.2727	0.7727	0.6336	0.6073
	Present	0.2729	0.2743	0.2746	0.7713	0.6334	0.6073
4	Brischetto (2009)	0.2429	0.2431	0.2432	1.0934	0.8321	0.7797
	Neves *et al*. (2012)	0.2723	0.2778	0.2785	1.0391	0.8202	0.7784
	Neves *et al*. (2013)	0.2696	0.2747	0.2753	1.0371	0.8199	0.7784
	Mantari and Granados (2015)	0.1877	0.1877	0.1877	1.0285	0.8191	0.7796
	Li *et al*. (2016)	0.2596	0.2609	0.2611	1.0815	0.8278	0.7797
	Present	0.2698	0.2718	0.2722	1.0878	0.8290	0.7797
10	Brischetto (2009)	0.1932	0.1944	0.1946	1.2172	0.8740	0.8077
	Neves *et al*. (2012)	0.2016	0.2059	0.2064	1.1780	0.8650	0.8050
	Neves *et al*. (2013)	0.1995	0.2034	0.2039	1.1752	0.8645	0.8050
	Mantari and Granados (2015)	0.1234	0.1234	0.1234	1.1108	0.8556	0.8074
	Li *et al*. (2016)	0.1897	0.1907	0.1909	1.2315	0.8724	0.8077
	Present	0.1985	0.2001	0.2004	1.2253	0.8745	0.8077

Table 3 Dimensionless center deflection $\bar{w}$ of square sandwich plate “A” under pure thermal load (t_3 = 0)

p	Theory	$\bar{w}$ (a/2, b/2, 0)				
		1-0-1	1-1-1	1-2-1	2-2-1	2-1-2
0	Zenkour and Alghamdi (2008)	0.480262	0.480262	0.480262	0.480262	0.480262
	Houari *et al*. (2013)	0.461634	0.461634	0.461634	0.461634	0.461634
	Li *et al*. (2016)	0.480262	0.480262	0.480262	0.480262	0.480262
	Present	0.480262	0.480262	0.480262	0.480262	0.480262
1	Zenkour and Alghamdi (2008)	0.636916	0.606292	0.582342	0.592604	0.621098
	Houari *et al*. (2013)	0.614565	0.586124	0.563416	0.573327	0.599933
	Li *et al*. (2016)	0.636891	0.606256	0.582302	0.592568	0.621067
	Present	0.636938	0.606324	0.582378	0.592635	0.621125
2	Zenkour and Alghamdi (2008)	0.671503	0.639361	0.609875	0.621581	0.656142
	Houari *et al*. (2013)	0.647135	0.618046	0.590491	0.601843	0.633340
	Li *et al*. (2016)	0.671486	0.639325	0.609829	0.621544	0.656115
	Present	0.671519	0.639392	0.609915	0.621613	0.656165

Table 3 Continued

p	Theory	$\bar{w}$ $(a/2, b/2, 0)$				
		1-0-1	1-1-1	1-2-1	2-2-1	2-1-2
3	Zenkour and Alghamdi (2008)	0.683572	0.653671	0.622467	0.634175	0.670275
	Houari *et al*. (2013)	0.658153	0.631600	0.602744	0.614121	0.646475
	Li *et al*. (2016)	0.683560	0.653638	0.622420	0.634139	0.670253
	Present	0.683582	0.653699	0.622507	0.634206	0.670294
4	Zenkour and Alghamdi (2008)	0.688803	0.661291	0.629533	0.640940	0.677321
	Houari *et al*. (2013)	0.662811	0.638705	0.609560	0.620663	0.652890
	Li *et al*. (2016)	0.688795	0.661260	0.629487	0.640905	0.677303
	Present	0.688810	0.661317	0.629573	0.640970	0.677337
5	Zenkour and Alghamdi (2008)	0.691420	0.665898	0.634003	0.645070	0.681343
	Houari *et al*. (2013)	0.665096	0.642948	0.613842	0.624629	0.656490
	Li *et al*. (2016)	0.691415	0.665869	0.633958	0.645036	0.681327
	Present	0.691425	0.665922	0.634042	0.645099	0.681357

Table 4 Dimensionless center deflection $\bar{w}$ of square sandwich plate "B" under pure thermal load ($t_3 = 0$)

