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Static responses for Graphene nanoplatlet reinforced aerobic sport plate

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Abstract. This work applies a detailed shear deformable based kinematic modeling of a graphene origami reinforced nanocomposite aerobic sport plate subjected to thermal and mechanical loading. The proposed model is application for analysis of the reinforced aerobic sport plate. The analytical bending analysis was performed using the virtual work principle. The behavioral relations were extended using the overall material properties derived from the previously developed relations of the experimental and statistical studies. The nanocomposite aerobic sport was composed of a copper matrix reinforced with graphene origami as a novel reinforcement. The overall material properties were developed with changes of thermal loads, volume fraction and folding parameter of aerobic sport plate. The numerical results were derived using the analytical works in terms of the significant import parameters. An increase in the displacements is observed with an increase in the thermal loads and folding parameter as well as decrease in volume fraction.

Keywords: aerobic plate; copper matrix; folding degree; graphene origami; micromechanical model; thickness stretched plate; volume fraction

1. Introduction

Application of new nanofillers and nanocomposite materials and compositions offers a new area for designers and engineers to arrive at more confidence and more efficient structures and structural elements. These materials are recently used in various situations because of their considerable high strength and less density that leads to low weight structures with high strength. Various nanofillers and nanocomposites in various configurations are suggested by materials scientists and chemists to arrive at more efficient structural elements and more responsive systems and structures. A review is presented here to justify our conclusion on the application of graphene origami in the noverl structural elements.

Dai *et al*. (2021, 2023) investigated impact of small sizes associated with nonlocal elasticity theory and geometric parameters on the stability and natural frequency responses of the sandwich composite nanoshell. Yang and Zhu (2023) studied wave dispersion characteristics of functionally graded nanocomposite reinforced nanoplate subjected to periodic loading. The results were explored with changes of geometric and material parameters of the nanoplate. Zhang *et al*. (2018) developed continuum-based formulation and finite element approach for small scale dependent vibrational results of the porous functionally graded nano materials and structures. Vali and Arefi (2023) developed an analytical-based analysis on the natural frequency responses of functionally graded reinforced graphene origami cylindrical curved panel using an advanced kinematic-based formulation and Hamilton's principle. The numerical based approach using the analytical approach were presented with changes of various distributions of graphene origami as well as geometric parameters in the thermal environment.

Yang *et al*. (2024) studied the impact of graphene origami reinforcement and its geometric and material characteristics on the electro-elastic bending results of a nanocomposite reinforced doubly curved shell. The results were presented in terms of significant material and geometric parameters of the reinforcement and shell structure. Advanced production methods using the chemical operations can be used for preparation of the advanced material structures with high strength and high efficiency properties (Bai *et al*. 2020, 2022, 2023, 2024). The new control method was developed by Cao *et al*. (2024) for analysis and control of the Yaw-Moment condition in the vehicle systems. The various control methods for analysis of intelligent material and systems using the advanced structural elements are recently discussed in the recent works (Chen *et al*. 2021, 2023, 2024, Chu *et al*. 2021, Deng *et al*. 2024). The impact of higher thermal loads was studied

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on the structural responses of the sandwich structure composed of steel tubes strengthen by skin layers reinforced with fiber reinforcements in the basalt form by Sheraz *et al.* 2025. Guan *et al.* 2025 studied the impact of metallurgical properties of the constituent materials and composition characteristics on the mechanical properties and responses of the alloy structures. Multi-field effect and microstructure characteristics of the composite structure and materials was studied on the novel properties the composite elements (Feng *et al.* 2025a, Guo *et al.* 2015, Zhao *et al.* 2024, Zha and Zhang 2024). The novel control of system procedure based on the advanced mathematical methods were developed in the recent works in the literature (Gao *et al.* 2017a, Ji *et al.* 2023, Ni *et al.* 2024, Peng *et al.* 2025).

A new control-based methodology was developed by Li *et al.* (2019b) for frequency responses analysis of a suspension system. The different suspension systems composed of novel structural elements can be used in the advanced vehicles in order to arrive at high level control-based systems as reported in the literature works (Li *et al.* 2020, 2021a, b, 2022a, Lu *et al.* 2024b). The new multi-functional materials for detecting the structural responses and for application in intelligent systems and structures are developed in the recent works (Li *et al.* 2024 a, b, Xiang *et al.* 2025, 2024). Deep learning based method are recently used for analysis and improvement of the structural elements (Lu *et al.* 2024a, Luo and Dong 2024, Lv *et al.* 2022, 2024a, Su *et al.* 2025b). The seismic behavior of the suspension system subjected to road condition and accounting the nonlinear constraints can be analyzed for better construction of these systems (Ma *et al.* 2022, Yang *et al.* 2025, Cong *et al.* 2024, Huang *et al.* 2022, Su *et al.* 2025a). Nano material and nano reinforcement structures are introduced for application in engineering instruments and structural elements (Wang *et al.* 2024a, 2025b, Li *et al.* 2019a, c). Rao *et al.* (2022) implemented a size dependent and shear deformable model for investigating the vibrational responses of the micro scale shells using the modified based coupled stress theory using the Hamilton's principle. Zhu *et al.* (2009) presented an experimental analysis on the effect of carbon nanotubes as a reinforcement on the tensile behavior of the nanocomposite reinforced beam. Wang *et al.* (2017) studied the impact of nonlinear geometric strain components on the static responses of the nanocomposite beam while rested on the elastic foundation. They developed state space mathematical method for dynamic responses of the functionally graded nanobeam with different boundary conditions. The hybrid analysis of advanced structural and architectural elements is recently analyzed using advanced methods (Xie *et al.* 2024 a, b, 2023, Xu *et al.* 2021, Chen *et al.* 2025a). New materials with extraordinary properties are proposed by material scientist in the literature works (Wu and Shen 2018, Wu *et al.* 2019, Zhang *et al.* 2025c, Chen *et al.* 2025b, Li *et al.* 2019d). composite science and technology can be used for improvement of the material properties of the nanofiller reinforced materials (Zhang *et al.* 2023 b, 2024a, b, c, Zhan *et al.* 2024). Improvement and more efficient materials with optimized composition were analyzed in the recent works (Yu *et al.* 2024, Liu *et al.* 2025, Wang *et al.* 2023, Feng *et al.* 2024, 2025b). The new production methods of novel composite materials and structures are suggested in the literature works.

A complete review study was presented with focus on the recent works on the advanced materials and compositions, nanocomposite, material production methods and various analysis methods in the literature works (Gao and Liu 2010a, b, c, Gao and Shen 2016, 2017). It is observed that static analysis of graphene origami reinforced nanocomposite plate is needed for future works as a novel analysis.

