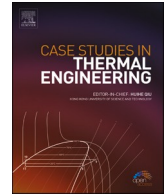




ELSEVIER

Contents lists available at ScienceDirect

Case Studies in Thermal Engineering

journal homepage: www.elsevier.com/locate/csite

Thermo-mechanical buckling analysis of FG-GNPs reinforced composites sandwich microplates using a trigonometric four-variable shear deformation theory

Jie Zheng^a, Chunwei Zhang^{a,*}, Farayi Musharavati^b, Afrasyab Khan^c,
Tamer A. Sebaey^{d,e}

^a Structural Vibration Control Group, Qingdao University of Technology, Qingdao, 266033, China

^b Department of Mechanical and Industrial Engineering, College of Engineering, Qatar University, P.O. Box 2713, Doha, Qatar

^c Institute of Engineering and Technology, Department of Hydraulics and Hydraulic and Pneumatic Systems, South Ural State University, Lenin Prospect 76, Chelyabinsk, 454080, Russian Federation

^d Engineering Management Department, College of Engineering, Prince Sultan University, Riyadh, Saudi Arabia

^e Mechanical Design and Production Department, Faculty of Engineering, Zagazig University, P.O. Box 44519, Zagazig, Sharkia, Egypt

ARTICLE INFO

Keywords:

Buckling analysis
Graphene nanoplatelets
Carbon nanotubes
Sandwich structures
Higher-order shear deformation theory
Modified strain gradient theory

ABSTRACT

The current study is aimed to investigate the thermo-mechanical buckling responses of the sandwich microplate with Graphene nanoplatelets (GNPs)-reinforced Epoxy core fully bonded to single-walled carbon nanotubes (SWCNTs)-reinforced piezoelectric patches. The face sheets were exposed to the electric field and the microplate was assumed to locate on the Pasternak elastic substrate. The GNPs and SWCNTs were dispersed throughout the core and face thickness according to some specific functions. To consider the shear deformation effect, tangential shear deformation theory (TSDT), as a trigonometric higher-order theory, was used. The size effects were also included through applying the modified strain gradient theory (MSGT). The virtual displacement principle was utilized to derive the governing equations and then by employing an analytical method, they were solved. The validity of the results was confirmed by comparing the results for simpler state with previously published ones. A parametric study is provided to observe behavior of the microstructure in different conditions. It was observed that GNPs and CNTs dispersion patterns play an important role in the microplate buckling behavior, as well as temperature variations. The outcomes of this work may help to manufacture more efficient engineering smart structures, such as micro/nanoelectromechanical systems.

1. Introduction

Micro and nano sandwich structures are used across a large-scale range of engineering applications including automotive, aerospace, biomedical manufacturers, and construction due to high stiffness and comparatively lightweight [1–3]. Carbon nanotubes (CNTs) reinforced functionally graded composites have full applications as structural members in advanced mechanical and aerospace industries [4–7]. Owing to electrical, thermal and mechanical characteristics such as excellent stiffness, high strength, and high value of aspect ratio but low density, CNTs have found considerable demand in several industrial and mechanical studies. Graphene

* Corresponding author.

E-mail address: zhangchunwei@qut.edu.cn (C. Zhang).

<https://doi.org/10.1016/j.csite.2021.101120>

Received 11 April 2021; Received in revised form 26 May 2021; Accepted 29 May 2021

Available online 3 June 2021

2214-157X/© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Nano-Platelets (GNPs)/Platelets (GPLs) have also attracted sufficient attention of scientists and engineers since it was found in 2004. Due to their particular properties in configuration, size, and even electrical, thermal, and mechanical characteristics, GNPs make progress in different polymeric elements [8]. Moreover, GNPs are identified as the best nano-fillers because of their stimulating properties. Employing these materials, higher stability conductivity and also higher electrical and thermal products will be produced. Therefore, the mechanical behavior of these structures investigated by the researchers [9–19].

Recent years have witnessed an extensive development in the beams, shells, and plates and the researchers have been trying to exploit new methods to improve or control their behaviors. Using a sandwich structure is one of the best approaches to achieve this goal. A softer core in comparison to stiffer face sheets is one of the most important features of the sandwich structures. Thus the selection of the appropriate substances for core and face sheets is of crucial importance in achieving the best results. Piezoelectric materials are the appropriate candidates to control and improve the performance of the structure. For example, Arshid and Khorshidvand [20] considered the effect of piezoelectric actuators which were fully bonded to a porous core on the vibrational behavior of the system. The effect of embedding a porous core on the free vibration behavior of laminated composite plates was considered by Safaei [21]. Li et al. [22] obtained the frequencies of fiber-reinforced composite cylindrical shells with bolt loosening boundary conditions. Moradi-Dastjerdi et al. [23] considered the static performance of agglomerated CNT-reinforced porous plates bonded with piezoceramic faces. In another study [24], they presented their results on the buckling behavior of porous CNT-reinforced plates integrated between active piezoelectric layers. Vibration analysis of a CNTs-reinforced composite plate was performed by Zhu et al. [25]. They applied the finite element method by using the first-order shear deformation theory (FSDT). They considered different types of CNTs distributions and boundary conditions. Stability analysis of three-phase sandwich panels which were nonlinearly imperfect was presented by Pham and Duc [26]. Stability and dynamic analyses of CNTs-reinforced concrete beam resting on elastic foundation conducted by Bourada et al. [27]. Al-Furjan et al. [28] considered the frequency responses of a sandwich disk with a lactic core, two middle layers containing fiber, and two outer layers (i.e. multi-scale hybrid nanocomposite). Agglomeration effects on the behavior of the nanocomposite of the piezoelectric cylinder were addressed by Loghman and Cheraghbak [29]. They assumed that the structure was under internal pressure and CNTs were selected as the reinforcement. Mirzaei and Kiani [30] used the refined mixture rule to analyze cylindrical panels made from FG-CNTs-reinforced composites. They considered different effects of CNTs on the results. A computational framework for propagated waves in a sandwich doubly curved nanocomposite panel provided by Al-Furjan et al. [31]. In another study [32], they presented a comprehensive computational approach for nonlinear thermal instability of the electrical nanocomposite disk based on a numerical method. Effect of nonlinear FG-CNT distribution on mechanical properties of FG nanocomposite beam investigated by Zerrouki et al. [33]. Also, Bendenia et al. [34] presented static and free vibration behaviors of nanocomposite sandwich plates reinforced by CNTs resting on the Pasternak elastic foundation. Uniformly distributed and FG distributions of aligned CNTs were considered for two types of sandwich plates such as the face sheet reinforced and homogeneous core and the homogeneous face sheet and reinforced core. Applying the Ritz method, Lei et al. [35] obtained the natural frequencies of FG-CNTs reinforced composites plates. They included the thermal effects on the results and investigated uniform and FG distribution of CNTs and presented their results. The dynamic response of piezoelectric FG sandwich cylindrical shells was investigated by Duc [36] considering the shear deformation effect. Also, Mehar et al. [37] applied the finite element methods to solve the nonlinear equations of a doubly curved FG-CNTs-reinforced composites shell. The structure was modeled by using higher-order shear deformation theory and Green-Lagrange strains. Yas and Samadi [38] explored the CNTs-reinforced composites Timoshenko beams by investigating vibration and buckling behavior. They applied the extended rule of mixture (ERM) to achieve effective properties. Liu et al. [39] considered the effect of GNPs reinforcement on the nonlinear resonance of an FG beam. Their consideration was based on the Euler-Bernoulli beams theory and they considered the GNPs were dispersed across the beam's thickness and investigated its effect on the results. Eyvazian et al. [40] studied about dynamic of GNPs reinforced composites shell which was under a moving harmonic load. Accordingly, they used FSDT to extract the equations. Habibi et al. [41] employed the generalized differential quadrature method to obtain the differential equations related to a GNPs reinforced nanoshell which was actuated by piezoelectric layers and obtained the critical voltage and natural frequencies of the aforementioned structure.

In recent years, many kinds of research have illustrated that when the characteristic length scale related to non-uniform plastic deformation is in the micro/nanoscale, materials show strong size effects [42]. The theories of classical plasticity cannot calculate this size dependence of material behavior at the small scales because their constitutive models own no inner length scale. Since investigating the size-dependent mechanical behavior of nano/micro-scaled structural systems can deliver important statistics for designers of micro/nano-scaled mechanism, some macroscopic continuum mechanics (containing strain gradient, modified strain gradient and nonlocal strain gradient theory (SGT), (MSGT) and (NSGT)) effectively industrialized and selected to evaluate the size-dependent effect. Thus, to give details about the size effects, developing strain gradient theory for small scale devices is required [43,44]. Li and Hu [45] presented nonlinear buckling analysis of Euler–Bernoulli beams based on a nonlocal strain gradient theory (NSGT), then they employed Hamilton's principle to obtain equations. Asghari et al. [46] derived both the motion equations and boundary conditions, applying the second strain gradient Timoshenko micro- and nano-beams theory which is appropriate to capture the size effects in micro- and nano-scale structures. Shojaeian et al. [47] presented mechanical-electrical buckling of FG electrostatic nano bridges that modified strain gradient theory is used. Thai et al. [48] debated on transient isogeometric and nonlinear static investigation of microplates employing modified strain gradient theories. Utilizing strain gradient theory, Hosseini et al. [49] analyzed various stress distributions in a single-walled carbon nanotube (SWCNT) under internal pressure to obtain the size-dependent behavior of the SWCNT. Malikan and Nguyen [50] obtained buckling of piezo-magneto-electric nanoplates in a hygrothermal atmosphere based on higher-order nonlocal strain gradient theory and a new variable plate method. Imani Aria and Biglari [51] proposed a nonlocal strain gradient model to study vibrational responses and buckling of microtubules in axons utilizing the finite element method to investigate different size effect parameters.

In addition, to take the shear deformations effect into account and to obtain more accurate results, different theories are used recently in which the shear deformation distribution is expressed as the function of thickness. Some of them such as FSDT, or Reddy's third-order theory are well-known and are used more than the others. The recent studies showed that using other types of shear deformation functions such as trigonometric or exponential also leads to more accurate results, especially for FG structures. For example, Tahir et al. [52] considered wave propagation of a ceramic-metal FG sandwich plate with different porosity distributions in a hygrothermal environment. They used a four-variable higher-order shear deformation theory to derive the equations and obtain the results. In another study, Hachemi et al. [53] provided bending analysis of FG plates using a new refined quasi-3D shear deformation theory and the concept of the neutral surface position. The mechanical buckling analysis of simply supported FG plates was carried out by Bakoura et al. [54] using a higher-order shear deformation theory in conjunction with the stress function method. Furthermore, A novel four-unknown integral model for buckling response of FG sandwich plates resting on elastic foundations under various boundary conditions using Galerkin's approach presented by Chikr et al. [55]. Menasria et al. [56] published their paper, which was about dynamic analysis of the FG sandwich plate seated on an elastic foundation with various kinds of support using refined shear deformation theory. Their model was simplified which the unknowns number were reduced. The zero-shear stresses at the free surfaces of the FG sandwich plate were ensured without introducing any correction factors. Porosity-dependent mechanical behaviors of FG plate using refined trigonometric shear deformation theory which was needless of the shear correction factor, presented by Bekkaye et al. [57]. As another example, Guellil et al. [58] used a higher-order shear deformation theory for bending analysis of FG plates under various boundary conditions.

The current study is aimed to analyze the thermo-mechanical behaviors of a small-scale sandwich microplate composing of three layers: an FG-GNPs-reinforced composite core and two piezo-electric-reinforced single-walled carbon nanotubes (SWCNTs) faces. The structure was located in a thermal environment and the effect of the temperature variations was assessed. Also, it was rested on a Pasternak elastic substrate including springs and shear layer. A trigonometric shear deformation theory uses a tangential function to account for the shear deformation effects and is known as the tangential shear deformation theory (TSDT). Furthermore, the size dependence was taken into account via MSGT with three material length-scale parameters. The governing equations were derived by the virtual displacements principle and variational approach then solved analytically. The literature review showed no study addressing such a microplate. The novelty of the present work lies in considering three-layered rectangular FG-GNPs-reinforced composite microplate which was integrated by CNTs-reinforced piezoelectric face sheets and subjected to an electric field in a thermal environment. The findings of this work will help in designing and creating more optimal engineering and smart structures such as sensors and actuators.

2. Mathematical formulations

As demonstrated in Fig. 1, a sandwich rectangular microplate composed of two face sheets and a core is taken into consideration. The core of the microstructure is made of FG-GNPs-reinforced Epoxy; while its top and bottom layers are SWCNTs-reinforced piezoelectric. An external voltage is applied to the faces of the microplate and the structure is rested on an elastic substrate simulated by the Pasternak type. The geometrical parameters of the microplate, namely its layers length, width, and heights (top, core, and bottom) are shown by a , b , h_t , h_c , and h_b , respectively. Moreover, the total thickness of the structure is shown by h_T .

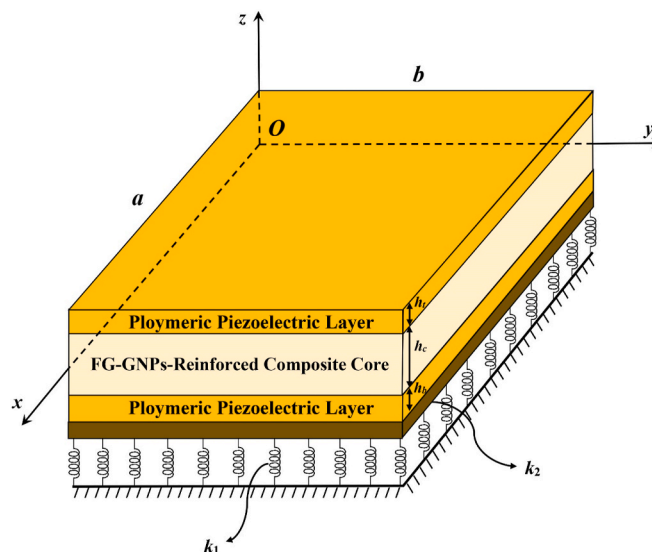


Fig. 1. Schematic diagram of the three-layered microplate on Pasternak substrate.

2.1. Constitutive relations

As mentioned earlier, the core and the face sheets of the microplate are composed of FG- GNPs-reinforced Epoxy and SWCNT-reinforced piezoelectric materials, respectively. The strain-stress relations for the core of this structure, the below equation can be used [59]:

$$\sigma_{ij}^c = Q_{ijkl}^c(z) \left(\varepsilon_{kl} - \alpha_{ij}^c(z) \Delta T \right) \tag{1}$$

in which the superscript *c* denotes the core. $\alpha_{ij}(z)$ is the thermal expansion coefficient which is the function of thickness, the temperature changes are shown by ΔT , while Q_{ijkl} shows the stiffness components which can be determined via the following relations [60]:

$$\begin{aligned} Q_{ii}^c &= \frac{(1 - \nu_c(z))E_c(z)}{(1 + \nu_c(z))(1 - 2\nu_c(z))}, i = 1, 2 \\ Q_{ij}^c &= Q_{ji}^c = \frac{\nu_c(z)E_c(z)}{(1 + \nu_c(z))(1 - 2\nu_c(z))}, i = 1, j = 2 \\ Q_{ii}^c &= \frac{E_c(z)}{2(1 + \nu_c(z))}, i = 4, 5, 6 \end{aligned} \tag{2}$$

$E_c(z)$ is Young's elasticity modulus and $\nu_c(z)$ obtain the Poisson's ratio of the core, these parameters varied along the thickness direction. To this end, Halpin-Tsai and ERM micromechanical schemes were employed. The previous works showed that the Halpin-Tsai model presents more accurate values for Young's modulus than the other micromechanical models. Therefore, Halpin-Tsai was used to determine the effective Young's elasticity modulus of the GNPs core [61]:

$$E_c(z) = \frac{E_M}{8} (3\kappa_1 + 5\kappa_2) \tag{3}$$

where E_M is Young's modulus of the matrix and:

$$\kappa_1 = \frac{1 + \zeta_L \eta_L V_{GNP}}{1 - \eta_L V_{GNP}}, \kappa_2 = \frac{1 + \zeta_W \eta_W V_{GNP}}{1 - \eta_W V_{GNP}} \tag{4}$$

The used parameters in Eq. (4) which are related to the geometrical properties of the GNPs have the following definitions [62]:

$$\zeta_L = 2 \frac{l_{GNP}}{h_{GNP}}, \zeta_W = 2 \frac{w_{GNP}}{h_{GNP}}, \tag{5}$$

$$\eta_W = \frac{(E_{GNP}/E_M) - 1}{(E_{GNP}/E_M) + \zeta_W}, \eta_L = \frac{(E_{GNP}/E_M) - 1}{(E_{GNP}/E_M) + \zeta_L} \tag{6}$$

Herein, l_{GNP} and h_{GNP} denotes the GNPs' length and thickness moreover, their width is shown by w_{GNP} . Likewise, E_{GNP} shows the elasticity modulus of reinforcements. Additionally, GNPs' volume fraction is defined as below [63]:

$$V_{GNP} = \frac{g_{GNP}(z)}{g_{GNP}(z) + \left(\rho_{GNP}/\rho_M \right) (1 - g_{GNP}(z))} \tag{7}$$

In the above equation, ρ is the density; the weight fraction of reinforcements is shown by g_{GNP} . If GNPs are dispersed through the core's thickness according to a parabolic function, their weight fraction follows from the below relation [64]:

$$g_{GNP}(z) = \frac{4}{h_c^2} \lambda_p W_{0GNP} z^2 \tag{8}$$

The values of λ_p (gradient index of GNPs) depend on the total GNPs percentage. For 0, 1/3, and 1% of GNPs, the values of λ_p are 0, 1, and 3, respectively.