p	Theory	$\bar{w}$ $(a/2, b/2, 0)$				
		1-2-2	1-1-1	1-2-1	2-2-1	2-1-2
0	Tounsi *et al*. (2013)	0.544640	0.569801	0.556060	0.576238	0.576238
	Li *et al*. (2016)	0.544619	0.569796	0.556044	0.576240	0.576240
	Present	0.544659	0.569806	0.556074	0.576236	0.576236
1	Tounsi *et al*. (2013)	0.573055	0.578804	0.577909	0.582578	0.579503
	Li *et al*. (2016)	0.573054	0.578809	0.577914	0.582593	0.579510
	Present	0.573056	0.578798	0.577904	0.582566	0.579497
2	Tounsi *et al*. (2013)	0.577551	0.580037	0.580945	0.584582	0.580018
	Li *et al*. (2016)	0.577555	0.580045	0.580957	0.584601	0.580025
	Present	0.577548	0.580029	0.580935	0.584565	0.580011
3	Tounsi *et al*. (2013)	0.578976	0.580412	0.581997	0.585807	0.580181
	Li *et al*. (2016)	0.578982	0.580421	0.582011	0.585829	0.580188
	Present	0.578971	0.580403	0.581984	0.585786	0.580174
4	Tounsi *et al*. (2013)	0.579572	0.580574	0.582554	0.586680	0.580249
	Li *et al*. (2016)	0.579579	0.580584	0.582570	0.586705	0.580257
	Present	0.579566	0.580566	0.582540	0.586658	0.580242
5	Tounsi *et al*. (2013)	0.579865	0.580663	0.582925	0.587346	0.580282
	Li *et al*. (2016)	0.579872	0.580673	0.582942	0.587373	0.580290
	Present	0.579859	0.580654	0.582909	0.587323	0.580275

$$\bar{\tau}_{xz} = \frac{h}{q_0 a} \tau_{xz} \left(0, \frac{b}{2}, z\right) \tag{33}$$

Table 2 contains the non-dimensional transverse displacement $\bar{w}$ of the mid-plane and non dimensional shear stresses $\bar{\tau}_{xz}$ of the FG sandwich plate made of (ZrO_2/Al) under sinusoidal loads for various values of the side-to-thickness ratio a/h and index p.

The obtained results are compared with the 2D and quasi-3D solution of Li *et al*. (2016) and Neves *et al*. (2013) respectively, and FSDT results of Mantari and Granados (2015a, b).

The shear correction factor of Mantari and Granados (2015a, b) is used to be k = 5, 6. It can be seen that the dimensionless displacement and shear stress predicted by the present 2D trigonometric theory are in excellent agreement quasi-3D solutions reported by Neves *et al*.

Table 5 Dimensionless center deflection $\bar{w}$ of square sandwich plate "A" under thermomechanical load (a/h = 10)

p	Theory	$\bar{w}$ (a/2, b/2, 0)			
		1-0-1	3-1-3	2-1-2	1-1-1
0	Zenkour and Alghamdi (2010) (SSDPT)	0.796783	0.796783	0.796783	0.796783
	Zenkour and Alghamdi (2010) (FSDPT)	0.895735	0.895735	0.895735	0.895735
	Li *et al*. (2016)	0.864140	0.864140	0.864140	0.864140
	Present	0.787002	0.787002	0.787002	0.787002
1	Zenkour and Alghamdi (2010) (SSDPT)	1.062840	1.045026	1.036213	1.011263
	Zenkour and Alghamdi (2010) (FSDPT)	1.190728	1.170533	1.160568	1.132449
	Li *et al*. (2016)	1.149038	1.130125	1.120741	1.094113
	Present	1.050078	1.032490	1.023787	0.999141
2	Zenkour and Alghamdi (2010) (SSDPT)	1.121608	1.105175	1.096094	1.068091
	Zenkour and Alghamdi (2010) (FSDPT)	1.257304	1.238234	1.227765	1.195703
	Li *et al*. (2016)	1.210756	1.193444	1.183826	1.154061
	Present	1.108126	1.091935	1.082982	1.055354
3	Zenkour and Alghamdi (2010) (SSDPT)	1.141655	1.128080	1.119793	1.092312
	Zenkour and Alghamdi (2010) (FSDPT)	1.280741	1.264724	1.255041	1.223232
	Li *et al*. (2016)	1.231675	1.217447	1.208690	1.179518
	Present	1.127875	1.114524	1.106366	1.079282
4	Zenkour and Alghamdi (2010) (SSDPT)	1.150192	1.138926	1.131428	1.105041
	Zenkour and Alghamdi (2010) (FSDPT)	1.290961	1.277527	1.268689	1.237931
	Li *et al*. (2016)	1.240542	1.228791	1.220879	1.192880
	Present	1.136264	1.125200	1.117826	1.091840
5	Zenkour and Alghamdi (2010) (SSDPT)	1.154412	1.144851	1.137993	1.112660
	Zenkour and Alghamdi (2010) (FSDPT)	1.296101	1.284626	1.276497	1.246833
	Li *et al*. (2016)	1.244905	1.234980	1.227750	1.200876
	Present	1.136262	1.131022	1.124282	1.099348

(2013). Increasing value of the power-law exponent p and decreasing value of the side-to-thickness ratio a/h, the non-dimensional deflection increases. The influence of the side-to-thickness ratio a/h on the non-dimensional transverse shear stress is insignificant.