2. Formulation

A novel model with thickness stretch ability including higher order modeling is extended for static deformation, strain and stress analyses of origami reinforced composite plate through virtual work principle. Generalized Hooke's law is used for derivation of the equations (Gao *et al.* 2017b).

Using the displacement relations along the various direction, we will have (Jing *et al.* 2024, Ni *et al.* 2025, Yang *et al.* 2014, 2022a, b):

$$\begin{aligned} u_x &= u - \mathrm{z}\frac{\partial w_b}{\partial x} - f\frac{\partial w_s}{\partial x} \\ v_y &= v - \mathrm{z}\frac{\partial w_b}{\partial y} - f\frac{\partial w_s}{\partial y} \\ u_z &= w_b + w_s + g\chi \end{aligned} \tag{1}$$

In which the various components are characterized as the stretching, shear and bending deflections denoted by $\chi,\ w_s,\ w_b$. In addition, the in plane displacements are denoted with u, v and z is measured from middle surface. The strain components are computed as follows (Hou *et al.* 2025, Huang *et al.* 2024, Lu *et al.* 2023):

$$\begin{aligned} \varepsilon_x &= \frac{\partial u}{\partial x} - \mathrm{z}\frac{\partial^2 w_b}{\partial x^2} - f(\mathrm{z})\frac{\partial^2 w_s}{\partial x^2}, \\ \varepsilon_y &= \frac{\partial v}{\partial x} - \mathrm{z}\frac{\partial^2 w_b}{\partial y^2} - f(\mathrm{z})\frac{\partial^2 w_s}{\partial y^2}, \varepsilon_z = \frac{dg}{dz}\chi, \\ \gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} - 2z\frac{\partial^2 w_b}{\partial x \partial y} - 2f(\mathrm{z})\frac{\partial^2 w_s}{\partial x \partial y}, \\ \gamma_{xz} &= g\left(\frac{\partial w_s}{\partial x} + \frac{\partial \chi}{\partial x}\right), \gamma_{yz} = g\left(\frac{\partial w_s}{\partial y} + \frac{\partial \chi}{\partial y}\right) \end{aligned} \tag{2}$$

In which the stress components are denoted with $\varepsilon_{ij},\ \gamma_{ij}$. Using the principle of virtual work, one can arrive at strain energy variational form δU as (Ma *et al.* 2025, Long *et al.* 2024, 2025)

$$\delta U = \iint \begin{pmatrix} \mathfrak{V}_x \frac{\partial u}{\partial x} - \mathfrak{W}_x \frac{\partial^2 w_b}{\partial x^2} - \mathfrak{X}_x \frac{\partial^2 w_s}{\partial x^2} \\ +\mathfrak{V}_y \frac{\partial v}{\partial y} - \mathfrak{W}_y \frac{\partial^2 w_b}{\partial y^2} - \mathfrak{X}_y \frac{\partial^2 w_s}{\partial y^2} \\ +\mathfrak{V}_z \chi + \mathfrak{V}_{xy} \frac{\partial u}{\partial y} + \mathfrak{V}_{xy} \frac{\partial v}{\partial x} \\ -2\mathfrak{W}_{xy} \frac{\partial^2 w_b}{\partial x \partial y} - 2\mathfrak{X}_{xy} \frac{\partial^2 w_s}{\partial x \partial y} \\ +\mathfrak{V}_{xz}\left(\frac{\partial \delta w_s}{\partial x} + \frac{\partial \delta \chi}{\partial x}\right) + \mathfrak{V}_{yz}\left(\frac{\partial \delta w_s}{\partial y} + \frac{\partial \delta \chi}{\partial y}\right) \end{pmatrix} \mathrm{d}x dy \tag{3}$$

In which the resultant components are denoted with $\mathfrak{V}_i, \mathfrak{W}_i, \mathfrak{X}_i$. By definition of the resultant components as:

$$\{\mathfrak{V}_x, \mathfrak{W}_x, \mathfrak{X}_x\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_x \{1, z, f(\mathrm{z})\} \mathrm{dz},$$
$$\{\mathfrak{V}_y, \mathfrak{W}_y, \mathfrak{X}_y\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_y \{1, z, f(\mathrm{z})\} \mathrm{dz},$$
$$\{\mathfrak{V}_z\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \sigma_z \frac{dg(\mathrm{z})}{dz} \mathrm{dz}, \tag{4}$$
$$\{\mathfrak{V}_{xy}, \mathfrak{W}_{xy}, \mathfrak{X}_{xy}\} = \int_{-h/2}^{h/2} \tau_{xy} \{1, z, f(\mathrm{z})\} \mathrm{dz},$$
$$\{\mathfrak{V}_{xz}, \mathfrak{V}_{yz}\} = \int_{-h/2}^{h/2} \{\tau_{xz}, \tau_{yz}\} g(\mathrm{z}) \mathrm{dz}.$$

Using above definition, the variation is simplified:

$$\delta U = \iint \begin{pmatrix} -\frac{\partial \mathfrak{V}_x}{\partial x}\delta u - \frac{\partial \mathfrak{V}_{xy}}{\partial y}\delta u - \frac{\partial \mathfrak{V}_y}{\partial y}\delta v \\ -\frac{\partial \mathfrak{V}_{xy}}{\partial x}\delta v - \frac{\partial^2 \mathfrak{W}_x}{\partial x^2}\delta w_b - \frac{\partial^2 \mathfrak{W}_y}{\partial y^2}\delta w_b \\ -2\frac{\partial^2 \mathfrak{W}_{xy}}{\partial x \partial y}\delta w_b - \frac{\partial^2 \mathfrak{X}_x}{\partial x^2}\delta w_s - \frac{\partial^2 \mathfrak{X}_y}{\partial y^2}\delta w_s \\ -2\frac{\partial^2 \mathfrak{X}_{xy}}{\partial x \partial y}\delta w_s - \frac{\partial \mathfrak{V}_{xz}}{\partial x}\delta w_s - \frac{\partial \mathfrak{V}_{yz}}{\partial y}\delta w_s \\ +\mathfrak{V}_z \delta\chi - \frac{\partial \mathfrak{V}_{xz}}{\partial x}\delta\chi - \frac{\partial \mathfrak{V}_{yz}}{\partial y}\delta\chi \end{pmatrix} \mathrm{d}x dy \tag{5}$$

Finally, one can complete the virtual work using computation of external work with accounting the pre-thermomechanical loads as well as transverse and foundation effect as follows: (Liu *et al*. 2022, 2024):

$$W = \int_0^L \left[q\delta u_z|_{z=+h/2} - F_f \delta u_z|_{z=-h/2} - \mathfrak{V}_x^T \frac{\partial^2 w}{\partial x^2} - \mathfrak{V}_y^T \frac{\partial^2 w}{\partial y^2} \right] \mathrm{d}x \tag{6}$$