Also, if GNPs' weight fraction assumed to be independent of the thickness (i.e. uniform), then:

$$g_{GNP}(z) = \lambda_U W_{0GNP} \tag{9}$$

For 0, 1/3, and 1% of GNPs, the values of λ_U are 0, 1/3, and 1, respectively.

Other properties of the face sheets are become acceptable via ERM, too [65]:

$$\left\{ \begin{matrix} \rho_c(z) \\ \nu_c(z) \\ \alpha_c(z) \end{matrix} \right\} = \left\{ \begin{matrix} \rho_{GNP} \\ \nu_{GNP} \\ \alpha_{GNP} \end{matrix} \right\} V_{GNP} + \left\{ \begin{matrix} \rho_M \\ \nu_M \\ \alpha_M \end{matrix} \right\} V_M \tag{10}$$

Furthermore, the stress-strain relations for SWCNT-reinforced piezoelectric face sheets at the presence of the electric field can be

written as [66]:

$$\sigma_{ij}^f = Q_{ijkl}^f(z) (\epsilon_{kl} - \alpha_{ij}^f(z) \Delta T) - e_{kij} E_k \tag{11}$$

where, e_{kij} denotes piezoelectric coefficients, the electric field is represented by E_k and Q_{ij} are stiffness matrix components which can be expressed by:

$$Q_{ii}^f = \frac{E_{iif}(z)}{1 - \nu_{12f}\nu_{21f}}, i = 1, 2 \quad Q_{12}^f = \nu_{21f} Q_{11}^f, \tag{12}$$

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

The following relations shows effective properties of CNTs face sheets [60,67]:

$$E_{11f}(z) = \eta_1 V_{CNT} E_{11}^{CNT} + V_m E_m, \tag{13a}$$

$$\frac{\eta_2}{E_{22f}(z)} = \frac{V_{CNT}}{E_{22}^{CNT}} + \frac{V_m}{E_m}, \tag{13b}$$

$$\frac{\eta_3}{G_{12f}} = \frac{V_{CNT}}{G_{12}^{CNT}} + \frac{V_m}{G_m} \tag{13c}$$

where longitudinal, transverse and shear Young’s moduli of the CNTs and matrix are shown by E_{11}^{CNT} , E_{22}^{CNT} , G_{12}^{CNT} , E_m , and G_m , one after another, and also, it is noted that $G_{13f} = G_{23f} = G_{12f}$. CNTs’ efficiency parameters are presented by η_i ($i = 1, 2, 3$). For $V_{CNT}^* = 0.12$ they are $\eta_1 = 0.137$, $\eta_2 = 1.022$, and $\eta_3 = 0.715$. Throughout the current paper, M refers to the matrix of the core and m refers to that of the faces. Thermo-electric properties of the face sheets can be obtained in the following relation [68]:

$$P_f = V_{CNT} \{P^{CNT}\} + V_m \{P^m\} \tag{14}$$

The material properties vector is shown by P_f denotes which includes:

$$P_f = \{Q_{ij}^f, e_{ij}, \kappa_{ij}, \alpha_{ij}^f\} \tag{15}$$

Also, for Poisson’s ratio the following relation is ruled:

$$\nu_{12f} = V_{CNT}^* \nu_{12}^{CNT} + V_m \nu_m \tag{16}$$

in which [69]:

$$V_{CNT}^* = \frac{w_{CNT}}{w_{CNT} + (\rho_{CNT}/\rho_m) - (\rho_{CNT}/\rho_m)w_{CNT}} \tag{17}$$

w_{CNT} represents the mass density of the reinforcements and densities of CNTs and the matrix are shown by ρ_{CNT} and ρ_m .

Five different distributions of the CNTs namely UU, FG-VA, FG-XX, and FG-OO are considered in this work. The following relation is ruled for each of the mentioned distribution patterns [70,71]:

$$V_{CNT}^i = \begin{cases} V_{CNT}^* \text{ UD} \\ \left[1 - \frac{2}{h_i} \left(z \mp \frac{h_c + h_i}{2} \right) \right] V_{CNT}^* \text{FG - A} \\ \left[1 + \frac{2}{h_i} \left(z \mp \frac{h_c + h_i}{2} \right) \right] V_{CNT}^* \text{FG - V} \quad i = t, b \\ 2 \left[1 - \frac{2}{h_i} \left(z \mp \frac{h_c + h_i}{2} \right) \right] V_{CNT}^* \text{FG - O} \\ \frac{4}{h_i} \left[\left| z \mp \frac{h_c + h_i}{2} \right| \right] V_{CNT}^* \text{FG - X} \end{cases} \tag{18}$$

The negative and the positive sign indicate the upper and the lower patches, respectively.

Also, electric displacement can be introduced using the following relation [72]:

$$D_i = e_{ijkl}\epsilon_{kl} + \kappa_{ik}E_k \tag{19}$$

where κ_{ik} is dielectric permeability. The electric potential is the summation of cosine and linear terms [73]:

$$\Phi(x, y, z) = -\cos\left(\frac{\pi z}{h_f}\right)\phi(x, y) + \frac{2z}{h_f}V_E \tag{20}$$

where V_E is the external applied electric voltage, and h_f shows the thickness of each face. To satisfy Maxwell's relations, the electric field can be defined as [74]:

$$E = -\nabla\Phi \tag{21}$$

As stated by Eqs. (20) and (21), the components of the electric field are obtained as:

$$\{E_x, E_y\} = -\left\{\frac{\partial\Phi}{\partial x}, \frac{\partial\Phi}{\partial y}\right\} = \left\{\frac{\partial\phi}{\partial x}, \frac{\partial\phi}{\partial y}\right\}\cos\left(\frac{\pi z}{h_f}\right), E_z = -\frac{\partial\Phi}{\partial z} = -\frac{2}{h_f}V_E - \frac{\pi}{h_f}\phi\sin\left(\frac{\pi z}{h_f}\right) \tag{22}$$

2.2. Kinematic relations

To analyze the aforementioned microstructure, the Cartesian coordinate system was used whose origin lied at the left corner of the microplate's mid-plane. Also, the displacement components of an arbitrary point of the microplate are described based on a novel shear deformations theory which suggests a tangential function for describing the shear deformation distribution across the thickness direction. Therefore, the displacement components of an arbitrary point using TSdT for microplates are defined as [75]:

$$\begin{aligned} U &= u - z\frac{\partial w_b}{\partial x} - \xi(z)w_s, \\ V &= v - z\frac{\partial w_b}{\partial y} - \xi(z)w_s, \\ W &= w_b + w_s \end{aligned} \tag{23}$$

In the above equation, the displacements of the microplate's mid-layer in x and y directions are respectively, presented by u and v . Furthermore, the transverse displacements due to shearing and bending are shown by w_s and w_b , respectively. Also, $\xi(z)$ is the shear deformation function that obeys the following relation based on TSdT:

$$\xi(z) = \tan\left(\frac{\pi z}{2h_f}\right)r^{\sec\left(\frac{\pi z}{2h_f}\right)}, \quad r = 0.03 \tag{24}$$

The strain components were determined concerning the displacements leading to the following terms [76,77]:

$$\begin{aligned} \epsilon_{xx} &= \frac{\partial u(x, y)}{\partial x} - z\frac{\partial^2 w_b(x, y)}{\partial x^2} - \xi(z)\frac{\partial^2 w_s(x, y)}{\partial x^2}, \\ \epsilon_{yy} &= \frac{\partial v(x, y)}{\partial y} - z\frac{\partial^2 w_b(x, y)}{\partial y^2} - \xi(z)\frac{\partial^2 w_s(x, y)}{\partial y^2}, \\ \gamma_{xy} &= \frac{1}{2}\left(\frac{\partial u(x, y)}{\partial y} + \frac{\partial v(x, y)}{\partial x}\right) - z\frac{\partial^2 w_b(x, y)}{\partial x\partial y} - \xi(z)\frac{\partial^2 w_s(x, y)}{\partial x\partial y}, \\ \gamma_{xz} &= -\frac{1}{2}\left(\xi_{,z}(z)\frac{\partial w_s(x, y)}{\partial x} - \frac{\partial w_s(x, y)}{\partial x}\right), \\ \gamma_{yz} &= -\frac{1}{2}\left(\xi_{,z}(z)\frac{\partial w_s(x, y)}{\partial y} - \frac{\partial w_s(x, y)}{\partial y}\right) \end{aligned} \tag{25}$$

where comma in the subscript denotes the derivative relative to z .

The variational approach and the virtual displacement principle were applied [78]:

$$\delta(U_T - W) = 0 \tag{26}$$

In Eq. (26), U_T and W are the strain energy and the work of externally applied loads.

The total strain energy of the under consideration microplate includes those of the core and face sheets (i.e. $U_T = U_c + U_f$), therefore [79]:

$$\begin{aligned}
 U_T &= \frac{1}{2} \int_A \int_{-h_c/2}^{h_c/2} \left(\sigma_{ij} \varepsilon_{ij} + p_i \gamma_i + \tau_{ijk}^{(1)} \eta_{ijk}^{(1)} + m_{ij}^{(s)} \chi_{ij}^{(s)} \right) dz dA + \\
 &\frac{1}{2} \int_A \int_{-h_c/2-h_b}^{-h_c/2} \left(\sigma_{ij}^f \varepsilon_{ij} + p_i \gamma_i + \tau_{ijk}^{(1)} \eta_{ijk}^{(1)} + m_{ij}^{(s)} \chi_{ij}^{(s)} - D_i E_i \right) dz dA + \\
 &\frac{1}{2} \int_A \int_{h_c/2}^{h_c/2+h_t} \left(\sigma_{ij}^f \varepsilon_{ij} + p_i \gamma_i + \tau_{ijk}^{(1)} \eta_{ijk}^{(1)} + m_{ij}^{(s)} \chi_{ij}^{(s)} - D_i E_i \right) dz dA
 \end{aligned} \tag{27}$$

As noted previously, the MSGT is used to demonstrate the scale influence on the vibrational behavior of the under consideration microstructure. In Eq. (27), p_i , $\tau_{ijk}^{(1)}$ and $m_{ij}^{(s)}$ are the higher-order stresses that can be shown as:

$$p_i = 2\mu l_0^2 \gamma_i, \quad \tau_{ijk}^{(1)} = 2\mu l_1^2 \eta_{ijk}^{(1)}, \quad m_{ij}^{(s)} = 2\mu l_2^2 \chi_{ij}^{(s)} \tag{28}$$

In the above equations, μ is the Lamé's ($E/2(1 + \nu)$) and δ_{ij} represents the Kronecker delta.

Also, l_0 , l_1 , and l_2 are independent length-scale parameters relevant to the dilatation gradients tensor γ_i , deviator stretch gradient tensor $\eta_{ijk}^{(1)}$, and symmetric rotation gradients $\chi_{ij}^{(s)}$, respectively [80]:

$$\gamma_i = \frac{\partial \varepsilon_{mm}}{\partial x_i}, \tag{29}$$

$$\eta_{ijk}^{(1)} = \frac{1}{3} \left[\left(\frac{\partial \varepsilon_{jk}}{\partial x_i} + \frac{\partial \varepsilon_{ki}}{\partial x_j} + \frac{\partial \varepsilon_{ij}}{\partial x_k} \right) - \frac{1}{5} \left(\delta_{ij} \left(\frac{\partial \varepsilon_{mm}}{\partial x_k} + 2 \frac{\partial \varepsilon_{mk}}{\partial x_m} \right) + \delta_{jk} \left(\frac{\partial \varepsilon_{mm}}{\partial x_i} + 2 \frac{\partial \varepsilon_{mi}}{\partial x_m} \right) + \delta_{ki} \left(\frac{\partial \varepsilon_{mm}}{\partial x_j} + 2 \frac{\partial \varepsilon_{mj}}{\partial x_m} \right) \right) \right], \tag{30}$$

$$\chi_{ij}^{(s)} = \frac{1}{4} \left(e_{imn} \frac{\partial^2 u_n}{\partial x_{mj}^2} + e_{jmn} \frac{\partial^2 u_n}{\partial x_{mi}^2} \right) \tag{31}$$

The displacement components of Eq. (23) replaced in the above equations, afterwards the components for the deviator stretch gradient, the dilatation gradients, and the symmetric rotation gradient tensors obtained.

To calculate variations of the total strain energy, the below relation is obtained:

$$\begin{aligned}
 \delta U_T &= \int_A \int_{-h_c/2}^{h_c/2} \left(\sigma_{ij} \delta \varepsilon_{ij} + p_i \delta \gamma_i + \tau_{ijk}^{(1)} \delta \eta_{ijk}^{(1)} + m_{ij}^{(s)} \delta \chi_{ij}^{(s)} \right) dz dA + \\
 &\int_A \int_{-h_c/2-h_b}^{-h_c/2} \left(\sigma_{ij}^f \delta \varepsilon_{ij} + p_i \delta \gamma_i + \tau_{ijk}^{(1)} \delta \eta_{ijk}^{(1)} + m_{ij}^{(s)} \delta \chi_{ij}^{(s)} - D_i \delta E_i \right) dz dA + \\
 &\int_A \int_{h_c/2}^{h_c/2+h_t} \left(\sigma_{ij}^f \delta \varepsilon_{ij} + p_i \delta \gamma_i + \tau_{ijk}^{(1)} \delta \eta_{ijk}^{(1)} + m_{ij}^{(s)} \delta \chi_{ij}^{(s)} - D_i \delta E_i \right) dz dA
 \end{aligned} \tag{32}$$

In this paper, the external works included three terms. The first term is related to the Pasternak substrate, while the second one is attributed to the in-plane loads, and the third one is due to the thermo-electrical loads [81]. Furthermore, as expressed before, the microstructure was rested on an elastic substrate bearing both normal and shear loads using springs and shear layers, respectively. Consequently, the work of this substrate can be determined by:

$$W_s = \frac{1}{2} \int_x \int_y \left[-F_s (w_b + w_s) \right] dx dy \tag{33}$$

where the substrate reaction force is presented by F_s consisting of springs and shear layer parameters as follows [82]:

$$F_s = k_1 (w_b + w_s) - k_2 \nabla^2 (w_b + w_s) \tag{34}$$

In the above equation, k_1 and k_2 are substrate parameters relating to the springs and shear layer, respectively.

Also, to obtain the work done by the in-plane loads, the mentioned expression may be employed [83]:

$$W_{in-plane} = \frac{1}{2} \int_x \int_y \left\{ N_x^0 \left(\frac{\partial (w_b + w_s)}{\partial x} \right)^2 + N_y^0 \left(\frac{\partial (w_b + w_s)}{\partial y} \right)^2 \right\} dx dy \tag{35}$$

that N_y^0 and N_x^0 are the axial applied in-plane loads indicating the mechanical loads a follows:

$$N_x^0 = \gamma_1 N_x \quad N_y^0 = \gamma_2 N_y \tag{36}$$

Herein, γ_2 and γ_1 denote the magnitude of the applied loads in y and x directions, respectively. In the case of biaxial buckling, both of the load magnitude is non-zero, whereas the uniaxial case, one of them equates to zero.