4.3 Bending analysis of sandwich plate "A" under thermal load

In this example, the pure thermoelastic bending analysis of a simply supported square FG sandwich plate "A " is conducted for combinations of metal and ceramic materials, where q = 0. The set of materials chosen is Titanium (metal) and Zirconia (ceramic). The following material properties for metal and ceramic used in the FGM sandwich plates are:

metal (Ti-6Al-4V):
E_m = 70 GPa, μ_m = 0.3, α_m = 10.3 (10^{-6}/K)
ceramic (ZrO_2):
E_c = 380 GPa, μ_c = 0.3, α_c = 7.11 (10^{-6}/K)

In this case, we assumed that a/h = 10, t_1 = 0, t_2 = 100 K and t_3 = 0. The non-dimensional deflection parameter utilized for pure temperature loading is

$$\bar{w} = \frac{h}{\alpha_0 t_2 a^2} w \left(\frac{a}{2}, \frac{b}{2}, z\right) \tag{34}$$

where $\alpha_0 = 10^{-6}$/K.

In Table 3, the non-dimensional deflection $\bar{w}$ for a FG sandwich plate "A" subjected to a thermal field varying linearly through the thickness (t_3 = 0) is presented for various values of the material index p and different configurations of FG sandwich plates (1-0-1, 1-1-1, 1-2-1,2-2-1 and 2-1-2). Numerical results are presented using different plate theories such as the sinusoidal shear deformation plate theory (SSDPT) obtained by Zenkour and Alghamdi (2008), quasi-3D solution of Houari *et al*. (2013), 2D refined trigonometric solution of Li *et al*. (2016) and the present theory. Inspection of Table 3 reveals that the present theory with only four unknowns gives identical results to those obtained by the sinusoidal shear deformation plate theory (SSDPT) developed by Zenkour and Alghamdi (2008) with five unknowns and those obtained by Li *et al*. (2016).

This indicates that the same accuracy is obtained with the present theory using a lower number of unknowns than other theories, and clearly highlights how the present theory is simpler and more easily deployed. It is noted that due to the thickness stretching effect the dimensionless center deflection obtained by Houari *et al*. (2013) is smaller than that of the present research at the same value of index p and layer thickness ratio. Also, we can see that the dimensionless deflection increases with the increase of index p.

4.4 Bending analysis of sandwich plate "B" under thermal load

Again, in this example, we considered the special case of the present study, where (a/h = 10, $t_1 = t_3 = q = 0$ and t_2 = 100 K), a simply supported square FG sandwich plate "B" under pure thermal load. The mechanical properties for metal and ceramic used in the FG sandwich plates are the same as those given in the example above. The expression of dimensionless deflection is utilized as Eq. (33).

Table 4 performs the dimensionless center deflection w for a FG sandwich plate of type B for various values of index p and various configurations of FG sandwich plates (1-0-1, 1-1-1, 1-2-1, 2-2-1 and 2-1-1). The obtained results of the deflections are compared with the 2D solutions of Li *et al*. (2016) and Tounsi *et al*. (2013), using refined parabolic shear deformation theory and refined trigonometric shear deformation with four unknowns only respectively. It is clearly seen that an excellent agreement is obtained in this comparison.

4.5 Bending analysis of sandwich plate "A" under thermomechanical loads

In this example, a simply supported square sandwich plate "A" under thermomechanical loads is considered.

The mechanical properties for metal and ceramic used in the FG sandwich plates are the same as those given in the example above. It is assumed that (a/h = 10, t_1 = 0, $t_2 = t_3$ = 100 K and q = 100 Pa). Different dimensionless quantities are used for thermomechanical loading as

$$\begin{aligned}\bar{w} &= \frac{10^3}{q_0 a^2/(E_0 h^3) + 10^3 \alpha_0 t_2 a^2/h}\, w\left(\frac{a}{2},\frac{b}{2}\right)\\ \bar{\sigma}_x &= \frac{10}{q_0 a^2/h^2 + 10\ \alpha_0 t_2 a^2/h^2}\,\sigma_x\left(\frac{a}{2},\frac{b}{2},z\right)\\ \bar{\tau}_{xz} &= \frac{10}{q_0 a/h + E_0 \alpha_0 t_2 a/(10h)}\,\tau_{xz}\left(0,\frac{b}{2},z\right)\end{aligned} \quad (35)$$

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

Numerical results are tabulated in Tables 5-7 and plotted in Figs. 2-5 using the present refined sinusoidal plate theory (SSDPT).

The results are compared to those computed by sinusoidal shear deformation theory (SSDT) with five unknowns, the first shear deformation theory (FSDT) developed by Zenkour and Alghamdi (2010) and with the 2D solutions of Li *et al*. (2016) with four unknowns only.

Table 5 compare the dimensionless center deflection $\bar{w}$ for an FGM sandwich plate subjected to mechanical and thermal loads for various value of index p and various configurations of sandwich plates. It is clearly observed that an excellent agreement is obtained in this comparison. Also, it shows that the deflections increase as the core thickness decreases whereas p increases. The maximum deflections occur for an FGM plate without core thickness (1-0-1) and this irrespective of the value of p.