In which N_x^T, N_y^T are pre-thermal. Substitution of variations of strain energy into principle of virtual works $\Pi = W - U$, and applying the principle of minimum total energy as $\delta\Pi = 0$ gives final governing equations as (Arefi *et al*. 2012, Arefi and Kiani 2020, Arefi 2016, 2018, 2020, Arefi and Zenkour 2016, 2017a, b, 2019):

$$\begin{gathered} \delta u\colon -\frac{\partial \mathfrak{V}_x}{\partial x} - \frac{\partial \mathfrak{V}_{xy}}{\partial y} = 0, \\ \delta v\colon -\frac{\partial \mathfrak{V}_y}{\partial y} - \frac{\partial \mathfrak{V}_{xy}}{\partial x} = 0, \\ \delta w_b\colon -\frac{\partial^2 \mathfrak{W}_x}{\partial x^2} - \frac{\partial^2 \mathfrak{W}_y}{\partial y^2} - 2\frac{\partial^2 \mathfrak{W}_{xy}}{\partial x \partial y} = \\ q - F_f - \mathfrak{V}_x^T \frac{\partial^2 w_b}{\partial x^2} - \mathfrak{V}_y^T \frac{\partial^2 w_b}{\partial y^2} \\ \delta w_s\colon -\frac{\partial^2 \mathfrak{X}_x}{\partial x^2} - \frac{\partial^2 \mathfrak{X}_y}{\partial y^2} - 2\frac{\partial^2 \mathfrak{X}_{xy}}{\partial x \partial y} - \frac{\partial \mathfrak{V}_{xz}}{\partial x} - \frac{\partial \mathfrak{V}_{yz}}{\partial y} =, \\ q - F_f - \mathfrak{V}_x^T \frac{\partial^2 w_s}{\partial x^2} - \mathfrak{V}_y^T \frac{\partial^2 w_s}{\partial y^2} \\ \delta\chi\colon \mathfrak{V}_z - \frac{\partial \mathfrak{V}_{xz}}{\partial x} - \frac{\partial \mathfrak{V}_{yz}}{\partial y} = \\ q - F_f - \mathfrak{V}_x^T \frac{\partial^2 \chi}{\partial x^2} - \mathfrak{V}_y^T g(0) \frac{\partial^2 \chi}{\partial y^2} \end{gathered} \tag{7}$$

The constitutive relations are developed as (Xiao *et al*. 2024, Yin *et al*. 2024, Zhu *et al*. 2022, Zhiqiang *et al*. 2024):

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{Bmatrix} = \frac{E}{(1-2\vartheta)(1+\vartheta)} \begin{bmatrix} 1-\vartheta & \vartheta & \vartheta & 0 & 0 & 0 \\ \vartheta & 1-\vartheta & \vartheta & 0 & 0 & 0 \\ \vartheta & \vartheta & 1-\vartheta & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\vartheta}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\vartheta}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\vartheta}{2} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} - \alpha T \\ \varepsilon_{yy} - \alpha T \\ \varepsilon_{zz} - \alpha T \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{Bmatrix} \tag{8}$$

The effective material properties are (Zhao *et al*. 2019)

$$\begin{gathered} E_{eff} = \frac{1+\xi\eta V_{Gr}}{1-\eta V_{Gr}} E_{Cu} \begin{pmatrix} 1.11 - 1.22V_{Gr} - 0.134\left(\frac{T}{T_0}\right) \\ +0.559V_{Gr}\left(\frac{T}{T_0}\right) - 5.5V_{Gr}H_{Gr} \\ +38V_{Gr}^2 H_{Gr} - 20.6V_{Gr}^2 H_{Gr}^2 \end{pmatrix}, \\ \nu_{eff} = (\nu_{Gr}V_{Gr} + \nu_{Cu}V_{Cu}) \\ \begin{pmatrix} 1.01 - 1.43V_{Gr} + 0.165\left(\frac{T}{T_0}\right) \\ -1.1V_{Gr}H_{Gr}\left(\frac{T}{T_0}\right) - 16.8V_{Gr}H_{Gr} \\ +16V_{Gr}^2 H_{Gr}^2 \end{pmatrix}, \\ \alpha_{eff} = (\alpha_{Gr}V_{Gr} + \alpha_{Cu}V_{Cu}) \\ \begin{pmatrix} 0.794 - 16.8V_{Gr}^2 - 0.0279\left(\frac{T}{T_0}\right)^2 \\ +0.182(1+V_{Gr})\left(\frac{T}{T_0}\right) \end{pmatrix} \end{gathered} \tag{9}$$

in which:

$$\begin{gathered} V_{Gr} = \frac{W_{Gr}}{W_{Gr} + \frac{\rho_{Gr}}{\rho_{Cu}}(1 - W_{Gr})}, \qquad V_{Cu} = 1 - V_{Gr}, \\ \eta = \frac{\frac{E_{Gr}}{E_{Cu}} - 1}{\frac{E_{Gr}}{E_{Cu}} + \xi}, \qquad \xi = 2\frac{l_{Gr}}{t_{Gr}} \end{gathered} \tag{10}$$

where E_{Gr}, E_{Cu} are modulus of elasticity of graphene origami nano material and Cu matrix, respectively, and l_{Gr}, t_{Gr} are length/thickness of graphene origami nano material, respectively and local temperature and reference temperature are characterized by T, T_0.

In which the details of resultant are computed as (Li *et al*. 2022b, 2024c, Jin *et al*. 2024):

$$\begin{gathered} \mathfrak{V}_{xx} = \mathfrak{Q}_1 \frac{\partial u_0}{\partial x} - \mathfrak{Q}_2 \frac{\partial^2 w_b}{\partial x^2} - \mathfrak{Q}_3 \frac{\partial^2 w_s}{\partial x^2} + \mathfrak{Q}_4 \frac{\partial v_0}{\partial y} \\ -\mathfrak{Q}_5 \frac{\partial^2 w_b}{\partial y^2} - \mathfrak{Q}_6 \frac{\partial^2 w_s}{\partial y^2} + \mathfrak{Q}_7 \chi - \mathfrak{Q}_1^T (T - T_0) \\ \mathfrak{V}_{yy} = \mathfrak{Q}_4 \frac{\partial u_0}{\partial x} - \mathfrak{Q}_5 \frac{\partial^2 w_b}{\partial x^2} - \mathfrak{Q}_6 \frac{\partial^2 w_s}{\partial x^2} + \mathfrak{Q}_1 \frac{\partial v_0}{\partial y} \\ -\mathfrak{Q}_2 \frac{\partial^2 w_b}{\partial y^2} - \mathfrak{Q}_3 \frac{\partial^2 w_s}{\partial y^2} + \mathfrak{Q}_7 \chi - \mathfrak{Q}_1^T (T - T_0) \end{gathered} \tag{11a}$$