The work of thermo-electric load can be evaluated by Eq. (37) [84]:

$$W_{TE} = \frac{1}{2} \int_x \int_y \left\{ (N_{TE_x}) \left(\frac{\partial (w_b + w_s)}{\partial x} \right)^2 + N_{TE_y} \left(\frac{\partial (w_b + w_s)}{\partial y} \right)^2 \right\} dx dy, \tag{37a}$$

$$N_{TE_x} = \int (Q_{11}^{cf} + Q_{12}^{cf}) \alpha_{11}^{cf} \Delta T dz - 2e_{31} V_E, \tag{37b}$$

$$N_{TE_y} = \int (Q_{12}^{cf} + Q_{22}^{cf}) \alpha_{22}^{cf} \Delta T dz - 2e_{31} V_E \tag{37c}$$

Differential governing equations can be achieved by inserting the obtained expressions for variations of the strain energy and the work of external loads in the virtual displacement relation, equating expressions for each coefficient to zero, which leads to the below equations:

δu :

$$\begin{aligned} & -\frac{\partial}{\partial x} N_{xx} - \frac{\partial}{\partial y} N_{xy} - \frac{1}{2} \frac{\partial^2}{\partial y^2} \alpha_8 - \frac{1}{2} \frac{\partial^2}{\partial y \partial x} \alpha_{10} + \frac{\partial^2}{\partial x^2} \alpha_{11} + \frac{\partial^2}{\partial y \partial x} \alpha_{14} + \frac{2}{5} \frac{\partial^2}{\partial x^2} \alpha_{19} - \frac{1}{5} \frac{\partial^2}{\partial y^2} \alpha_{19} \\ & - \frac{2}{5} \frac{\partial^2}{\partial y \partial x} \alpha_{23} - \frac{3}{5} \frac{\partial^2}{\partial x^2} \alpha_{29} + \frac{4}{5} \frac{\partial^2}{\partial y^2} \alpha_{29} - \frac{3}{5} \frac{\partial^2}{\partial x^2} \alpha_{37} + \frac{1}{5} \frac{\partial^2}{\partial y^2} \alpha_{37} + \frac{8}{5} \frac{\partial^2}{\partial y \partial x} \alpha_{33} - \frac{2}{5} \frac{\partial^2}{\partial y \partial x} \alpha_{41} = 0 \end{aligned} \tag{38}$$

δv :

$$\begin{aligned} & -\frac{\partial}{\partial y} N_{yy} - \frac{\partial}{\partial x} N_{xy} + \frac{1}{2} \frac{\partial^2}{\partial x^2} \alpha_{10} + \frac{1}{2} \frac{\partial^2}{\partial y \partial x} \alpha_8 + \frac{\partial^2}{\partial y^2} \alpha_{14} + \frac{\partial^2}{\partial y \partial x} \alpha_{11} - \frac{2}{5} \frac{\partial^2}{\partial x^2} \alpha_{23} + \frac{2}{5} \frac{\partial^2}{\partial y^2} \alpha_{23} \\ & - \frac{2}{5} \frac{\partial^2}{\partial y \partial x} \alpha_{19} - \frac{3}{5} \frac{\partial^2}{\partial y^2} \alpha_{33} + \frac{4}{5} \frac{\partial^2}{\partial x^2} \alpha_{33} - \frac{3}{5} \frac{\partial^2}{\partial y^2} \alpha_{41} - \frac{1}{5} \frac{\partial^2}{\partial x^2} \alpha_{41} + \frac{8}{5} \frac{\partial^2}{\partial y \partial x} \alpha_{29} - \frac{2}{5} \frac{\partial^2}{\partial y \partial x} \alpha_{37} = 0 \end{aligned} \tag{39}$$

δw_b :

$$\begin{aligned} & -2 \frac{\partial^2}{\partial y \partial x} \alpha_{50} - \frac{4}{5} \frac{\partial^2}{\partial y^2} \alpha_{47} + \frac{1}{5} \frac{\partial^2}{\partial x^2} \alpha_{47} + \frac{1}{5} \frac{\partial^2}{\partial y^2} \alpha_{45} - \frac{4}{5} \frac{\partial^2}{\partial x^2} \alpha_{45} + \frac{3}{5} \frac{\partial^3}{\partial y \partial x^2} \alpha_{42} + \frac{3}{5} \frac{\partial^3}{\partial y^3} \alpha_{42} \\ & - \frac{12}{5} \frac{\partial^3}{\partial y \partial x^2} \alpha_{34} + \frac{3}{5} \frac{\partial^3}{\partial y^3} \alpha_{34} + \frac{3}{5} \frac{\partial^3}{\partial x \partial y^2} \alpha_{38} + \frac{3}{5} \frac{\partial^3}{\partial x^3} \alpha_{38} - \frac{12}{5} \frac{\partial^3}{\partial y^2 \partial x} \alpha_{30} + \frac{3}{5} \frac{\partial^3}{\partial x^3} \alpha_{30} + \frac{1}{5} \frac{\partial^2}{\partial y^2} \alpha_{27} \\ & + \frac{1}{5} \frac{\partial^2}{\partial x^2} \alpha_{27} + \frac{3}{5} \frac{\partial^3}{\partial x^2 \partial y} \alpha_{24} - \frac{2}{5} \frac{\partial^3}{\partial y^3} \alpha_{24} - \frac{\partial^3}{\partial y^2 \partial x} \alpha_{30} - \frac{\partial^3}{\partial y^3} \alpha_{15} - \frac{\partial^3}{\partial x^2 \partial y} \alpha_{15} - \frac{\partial^2}{\partial x^2} \alpha_{17} - \frac{\partial^2}{\partial y^2} \alpha_{17} \\ & - \frac{2}{5} \frac{\partial^3}{\partial x^3} \alpha_{20} + \frac{3}{5} \frac{\partial^3}{\partial y^2 \partial x} \alpha_{20} - \frac{\partial^3}{\partial x^3} \alpha_{12} - \frac{\partial^2}{\partial x^2} \alpha_5 + \frac{\partial^2}{\partial y^2} \alpha_5 - \frac{\partial^2}{\partial y \partial x} \alpha_3 + \frac{\partial^2}{\partial y \partial x} \alpha_1 - 2 \frac{\partial^2}{\partial y \partial x} M_{xyb} \\ & - \frac{\partial^2}{\partial x^2} M_{xxb} - \frac{\partial^2}{\partial y^2} M_{yyb} - k_2 \frac{\partial^2 w}{\partial x^2} - k_2 \frac{\partial^2 w}{\partial y^2} + k_1 w - N_x^0 \frac{\partial^2 w}{\partial x^2} - N_y^0 \frac{\partial^2 w}{\partial y^2} - N_{TE_x} \frac{\partial^2 w}{\partial x^2} \\ & - N_{TE_y} \frac{\partial^2 w}{\partial y^2} = 0 \end{aligned} \tag{40}$$

δw_s :

$$\begin{aligned}
 & \frac{1}{2} \frac{\partial}{\partial x} \alpha_7 - \frac{1}{2} \frac{\partial^2}{\partial x^2} \alpha_5 + \frac{1}{2} \frac{\partial^2}{\partial y^2} \alpha_5 - \frac{1}{2} \frac{\partial^2}{\partial y \partial x} \alpha_3 + \frac{1}{2} \frac{\partial^2}{\partial y \partial x} \alpha_1 - \frac{1}{2} \frac{\partial^2}{\partial x^2} \alpha_6 + \frac{1}{2} \frac{\partial^2}{\partial y^2} \alpha_6 \\
 & - \frac{12}{5} \frac{\partial^3}{\partial y^2 \partial x} \alpha_{31} + \frac{3}{5} \frac{\partial^3}{\partial x^3} \alpha_{31} - \frac{1}{2} \frac{\partial^2}{\partial y \partial x} \alpha_5 + \frac{1}{2} \frac{\partial^2}{\partial y \partial x} \alpha_3 - \frac{1}{5} \frac{\partial^2}{\partial y^2} \alpha_{27} - \frac{1}{5} \frac{\partial^2}{\partial x^2} \alpha_{27} \\
 & - 2 \frac{\partial^2}{\partial y \partial x} M_{xys} + \frac{1}{5} \frac{\partial^2}{\partial y^2} \alpha_{28} - \frac{\partial^2}{\partial x^2} M_{xxs} - \frac{\partial^2}{\partial y^2} M_{yys} + \frac{1}{5} \frac{\partial^2}{\partial x^2} \alpha_{28} - \frac{1}{5} \frac{\partial}{\partial y} \alpha_{26} \\
 & + \frac{3}{5} \frac{\partial^3}{\partial x^2 \partial y} \alpha_{25} - \frac{2}{5} \frac{\partial^3}{\partial y^3} \alpha_{25} - \frac{1}{5} \frac{\partial}{\partial x} \alpha_{22} + \frac{3}{5} \frac{\partial^3}{\partial y^2 \partial x} \alpha_{21} - \frac{2}{5} \frac{\partial^3}{\partial x^3} \alpha_{21} - \frac{\partial^2}{\partial y^2} \alpha_{10} - \frac{1}{5} \frac{\partial}{\partial x} \alpha_{32} \\
 & - \frac{\partial^2}{\partial x^2} \alpha_{18} - \frac{\partial^3}{\partial x^2 \partial y} \alpha_{16} - \frac{\partial^3}{\partial y^3} \alpha_{16} - \frac{\partial^3}{\partial y^2 \partial x} \alpha_{13} - \frac{\partial^3}{\partial x^3} \alpha_{13} - 2 \frac{\partial^2}{\partial y \partial x} \alpha_{37} + 2 \frac{\partial^2}{\partial y \partial x} \alpha_{50} \\
 & + \frac{4}{5} \frac{\partial^2}{\partial y^2} \alpha_{48} - \frac{1}{5} \frac{\partial^2}{\partial x^2} \alpha_{48} - \frac{4}{5} \frac{\partial^2}{\partial y^2} \alpha_{48} + \frac{1}{5} \frac{\partial^2}{\partial x^2} \alpha_{48} - \frac{1}{5} \frac{\partial^2}{\partial y^2} \alpha_{46} + \frac{4}{5} \frac{\partial^2}{\partial x^2} \alpha_{46} + \frac{1}{5} \frac{\partial^2}{\partial y^2} \alpha_{46} \\
 & - \frac{4}{5} \frac{\partial^2}{\partial x^2} \alpha_{46} + \frac{4}{5} \frac{\partial}{\partial y} \alpha_{44} + \frac{3}{5} \frac{\partial^3}{\partial y \partial x^2} \alpha_{43} + \frac{3}{5} \frac{\partial^3}{\partial y^3} \alpha_{43} - \frac{1}{2} \frac{\partial}{\partial y} \alpha_{14} - \frac{1}{5} \frac{\partial}{\partial y} \alpha_{36} - \frac{12}{5} \frac{\partial^3}{\partial y \partial x^2} \alpha_{35} \\
 & + \frac{3}{5} \frac{\partial^3}{\partial y^3} \alpha_{35} + \frac{4}{5} \frac{\partial}{\partial x} \alpha_{40} + \frac{3}{5} \frac{\partial^3}{\partial x \partial y^2} \alpha_{39} + \frac{3}{5} \frac{\partial^3}{\partial x^3} \alpha_{39} - k_2 \frac{\partial^2 w}{\partial x^2} - k_2 \frac{\partial^2 w}{\partial y^2} + k_1 w - N_x \frac{\partial^2 w}{\partial x^2} - N_y \frac{\partial^2 w}{\partial y^2} - N_{TE_x} \frac{\partial^2 w}{\partial x^2} - N_{TE_y} \frac{\partial^2 w}{\partial y^2} = 0
 \end{aligned} \tag{41}$$

$\delta \phi$:

$$\frac{\partial}{\partial x} H_x + \frac{\partial}{\partial y} H_y + H_z = 0 \tag{42}$$

in which:

$$\begin{aligned}
 & \begin{pmatrix} N_{xx} \\ yy \\ M_{xxb} \\ yyb \\ M_{xys} \\ yys \end{pmatrix} = \int_z \left(Q_{11} \begin{bmatrix} 1 & -z & -\xi(z) \\ z & -z^2 & -z\xi(z) \\ 12 \begin{bmatrix} \xi(z) & -z\xi(z) & -\xi(z)^2 \end{bmatrix} \end{bmatrix} + Q_{12} \begin{bmatrix} 1 & -z & -\xi(z) \\ z & -z^2 & -z\xi(z) \\ 22 \begin{bmatrix} \xi(z) & -z\xi(z) & -\xi(z)^2 \end{bmatrix} \end{bmatrix} - E_e \begin{bmatrix} 1 \\ z \\ \xi(z) \end{bmatrix} \right) \\
 & \left\{ \frac{\partial u}{\partial x}, \frac{\partial^2 w_b}{\partial x^2}, \frac{\partial^2 w_s}{\partial x^2}, \frac{\partial v}{\partial y}, \frac{\partial^2 w_b}{\partial y^2}, \frac{\partial^2 w_s}{\partial y^2}, \phi \right\}^T dz, \\
 & \begin{pmatrix} N_{xy} \\ M_{yxb} \\ M_{yys} \end{pmatrix} = \int_z Q_{66} \begin{bmatrix} 1 & -2z & -\xi(z) & 1 \\ z & -2z^2 & -z\xi(z) & z \\ \xi(z) & -2z\xi(z) & -\xi(z)^2 & \xi(z) \end{bmatrix} \left\{ \frac{\partial u}{\partial y}, \frac{\partial^2 w_b}{\partial x \partial y}, \frac{\partial^2 w_s}{\partial x \partial y}, \frac{\partial v}{\partial x} \right\}^T dz, \\
 & H_x = \int_z \cos\left(\frac{\pi z}{h_f}\right) \left(-e_{15} \xi'(z) \frac{\partial w_s}{\partial x} + e_{15} \frac{\partial w_s}{\partial x} + \kappa_{11} \cos\left(\frac{\pi z}{h_f}\right) \frac{\partial \phi}{\partial x} \right) dz, \\
 & H_y = \int_z \cos\left(\frac{\pi z}{h_f}\right) \left(-e_{24} \xi'(z) \frac{\partial w_s}{\partial y} + e_{24} \frac{\partial w_s}{\partial y} + \kappa_{22} \cos\left(\frac{\pi z}{h_f}\right) \frac{\partial \phi}{\partial y} \right) dz, \\
 & H_z = \int_z \frac{\pi}{h_f} \sin\left(\frac{\pi z}{h_f}\right) \left(e_{31} \frac{\partial u}{\partial x} - z e_{31} \frac{\partial^2 w_b}{\partial x^2} - \xi(z) \left(e_{31} \frac{\partial^2 w_s}{\partial x^2} + e_{32} \frac{\partial v}{\partial y} - z e_{32} \frac{\partial^2 w_b}{\partial y^2} \right. \right. \\
 & \left. \left. - \xi(z) e_{32} \frac{\partial^2 w_s}{\partial y^2} - \frac{2}{h_f} \kappa_{33} \phi_0 - \frac{2\pi}{h_f} \sin\left(\frac{\pi z}{h_f}\right) \kappa_{33} \phi \right) dz, \\
 & \begin{pmatrix} \alpha_1 \\ \alpha_2 \end{pmatrix} = \int_z G l_0^2 \begin{bmatrix} 2 & 1 + \xi'(z) \\ 2\xi'(z) & \xi'(z)(1 + \xi'(z)^2) \end{bmatrix} \begin{pmatrix} \frac{\partial^2 w_b}{\partial x \partial y} \\ \frac{\partial^2 w_s}{\partial x \partial y} \end{pmatrix} dz,
 \end{aligned}$$