Table 6 Effect of aspect ratio a/b on dimensionless center deflection $\bar{w}$ of sandwich plate "A" under thermo-mechanical load (a/h = 10, p = 3)

Scheme	Theory	$\bar{w}$ (a/2, b/2)				
		a/b = 1	a/b = 2	a/b = 3	a/b = 4	a/b = 5
1-0-1	Zenkour and Alghamdi (2010) (SSDPT)	1.141655	0.447872	0.222403	0.130406	0.085094
	Zenkour and Alghamdi (2010) (FSDPT)	1.280741	0.503607	0.250355	0.146917	0.095948
	Li *et al*. (2016)	1.231675	0.492573	0.246212	0.144771	0.094608
	Present	1.127875	0.442339	0.219620	0.128755	0.084003
3-1-3	Zenkour and Alghamdi (2010) (SSDPT)	1.128080	0.442695	0.219904	0.128992	0.084212
	Zenkour and Alghamdi (2010) (FSDPT)	1.264724	0.497383	0.247274	0.145112	0.094770
	Li *et al*. (2016)	1.217447	0.486952	0.243459	0.143199	0.093619
	Present	1.114524	0.437259	0.217175	0.127377	0.083149
2-1-2	Zenkour and Alghamdi (2010) (SSDPT)	1.119793	0.439521	0.218366	0.128116	0.083662
	Zenkour and Alghamdi (2010) (FSDPT)	1.255041	0.493613	0.245406	0.144017	0.094055
	Li *et al*. (2016)	1.208690	0.483486	0.241757	0.142222	0.093002
	Present	1.106366	0.434140	0.215666	0.126521	0.082614
1-1-1	Zenkour and Alghamdi (2010) (SSDPT)	1.092312	0.428955	0.213223	0.125175	0.081803
	Zenkour and Alghamdi (2010) (FSDPT)	1.223232	0.481212	0.239259	0.140414	0.091704
	Li *et al*. (2016)	1.179518	0.471920	0.236060	0.138942	0.090916
	Present	1.079282	0.423741	0.210614	0.123639	0.080798

Table 7 Dimensionless normal stress $\bar{\sigma}_x$ of square sandwich plate “A” under thermomechanicalload (a/h = 10)

p	Theory	$\overline{\sigma_x}(a/2, b/2, h/2)$			
		1-0-1	3-1-3	2-1-2	1-1-1
0	Zenkour and Alghamdi (2010) (SSDPT)	-2.388909	-2.388909	-2,388909	-2,388909
	Zenkour and Alghamdi (2010) (FSDPT)	-3.597007	-3.597007	-3.597007	-3.597007
	Li *et al*. (2016)	-3.119484	-3.119484	-3.119484	-3.119484
	Present	-2.327976	-2.327976	-2.327976	-2.327976
1	Zenkour and Alghamdi (2010) (SSDPT)	-2.406797	-2.494126	-2.537365	-2.659816
	Zenkour and Alghamdi (2010) (FSDPT)	-3,471099	-3,569762	-3,618476	-3,756017
	Li *et al*. (2016)	-3.116975	-3.220177	-3.271398	-3.416748
	Present	-2.350110	-2.436358	-2.479071	-2.600063
2	Zenkour and Alghamdi (2010) (SSDPT)	-2.118721	-2.199231	-2.243800	-2.381343
	Zenkour and Alghamdi (2010) (FSDPT)	-3.145662	-3.238636	-3.289757	-3.446485
	Li *et al*. (2016)	-2.780614	-2.874999	-2.927462	-3.089861
	Present	-2.065504	-2.144869	-2.188832	-2.324589
3	Zenkour and Alghamdi (2010) (SSDPT)	-2.020416	-2.086818	-2.127487	-2.262512
	Zenkour and Alghamdi (2010) (FSDPT)	-3.031284	-3.109180	-3.156414	-3.311823
	Li *et al*. (2016)	-2.666776	-2.744324	-2.792076	-2.951191
	Present	-1.968620	-2.033967	-2.074031	-2.207176
4	Zenkour and Alghamdi (2010) (SSDPT)	-1.978593	-2.033567	-2.070352	-2.200020
	Zenkour and Alghamdi (2010) (FSDPT)	-2.981507	-3.046666	-3.089733	-3.239941
	Li *et al*. (2016)	-2.618570	-2.682632	-2.725778	-2.878466
	Present	-1.927498	-1.981529	-2.017732	-2.145503
5	Zenkour and Alghamdi (2010) (SSDPT)	-1.957959	-2.004482	-2.038109	-2.162596
	Zenkour and Alghamdi (2010) (FSDPT)	-2.956534	-3.012040	-3.051612	-3.196423
	Li *et al*. (2016)	-2.594862	-2.648999	-2.688425	-2.834977
	Present	-1.907251	-1.952932	-1.986005	-2.108615

Table 6 compares the dimensionless center deflection $\bar{w}$ of a sandwich plate “Type A” under thermomechanical loads with p = 3 for different values of aspect ratios and various configuration of sandwich plates. It is can be seen that the dimensionless center deflection $\bar{w}$ decrease as the aspect ratio a/b increases and once again the maximum deflections occur for the (1-0-1) FGM rectangular plate.