$$\mathfrak{M}_{xx} = \mathfrak{Q}_8 \frac{\partial u_0}{\partial x} - \mathfrak{Q}_9 \frac{\partial^2 w_b}{\partial x^2} - \mathfrak{Q}_{10} \frac{\partial^2 w_s}{\partial x^2} + \mathfrak{Q}_{11} \frac{\partial v_0}{\partial y}$$
$$-\mathfrak{Q}_{12} \frac{\partial^2 w_b}{\partial y^2} - \mathfrak{Q}_{13} \frac{\partial^2 w_s}{\partial y^2} + \mathfrak{Q}_{14}\chi - \mathfrak{Q}_2^T (T - T_0)$$

$$\mathfrak{M}_{yy} = \mathfrak{Q}_{11} \frac{\partial u_0}{\partial x} - \mathfrak{Q}_{12} \frac{\partial^2 w_b}{\partial x^2} - \mathfrak{Q}_{13} \frac{\partial^2 w_s}{\partial x^2} + \mathfrak{Q}_8 \frac{\partial v_0}{\partial y}$$
$$-\mathfrak{Q}_9 \frac{\partial^2 w_b}{\partial y^2} - \mathfrak{Q}_{10} \frac{\partial^2 w_s}{\partial y^2} + \mathfrak{Q}_{14}\chi - \mathfrak{Q}_2^T (T - T_0)$$

$$\mathfrak{X}_{xx} = \mathfrak{Q}_{15} \frac{\partial u_0}{\partial x} - \mathfrak{Q}_{16} \frac{\partial^2 w_b}{\partial x^2} - \mathfrak{Q}_{17} \frac{\partial^2 w_s}{\partial x^2} + \mathfrak{Q}_{18} \frac{\partial v_0}{\partial y}$$
$$-\mathfrak{Q}_{19} \frac{\partial^2 w_b}{\partial y^2} - \mathfrak{Q}_{20} \frac{\partial^2 w_s}{\partial y^2} + \mathfrak{Q}_{21}\chi - \mathfrak{Q}_3^T (T - T_0)$$

$$\mathfrak{X}_{yy} = \mathfrak{Q}_{18} \frac{\partial u_0}{\partial x} - \mathfrak{Q}_{19} \frac{\partial^2 w_b}{\partial x^2} - \mathfrak{Q}_{20} \frac{\partial^2 w_s}{\partial x^2} + \mathfrak{Q}_{15} \frac{\partial v_0}{\partial y}$$
$$-\mathfrak{Q}_{16} \frac{\partial^2 w_b}{\partial y^2} - \mathfrak{Q}_{17} \frac{\partial^2 w_s}{\partial y^2} + \mathfrak{Q}_{21}\chi - \mathfrak{Q}_3^T (T - T_0)$$

$$\mathfrak{V}_{xy} = \mathfrak{Q}_{22} \frac{\partial u_0}{\partial y} + \mathfrak{Q}_{22} \frac{\partial v_0}{\partial x} - 2\mathfrak{Q}_{23} \frac{\partial^2 w_b}{\partial x \partial y} - 2\mathfrak{Q}_{24} \frac{\partial^2 w_s}{\partial x \partial y}$$

$$\mathfrak{M}_{xy} = \mathfrak{Q}_{25} \frac{\partial u_0}{\partial y} + \mathfrak{Q}_{25} \frac{\partial v_0}{\partial x} - 2\mathfrak{Q}_{26} \frac{\partial^2 w_b}{\partial x \partial y} - 2\mathfrak{Q}_{27} \frac{\partial^2 w_s}{\partial x \partial y}$$

$$\mathfrak{X}_{xy} = \mathfrak{Q}_{28} \frac{\partial u_0}{\partial y} + \mathfrak{Q}_{28} \frac{\partial v_0}{\partial x} - 2\mathfrak{Q}_{29} \frac{\partial^2 w_b}{\partial x \partial y} - 2\mathfrak{Q}_{30} \frac{\partial^2 w_s}{\partial x \partial y}$$

$$\mathfrak{V}_{zz} = \mathfrak{Q}_{32} \frac{\partial u_0}{\partial x} - \mathfrak{Q}_{33} \frac{\partial^2 w_b}{\partial x^2} - \mathfrak{Q}_{34} \frac{\partial^2 w_s}{\partial x^2} + \mathfrak{Q}_{32} \frac{\partial v_0}{\partial y}$$
$$-\mathfrak{Q}_{33} \frac{\partial^2 w_b}{\partial y^2} - \mathfrak{Q}_{34} \frac{\partial^2 w_s}{\partial y^2} + \mathfrak{Q}_{31}\chi - \mathfrak{Q}_4^T (T - T_0)$$

$$\mathfrak{V}_{xz} = \mathfrak{Q}_{35} \left(\frac{\partial w_s}{\partial x} + \frac{\partial \chi}{\partial x} \right), \mathfrak{V}_{yz} = \mathfrak{Q}_{35} \left(\frac{\partial w_s}{\partial y} + \frac{\partial \chi}{\partial y} \right)$$