$$\begin{aligned} \left\{ \begin{matrix} \alpha_3 \\ \alpha_4 \end{matrix} \right\} &= \int_z G l_0^2 \begin{bmatrix} 2 & -1 - \xi'(z) \\ 2\xi'(z) & -\xi'(z)(1 + \xi'(z)^2) \end{bmatrix} \left\{ \begin{matrix} \frac{\partial^2 w_b}{\partial x \partial y} \\ \frac{\partial^2 w_s}{\partial x \partial y} \end{matrix} \right\} dz, \\ \left\{ \begin{matrix} \alpha_5 \\ \alpha_6 \end{matrix} \right\} &= \int_z G l_0^2 \begin{bmatrix} 1 & \frac{1}{2}(1 + \xi'(z)) & -1 & -\frac{1}{2}(1 + \xi'(z)) \\ \xi'(z) & \frac{1}{2}(1 + \xi'(z)) & -\xi'(z) & -\frac{1}{2}(1 + \xi'(z)) \end{bmatrix} \\ &\quad \left\{ \frac{\partial^2 w_b}{\partial y^2}, \frac{\partial^3 w_s}{\partial y^2}, \frac{\partial^2 w_b}{\partial x^2}, \frac{\partial^3 w_s}{\partial x^2} \right\}^T dz, \\ \left\{ \begin{matrix} \alpha_7 \\ \alpha_8 \end{matrix} \right\} &= \int_z \frac{1}{2} G l_0^2 \begin{bmatrix} \xi''(z)^2 & \xi''(z) & -\xi''(z) \\ \xi''(z) & 1 & -1 \end{bmatrix} \left\{ \frac{\partial w_s}{\partial y}, \frac{\partial^2 v}{\partial x^2}, \frac{\partial^2 u}{\partial x \partial y} \right\}^T dz, \\ \left\{ \begin{matrix} \alpha_9 \\ \alpha_{10} \end{matrix} \right\} &= \int_z \frac{1}{2} G l_0^2 \begin{bmatrix} -\xi''(z)^2 & \xi''(z) & -\xi''(z) \\ -\xi''(z) & 1 & -1 \end{bmatrix} \left\{ \frac{\partial w_s}{\partial x}, \frac{\partial^2 v}{\partial x \partial y}, \frac{\partial^2 u}{\partial y^2} \right\}^T dz, \\ \left\{ \begin{matrix} \alpha_{11} \\ \alpha_{12} \\ \alpha_{13} \end{matrix} \right\} &= \int_z 2 G l_1^2 \begin{bmatrix} 1 & -z & -\xi(z) & 1 & -z & -\xi(z) \\ z & -z^2 & -z\xi(z) & z & -z^2 & -z\xi(z) \\ \xi(z) & -z\xi(z) & -\xi(z)^2 & \xi(z) & -z\xi(z) & -\xi(z)^2 \end{bmatrix} \\ &\quad \left\{ \frac{\partial^2 u}{\partial x^2}, \frac{\partial^3 w_b}{\partial x^3}, \frac{\partial^3 w_s}{\partial x^3}, \frac{\partial^2 v}{\partial x \partial y}, \frac{\partial^3 w_b}{\partial x \partial y^2}, \frac{\partial^3 w_s}{\partial x \partial y^2} \right\}^T dz, \\ \left\{ \begin{matrix} \alpha_{14} \\ \alpha_{15} \\ \alpha_{16} \end{matrix} \right\} &= \int_z 2 G l_1^2 \begin{bmatrix} 1 & -z & -\xi(z) & 1 & -z & -\xi(z) \\ z & -z^2 & -z\xi(z) & z & -z^2 & -z\xi(z) \\ \xi(z) & -z\xi(z) & -\xi(z)^2 & \xi(z) & -z\xi(z) & -\xi(z)^2 \end{bmatrix} \\ &\quad \left\{ \frac{\partial^2 u}{\partial x \partial y}, \frac{\partial^3 w_b}{\partial x^2 \partial y}, \frac{\partial^3 w_s}{\partial x^2 \partial y}, \frac{\partial^2 v}{\partial y^2}, \frac{\partial^3 w_b}{\partial y^3}, \frac{\partial^3 w_s}{\partial y^3} \right\}^T dz, \\ \left\{ \begin{matrix} \alpha_{17} \\ \alpha_{18} \end{matrix} \right\} &= - \int_z 2 G l_1^2 \begin{bmatrix} 1 & \xi'(z) & 1 & \xi'(z) \\ \xi'(z) & \xi'(z)^2 & \xi'(z) & \xi'(z)^2 \end{bmatrix} \left\{ \frac{\partial^2 w_b}{\partial x^2}, \frac{\partial^2 w_s}{\partial x^2}, \frac{\partial^2 w_b}{\partial y^2}, \frac{\partial^2 w_s}{\partial y^2} \right\}^T dz, \\ \left\{ \begin{matrix} \alpha_{19} \\ \alpha_{20} \\ \alpha_{21} \\ \alpha_{22} \end{matrix} \right\} &= \int_z \frac{4}{5} l_2^2 G \begin{bmatrix} 1 & -z & -\xi(z) & -1 & z & -\xi(z) & -1 & \frac{1}{2}\xi''(z) \\ z & -z^2 & -z\xi(z) & -z & z^2 & -z\xi(z) & -z & \frac{1}{2}z\xi''(z) \\ \xi(z) & -z\xi(z) & -z\xi(z)^2 & -\xi(z) & z\xi(z) & -\xi(z)^2 & -\xi(z) & \frac{1}{2}\xi(z)\xi''(z) \\ \xi''(z) & -z\xi''(z) & -\xi''(z)\xi(z) & -\xi''(z) & z\xi''(z) & -\xi(z)\xi''(z) & -\xi''(z) & \frac{1}{2}\xi''(z)^2 \end{bmatrix} \\ &\quad \left\{ \frac{\partial^2 u}{\partial x^2}, \frac{\partial^3 w_b}{\partial x^3}, \frac{\partial^3 w_s}{\partial x^3}, \frac{\partial^2 v}{\partial x \partial y}, \frac{\partial^3 w_b}{\partial x \partial y^2}, \frac{\partial^3 w_s}{\partial x \partial y^2}, \frac{\partial^2 u}{\partial y^2}, \frac{\partial v_x}{\partial x} \right\}^T dz, \\ \left\{ \begin{matrix} \alpha_{23} \\ \alpha_{24} \\ \alpha_{25} \\ \alpha_{26} \end{matrix} \right\} &= \int_z \frac{4}{5} l_2^2 G \begin{bmatrix} 1 & -z & -\xi(z) & -1 & z & \xi(z) & -1 & \frac{1}{2}\xi''(z) \\ z & -z^2 & -z\xi(z) & -z & z^2 & z\xi(z) & -z & \frac{1}{2}z\xi''(z) \\ \xi(z) & -z\xi(z) & -z\xi(z)^2 & -\xi(z) & z\xi(z) & \xi(z)^2 & -\xi(z) & \frac{1}{2}\xi(z)\xi''(z) \\ \xi''(z) & -z\xi''(z) & -\xi''(z)\xi(z) & -\xi''(z) & z\xi''(z) & \xi(z)\xi''(z) & -\xi''(z) & \frac{1}{2}\xi''(z)^2 \end{bmatrix} \\ &\quad \left\{ \frac{\partial^2 v}{\partial y^2}, \frac{\partial^3 w_b}{\partial y^3}, \frac{\partial^3 w_s}{\partial y^3}, \frac{\partial^2 u}{\partial x \partial y}, \frac{\partial^3 w_b}{\partial x \partial y^2}, \frac{\partial^3 w_s}{\partial x \partial y^2}, \frac{\partial^2 v}{\partial x^2}, \frac{\partial v_x}{\partial y} \right\}^T dz, \end{aligned}$$

$$\left\{ \begin{matrix} \alpha_{27} \\ \alpha_{28} \end{matrix} \right\} = \int_z \frac{2}{5} G l_2^2 \begin{bmatrix} 1 & 2\xi'(z) - 1 & 1 & \xi'(z) \\ \xi'(z) & 2\xi'(z)^2 - 1 & \xi'(z) & \xi'(z)^2 \end{bmatrix} \left\{ \frac{\partial^2 w_b}{\partial x^2}, \frac{\partial^3 w_s}{\partial x^3}, \frac{\partial^2 w_b}{\partial y^2}, \frac{\partial^3 w_s}{\partial y^3} \right\}^T dz,$$

$$\left\{ \begin{matrix} \alpha_{29} \\ \alpha_{30} \\ \alpha_{31} \\ \alpha_{32} \end{matrix} \right\} = \int_z \frac{2}{5} l_2^2 G \begin{bmatrix} -1 & z & -\xi(z) & \frac{8}{3} & -4z & 4\xi(z) & \frac{4}{3} & -\frac{1}{3}\xi''(z) \\ -z & z^2 & -z\xi(z) & \frac{8}{3}z & -4z^2 & 4z\xi(z) & \frac{4}{3}z & -\frac{1}{3}z\xi''(z) \\ -\xi(z) & z\xi(z) & -z\xi(z)^2 & \frac{8}{3}\xi(z) & -4z\xi(z) & 4\xi(z)^2 & \frac{4}{3}\xi(z) & -\frac{1}{3}\xi(z)\xi''(z) \\ -\xi''(z) & z\xi''(z) & -\xi''(z)\xi(z) & \frac{8}{3}\xi''(z) & -4z\xi''(z) & 4\xi(z)\xi''(z) & \frac{4}{3}\xi''(z) & -\frac{1}{3}\xi''(z)^2 \end{bmatrix}$$

$$\left\{ \frac{\partial^2 u}{\partial x^2}, \frac{\partial^3 w_b}{\partial x^3}, \frac{\partial^3 w_s}{\partial x^3}, \frac{\partial^2 v}{\partial x \partial y}, \frac{\partial^3 w_b}{\partial y^2 \partial x}, \frac{\partial^2 u}{\partial x^2}, \frac{\partial^3 w_s}{\partial y^2 \partial x}, \frac{\partial v}{\partial x} \right\}^T dz,$$

$$\left\{ \begin{matrix} \alpha_{33} \\ \alpha_{34} \\ \alpha_{35} \\ \alpha_{36} \end{matrix} \right\} = \int_z \frac{2}{5} l_2^2 G \begin{bmatrix} -1 & z & \xi(z) & \frac{8}{3} & -4z & 4\xi(z) & \frac{4}{3} & -\frac{1}{3}\xi''(z) \\ -z & z^2 & z\xi(z) & \frac{8}{3}z & -4z^2 & 4z\xi(z) & \frac{4}{3}z & -\frac{1}{3}z\xi''(z) \\ -\xi(z) & z\xi(z) & z\xi(z)^2 & \frac{8}{3}\xi(z) & -4z\xi(z) & 4\xi(z)^2 & \frac{4}{3}\xi(z) & -\frac{1}{3}\xi(z)\xi''(z) \\ -\xi''(z) & z\xi''(z) & \xi''(z)\xi(z) & \frac{8}{3}\xi''(z) & -4z\xi''(z) & 4\xi(z)\xi''(z) & \frac{4}{3}\xi''(z) & -\frac{1}{3}\xi''(z)^2 \end{bmatrix}$$

$$\left\{ \frac{\partial^2 v}{\partial y^2}, \frac{\partial^3 w_b}{\partial y^3}, \frac{\partial^3 w_s}{\partial y^3}, \frac{\partial^2 u}{\partial x \partial y}, \frac{\partial^3 w_b}{\partial x^2 \partial y}, \frac{\partial^3 w_s}{\partial x^2 \partial y}, \frac{\partial^2 v}{\partial x^2}, \frac{\partial v}{\partial x} \right\}^T dz,$$

$$\left\{ \begin{matrix} \alpha_{37} \\ \alpha_{38} \\ \alpha_{39} \\ \alpha_{40} \end{matrix} \right\} = \int_z \frac{2}{5} l_2^2 G \begin{bmatrix} -1 & z & \xi(z) & \frac{2}{3} & -z & \xi(z) & -\frac{1}{3} & -\frac{4}{3}\xi''(z) \\ -z & z^2 & z\xi(z) & \frac{2}{3}z & -z^2 & z\xi(z) & -\frac{1}{3}z & -\frac{4}{3}z\xi''(z) \\ -\xi(z) & z\xi(z) & z\xi(z)^2 & \frac{2}{3}\xi(z) & -z\xi(z) & \xi(z)^2 & -\frac{1}{3}\xi(z) & -\frac{4}{3}\xi(z)\xi''(z) \\ -\xi''(z) & z\xi''(z) & \xi''(z)\xi(z) & \frac{2}{3}\xi''(z) & -z\xi''(z) & \xi(z)\xi''(z) & -\frac{1}{3}\xi''(z) & -\frac{4}{3}\xi''(z)^2 \end{bmatrix}$$

$$\left\{ \frac{\partial^2 u}{\partial x^2}, \frac{\partial^3 w_b}{\partial x^3}, \frac{\partial^3 w_s}{\partial x^3}, \frac{\partial^2 v}{\partial x \partial y}, \frac{\partial^3 w_b}{\partial y^2 \partial x}, \frac{\partial^3 w_s}{\partial y^2 \partial x}, \frac{\partial^2 u}{\partial y^2}, \frac{\partial v}{\partial x} \right\}^T dz,$$

$$\left\{ \begin{matrix} \alpha_{41} \\ \alpha_{42} \\ \alpha_{43} \\ \alpha_{44} \end{matrix} \right\} = \int_z \frac{2}{5} l_2^2 G \begin{bmatrix} -1 & z & \xi(z) & -\frac{2}{3} & z & \xi(z) & -\frac{1}{3} & -\frac{4}{3}\xi''(z) \\ -z & z^2 & z\xi(z) & -\frac{2}{3}z & z^2 & z\xi(z) & -\frac{1}{3}z & -\frac{4}{3}z\xi''(z) \\ -\xi(z) & z\xi(z) & z\xi(z)^2 & -\frac{2}{3}\xi(z) & z\xi(z) & \xi(z)^2 & -\frac{1}{3}\xi(z) & -\frac{4}{3}\xi(z)\xi''(z) \\ -\xi''(z) & z\xi''(z) & \xi''(z)\xi(z) & -\frac{2}{3}\xi''(z) & z\xi''(z) & \xi(z)\xi''(z) & -\frac{1}{3}\xi''(z) & -\frac{4}{3}\xi''(z)^2 \end{bmatrix}$$

$$\left\{ \frac{\partial^2 v}{\partial y^2}, \frac{\partial^3 w_b}{\partial y^3}, \frac{\partial^3 w_s}{\partial y^3}, \frac{\partial^2 u}{\partial x \partial y}, \frac{\partial^3 w_b}{\partial x^2 \partial y}, \frac{\partial^3 w_s}{\partial x^2 \partial y}, \frac{\partial^2 v}{\partial x^2}, \frac{\partial v}{\partial y} \right\}^T dz,$$

$$\left\{ \begin{matrix} \alpha_{45} \\ \alpha_{46} \end{matrix} \right\} = \int_z \frac{2}{15} G l_2^2 \begin{bmatrix} -4 - 8\xi'(z) + 412\xi''(z) - 1 - 4\xi'(z) - 4\xi''(z) \\ -8\xi'(z)^2 + 4\xi'(z)\xi''(z) + 2\xi''(z)^2 - \xi'(z) \end{bmatrix}$$

$$\left\{ \frac{\partial^2 w_b}{\partial x^2}, \frac{\partial^3 w_s}{\partial x^3}, \frac{\partial^2 w_b}{\partial y^2}, \frac{\partial^3 w_s}{\partial y^3} \right\}^T dz,$$

$$\begin{aligned} \begin{Bmatrix} \alpha_{47} \\ \alpha_{48} \end{Bmatrix} &= \int_z \frac{2}{15} G I_2^2 \begin{bmatrix} -1 - 2\xi'(z) + 148\xi'(z) + 4 - \xi'(z) - \xi'(z) \\ -2\xi'(z)^2 + \xi(z) 4\xi'(z) 8\xi'(z)^2 + 4\xi'(z) \end{bmatrix} \\ &\left\{ \frac{\partial^2 w_b}{\partial x^2}, \frac{\partial^2 w_s}{\partial x^2}, \frac{\partial^2 w_b}{\partial y^2}, \frac{\partial^2 w_s}{\partial y^2} \right\}^T dz, \\ \begin{Bmatrix} \alpha_{49} \\ \alpha_{50} \end{Bmatrix} &= \int_z \frac{2}{3} G I_2^2 \begin{bmatrix} -2\xi'(z) + \xi'(z) & -1 \\ -2\xi'(z)^2 + \xi(z)^2 & -\xi'(z) \end{bmatrix} \begin{Bmatrix} \frac{\partial^2 w_s}{\partial y \partial x} \\ \frac{\partial^2 w_b}{\partial y \partial x} \end{Bmatrix} dz \end{aligned} \tag{43}$$

3. Analytical solution scheme

The displacements can be considered as functions satisfying the simply supported boundary conditions at the edges of the structure. So, the following functions can be considered for displacement components [85]:

$$\begin{Bmatrix} u \\ v \\ w_b \\ w_s \\ \phi \end{Bmatrix} = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \begin{Bmatrix} U \cos\left(\frac{m\pi}{L}x\right) \sin\left(\frac{n\pi}{W}y\right) \\ V \sin\left(\frac{m\pi}{L}x\right) \cos\left(\frac{n\pi}{W}y\right) \\ W_b \sin\left(\frac{m\pi}{L}x\right) \sin\left(\frac{n\pi}{W}y\right) \\ W_s \sin\left(\frac{m\pi}{L}x\right) \sin\left(\frac{n\pi}{W}y\right) \\ \Phi \sin\left(\frac{m\pi}{L}x\right) \sin\left(\frac{n\pi}{W}y\right) \end{Bmatrix} \tag{44}$$

where $U, V, W_b, W_s,$ and Φ are amplitudes of displacements and the electric potential of the microplate, respectively. Also, m and n are the respective wavenumbers along x and y axes. Substituting the proposed functions in the governing equations:

$$\left([K_e] - \begin{Bmatrix} P_{cr} \\ T_{cr} \end{Bmatrix} [K_g] \right) \{X\} = 0 \tag{45}$$

Here, $[K_e]$ is stiffness and $[K_g]$ is the geometric stiffness matrixes. Their components are presented in ‘‘Appendix’’, P_{cr} and T_{cr} denote the critical buckling load and temperature, respectively. The critical buckling load and temperature of the microstructure can be obtained by solving Eq. (45) eigenvalue problem.