Table 7 presents the dimensionless normal stress $\bar{\sigma}_x$ of a square sandwich plate “Type A” for various value of index p and various layer thickness ratios. It can be seen that the normal stress $\bar{\sigma}_x$ decreases as the core thickness decreases. The smallest normal stress occurs for the (1-0-1) FGM plate.

The effect of layer thickness ratio on dimensionless normal stress is insignificant for fully ceramic plates ($p = 0$).

Fig. 2 shows the variation of the normal stress $\bar{\sigma}_x$ on the thickness of the (1-2-1) and (2-2-1) plates sandwich FG “Type A” for divers value of index p. The curve reveals a continuation of the axial stress over the entire thickness of the plate, exhibiting a non-linear variation over the entire thickness of the plate, where is remarkable between the layers. The minimal stress is at the upper surface (compressing stress) and the maximum stress (tensile stress) at the bottom surface.

Fig. 3 comprises the plots of the transverse shear stress τ_{xz} across the thickness of the symmetric and non-symmetric plate configuration (1-2-1) and (2-2-1) in that order, with various values of index p, the result indicates that the shear stress distribution over the thickness of the plate is parabolic. The shear force intensity varies from zero at the top and bottom, to a maximum value at a point in the central layer.

Figs. 4 and 5 demonstrate the sensitivity of the normal stress $\bar{\sigma}_x$ and the transverse shear stress τ_{xz} to the change in the value of the thermal load t_3, where the diagrams describe the distributions across the thickness of the dimensionless normal stress $\bar{\sigma}_x$ and the transverse shear stress τ_{xz} through-the-thickness of the (1-2-1) FG sandwich plate “A” with (p = 1.5).

4.6 Bending analysis of sandwich plate “B” under thermomechanical loads

In this example, a simply supported square sandwich plate “B” under thermomechanical loads is considered. The same mechanical properties for metal and ceramic of the

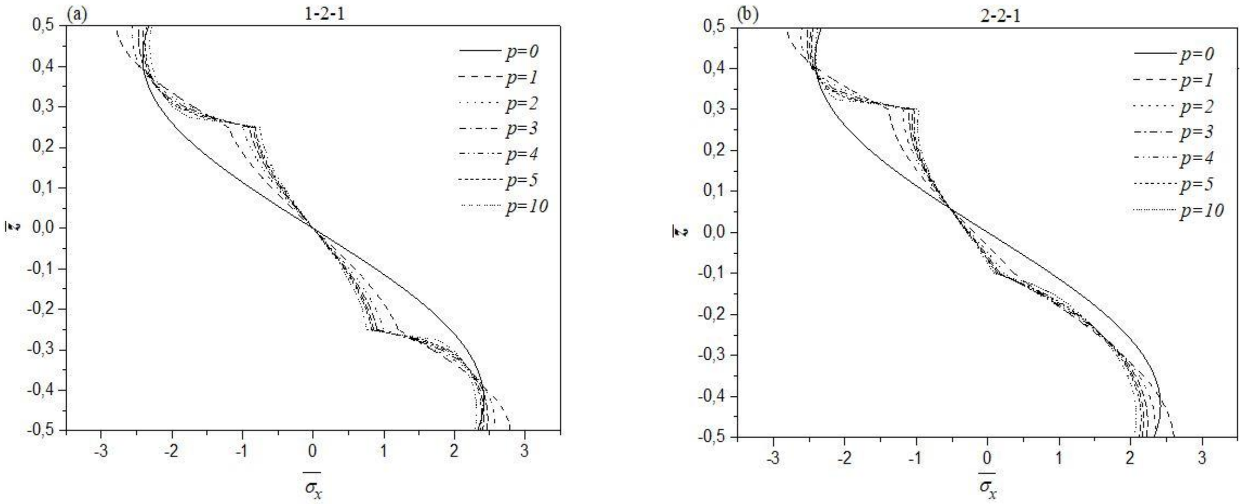

Fig. 2 Variation of normal stress $\bar{\sigma}_x$ through the plate thickness for two layer thickness ratios of FGM sandwich plates “A”: (a) (1-2-1); and (b) (2-2-1)