In which

$$\{\mathfrak{Q}_1^T, \mathfrak{Q}_2^T, \mathfrak{Q}_3^T, \mathfrak{Q}_4^T\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E\alpha}{(1 - 2\vartheta)} \{1, z, f, g'\} \mathrm{dz}$$
$$\{\mathfrak{Q}_1, \mathfrak{Q}_2, \mathfrak{Q}_3\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E(1 - \vartheta)}{(1 - 2\vartheta)(1 + \vartheta)} \{1, z, f\} \mathrm{dz},$$
$$\{\mathfrak{Q}_4, \mathfrak{Q}_5, \mathfrak{Q}_6\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E\vartheta}{(1 - 2\vartheta)(1 + \vartheta)} \{1, z, f\} \mathrm{dz},$$
$$\{\mathrm{P}_7\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E\vartheta g'}{(1 - 2\vartheta)(1 + V)} \mathrm{dz}$$
$$\{\mathfrak{Q}_8, \mathfrak{Q}_9, \mathfrak{Q}_{10}\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E(1 - \vartheta)}{(1 - 2\vartheta)(1 + \vartheta)} z\{1, z, f\} \mathrm{dz},$$
$$\{\mathfrak{Q}_{11}, \mathfrak{Q}_{12}, \mathfrak{Q}_{13}\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E\vartheta}{(1 - 2\vartheta)(1 + \vartheta)} z\{1, z, f\} \mathrm{dz}, \tag{11b}$$
$$\{\mathrm{P}_{14}\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E\vartheta g'}{(1 - 2\vartheta)(1 + \vartheta)} \mathrm{zdz}$$
$$\{\mathfrak{Q}_{15}, \mathfrak{Q}_{16}, \mathfrak{Q}_{17}\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E(1 - \vartheta)}{(1 - 2\vartheta)(1 + \vartheta)} f\{1, z, f\} \mathrm{dz},$$
$$\{\mathfrak{Q}_{18}, \mathfrak{Q}_{19}, \mathfrak{Q}_{20}\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E\vartheta}{(1 - 2\vartheta)(1 + \vartheta)} f\{1, z, f\} \mathrm{dz},$$
$$\{\mathfrak{Q}_{21}\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E\vartheta g'}{(1 - 2\vartheta)(1 + \vartheta)} f \mathrm{dz}$$
$$\{\mathfrak{Q}_{22}, \mathfrak{Q}_{23}, \mathfrak{Q}_{24}\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E}{(1 - 2\vartheta)(1 + \vartheta)} \frac{1 - 2\vartheta}{2} \{1, z, f\} \mathrm{dz}$$
$$\{\mathfrak{Q}_{25}, \mathfrak{Q}_{26}, \mathfrak{Q}_{27}\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E}{(1 - 2\vartheta)(1 + \vartheta)} \frac{1 - 2\vartheta}{2} z\{1, z, f\} \mathrm{dz}$$
$$\{\mathfrak{Q}_{28}, \mathfrak{Q}_{29}, \mathfrak{Q}_{30}\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E}{(1 - 2\vartheta)(1 + \vartheta)} \frac{1 - 2\vartheta}{2} f\{1, z, f\} \mathrm{dz}$$
$$\{\mathfrak{Q}_{31}, \mathfrak{Q}_{32}, \mathfrak{Q}_{33}, \mathfrak{Q}_{34}\}$$
$$= \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E}{(1 - 2\vartheta)(1 + \vartheta)} \frac{dg}{dz} \{(1 - \vartheta)g', \vartheta, z\vartheta, f\vartheta\} \mathrm{dz},$$
$$\{\mathfrak{Q}_{35}\} = \int_{-\frac{h}{2}}^{\frac{h}{2}} \frac{E}{(1 - 2\vartheta)(1 + \vartheta)} \frac{1 - 2\vartheta}{2} g^2 \mathrm{dz}$$

One can arrive at governing equations using the minimization as follows:

$$\delta u: \mathfrak{Q}_1 \frac{\partial^2 u_0}{\partial x^2} + \mathfrak{Q}_{22} \frac{\partial^2 u_0}{\partial y^2} + (\mathfrak{Q}_4 + \mathfrak{Q}_{22}) \frac{\partial^2 v_0}{\partial x \partial y}$$
$$-\mathfrak{Q}_2 \frac{\partial^3 w_b}{\partial x^3} - (2\mathfrak{Q}_{23} + \mathfrak{Q}_5) \frac{\partial^3 w_b}{\partial x \partial y^2} - \mathfrak{Q}_3 \frac{\partial^3 w_s}{\partial x^3}$$
$$-(\mathfrak{Q}_6 + 2\mathfrak{Q}_{24}) \frac{\partial^3 w_s}{\partial x \partial y^2} + \mathfrak{Q}_7 \frac{\partial \chi}{\partial x} = 0,$$
$$\delta v: (\mathfrak{Q}_4 + \mathfrak{Q}_{22}) \frac{\partial^2 u_0}{\partial x \partial y} + \mathfrak{Q}_{22} \frac{\partial^2 v_0}{\partial x^2} + \mathfrak{Q}_1 \frac{\partial^2 v_0}{\partial y^2}$$
$$-\mathfrak{Q}_2 \frac{\partial^3 w_b}{\partial y^3} - (\mathfrak{Q}_5 + 2\mathfrak{Q}_{23}) \frac{\partial^3 w_b}{\partial x^2 \partial y} - \mathfrak{Q}_3 \frac{\partial^3 w_s}{\partial y^3}$$
$$-(\mathfrak{Q}_6 + 2\mathfrak{Q}_{24}) \frac{\partial^3 w_s}{\partial x^2 \partial y} + \mathfrak{Q}_7 \frac{\partial \chi}{\partial y} = 0,$$
$$\delta w_b: \mathfrak{Q}_8 \frac{\partial^3 u_0}{\partial x^3} + (\mathfrak{Q}_{11} + 2\mathfrak{Q}_{25}) \frac{\partial^3 u_0}{\partial x \partial y^2} + \mathfrak{Q}_8 \frac{\partial^3 v_0}{\partial y^3}$$
$$+(\mathfrak{Q}_{11} + 2\mathfrak{Q}_{25}) \frac{\partial^3 v_0}{\partial x^2 \partial y} - \mathfrak{Q}_9 \frac{\partial^4 w_b}{\partial x^4} - \mathfrak{Q}_9 \frac{\partial^4 w_b}{\partial y^4}$$
$$(\mathfrak{Q}_{12} + 4\mathfrak{Q}_{26} + \mathfrak{Q}_{12}) \frac{\partial^4 w_b}{\partial x^2 \partial y^2} - \mathfrak{Q}_{10} \frac{\partial^4 w_s}{\partial x^4} - \mathfrak{Q}_{10} \frac{\partial^4 w_s}{\partial y^4}$$
$$-(\mathfrak{Q}_{13} + \mathfrak{Q}_{13} + 4\mathfrak{Q}_{27}) \frac{\partial^4 w_s}{\partial x^2 \partial y^2} + \mathfrak{Q}_{14} \frac{\partial^2 \chi}{\partial x^2} + \mathfrak{Q}_{14} \frac{\partial^2 \chi}{\partial y^2}$$
$$= -q + F_f + N_x^T \frac{\partial^2 w_b}{\partial x^2} + N_y^T \frac{\partial^2 w_b}{\partial y^2}, \tag{12}$$
$$\delta w_s: \mathfrak{Q}_{15} \frac{\partial^3 u_0}{\partial x^3} + (\mathfrak{Q}_{18} + 2\mathfrak{Q}_{28}) \frac{\partial^3 u_0}{\partial x \partial y^2} + \mathfrak{Q}_{15} \frac{\partial^3 v_0}{\partial y^3}$$
$$+(\mathfrak{Q}_{18} + 2\mathfrak{Q}_{28}) \frac{\partial^3 v_0}{\partial x^2 \partial y} - \mathfrak{Q}_{16} \frac{\partial^4 w_b}{\partial x^4}$$
$$-(\mathfrak{Q}_{19} + 4\mathfrak{Q}_{29} + \mathfrak{Q}_{19}) \frac{\partial^4 w_b}{\partial x^2 \partial y^2} - \mathfrak{Q}_{16} \frac{\partial^4 w_b}{\partial y^4} - \mathfrak{Q}_{17} \frac{\partial^4 w_s}{\partial x^4}$$
$$-\mathfrak{Q}_{17} \frac{\partial^4 w_s}{\partial y^4} - (\mathfrak{Q}_{20} + 4\mathfrak{Q}_{30} + \mathfrak{Q}_{20}) \frac{\partial^4 w_s}{\partial x^2 \partial y^2}$$
$$+\mathfrak{Q}_{35} \frac{\partial^2 w_s}{\partial x^2} + \mathfrak{Q}_{35} \frac{\partial^2 w_s}{\partial y^2} + (\mathfrak{Q}_{35} + \mathfrak{Q}_{21}) \frac{\partial^2 \chi}{\partial x^2}$$
$$+(\mathfrak{Q}_{35} + \mathfrak{Q}_{21}) \frac{\partial^2 \chi}{\partial y^2} = -q + F_f + N_x^T \frac{\partial^2 w_b}{\partial x^2} + N_y^T \frac{\partial^2 w_b}{\partial y^2}$$
$$\delta \chi: -\mathfrak{Q}_{32} \frac{\partial u_0}{\partial x} - \mathfrak{Q}_{32} \frac{\partial v_0}{\partial y} + \mathfrak{Q}_{33} \frac{\partial^2 w_b}{\partial x^2} + \mathfrak{Q}_{33} \frac{\partial^2 w_b}{\partial y^2}$$
$$+(\mathfrak{Q}_{35} + \mathfrak{Q}_{34}) \frac{\partial^2 w_s}{\partial x^2} + (\mathfrak{Q}_{35} + \mathfrak{Q}_{34}) \frac{\partial^2 w_s}{\partial y^2}$$
$$+\mathfrak{Q}_{35} \frac{\partial^2 \chi}{\partial x^2} + \mathfrak{Q}_{35} \frac{\partial^2 \chi}{\partial y^2} - \mathfrak{Q}_{31}\chi = -qg\left(+\frac{h}{2}\right)$$
$$+F_f g\left(-\frac{h}{2}\right) + N_x^T g(0) \frac{\partial^2 \chi}{\partial x^2} + N_y^T g(0) \frac{\partial^2 \chi}{\partial y^2}$$