4. Results and discussion

In the first phase, the results were compared with the previously published data to ensure their reliability and accuracy. To this end, since the present work is the first analysis with the aforementioned specifications and there is no similar work in the other open literature, the authors neglected some parameters to make the results comparable to other papers. Therefore, the dimensionless critical buckling loads for an FG-GNPs-reinforced composites microplate were obtained and compared with those of Song et al. [86]. To derive the results, the thicknesses of the faces were set to zero implying that the results were obtained for an FG-GNPs-reinforced microplate according to CET. Moreover, the effects of the foundation and thermal environment were not included in this part. The results were presented for two cases, namely uniaxial and biaxial loading conditions and also, for different weight fraction of GPLs. According to Table 1, the current results and those of Song et al. [86] coincided suggesting a good agreement. The non-dimensional critical buckling load in Table 1 is shown by Na^2/Eh_T^3 . Noteworthy, the slight difference between the results can be due to differences in displacement field theories used by Song et al. [86] and the present study and also, the different approaches used to derive the differential equations. Therefore, the results and their accuracy are verified. In the following, the results regarding all of the parameters are presented. The thermo-mechanical properties of the core and the faces are presented in Tables 2 and 3 ([87,88]). Moreover, the total height of the microplate was taken 150 μm and the length-scale parameters, i.e. $l_0, l_1,$ and l_2 were set equal to each other (l), ten times smaller than h_T . Also, the core’s and faces’ thickness is $0.8h_T$ and $0.1h_T$, respectively. It must be noted that for all of the following graphs, unless

Table 1
Comparing the results in a simpler state with those of Song et al. [86].

(γ_x, γ_y)	Source	g_{GNP}					
		Pure Epoxy	0.2%	0.4%	0.8%	1.0%	1.2%
(1,1)	Present	0.0018	0.0030	0.0042	0.0066	0.0079	0.0091
	Ref. [86]	0.0018	0.0029	0.0041	0.0064	0.0076	0.0088
(1,0)	Present	0.0036	0.0061	0.0085	0.0132	0.0157	0.0180
	Ref. [86]	0.0035	0.0058	0.0082	0.0128	0.0152	0.0175

Table 2
Thermo-mechanical properties of the Epoxy-reinforced GNPs core [87].

Properties	GNPs Reinforcement	Epoxy Matrix
E	1.01 TPa	130 GPa
N	0.186	0.34
L	2.5 μm	-
W	1.5 μm	-
H	1.5 nm	-
A	$2.35 \times 10^{-5} K^{-1}$	$8.2 \times 10^{-5} K^{-1}$

Table 3
Thermo-mechanical properties of the piezoelectric-reinforced SWCNTs faces [88].

Properties	SWCNTs Reinforcements	PVDF Matrix
E_{11}	5.64 TPa	2.2 GPa
E_{22}	7.08 TPa	-
G_{12}	1.9445 TPa	-
N	0.175	0.384
e_{31}	0	-0.13 C/m ²
e_{32}	0	-0.45 C/m ²
e_{15}	0	-0.009 C/m ²
$\kappa_{11} = \kappa_{22}$	0	0.1107 nF/m ²
κ_{33}	0	0.1061 nF/m ²
α_{11}	$3.4584 \times 10^{-6} K^{-1}$	$4.1682 \times 10^{-6} K^{-1}$
α_{22}	$5.1682 \times 10^{-6} K^{-1}$	-

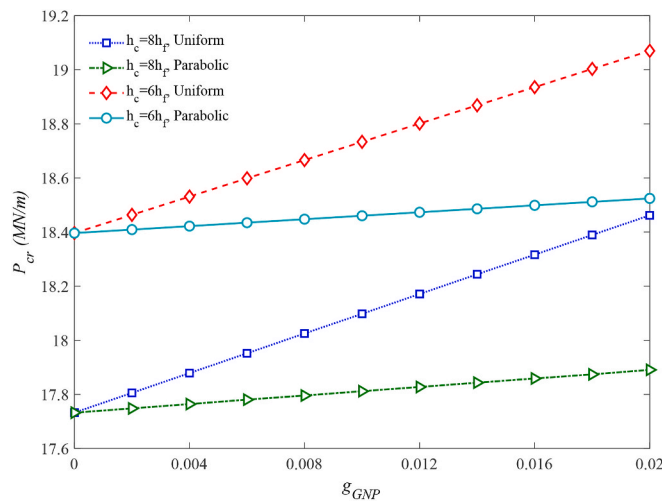


Fig. 2. Effect of GNPs content on the critical buckling load for various thickness ratios and two types of GNPs dispersion pattern.

otherwise expressed, the length and width of the microplate are equal to each other ($a = b = 10h_T$) and the distribution patterns of both GNPs and CNTs are uniform.

In the next step, the results are presented and discussed in detail in the following. Fig. 2 depicts since enhancement in GNPs volume fraction, makes the structure stiffer, therefore, the critical buckling load in both considered GNPs dispersion types increases. Also, as can be seen, the predicted results in the uniform pattern of GNPs dispersion are generally higher than those of the parabolic pattern. This figure also considers the effect of thickness ratio on the P_{cr} which states as the core's to faces' thickness ratio becomes larger, the critical buckling loads manner differently and it decreases due to a reduction in stiffness of the microplate. Fig. 3 investigates the effects of temperature variations and also, CNTs volume fraction on the mechanical buckling response of the microstructure. It can be found that as the temperature increases concerning the ambient temperature, the stiffness of the model reduces, and actually, lead to a decrease in the critical buckling load. Also, increasing the CNTs' volume fraction which means an enhancement in stiffness of the microplate, increases the critical buckling load. This figure is plotted for uniform and parabolic patterns of GNPs dispersion and pure Epoxy which is free of GNPs and consequently, has the lowest stiffness in comparison to other cases. Table 4 shows the critical buckling load for different cases such as temperatures, externally applied electric potential, and uniaxial/biaxial loading conditions. Regarding this table, generally, the biaxial loading condition leads to fewer results in comparison to the uniaxial one. Furthermore, it is seen

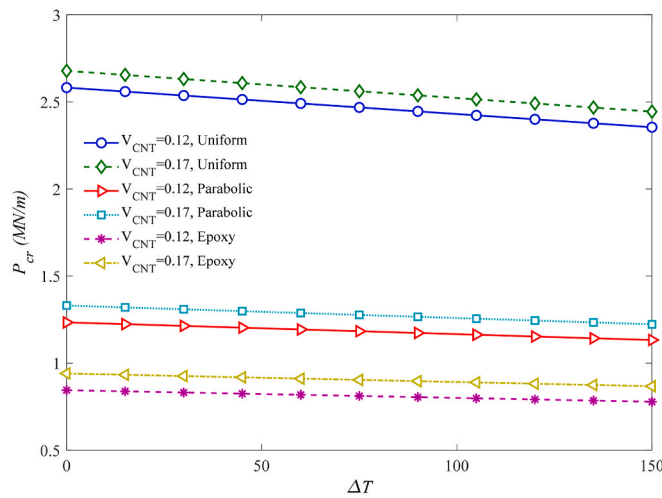


Fig. 3. Effect of temperature changes on the critical buckling load for different CNTs' volume fraction.

Table 4

Effect of temperature and applied electric potential variations on the critical buckling load in different loading conditions.

a/h_T	(γ_x, γ_y)	ΔT			V_E		
		0	40	80	-1000	1000	5000
10	(1,1)	2.2075	2.1890	2.1706	2.2077	2.2072	2.2063
	(0,1)	7.1743	7.1144	7.0544	7.1750	7.1735	7.1706
	(1,0)	3.1886	3.1619	3.1353	3.1889	3.1882	3.1869
15	(1,1)	2.5668	2.5488	2.5308	2.5670	2.5665	2.5656
	(0,1)	5.1335	5.0976	5.0617	5.1340	5.1331	5.1312
	(1,0)	5.1335	5.0976	5.0617	5.1340	5.1331	5.1312
20	(1,1)	0.9089	0.8912	0.8736	0.9091	0.9086	0.9077
	(0,1)	1.4201	1.3925	1.3650	1.4204	1.4197	1.4183
	(1,0)	2.5246	2.4756	2.4267	2.5252	2.5240	2.5214

Table 5

Effect of length-scale parameter and length to thickness ratio of the microplate on the critical buckling load in different loading conditions.

a/h_T	(γ_x, γ_y)	l/h_T				
		0.01	0.1	0.4	0.8	1
10	(1,1)	0.0050	0.0053	0.0092	0.0215	0.0303
	(0,1)	0.0163	0.0171	0.0298	0.0699	0.0985
	(1,0)	0.0072	0.0076	0.0132	0.0311	0.0438
15	(1,1)	0.0060	0.0061	0.0085	0.0161	0.0216
	(0,1)	0.0119	0.0123	0.0170	0.0170	0.0432
	(1,0)	0.0119	0.0123	0.0170	0.0170	0.0432
20	(1,1)	0.0020	0.0022	0.0093	0.0152	0.0195
	(0,1)	0.0032	0.0034	0.0145	0.0237	0.0305
	(1,0)	0.0057	0.0060	0.0257	0.0422	0.0542

although increasing both temperature and electric potential leads the critical buckling load to reduce, increasing length-to-height of the microplate, tends the results to enhance. Also, Table 5 presents the critical buckling temperatures for several of the nondimensional length-scale parameter and shows its increasing makes the microstructure stiffer which accordingly, the critical buckling temperature enhances. It can be found in Fig. 4 which is plotted for different patterns of CNTs distribution. According to Fig. 4, the FG-VA pattern leads to the highest critical load of buckling, but FG-OO leads to the lowest ones. It occurs due to the agglomeration of CNTs in the surfaces concerning the lower heights. Therefore, the stiffness of the facesheets in FG-VA is more than the other types. On the other hand, based on Fig. 4, as the plate's length becomes more than its height, its rigidity reduces and the critical buckling load tends to reduce. Fig. 5a and b compare the predicted results (i.e. both critical buckling load and temperature) for micro and macro models. It is understood that accounting the size effects lead to the results to enhance. Also, comparing the MCST-based results and those of MSGT

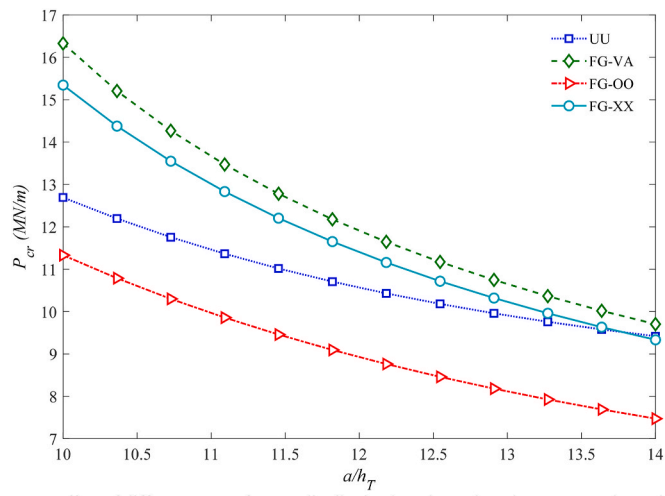
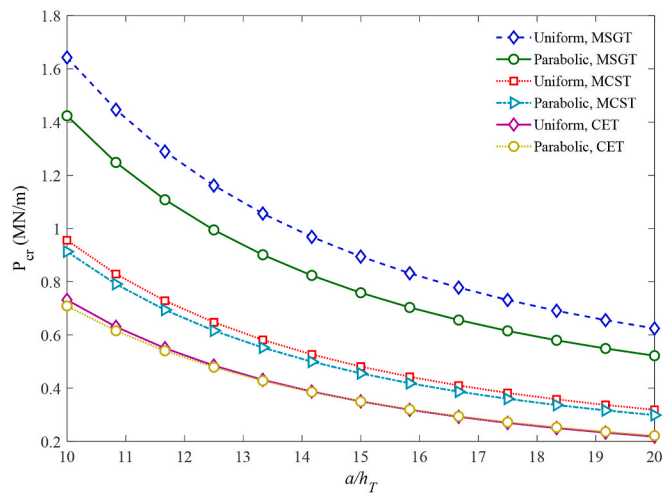
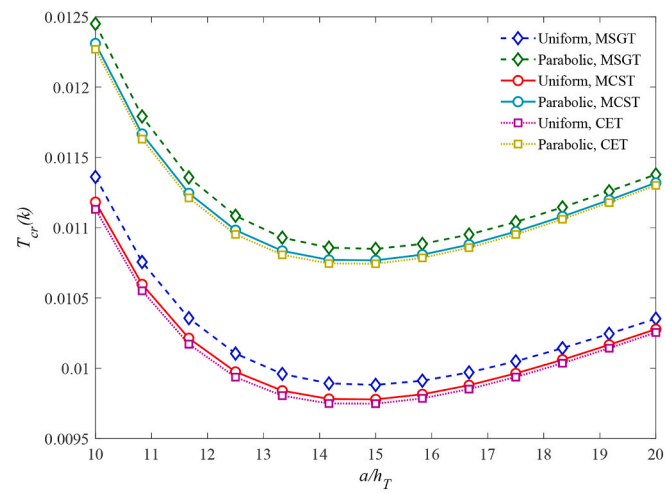


Fig. 4. Effect of different types of CNTs distribution based on microplate aspect ratio on the critical buckling load.



(a)



(b)

Fig. 5. Comparing the predicted a) critical buckling load; b) critical buckling temperature by MSG, MCS, and CE theories.

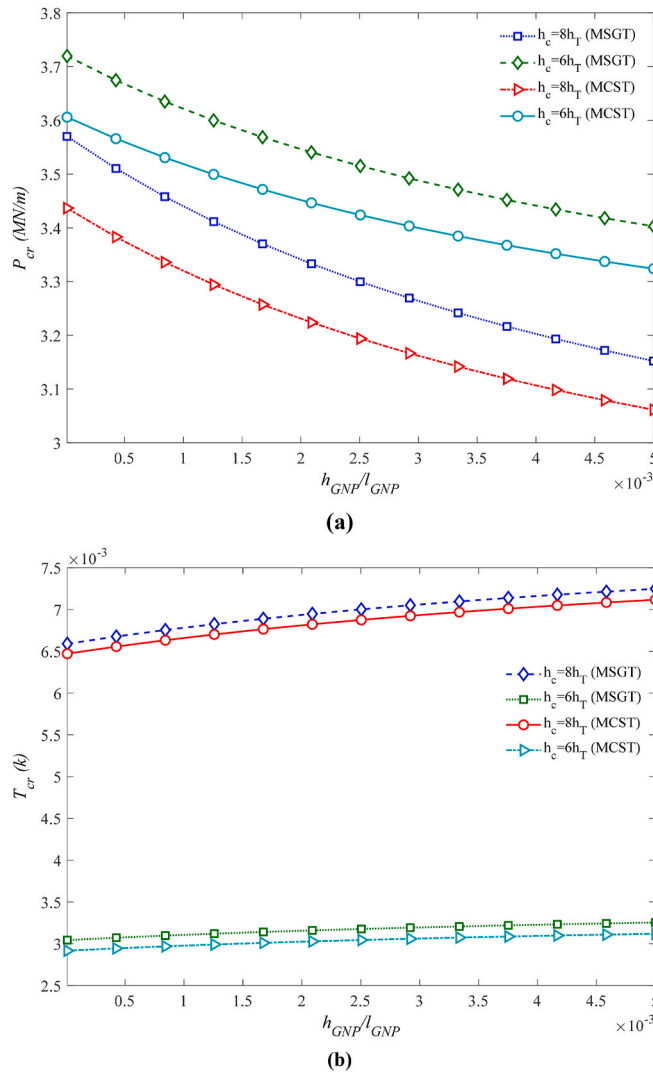


Fig. 6. Effect of GNPs' height-to-length ratio on the a) critical buckling load; b) critical buckling temperature.

shows that accounting for all three length-scale parameters tends the results to enhance due to considering dilatation gradients and deviatoric stretch gradient tensors. Fig. 6a and b illustrate the influence of GNPs' geometrical specifications on both critical buckling load and temperature. It is seen that although increasing h_{GNPs}/l_{GNPs} ratio tends the buckling load to reduce, the buckling temperature leads to an increase. A similar manner is seen in Arefi et al. [89] work. Also, it is true for both MCS and MSG theories and all thickness ratios. Figs. 7 and 8 depict the effect of substrate parameters on both critical buckling and temperature load, respectively. Fig. 7 is plotted for different values of ΔT and it is observed that increasing both Winkler and Pasternak parameters enhances the critical buckling load due to increase in the microstructure's rigidity. Also, a similar effect is seen in Fig. 8 but for critical buckling temperature. It means increasing k_1 and k_2 , makes the critical buckling temperature more.