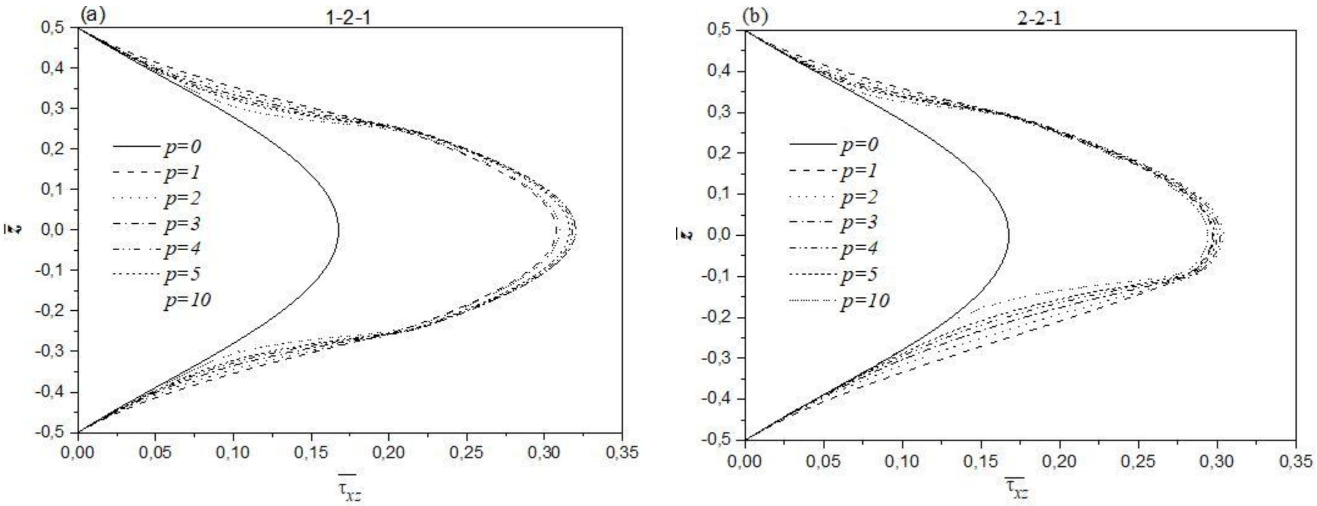

Fig. 3 Variation of shear stress $\bar{\tau}_{xz}$ through the plate thickness for two layer thickness ratios of FGM sandwich plates “A”: (a) (1-2-1); and (b) (2-2-1)

initial FG sandwich plates are used. It is assumed that (a/h = 10, t_1 = 0, t_2 = t_3 = 100 K and q = 100 Pa).

The results are compared to those computed by, the first shear deformation theory (FSDT), the third order shear deformation theory (SSDT) with five unknowns and with the 2D solutions sinusoidal shear deformation theory (SSDT) of Li *et al*. (2016) with four unknowns only.

Table 8 shows the results of the dimensionless deflection $\bar{w}$ for a FG sandwich plate “Type B” under a thermomechanical load, with variable index p = 0.5, 1, 2, 3, 4 and 5, and various configuration of the plate 2-1-2, 1-1-1, 2-2-1 and 1-2-1. We can see from this table that, as the index p raise, a minor increase of the dimensionless deflection is observed.

Table 9 exposes the dimensionless deflection $\bar{w}$ for a FG sandwich plate “Type B” subjected to mechanical and thermal loads, with index p = 3, and various values of aspect ratios and layer thickness ratios. As the aspect ratio a/b augments, the dimensionless deflection $\bar{w}$ of sandwich

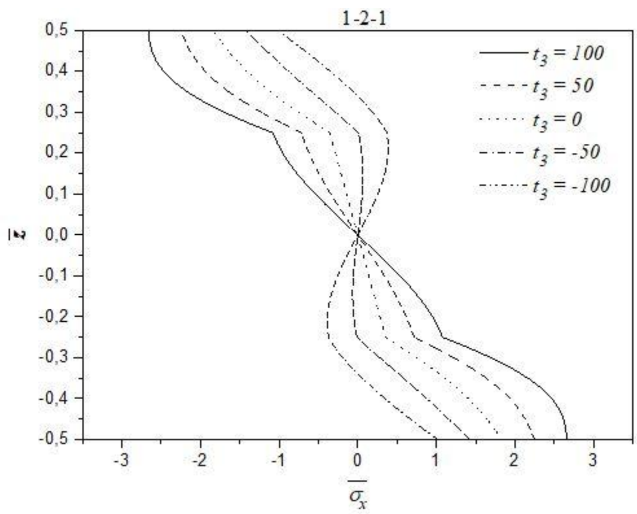

Fig. 4 Effect of the thermal load t_3 on the normal stress $\bar{\sigma}_x$ of the (1-2-1) FGM sandwich plate “A” with (p = 1.5)

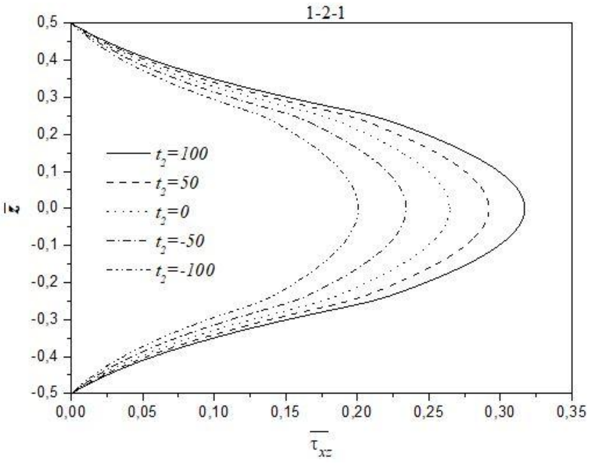

Fig. 5 Effect of the thermal load t_3 on the normal shear stress $\bar{\tau}_{xz}$ of the (1-2-1) FGM sandwich plate “A” with (p = 1.5)