Table 1 Variation in in-plain strain component ε_x along the thickness direction with variation in thermal load

Z	T=315	T=320	T=325	T=330	T=335	T=340
-0.025	0.0010660	0.0010663	0.0010666	0.0010669	0.0010672	0.0010674
-0.024	0.0010229	0.0010232	0.0010235	0.0010238	0.0010240	0.0010242
-0.023	0.0009798	0.0009801	0.0009804	0.0009807	0.0009809	0.0009811
-0.022	0.0009368	0.0009371	0.0009374	0.0009376	0.0009378	0.0009380
-0.021	0.0008938	0.0008941	0.0008944	0.0008946	0.0008948	0.0008950
-0.020	0.0008509	0.0008512	0.0008514	0.0008517	0.0008519	0.0008520
-0.019	0.0008081	0.0008083	0.0008085	0.0008087	0.0008089	0.0008091
-0.018	0.0007652	0.0007655	0.0007657	0.0007659	0.0007661	0.0007662
-0.017	0.0007224	0.0007227	0.0007229	0.0007231	0.0007232	0.0007234
-0.016	0.0006797	0.0006799	0.0006801	0.0006803	0.0006804	0.0006806
-0.015	0.0006370	0.0006372	0.0006374	0.0006376	0.0006377	0.0006378
-0.014	0.0005944	0.0005945	0.0005947	0.0005949	0.0005950	0.0005951
-0.013	0.0005517	0.0005519	0.0005521	0.0005522	0.0005523	0.0005524
-0.012	0.0005091	0.0005093	0.0005094	0.0005096	0.0005097	0.0005098
-0.011	0.0004666	0.0004667	0.0004669	0.0004670	0.0004671	0.0004672
-0.010	0.0004241	0.0004242	0.0004243	0.0004244	0.0004245	0.0004246
-0.009	0.0003816	0.0003817	0.0003818	0.0003819	0.0003820	0.0003821
-0.008	0.0003391	0.0003392	0.0003393	0.0003394	0.0003395	0.0003395
-0.007	0.0002967	0.0002968	0.0002969	0.0002969	0.0002970	0.0002970
-0.006	0.0002543	0.0002543	0.0002544	0.0002545	0.0002545	0.0002546
-0.005	0.0002119	0.0002119	0.0002120	0.0002120	0.0002121	0.0002121
-0.004	0.0001695	0.0001695	0.0001696	0.0001696	0.0001696	0.0001697
-0.003	0.0001271	0.0001271	0.0001272	0.0001272	0.0001272	0.0001272
-0.002	0.0000847	0.0000847	0.0000848	0.0000848	0.0000848	0.0000848
-0.001	0.0000424	0.0000424	0.0000424	0.0000424	0.0000424	0.0000424
0.000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
0.001	-0.0000424	-0.0000424	-0.0000424	-0.0000424	-0.0000424	-0.0000424
0.002	-0.0000847	-0.0000847	-0.0000848	-0.0000848	-0.0000848	-0.0000848
0.003	-0.0001271	-0.0001271	-0.0001272	-0.0001272	-0.0001272	-0.0001272
0.004	-0.0001695	-0.0001695	-0.0001696	-0.0001696	-0.0001696	-0.0001697
0.005	-0.0002119	-0.0002119	-0.0002120	-0.0002120	-0.0002121	-0.0002121
0.006	-0.0002543	-0.0002543	-0.0002544	-0.0002545	-0.0002545	-0.0002546
0.007	-0.0002967	-0.0002968	-0.0002969	-0.0002969	-0.0002970	-0.0002970
0.008	-0.000339117	-0.0003392	-0.0003393	-0.0003394	-0.0003395	-0.0003395
0.009	-0.000381582	-0.0003817	-0.0003818	-0.0003819	-0.0003820	-0.0003821
0.010	-0.000424074	-0.0004242	-0.0004243	-0.0004244	-0.0004245	-0.0004246
0.011	-0.000466595	-0.0004667	-0.0004669	-0.0004670	-0.0004671	-0.0004672
0.012	-0.000509146	-0.0005093	-0.0005094	-0.0005096	-0.0005097	-0.0005098
0.013	-0.000551731	-0.0005519	-0.0005521	-0.0005522	-0.0005523	-0.0005524
0.014	-0.000594351	-0.0005945	-0.0005947	-0.0005949	-0.0005950	-0.0005951
0.015	-0.000637009	-0.0006372	-0.0006374	-0.0006376	-0.0006377	-0.0006378
0.016	-0.000679707	-0.0006799	-0.0006801	-0.0006803	-0.0006804	-0.0006806
0.017	-0.000722445	-0.0007227	-0.0007229	-0.0007231	-0.0007232	-0.0007234
0.018	-0.000765227	-0.0007655	-0.0007657	-0.0007659	-0.0007661	-0.0007662
0.019	-0.000808052	-0.0008083	-0.0008085	-0.0008087	-0.0008089	-0.0008091
0.020	-0.000850923	-0.0008512	-0.0008514	-0.0008517	-0.0008519	-0.0008520