5. Conclusions

The novelty of the present work lies in considering three-layered rectangular FG-GNPs-reinforced composite microplate which was integrated by SWCNTs-reinforced piezoelectric patches and it is rested on the Pasternak model of the elastic substrate. This study investigated the thermo-mechanical buckling responses of this rectangular microplate. To account for the shear deformation effect, TSDT, as a trigonometric theory, was employed and MSGT with three length-scale parameters was selected to study the scale influence. Based on the virtual displacement principle, the governing equations were mathematically derived. The results were validated with the known data in the literature. It is found that adding the GNPs to the core Epoxy matrix enhanced both critical buckling load and temperature. Also, among different patterns of GNPs dispersion, the parabolic pattern leads to the highest buckling load and temperature. Comparing different patterns of CNTs distribution along with the faces' thickness shows that FG-VA and FG-OO resulted in

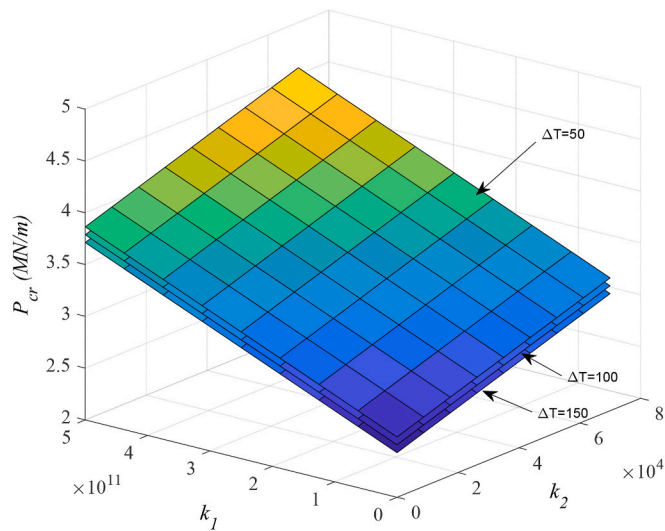


Fig. 7. Effect of Pasternak substrate parameters on the critical buckling load.

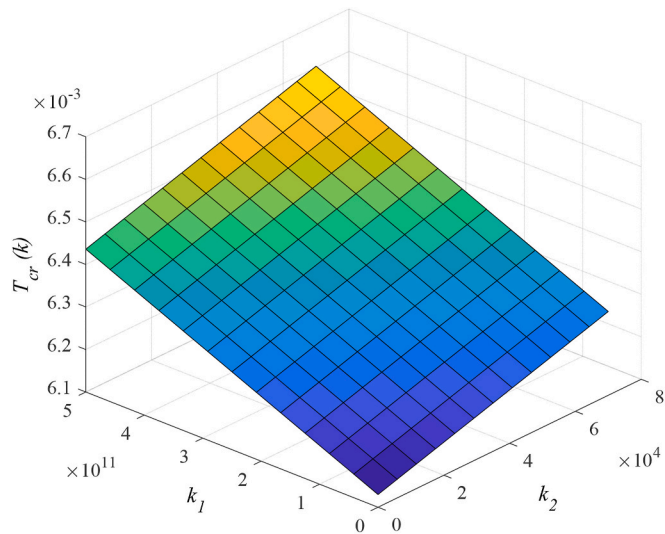


Fig. 8. Effect of Pasternak substrate parameters on the critical buckling temperature.

the maximum and minimum critical buckling loads and temperatures, respectively. Moreover, increasing the externally applied voltage to the faces increased the softness of the structure, hence, declining its critical buckling load. The predicted results by MSGT are generally higher than those of MCST due to additional length-scale parameters and considered effects. Furthermore, increasing the temperature above the ambient one decreased the results due to a reduction in the stiffness of the microplate. As the last conclusion, adding the elastic substrate increased the rigidity of the microstructure and accordingly, enhanced the critical buckling load and temperature.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

The non-zero components of matrices of Eq. (45) are defined as:

$$K_{11} = \frac{1}{2}T_0\alpha^2\beta^2 + 2K_0\alpha^2\beta^2 + \frac{14}{15}G_0\alpha^2\beta^2 + 2K_0\alpha^4 + \frac{4}{5}G_0\alpha^4 + Q_{110}\alpha^2 + Q_{660}\beta^2 + \frac{1}{2}T_0\beta^4 + \frac{2}{5}G_0\beta^4, \tag{A-1}$$

$$K_{12} = -\frac{1}{2}T_0\alpha^3\beta + 2K_0\alpha^3\beta + 2K_0\alpha\beta^3 + \frac{4}{15}G_0\alpha^3\beta + Q_{120}\alpha\beta + Q_{660}\alpha\beta - \frac{1}{2}T_0\alpha\beta^3, \tag{A-2}$$

$$K_{13} = -4K_1\alpha^3\beta^2 - 2K_1\alpha\beta^4 - \frac{6}{5}G_1\alpha^3\beta^2 - Q_{121}\alpha\beta^2 - 2Q_{661}\alpha\beta^2 - \frac{2}{5}G_1\alpha\beta^4 - 2K_1\alpha^5 - \frac{4}{5}G_1\alpha^5 - Q_{111}\alpha^3, \tag{A-3}$$

$$K_{14} = -4K_3\alpha^3\beta^2 - 2K_3\alpha\beta^4 - \frac{6}{5}G_3\alpha^3\beta^2 - Q_{123}\alpha\beta^2 - 2Q_{663}\alpha\beta^2 - \frac{2}{5}G_3\alpha\beta^4 - 2K_3\alpha^5 - \frac{4}{5}G_3\alpha^5 - Q_{113}\alpha^3, \tag{A-4}$$

$$K_{15} = -Q_{136}\alpha, \tag{A-5}$$

$$K_{21} = 2K_0\alpha\beta^3 + 2K_0\alpha^3\beta + \frac{4}{15}G_0\alpha^3\beta + \frac{4}{15}G_0\alpha\beta^3 + Q_{120}\alpha\beta + Q_{660}\alpha\beta - \frac{1}{2}T_0\alpha^3\beta - \frac{1}{2}T_0\alpha\beta^3, \tag{A-6}$$

$$K_{22} = 2K_0\alpha^2\beta^2 + \frac{4}{3}G_0\alpha^2\beta^2 + \frac{1}{2}T_0\alpha^2\beta^2 + Q_{220}\beta^2 + Q_{660}\alpha^2 + \frac{1}{2}T_0\alpha^4 + 2K_0\beta^4 + \frac{8}{15}G_0\alpha^4 + \frac{4}{5}G_0\beta^4, \tag{A-7}$$

$$K_{23} = -4K_1\alpha^2\beta^3 - 2K_1\alpha^4\beta - \frac{8}{5}G_1\alpha^2\beta^3 - \frac{4}{5}G_1\alpha^4\beta - Q_{121}\alpha^2\beta - 2Q_{661}\alpha^2\beta - Q_{221}\beta^3 - 2K_1\beta^5 - \frac{4}{5}G_1\beta^5, \tag{A-8}$$

$$K_{24} = -4K_3\alpha^2\beta^3 - 2K_3\alpha^4\beta - \frac{8}{5}G_3\alpha^2\beta^3 - \frac{4}{5}G_3\alpha^4\beta - Q_{123}\alpha^2\beta - 2Q_{663}\alpha^2\beta - Q_{223}\beta^3 - 2K_3\beta^5 - \frac{4}{5}G_3\beta^5, \tag{A-9}$$

$$K_{25} = -Q_{236}\beta \tag{A-10}$$

$$K_{31} = 4K_1\alpha^3\beta^2 + 2K_1\alpha\beta^4 - 2Q_{661}\alpha\beta^2 + \frac{4}{5}G_1\alpha\beta^4 - Q_{121}\alpha\beta^2 + \frac{8}{5}G_1\alpha^3\beta^2 - Q_{111}\alpha^3 + \frac{4}{5}G_1\alpha^5 + 2K_1\alpha^5, \tag{A-11}$$

$$K_{32} = 2K_1\alpha^4\beta + 4K_1\alpha^2\beta^3 - 2Q_{661}\alpha^2\beta + \frac{8}{5}G_1\alpha^2\beta^3 - Q_{121}\alpha^2\beta + \frac{4}{5}G_1\alpha^4\beta - Q_{221}\beta^3 + 2K_1\beta^5 + \frac{4}{5}G_1\beta^5, \tag{A-12}$$

$$\begin{aligned}
K_{33} = & -2 K_2 \alpha^2 \beta^4 - 4 K_2 \alpha^4 \beta^2 - 4 K_2 \alpha^2 \beta^4 + 4 K_0 \alpha^2 \beta^2 + \frac{88}{75} G_0 \alpha^2 \beta^2 + 4 Q_{662} \alpha^2 \beta^2 \\
& - \frac{12}{5} G_2 \alpha^2 \beta^4 - 2 K_2 \alpha^4 \beta^2 + 2 Q_{122} \alpha^2 \beta^2 - \frac{12}{5} G_2 \alpha^4 \beta^2 + Q_{112} \alpha^4 + Q_{222} \beta^4 \\
& - \frac{4}{5} G_2 \alpha^6 + \frac{8}{75} G_0 \beta^4 - 2 K_2 \alpha^6 - 2 K_2 \beta^6 + 2 K_0 \beta^4 + \frac{8}{15} G_0 \alpha^4 - \frac{4}{5} G_2 \beta^6 \\
& + 2 T_0 \beta^4 + 2 T_0 \alpha^4 + 2 K_0 \alpha^4 + k_2 \alpha^2 + k_2 \beta^2 + k_1 - N_{TE\alpha} \beta^2 - N_{TE\beta} \alpha^2,
\end{aligned} \tag{A-13}$$

$$\begin{aligned}
K_{34} = & Q_{224} \beta^4 + T_1 \beta^4 + T_1 \alpha^4 + Q_{114} \alpha^4 - 2 K_4 \alpha^6 + 2 K_6 \beta^4 \\
& + \frac{8}{15} G_6 \alpha^4 + \frac{8}{75} G_6 \beta^4 + 2 K_6 \alpha^4 - 2 K_4 \beta^6 - \frac{4}{5} G_4 \alpha^6 \\
& - \frac{4}{5} G_4 \beta^6 - 6 K_4 \alpha^2 \beta^4 + 4 Q_{664} \alpha^2 \beta^2 - 6 K_4 \alpha^4 \beta^2 + 4 K_6 \alpha^2 \beta^2 + \frac{88}{75} G_6 \alpha^2 \beta^2 \\
& - \frac{12}{5} G_4 \alpha^2 \beta^4 + 2 Q_{124} \alpha^2 \beta^2 - \frac{12}{5} G_4 \alpha^4 \beta^2 + T_0 \alpha^4 + T_0 \beta^4 + k_1 - N_{TE\alpha} \alpha^2 - N_{TE\beta} \beta^2 \\
& + k_2 \alpha^2 + k_2 \beta^2,
\end{aligned} \tag{A-14}$$

$$K_{35} = Q_{137} \alpha^2 + Q_{237} \beta^2, \tag{A-15}$$

$$\begin{aligned}
K_{41} = & 2 K_3 \alpha^5 - Q_{113} \alpha^3 + \frac{4}{5} G_3 \alpha^5 + 2 K_3 \alpha \beta^4 + \frac{8}{5} G_3 \alpha^3 \beta^2 - Q_{123} \alpha \beta^2 + 4 K_3 \alpha^3 \beta^2 \\
& - 2 Q_{663} \alpha \beta^2 + \frac{4}{5} G_3 \alpha \beta^4,
\end{aligned} \tag{A-16}$$

$$\begin{aligned}
K_{42} = & 2 K_3 \beta^5 - Q_{223} \beta^3 + \frac{4}{5} G_3 \beta^5 + 2 K_3 \alpha^4 \beta - Q_{123} \alpha^2 \beta + \frac{4}{5} G_3 \alpha^4 \beta \\
& + 4 K_3 \alpha^2 \beta^3 - 2 Q_{663} \alpha^2 \beta + \frac{8}{5} G_3 \alpha^2 \beta^3,
\end{aligned} \tag{A-17}$$

$$\begin{aligned}
K_{43} = & Q_{224} \beta^4 + T_1 \beta^4 + T_1 \alpha^4 + Q_{114} \alpha^4 - 2 K_4 \alpha^6 + 2 K_6 \beta^4 + \frac{8}{15} G_6 \alpha^4 + \frac{8}{75} G_6 \beta^4 \\
& + 2 K_6 \alpha^4 - 2 K_4 \beta^6 - \frac{4}{5} G_4 \alpha^6 - \frac{4}{5} G_4 \beta^6 - 6 K_4 \alpha^2 \beta^4 + 4 Q_{664} \alpha^2 \beta^2 - 6 K_4 \alpha^4 \beta^2 \\
& + 4 K_6 \alpha^2 \beta^2 - \frac{4}{25} G_6 \alpha^2 \beta^2 - \frac{12}{5} G_4 \alpha^2 \beta^4 + 2 Q_{124} \alpha^2 \beta^2 - \frac{12}{5} G_4 \alpha^4 \beta^2 + T_0 \alpha^4 \\
& + T_0 \beta^4 + k_2 \alpha^2 + k_2 \beta^2 + k_1 - N_{TE\alpha} \beta^2 - N_{TE\beta} \alpha^2,
\end{aligned} \tag{A-18}$$

$$\begin{aligned}
K_{44} = & -\frac{12}{5} G_5 \alpha^4 \beta^2 - 6 K_5 \alpha^2 \beta^4 + 2 Q_{125} \alpha^2 \beta^2 - 6 K_5 \alpha^4 \beta^2 + 4 Q_{665} \alpha^2 \beta^2 - \frac{12}{5} G_5 \alpha^2 \beta^4 \\
& + 4 K_7 \alpha^2 \beta^2 + \frac{88}{75} G_7 \alpha^2 \beta^2 + Q_{225} \beta^4 + Q_{552} \alpha^2 + Q_{115} \alpha^4 + \frac{1}{2} T_2 \beta^4 - 2 K_5 \beta^6 \\
& + \frac{1}{2} T_4 \beta^2 - \frac{4}{5} G_5 \beta^6 + 2 K_7 \alpha^4 - \frac{4}{5} G_5 \alpha^6 + 2 K_7 \beta^4 - 2 K_5 \alpha^6 + \frac{1}{2} T_4 \alpha^2 + \frac{8}{75} G_7 \beta^4 \\
& + \frac{1}{2} T_2 \alpha^4 + \frac{8}{15} G_7 \alpha^4 + T_1 \beta^4 + T_1 \alpha^4 + \frac{1}{2} T_0 \alpha^4 + \frac{1}{2} T_0 \beta^4 + k_1 - N_{TE\alpha} \alpha^2 - N_{TE\beta} \beta^2 \\
& + k_2 \alpha^2 + k_2 \beta^2,
\end{aligned} \tag{A-19}$$

$$K_{45} = Q_{138} \alpha^2 + Q_{238} \beta^2, \tag{A-20}$$

$$K_{51} = -Q_{136} \alpha, \tag{A-21}$$

$$K_{52} = -Q_{236} \beta, \tag{A-22}$$

$$K_{53} = Q_{137} \alpha^2 + Q_{237} \beta^2, \tag{A-23}$$

$$K_{54} = Q_{138} \alpha^2 + Q_{238} \beta^2, \tag{A-24}$$

$$K_{55} = -R_{111} \alpha^2 - R_{221} \beta^2 - R_{331}, \tag{A-25}$$

in which:

$$\begin{aligned}
 Q_{110}, Q_{111}, Q_{112}, Q_{113}, Q_{114}, Q_{115} &= \int_{\frac{h_c}{2}}^{\frac{h_c}{2}+h_t} Q_{11}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz \\
 &+ \int_{-\frac{h_c}{2}}^{\frac{h_c}{2}} Q_{11c}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz \\
 &+ \int_{-\frac{h_c}{2}-h_b}^{\frac{h_c}{2}} Q_{11}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz
 \end{aligned} \tag{A-28}$$

$$\begin{aligned}
 Q_{120}, Q_{121}, Q_{122}, Q_{123}, Q_{124}, Q_{125} &= \int_{\frac{h_c}{2}}^{\frac{h_c}{2}+h_t} Q_{12}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz \\
 &+ \int_{-\frac{h_c}{2}}^{\frac{h_c}{2}} Q_{12c}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz \\
 &+ \int_{-\frac{h_c}{2}-h_b}^{\frac{h_c}{2}} Q_{12}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz
 \end{aligned} \tag{A-29}$$

$$\begin{aligned}
 Q_{220}, Q_{221}, Q_{222}, Q_{223}, Q_{224}, Q_{225} &= \int_{\frac{h_c}{2}}^{\frac{h_c}{2}+h_t} Q_{22}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz \\
 &+ \int_{-\frac{h_c}{2}}^{\frac{h_c}{2}} Q_{22c}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz \\
 &+ \int_{-\frac{h_c}{2}-h_b}^{\frac{h_c}{2}} Q_{22}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz
 \end{aligned} \tag{A-30}$$