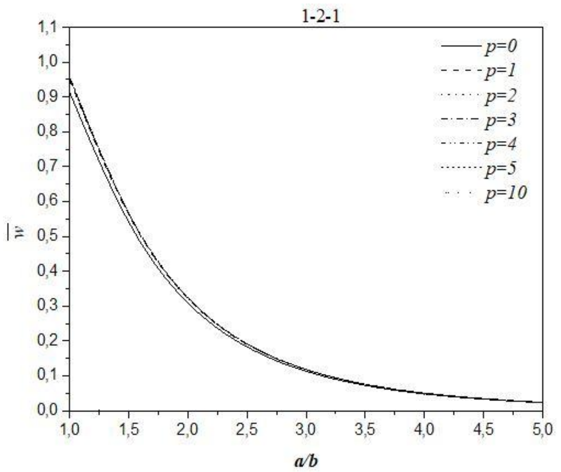

Fig. 6 Dimensionless center deflection $\bar{w}$ as a function of the aspect ratio a/b of the (1-2-1) FGM sandwich plate “B” (t_2 = t_3 = 100)

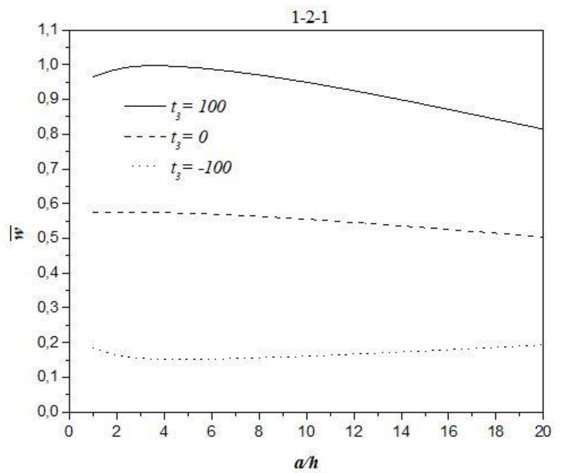

Fig. 7 Effect of the thermal load t_3 on dimensionless center deflection $\bar{w}$ of the (1-2-1) FGM sandwich plate “B” versus a/h with (p = 1)

plate “Type B” diminishes.

Fig 6 describes the inverse relationship between the dimensionless deflection $\bar{w}$ and the aspect ratio a/b of a FG sandwich plate “Type B” (1-2-1) for p = 0.5, 1, 2, 3, 4, 5 and 10. With increasing of the aspect ratio, the dimensionless deflection $\bar{w}$ decreases. The curves presents the same value of the deflection, the decrease is important where the ratio a/b is less than 3.

Fig. 7 express the influence of the side-to-thickness ratio a/h and the thermal load t_3 on the dimensionless center deflection $\bar{w}$ for the (1-2-1) FG sandwich plate “Type B” (p = 1). The influence of the thermal load t_3 is important on the dimensionless deflection $\bar{w}$ .The influence of the side-to-thickness ratio a/h is minor.

Fig 8 shows the distributions of the normal stress $\bar{\sigma}_x$ through-the-thickness of the (1-2-1) and (2-2 1) FG sandwich plate “Type B” for p = 0.5, 1, 2, 3, 4, 5 and 10. The curve exhibits a non-linear variation over the entire thickness of the plate of the normal stress. The maximum stress (tensile stress) is at the lower surface, while the minimum stress (compressive stress) occurs at a point of the central layer and near the upper face.