Table 1 Continued

Z	T=315	T=320	T=325	T=330	T=335	T=340
0.021	-0.00089384	-0.0008941	-0.0008944	-0.0008946	-0.0008948	-0.0008950
0.022	-0.000936805	-0.0009371	-0.0009374	-0.0009376	-0.0009378	-0.0009380
0.023	-0.000979817	-0.0009801	-0.0009804	-0.0009807	-0.0009809	-0.0009811
0.024	-0.001022878	-0.0010232	-0.0010235	-0.0010238	-0.0010240	-0.0010242
0.025	-0.001065988	-0.0010663	-0.0010666	-0.0010669	-0.0010672	-0.0010674

Table 2 variation in out of plane strain component ε_z along the thickness direction with variation in thermal load

Z	T=315	T=320	T=325	T=330	T=335	T=340
-0.025	-0.0013622	-0.0013685	-0.0013748	-0.0013810	-0.0013873	-0.0013935
-0.024	-0.0013595	-0.0013658	-0.0013721	-0.0013783	-0.0013846	-0.0013908
-0.023	-0.0013514	-0.0013577	-0.0013639	-0.0013701	-0.0013764	-0.0013825
-0.022	-0.0013381	-0.0013442	-0.0013504	-0.0013566	-0.0013627	-0.0013688
-0.021	-0.0013194	-0.0013255	-0.0013316	-0.0013376	-0.0013437	-0.0013497
-0.020	-0.0012955	-0.0013015	-0.0013075	-0.0013134	-0.0013194	-0.0013253
-0.019	-0.0012665	-0.0012724	-0.0012782	-0.0012841	-0.0012899	-0.0012957
-0.018	-0.0012325	-0.0012382	-0.0012439	-0.0012496	-0.0012553	-0.0012609
-0.017	-0.0011937	-0.0011992	-0.0012047	-0.0012102	-0.0012157	-0.0012212
-0.016	-0.0011501	-0.0011554	-0.0011608	-0.0011660	-0.0011713	-0.0011766
-0.015	-0.0011020	-0.0011071	-0.0011122	-0.0011173	-0.0011223	-0.0011274
-0.014	-0.0010496	-0.0010544	-0.0010593	-0.0010641	-0.0010689	-0.0010737
-0.013	-0.0009930	-0.0009976	-0.0010022	-0.0010067	-0.0010113	-0.0010158
-0.012	-0.0009325	-0.0009368	-0.0009411	-0.0009454	-0.0009497	-0.0009539
-0.011	-0.0008683	-0.0008723	-0.0008763	-0.0008803	-0.0008843	-0.0008883
-0.010	-0.0008007	-0.0008044	-0.0008081	-0.0008118	-0.0008154	-0.0008191
-0.009	-0.0007299	-0.0007333	-0.0007366	-0.0007400	-0.0007433	-0.0007467
-0.008	-0.0006562	-0.0006593	-0.0006623	-0.0006653	-0.0006683	-0.0006713
-0.007	-0.0005800	-0.0005827	-0.0005853	-0.0005880	-0.0005907	-0.0005933
-0.006	-0.0005015	-0.0005038	-0.0005061	-0.0005084	-0.0005107	-0.0005130
-0.005	-0.0004209	-0.0004229	-0.0004248	-0.0004268	-0.0004287	-0.0004306
-0.004	-0.0003388	-0.0003403	-0.0003419	-0.0003434	-0.0003450	-0.0003466
-0.003	-0.0002552	-0.0002564	-0.0002576	-0.0002588	-0.0002600	-0.0002611
-0.002	-0.0001707	-0.0001715	-0.0001723	-0.0001731	-0.0001739	-0.0001747
-0.001	-0.0000855	-0.0000859	-0.0000863	-0.0000867	-0.0000871	-0.0000875
0.000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
0.001	0.0000855	0.0000859	0.0000863	0.0000867	0.0000871	0.0000875
0.002	0.0001707	0.0001715	0.0001723	0.0001731	0.0001739	0.0001747
0.003	0.0002552	0.0002564	0.0002576	0.0002588	0.0002600	0.0002611
0.004	0.0003388	0.0003403	0.0003419	0.0003434	0.0003450	0.0003466
0.005	0.0004209	0.0004229	0.0004248	0.0004268	0.0004287	0.0004306
0.006	0.0005015	0.0005038	0.0005061	0.0005084	0.0005107	0.0005130
0.007	0.0005800	0.0005827	0.0005853	0.0005880	0.0005907	0.0005933
0.008	0.0006562	0.0006593	0.0006623	0.0006653	0.0006683	0.0006713
0.009	0.0007299	0.0007333	0.0007366	0.0007400	0.0007433	0.0007467
0.010	0.0008007	0.0008044	0.0008081	0.0008118	0.0008154	0.0008191
0.011	0.0008683	0.0008723	0.0008763	0.0008803	0.0008843	0.0008883
0.012	0.0009325	0.0009368	0.0009411	0.0009454	0.0009497	0.0009539

Table 2 Continued

Z	T=315	T=320	T=325	T=330	T=335	T=340
0.013	0.0009930	0.0009976	0.0010022	0.0010067	0.0010113	0.0010158
0.014	0.0010496	0.0010544	0.0010593	0.0010641	0.0010689	0.0010737
0.015	0.0011020	0.0011071	0.0011122	0.0011173	0.0011223	0.0011274
0.016	0.0011501	0.0011554	0.0011608	0.0011660	0.0011713	0.0011766
0.017	0.0011937	0.0011992	0.0012047	0.0012102	0.0012157	0.0012212
0.018	0.0012325	0.0012382	0.0012439	0.0012496	0.0012553	0.0012609
0.019	0.0012665	0.0012724	0.0012782	0.0012841	0.0012899	0.0012957
0.020	0.0012955	0.0013015	0.0013075	0.0013134	0.0013194	0.0013253
0.021	0.0013194	0.0013255	0.0013316	0.0013376	0.0013437	0.0013497
0.022	0.0013381	0.0013442	0.0013504	0.0013566	0.0013627	0.0013688
0.023	0.0013514	0.0013577	0.0013639	0.0013701	0.0013764	0.0013825
0.024	0.0013595	0.0013658	0.0013721	0.0013783	0.0013846	0.0013908
0.025	0.0013622	0.0013685	0.0013748	0.0013810	0.0013873	0.0013935