$$\begin{aligned}
 Q_{660}, Q_{661}, Q_{662}, Q_{663}, Q_{664}, Q_{665} &= \int_{\frac{h_c}{2}}^{\frac{h_c}{2}+h_t} Q_{66}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz \\
 &+ \int_{-\frac{h_c}{2}}^{\frac{h_c}{2}} Q_{66c}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz \\
 &+ \int_{-\frac{h_c}{2}-h_b}^{\frac{h_c}{2}} Q_{66}(z) (1, z, z^2, \xi(z), z\xi(z), \xi(z)^2) dz
 \end{aligned} \tag{A-31}$$

$$Q_{136}, Q_{137}, Q_{138} = \int_{\frac{h_c}{2}}^{\frac{h_c}{2}+h_t} e_{13} \left(\frac{\pi}{h_t} \sin \left(\frac{\pi z}{h_t} \right) \right) (1, z, \xi(z)) dz + \int_{-\frac{h_c}{2}-h_b}^{-\frac{h_c}{2}} e_{13} \left(\frac{\pi}{h_t} \sin \left(\frac{\pi z}{h_t} \right) \right) (1, z, \xi(z)) dz \tag{A-32}$$

$$Q_{236}, Q_{237}, Q_{238} = \int_{\frac{h_c}{2}}^{\frac{h_c}{2}+h_t} e_{23} \left(\frac{\pi}{h_t} \sin \left(\frac{\pi z}{h_t} \right) \right) (1, z, \xi(z)) dz + \int_{-\frac{h_c}{2}-h_b}^{-\frac{h_c}{2}} e_{23} \left(\frac{\pi}{h_t} \sin \left(\frac{\pi z}{h_t} \right) \right) (1, z, \xi(z)) dz \tag{A-33}$$

$$R_{111}, R_{221} = \int_{\frac{h_c}{2}}^{\frac{h_c}{2}+h_t} (\kappa_{11}, \kappa_{22}) \left(\cos \left(\frac{\pi z}{h_t} \right) \right)^2 dz + \int_{-\frac{h_c}{2}-h_b}^{-\frac{h_c}{2}} (\kappa_{11}, \kappa_{22}) \left(\cos \left(\frac{\pi z}{h_b} \right) \right)^2 dz \tag{A-34}$$

$$R_{333} = \int_{\frac{h_c}{2}}^{\frac{h_c}{2}+h_t} (\kappa_{33}) \left(\frac{\pi}{h_t^2} \sin \left(\frac{\pi z}{h_t} \right) \right) \left(\pi^2 \sin \left(\frac{\pi z}{h_t} \right) \right) dz + \int_{-\frac{h_c}{2}-h_b}^{-\frac{h_c}{2}} (\kappa_{33}) \left(\frac{\pi}{h_b^2} \sin \left(\frac{\pi z}{h_b} \right) \right) \left(\pi^2 \sin \left(\frac{\pi z}{h_b} \right) \right) dz \tag{A-35}$$

$$\begin{aligned}
 T_0, T_1, T_2, T_3, T_4, T_5 &= \int_i^j l_0^2 G (1, \xi'(z), \xi'(z)^2, \xi''(z), \xi''(z)^2) dz \\
 &+ \int_{-\frac{h_c}{2}}^{\frac{h_c}{2}} l_0^2 G (1, \xi'(z), \xi'(z)^2, \xi''(z), \xi''(z)^2) dz
 \end{aligned} \tag{A-36}$$

$$\begin{aligned}
& K_0, K_1, K_2, K_3, K_4, K_5, K_6, K_7 \\
& = \int_i^j l_1^2 G(1, z, z^2, \xi(z), z\xi(z), \xi(z)^2, \xi'(z), \xi'(z)^2) dz \\
& + \int_{-\frac{h_c}{2}}^{\frac{h_c}{2}} l_1^2 G(1, z, z^2, \xi(z), z\xi(z), \xi(z)^2, \xi'(z), \xi'(z)^2) dz
\end{aligned} \tag{A-37}$$

$$\begin{aligned}
& G_0, G_1, G_2, G_3, G_4, G_5, G_6, G_7, G_8 = \\
& \int_i^j l_2^2 G(1, z, z^2, \xi(z), z\xi(z), \xi(z)^2, \xi'(z), \xi'(z)^2) dz \\
& + \int_{-\frac{h_c}{2}}^{\frac{h_c}{2}} l_2^2 G(1, z, z^2, \xi(z), z\xi(z), \xi(z)^2, \xi'(z), \xi'(z)^2) dz \\
& i = \frac{h_c}{2}, -\frac{h_c}{2} - h_b \quad j = \frac{h_c}{2} + h_t, -\frac{h_c}{2}
\end{aligned} \tag{A-38}$$

References

- [1] S. Chen, M.K. Hassanzadeh-Aghdam, R. Ansari, An analytical model for elastic modulus calculation of SiC whisker-reinforced hybrid metal matrix nanocomposite containing SiC nanoparticles, *J. Alloys Compd.* 767 (2018) 632–641, <https://doi.org/10.1016/j.jallcom.2018.07.102>.
- [2] N. Gao, L. Tang, J. Deng, K. Lu, H. Hou, K. Chen, Design, fabrication and sound absorption test of composite porous metamaterial with embedding I-plates into porous polyurethane sponge, *Appl. Acoust.* 175 (2021), 107845, <https://doi.org/10.1016/j.apacoust.2020.107845>.
- [3] A. Eyvazian, A.M. Hamouda, F. Tarlochan, S. Mohsenizadeh, A.A. Dastjerdi, Damping and vibration response of viscoelastic smart sandwich plate reinforced with non-uniform Graphene platelet with magnetorheological fluid core, *Steel Compos. Struct.* 33 (2019) 891–906, <https://doi.org/10.12989/scs.2019.33.6.891>.
- [4] M. Rezaiee-Pajand, E. Sobhani, A.R. Masoodi, Free vibration analysis of functionally graded hybrid matrix/fiber nanocomposite conical shells using multiscale method, *Aero. Sci. Technol.* 105 (2020), 105998, <https://doi.org/10.1016/j.ast.2020.105998>.
- [5] J. Liu, C. Wang, H. Sun, H. Wang, F. Rong, L. He, Y. Lou, S. Zhang, Z. Zhang, M. Du, CoOx/CoNy nanoparticles encapsulated carbon-nitride nanosheets as an efficiently trifunctional electrocatalyst for overall water splitting and Zn-air battery, *Appl. Catal. B Environ.* 279 (2020), 119407, <https://doi.org/10.1016/j.apcatb.2020.119407>.
- [6] R.B. Mahani, A. Eyvazian, F. Musharavati, T.A. Sebaey, P. Talebizadehsardari, Thermal buckling of laminated Nano-Composite conical shell reinforced with graphene platelets, *Thin-Walled Struct.* 155 (2020), 106913, <https://doi.org/10.1016/j.tws.2020.106913>.
- [7] A. Eyvazian, F. Musharavati, F. Tarlochan, A. Pasharavesh, D.K. Rajak, M.B. Husain, T.N. Tran, Free vibration of FG-GPLRC conical panel on elastic foundation, *Struct. Eng. Mech.* 75 (2020) 1–18, <https://doi.org/10.12989/SEM.2020.75.1.001>.
- [8] P. Wang, T. Yao, Z. Li, W. Wei, Q. Xie, W. Duan, H. Han, A superhydrophobic/electrothermal synergistically anti-icing strategy based on graphene composite, *Compos. Sci. Technol.* 198 (2020), 108307, <https://doi.org/10.1016/j.compscitech.2020.108307>.
- [9] W. Gao, Z. Qin, F. Chu, Wave propagation in functionally graded porous plates reinforced with graphene platelets, *Aero. Sci. Technol.* 102 (2020), 105860, <https://doi.org/10.1016/j.ast.2020.105860>.
- [10] C. Liu, F. Wang, L. He, X. Deng, J. Liu, Y. Wu, Experimental and numerical investigation on dynamic responses of the umbrella membrane structure excited by heavy rainfall, *J. Vib. Contr.* 27 (2021) 675–684, <https://doi.org/10.1177/1077546320932691>.
- [11] B. Safaei, F.H. Khoda, A.M. Fattahi, Non-classical plate model for single-layered graphene sheet for axial buckling, *Adv. Nano Res.* 7 (2019) 265–275, <https://doi.org/10.12989/anr.2019.7.4.265>.
- [12] D. Yan, Y. Zheng, W. Wang, Q. Chen, Modeling and dynamic analyses of the bulb turbine blade with crack fault, *Appl. Math. Model.* 89 (2021) 731–751, <https://doi.org/10.1016/j.apm.2020.08.005>.
- [13] D. Yan, W. Wang, Q. Chen, Fractional-order modeling and nonlinear dynamic analyses of the rotor-bearing-seal system, *Chaos, Solit. Fractals* 133 (2020), 109640, <https://doi.org/10.1016/j.chaos.2020.109640>.
- [14] P. Talebizadehsardari, A. Eyvazian, M.G. Azandariani, T.N. Tran, D.K. Rajak, R.B. Mahani, Buckling analysis of smart beams based on higher order shear deformation theory and numerical method, *Steel Compos. Struct.* 35 (2020) 635–640, <https://doi.org/10.12989/SCS.2020.35.5.635>.
- [15] P. Talebizadehsardari, A. Eyvazian, M. Asmael, B. Karami, D. Shahsavari, R.B. Mahani, Static bending analysis of functionally graded polymer composite curved beams reinforced with carbon nanotubes, *Thin-Walled Struct.* 157 (2020), 107139, <https://doi.org/10.1016/j.tws.2020.107139>.
- [16] M.S.H. Al-Furjan, M. Habibi, J. Ni, D. won Jung, A. Tounsi, Frequency simulation of viscoelastic multi-phase reinforced fully symmetric systems, *Eng. Comput.* (2020) 1–17, <https://doi.org/10.1007/s00366-020-01200-x>.
- [17] M.S.H. Al-Furjan, M. Habibi, A. Ghabussi, H. Safarpour, M. Safarpour, A. Tounsi, Non-polynomial framework for stress and strain response of the FG-GPLRC disk using three-dimensional refined higher-order theory, *Eng. Struct.* 228 (2021), 111496, <https://doi.org/10.1016/j.engstruct.2020.111496>.
- [18] M.S.H. Al-Furjan, M. Habibi, A. rahimi, G. Chen, H. Safarpour, M. Safarpour, A. Tounsi, Chaotic simulation of the multi-phase reinforced thermo-elastic disk using GDQM, *Eng. Comput.* (2020) 1–24, <https://doi.org/10.1007/s00366-020-01144-2>.
- [19] B. Safaei, N.A. Ahmed, A.M. Fattahi, Free vibration analysis of polyethylene/CNT plates, *Eur. Phys. J. Plus.* 134 (2019) 271, <https://doi.org/10.1140/epjp/i2019-12650-x>.
- [20] E. Arshid, A.R. Khorshidvand, Free vibration analysis of saturated porous FG circular plates integrated with piezoelectric actuators via differential quadrature method, *Thin-Walled Struct.* 125 (2018) 220–233, <https://doi.org/10.1016/j.tws.2018.01.007>.
- [21] B. Safaei, The effect of embedding a porous core on the free vibration behavior of laminated composite plates, *Steel Compos. Struct.* 35 (2020) 659–670, <https://doi.org/10.12989/scs.2020.35.5.659>. (Accessed 27 November 2020).
- [22] H. Li, H. Lv, H. Sun, Z. Qin, J. Xiong, Q. Han, J. Liu, X. Wang, Nonlinear vibrations of fiber-reinforced composite cylindrical shells with bolt loosening boundary conditions, *J. Sound Vib.* 496 (2021), 115935, <https://doi.org/10.1016/j.jsv.2021.115935>.
- [23] R. Moradi-Dastjerdi, K. Behdinan, B. Safaei, Z. Qin, Static performance of agglomerated CNT-reinforced porous plates bonded with piezoceramic faces, *Int. J. Mech. Sci.* 188 (2020), <https://doi.org/10.1016/j.ijmeccsci.2020.105966>.