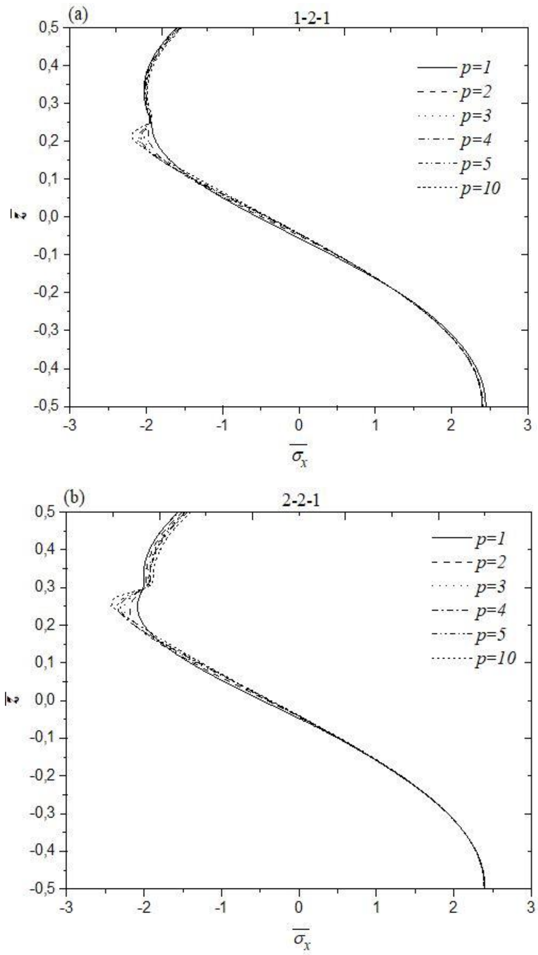

Fig. 8 variation of normal stress $\bar{\sigma}_x$ through the plate thickness for two layer thickness ratios of FGM sandwich plates “B”: (a) (1-2-1); and (b) (2-2-1)

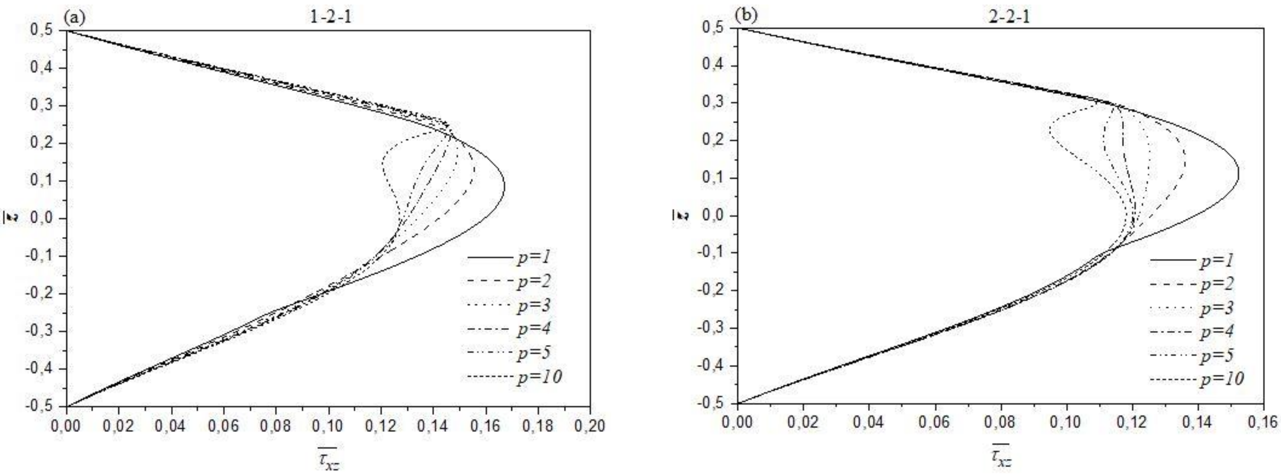

Fig. 9 Variation of shear stress $\bar{\tau}_{xz}$ through the plate thickness for two layer thickness ratios of FGM sandwich plates "B": (a) (1-2-1); and (b) (2-2-1)

Fig. 9 includes plots of the transverse shear stress τ_{xz} across the thickness of the symmetric and non-symmetric late configuration (1-2-1) and (2-2-1) in that order, with various values of index *p*, The transverse stress is irregular at the central layer , the minimum value appears at a point in the central layer and near the upper surface sheet.

5. Conclusions

In this work, the thermo-mechanical bending response of two types of sandwich plates made of graded material (FGM) is studied, using a novel refined four-variable plate model. The governing equations are written on the basis of the virtual work principle; the analytic solutions of these equations are obtained using Navier method. A comparison with the results of the literature is made to verify the accuracy and efficiency of this theory. The influences of volume fraction distribution, form factor and thermal loading on the characteristics of mechanical, thermo-elastic and thermo-mechanical bending are examined. An improvement of the present study will be considered in the future work to consider the thickness stretching effect by using quasi-3D shear deformation models (Bessaim *et al*. 2013, Belabed *et al*. 2014, Hebali *et al*. 2014, Bousahla *et al*. 2014, Bourada *et al*. 2015, Larbi Chaht *et al*. 2015, Hamidi *et al*. 2015, Bennoun *et al*. 2016, Draiche *et al*. 2016, Ait Atmane *et al*. 2017, Bouhadra *et al*. 2018, Bouafia *et al*. 2017, Sekkal *et al*. 2017b, Benahmed *et al*. 2017, Abualnour *et al*. 2018, Karami *et al*. 2018d, e, Benchohra *et al*. 2018, Younsi *et al*. 2018, Bendaho *et al*. 2019, Boutaleb *et al*. 2019, Boukhlif *et al*. 2019, Boulefrakh *et al*. 2019, Zarga *et al*. 2019, Zaoui *et al*. 2019, Khiloun *et al*. 2019).

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