- [24] R. Moradi-Dastjerdi, K. Behdinin, B. Safaei, Z. Qin, Buckling behavior of porous CNT-reinforced plates integrated between active piezoelectric layers, *Eng. Struct.* 222 (2020), <https://doi.org/10.1016/j.engstruct.2020.111141>.
- [25] P. Zhu, Z.X. Lei, K.M. Liew, Static and free vibration analyses of carbon nanotube-reinforced composite plates using finite element method with first order shear deformation plate theory, *Compos. Struct.* 94 (2012) 1450–1460, <https://doi.org/10.1016/j.compstruct.2011.11.010>.
- [26] P. Van Thu, N.D. Duc, Nonlinear stability analysis of imperfect three-phase sandwich laminated polymer nanocomposite panels resting on elastic foundations in thermal environments, *VNU J. Sci. Math.* 32 (2016) 20–36. <https://js.vnu.edu.vn/Map/article/view/423>. (Accessed 14 June 2019).
- [27] F. Bourada, A.A. Bousahla, A. Tounsi, A. Bedia, S.R. Mahmoud, K.H. Benrahou, A. Tounsi, Stability and dynamic analyses of SW-CNT reinforced concrete beam resting on elastic-foundation, *Comput. Concr.* 25 (2020) 485–495, <https://doi.org/10.12989/CAC.2020.25.6.485>.
- [28] M.S.H. Al-Furjan, A. Hatami, M. Habibi, L. Shan, A. Tounsi, On the vibrations of the imperfect sandwich higher-order disk with a lactic core using generalize differential quadrature method, *Compos. Struct.* 257 (2021), 113150, <https://doi.org/10.1016/j.compstruct.2020.113150>.
- [29] A. Loghman, A. Cheraghbak, Agglomeration effects on electro-magneto-thermo elastic behavior of nano-composite piezoelectric cylinder, *Polym. Compos.* 39 (2018) 1594–1603, <https://doi.org/10.1002/pc.24104>.
- [30] M. Mirzaei, Y. Kiani, Free vibration of functionally graded carbon nanotube reinforced composite cylindrical panels, *Compos. Struct.* 142 (2016) 45–56, <https://doi.org/10.1016/J.COMPSTRUCT.2015.12.071>.
- [31] M.S.H. Al-Furjan, M. Habibi, D. won Jung, S. Sadeghi, H. Safarpour, A. Tounsi, G. Chen, A computational framework for propagated waves in a sandwich doubly curved nanocomposite panel, *Eng. Comput.* (2020) 1–18, <https://doi.org/10.1007/s00366-020-01130-8>.
- [32] M.S.H. Al-Furjan, H. Safarpour, M. Habibi, M. Safarpour, A. Tounsi, A comprehensive computational approach for nonlinear thermal instability of the electrically FG-GPLRC disk based on GDQ method, *Eng. Comput.* (2020) 1–18, <https://doi.org/10.1007/s00366-020-01088-7>.
- [33] R. Zerrouki, A. Karas, M. Zidour, A.A. Bousahla, A. Tounsi, F. Bourada, A. Tounsi, K.H. Benrahou, S.R. Mahmoud, Effect of nonlinear FG-CNT distribution on mechanical properties of functionally graded nano-composite beam, *Struct. Eng. Mech.* 78 (2021) 117–124, <https://doi.org/10.12989/sem.2021.78.2.117>.
- [34] N. Bendenia, M. Zidour, A.A. Bousahla, F. Bourada, A. Tounsi, K.H. Benrahou, E.A.A. Bedia, S.R. Mahmoud, A. Tounsi, Deflections, stresses and free vibration studies of FG-CNT reinforced sandwich plates resting on Pasternak elastic foundation, *Comput. Concr.* 26 (2020) 213–226, <https://doi.org/10.12989/cac.2020.26.3.213>.
- [35] B.A. Selim, L.W. Zhang, K.M. Liew, Vibration analysis of CNT reinforced functionally graded composite plates in a thermal environment based on Reddy's higher-order shear deformation theory, *Compos. Struct.* 156 (2016) 276–290, <https://doi.org/10.1016/j.compstruct.2015.10.026>.
- [36] D.D. Nguyen, Nonlinear thermo- electro-mechanical dynamic response of shear deformable piezoelectric sigmoid functionally graded sandwich circular cylindrical shells on elastic foundations, *J. Sandw. Struct. Mater.* 20 (2018) 351–378, <https://doi.org/10.1177/1099636216653266>.
- [37] K. Mehar, S.K. Panda, T.Q. Bui, T.R. Mahapatra, Nonlinear thermoelastic frequency analysis of functionally graded CNT-reinforced single/doubly curved shallow shell panels by FEM, *J. Therm. Stresses* 40 (2017) 899–916, <https://doi.org/10.1080/01495739.2017.1318689>.
- [38] M.H. Yas, N. Samadi, Free vibrations and buckling analysis of carbon nanotube-reinforced composite Timoshenko beams on elastic foundation, *Int. J. Pres. Ves. Pip.* 98 (2012) 119–128, <https://doi.org/10.1016/J.IJPVP.2012.07.012>.
- [39] H. Liu, H. Wu, Z. Lyu, Nonlinear resonance of FG multilayer beam-type nanocomposites: effects of graphene nanoplatelet-reinforcement and geometric imperfection, *Aero. Sci. Technol.* 98 (2020), 105702, <https://doi.org/10.1016/j.ast.2020.105702>.
- [40] A. Eyvazian, D. Shahsavari, B. Karami, On the dynamic of graphene reinforced nanocomposite cylindrical shells subjected to a moving harmonic load, *Int. J. Eng. Sci.* 154 (2020), 103339, <https://doi.org/10.1016/j.ijengsci.2020.103339>.
- [41] M. Habibi, A. Taghdir, H. Safarpour, Stability analysis of an electrically cylindrical nanoshell reinforced with graphene nanoplatelets, *Compos. B Eng.* 175 (2019), 107125, <https://doi.org/10.1016/j.compositesb.2019.107125>.
- [42] B. Safaei, A.M. Fattahi, Free vibrational response of single-layered graphene sheets embedded in an elastic matrix using different nonlocal plate models, *Mechanika* 23 (2017) 678–687, <https://doi.org/10.5755/j01.mech.23.5.14883>.
- [43] M. Khorasani, A. Eyvazian, M. Karbon, A. Tounsi, L. Lampani, T.A. Sebaey, Magneto-electro-elastic vibration analysis of modified couple stress-based three-layered micro rectangular plates exposed to multi-physical fields considering the flexoelectricity effects, *Smart Struct. Syst.* 26 (2020) 331–343, <https://doi.org/10.12989/sss.2020.26.3.331>.
- [44] S. Sahmani, B. Safaei, Large-amplitude oscillations of composite conical nanoshells with in-plane heterogeneity including surface stress effect, *Appl. Math. Model.* 89 (2021) 1792–1813, <https://doi.org/10.1016/j.apm.2020.08.039>.
- [45] L. Li, Y. Hu, Buckling analysis of size-dependent nonlinear beams based on a nonlocal strain gradient theory, *Int. J. Eng. Sci.* 97 (2015) 84–94, <https://doi.org/10.1016/j.ijengsci.2015.08.013>.
- [46] M. Asghari, S.A. Momeni, R. Vatanikhah, The second strain gradient theory-based Timoshenko beam model, *J. Vib. Contr.* 23 (2015) 2155–2166, <https://doi.org/10.1177/1077546315611822>.
- [47] M. Shojaeian, Y.T. Beni, H. Ataei, Electromechanical buckling of functionally graded electrostatic nanobridges using strain gradient theory, *Acta Astronaut.* 118 (2016) 62–71, <https://doi.org/10.1016/j.actaastro.2015.09.015>.
- [48] S. Thai, H.-T. Thai, T.P. Vo, H. Nguyen-Xuan, Nonlinear static and transient isogeometric analysis of functionally graded microplates based on the modified strain gradient theory, *Eng. Struct.* 153 (2017) 598–612, <https://doi.org/10.1016/j.engstruct.2017.10.002>.
- [49] M. Hosseini, H.H. Gorgani, M. Shishesaz, A. Hadi, Size-dependent stress analysis of single-wall carbon nanotube based on strain gradient theory, *Int. J. Appl. Mech.* (2017), 1750087, <https://doi.org/10.1142/S1758825117500879>, 09.
- [50] M. Malikan, V.B. Nguyen, Buckling analysis of piezo-magnetolectric nanoplates in hygrothermal environment based on a novel one variable plate theory combining with higher-order nonlocal strain gradient theory, *Phys. E Low-Dimensional Syst. Nanostructures.* 102 (2018) 8–28, <https://doi.org/10.1016/j.physe.2018.04.018>.
- [51] A. Imani Aria, H. Biglari, Computational vibration and buckling analysis of microtubule bundles based on nonlocal strain gradient theory, *Appl. Math. Comput.* 321 (2018) 313–332, <https://doi.org/10.1016/j.amc.2017.10.050>.
- [52] S.I. Tahir, A. Chikh, A. Tounsi, M.A. Al-Osta, S.U. Al-Dulajjan, M.M. Al-Zahrani, Wave propagation analysis of a ceramic-metal functionally graded sandwich plate with different porosity distributions in a hygro-thermal environment, *Compos. Struct.* 269 (2021), 114030, <https://doi.org/10.1016/j.compstruct.2021.114030>.
- [53] H. Hachemi, A.A. Bousahla, A. Kaci, F. Bourada, A. Tounsi, K.H. Benrahou, A. Tounsi, M.M. Al-Zahrani, S.R. Mahmoud, Bending analysis of functionally graded plates using a new refined quasi-3D shear deformation theory and the concept of the neutral surface position, *Steel Compos. Struct.* 39 (2021) 51–64, <https://doi.org/10.12989/scs.2021.39.1.051>.
- [54] A. Bakoura, F. Bourada, A.A. Bousahla, A. Tounsi, K.H. Benrahou, A. Tounsi, M.M. Al-Zahrani, S.R. Mahmoud, Buckling analysis of functionally graded plates using HSDT in conjunction with the stress function method, *Comput. Concr.* 27 (2021) 73–83, <https://doi.org/10.12989/cac.2021.27.1.073>.
- [55] S.C. Chikr, A. Kaci, A.A. Bousahla, F. Bourada, A. Tounsi, E.A. Bedia, S.R. Mahmoud, K.H. Benrahou, A. Tounsi, A novel four-unknown integral model for buckling response of FG sandwich plates resting on elastic foundations under various boundary conditions using Galerkin's approach, *Geomech. Eng.* 21 (2020) 471–487, <https://doi.org/10.12989/GAE.2020.21.5.471>.
- [56] A. Menasria, A. Kaci, A.A. Bousahla, F. Bourada, A. Tounsi, K.H. Benrahou, A. Tounsi, E.A. Adda Bedia, S.R. Mahmoud, A four-unknown refined plate theory for dynamic analysis of FG-sandwich plates under various boundary conditions, *Steel Compos. Struct.* 36 (2020) 355–367, <https://doi.org/10.12989/scs.2020.36.3.355>.
- [57] T.H.L. Bekkaye, B. Fahsi, A.A. Bousahla, F. Bourada, A. Tounsi, K.H. Benrahou, A. Tounsi, M.M. Al-Zahrani, Porosity-dependent mechanical behaviors of FG plate using refined trigonometric shear deformation theory, *Comput. Concr.* 26 (2020) 439–450, <https://doi.org/10.12989/cac.2020.26.5.439>.
- [58] M. Guellil, H. Saidi, F. Bourada, A.A. Bousahla, A. Tounsi, M.M. Al-Zahrani, M. Hussain, S.R. Mahmoud, Influences of porosity distributions and boundary conditions on mechanical bending response of functionally graded plates resting on Pasternak foundation, *Steel Compos. Struct.* 38 (2021) 1–15, <https://doi.org/10.12989/scs.2021.38.1.001>.

- [59] J. Li, G. Wang, S. Liu, J. Lin, Y. Guan, G. Zhao, H. Naceur, D. Coutellier, T. Wu, Efficient thermomechanical analysis of functionally graded structures using the symmetric SPH method, *Case Stud. Therm. Eng.* 25 (2021), 100889, <https://doi.org/10.1016/j.csite.2021.100889>.
- [60] S. Amir, Z. Soleimani-Javid, E. Arshid, Size-dependent free vibration of sandwich micro beam with porous core subjected to thermal load based on SSDBT, *ZAMM Zeitschrift Fur Angew. Math. Und Mech.* 99 (2019) 1–21, <https://doi.org/10.1002/zamm.201800334>.
- [61] M.H. Yas, S. Rahimi, Thermal buckling analysis of porous functionally graded nanocomposite beams reinforced by graphene platelets using Generalized differential quadrature method, *Aero. Sci. Technol.* 107 (2020), 106261, <https://doi.org/10.1016/j.ast.2020.106261>.
- [62] B. Karami, P. Gheisari, S.M.R. Nazemosadat, P. Akbari, D. Shahsavari, M. Naghizadeh, B. Karami, P. Gheisari, S.M.R. Nazemosadat, P. Akbari, D. Shahsavari, M. Naghizadeh, Elastic wave characteristics of graphene nanoplatelets reinforced composite nanoplates, *Struct. Eng. Mech.* 74 (2020) 819, <https://doi.org/10.12989/SEM.2020.74.6.809>.
- [63] E. Arshid, S. Amir, A. Loghman, Thermal buckling analysis of FG graphene nanoplatelets reinforced porous nanocomposite MCST-based annular/circular microplates, *Aero. Sci. Technol.* (2021), 106561, <https://doi.org/10.1016/j.ast.2021.106561>.
- [64] E. Arshid, S. Amir, Size-dependent vibration analysis of fluid-infiltrated porous curved microbeams integrated with reinforced functionally graded graphene platelets face sheets considering thickness stretching effect, *Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl.* (2021), 146442072098555, <https://doi.org/10.1177/1464420720985556>.
- [65] M. Khorasani, Z. Soleimani-Javid, E. Arshid, L. Lampani, Ö. Civalek, Thermo-elastic buckling of honeycomb micro plates integrated with FG-GNPs reinforced Epoxy skins with stretching effect, *Compos. Struct.* (2020), 113430, <https://doi.org/10.1016/j.compstruct.2020.113430>.
- [66] E. Arshid, A. Kiani, S. Amir, M. Zarghami Dehaghani, Asymmetric free vibration analysis of first-order shear deformable functionally graded magneto-electro-thermo-elastic circular plates, *Proc. Inst. Mech. Eng. Part C J. Mech. Eng. Sci.* 233 (2019) 5659–5675, <https://doi.org/10.1177/0954406219850598>.
- [67] E. Arshid, H. Arshid, S. Amir, S.B. Mousavi, Free vibration and buckling analyses of FG porous sandwich curved microbeams in thermal environment under magnetic field based on modified couple stress theory, *Arch. Civ. Mech. Eng.* 21 (2021) 6, <https://doi.org/10.1007/s43452-020-00150-x>.
- [68] Y. Wang, T. Fu, W. Zhang, An accurate size-dependent sinusoidal shear deformable framework for GNP-reinforced cylindrical panels: applications to dynamic stability analysis, *Thin-Walled Struct.* 160 (2021), 107400, <https://doi.org/10.1016/j.tws.2020.107400>.
- [69] S. Natarajan, M. Habousi, G. Manickam, Application of higher-order structural theory to bending and free vibration analysis of sandwich plates with CNT reinforced composite facesheets, *Compos. Struct.* 113 (2014) 197–207, <https://doi.org/10.1016/j.compstruct.2014.03.007>.
- [70] K. Mehar, S.K. Panda, Thermal free vibration behavior of FG-CNT reinforced sandwich curved panel using finite element method, *Polym. Compos.* (2017), <https://doi.org/10.1002/pc>.
- [71] S. Amir, E. Arshid, S.M.A. Rasti-alhosseini, A. Loghman, Quasi-3D tangential shear deformation theory for size-dependent free vibration analysis of three-layered FG porous micro rectangular plate integrated by nano-composite faces in hygrothermal environment, *J. Therm. Stresses* (2019) 1–24, <https://doi.org/10.1080/01495739.2019.1660601>, 0.
- [72] K.K. Zúr, M. Arefi, J. Kim, J.N. Reddy, Free vibration and buckling analyses of magneto-electro-elastic FGM nanoplates based on nonlocal modified higher-order sinusoidal shear deformation theory, *Compos. B Eng.* 182 (2020), 107601, <https://doi.org/10.1016/j.compositesb.2019.107601>.
- [73] S. Amir, E. Arshid, M.R. Ghorbanpour Arani, Size-dependent magneto-electro-elastic vibration analysis of FG saturated porous annular/circular micro sandwich plates embedded with nano-composite face sheets subjected to multi-physical pre loads, *Smart Struct. Syst.* 23 (2019) 429–447, <https://doi.org/10.12989/sss.2019.23.5.429>.
- [74] M.H. Shojaeefard, H. Saeidi Googarchin, M. Mahinzare, M. Adibi, Vibration and buckling analysis of a rotary functionally graded piezomagnetic nanoshell embedded in viscoelastic media, *J. Intell. Mater. Syst. Struct.* 29 (2018) 2344–2361, <https://doi.org/10.1177/1045389X18770856>.
- [75] F. Ebrahimi, A. Jafari, M.R. Barati, Free vibration analysis of smart porous plates subjected to various physical fields considering neutral surface position, *Arabian J. Sci. Eng.* 42 (2017) 1865–1881, <https://doi.org/10.1007/s13369-016-2348-3>.
- [76] D.O. Brush, B.O. Alroth, J.W. Hutchinson, *Buckling of bars, plates, and shells*, *J. Appl. Mech.* 42 (1975) 911.
- [77] A.A. Hamzah, H.K. Jobair, O.I. Abdullah, E.T. Hashim, L.A. Sabri, An investigation of dynamic behavior of the cylindrical shells under thermal effect, *Case Stud. Therm. Eng.* 12 (2018) 537–545, <https://doi.org/10.1016/j.csite.2018.07.007>.
- [78] M. Mohammadimehr, E. Arshid, S.M.A.R. Alhosseini, S. Amir, M.R.G. Arani, Free vibration analysis of thick cylindrical MEE composite shells reinforced CNTs with temperature-dependent properties resting on viscoelastic foundation, *Struct. Eng. Mech.* 70 (2019) 683–702, <https://doi.org/10.12989/sem.2019.70.6.683>.
- [79] R. Ansari, M.F. Shojaei, V. Mohammadi, R. Gholami, H. Rouhi, Size-dependent thermal buckling and postbuckling of functionally graded annular microplates based on the modified strain gradient theory, *J. Therm. Stresses* 37 (2014) 174–201, <https://doi.org/10.1080/01495739.2013.839767>.
- [80] Y. Ma, Y. Gao, W. Yang, D. He, Free vibration of a micro-scale composite laminated Reddy plate using a finite element method based on the new modified couple stress theory, *Results Phys.* 16 (2020), 102903, <https://doi.org/10.1016/j.rinp.2019.102903>.
- [81] Q. Li, P. Hou, Three-dimensional Green's functions for fluid and isotropic thermoelastic solid two-phase materials under heat loading, *Case Stud. Therm. Eng.* 20 (2020), 100631, <https://doi.org/10.1016/j.csite.2020.100631>.
- [82] E. Arshid, A.R. Khorshidvand, S.M. Khorshidvand, The effect of porosity on free vibration of SPFG circular plates resting on visco-Pasternak elastic foundation based on CPT, FSDT and TSDT, *Struct. Eng. Mech.* 70 (2019) 97–112, <https://doi.org/10.12989/sem.2019.70.1.097>.
- [83] M. Sobhy, An accurate shear deformation theory for vibration and buckling of FGM sandwich plates in hygrothermal environment, *Int. J. Mech. Sci.* 110 (2016) 62–77, <https://doi.org/10.1016/j.ijmecsci.2016.03.003>.
- [84] T.T. Tran, P.C. Nguyen, Q.H. Pham, Vibration analysis of FGM plates in thermal environment resting on elastic foundation using ES-MITC3 element and prediction of ANN, *Case Stud. Therm. Eng.* 24 (2021), 100852, <https://doi.org/10.1016/j.csite.2021.100852>.
- [85] E. Arshid, M. Khorasani, Z. Soleimani-Javid, S. Amir, A. Tounsi, Porosity-dependent vibration analysis of FG microplates embedded by polymeric nanocomposite patches considering hygrothermal effect via an innovative plate theory, *Eng. Comput.* (2021) 1–22, <https://doi.org/10.1007/s00366-021-01382-y>.
- [86] M. Song, J. Yang, S. Kitipornchai, Bending and buckling analyses of functionally graded polymer composite plates reinforced with graphene nanoplatelets, *Compos. B Eng.* 134 (2018) 106–113, <https://doi.org/10.1016/j.compositesb.2017.09.043>.
- [87] E. Arshid, S. Amir, A. Loghman, Static and dynamic analyses of FG-GNPs reinforced porous nanocomposite annular micro-plates based on MSGT, *Int. J. Mech. Sci.* 180 (2020), 105656, <https://doi.org/10.1016/j.ijmecsci.2020.105656>.
- [88] H. Mallek, H. Jrad, M. Wali, F. Dammak, Nonlinear dynamic analysis of piezoelectric-bonded FG-CNTR composite structures using an improved FSDT theory, *Eng. Comput.* (2019) 1–19, <https://doi.org/10.1007/s00366-019-00891-1>.
- [89] M. Arefi, E. Mohammad-Rezaei Bidgoli, T. Rabczuk, Thermo-mechanical buckling behavior of FG GNP reinforced micro plate based on MSGT, *Thin-Walled Struct.* 142 (2019) 444–459, <https://doi.org/10.1016/j.tws.2019.04.054>.