3. Solution

The analytical solution procedure is extended in this section using the analytical approach (Navier's technique). In order to satisfy simply conditions at all edges to remove deformation and moments, one can use the bi-trigonometric functions as follows:

$$\begin{Bmatrix} u_0 \\ v_0 \\ w_b \\ w_s \\ \chi \end{Bmatrix} = \sum_{n=1}^{\infty} \begin{Bmatrix} U_{mn} cos\xi x sin\zeta y \\ V_{mn} sin\xi x cos\zeta y \\ W_{mn}^{b} sin\xi x sin\zeta y \\ W_{mn}^{s} sin\xi x sin\zeta y \\ X_{mn} sin\xi x sin\zeta y \end{Bmatrix} \tag{13}$$

where $U_{mn}, V_{mn}, W_{mn}^{b}, W_{mn}^{s}, X_{mn}$ are unknown coefficients $\xi = \frac{m\pi}{a}, \zeta = \frac{n\pi}{b}$. Using the solution of harmonic type using the sinusoidal functions, and substitution into governing equations, one can arrive at the governing equations as $[K]\{X\} = \{F\}$ (Arefi and Bidgoli 2019, Arefi *et al.* 2022, Adab and Arefi 2022, Arefi and Civalek 2020, Bidgoli *et al.* 2020).

4. Numerical results and discussion

Deformation, strain and stress parametric analyses of a composite plate composed of cooper matrix reinforced with graphene origami are explored in this section. The characteristic materials are assumed as follows:

$E_{Cu} = 65.79GPa, \quad E_{Gr} = 929.57GPa,$

$\vartheta_{Cu} = 0.387, \quad \vartheta_{Gr} = 0.22,$

$\alpha_{Cu} = 16.51 \times 10^{-6} \frac{1}{K^{O}}, \quad \vartheta_{Gr} = -3.98 \times 10^{-6} \frac{1}{K^{O}},$

$l_{Gr} = 83.76 \times 10^{-10} m, \quad t_{Gr} = 3.4 \times 10^{-10} m,$

Table 1 provided a detailed parametric result investigating impact of radial location and thermal loads on the variation of in-plane strain ε_x. The results show an increase in in-plane strain component with an enhancement in the thermal loads unlike the radial coordinate that leads to decrease in same component.

Table 2 addresses a detailed parametric result investigating impact of radial location and thermal loads on the variation of out of plane strain ε_z. The results show an increase in in-plane strain component with an enhancement in the thermal loads unlike the radial coordinate that leads to decrease in same component.

Table 3 presents a detailed parametric result investigating impact of radial location and thermal loads on the variation of in-plane shear strain γ_{xy}. The results show an increase in in-plane strain component with an enhancement in the thermal loads unlike the radial coordinate that leads to decrease in same component.

Table 4 presents a detailed parametric result investigating impact of radial location and thermal loads on the variation of out of plane shear strain. The results show an increase in out of plane shear strain component γ_{xz} with an enhancement in the thermal loads unlike the radial coordinate that leads to decrease in same component. It is observed that the shear strains are zero at top and bottom based on the employing the appropriate shape functions.

Table 5 presents a detailed parametric result investigating impact of radial location and thermal loads on the variation of in-plane normal component σ_x. The results show an increase in in-plane normal component σ_x with an enhancement in the thermal loads.

Table 6 presents a detailed parametric result investigating impact of radial location and thermal loads on the variation of out of plane normal component σ_z. The results show an increase in in-plane normal component σ_x with an enhancement in the thermal loads.

Table 7 presents a detailed parametric result investigating impact of radial location and thermal loads on the variation of in- plane shear stress component τ_{xy}. The results show decrease in in- plane shear stress component τ_{xy} with an enhancement in the thermal loads.

Table 8 presents a detailed parametric result investigating impact of radial location and thermal loads on the variation of out of plane shear stress component τ_{xz}. The results show decrease in out of plane shear stress component τ_{xz} with an enhancement in the thermal loads.

Table 3 variation in in-plane shear strain component γ_{xy} along the thickness direction with variation in thermal load

Z	T=315	T=320	T=325	T=330	T=335	T=340
-0.025	-0.0021320	-0.0021327	-0.0021333	-0.0021338	-0.0021343	-0.0021348
-0.024	-0.0020458	-0.0020464	-0.0020470	-0.0020475	-0.0020480	-0.0020484
-0.023	-0.0019596	-0.0019603	-0.0019608	-0.0019613	-0.0019618	-0.0019622
-0.022	-0.0018736	-0.0018742	-0.0018747	-0.0018752	-0.0018757	-0.0018760
-0.021	-0.0017877	-0.0017882	-0.0017888	-0.0017892	-0.0017896	-0.0017900
-0.020	-0.0017018	-0.0017024	-0.0017029	-0.0017033	-0.0017037	-0.0017040
-0.019	-0.0016161	-0.0016166	-0.0016171	-0.0016175	-0.0016179	-0.0016182
-0.018	-0.0015305	-0.0015309	-0.0015314	-0.0015318	-0.0015321	-0.0015324
-0.017	-0.0014449	-0.0014453	-0.0014458	-0.0014461	-0.0014465	-0.0014467
-0.016	-0.0013594	-0.0013598	-0.0013602	-0.0013606	-0.0013609	-0.0013611
-0.015	-0.0012740	-0.0012744	-0.0012748	-0.0012751	-0.0012754	-0.0012756
-0.014	-0.0011887	-0.0011891	-0.0011894	-0.0011897	-0.0011900	-0.0011902
-0.013	-0.0011035	-0.0011038	-0.0011041	-0.0011044	-0.0011046	-0.0011049
-0.012	-0.0010183	-0.0010186	-0.0010189	-0.0010192	-0.0010194	-0.0010196
-0.011	-0.0009332	-0.0009335	-0.0009337	-0.0009340	-0.0009342	-0.0009344
-0.010	-0.0008481	-0.0008484	-0.0008487	-0.0008489	-0.0008491	-0.0008492
-0.009	-0.0007632	-0.0007634	-0.0007636	-0.0007638	-0.0007640	-0.0007641
-0.008	-0.0006782	-0.0006784	-0.0006786	-0.0006788	-0.0006790	-0.0006791
-0.007	-0.0005933	-0.0005935	-0.0005937	-0.0005939	-0.0005940	-0.0005941
-0.006	-0.0005085	-0.0005087	-0.0005088	-0.0005089	-0.0005090	-0.0005091
-0.005	-0.0004237	-0.0004238	-0.0004240	-0.0004241	-0.0004242	-0.0004242
-0.004	-0.0003389	-0.0003390	-0.0003391	-0.0003392	-0.0003393	-0.0003393
-0.003	-0.0002542	-0.0002543	-0.0002543	-0.0002544	-0.0002544	-0.0002545
-0.002	-0.0001694	-0.0001695	-0.0001695	-0.0001696	-0.0001696	-0.0001696
-0.001	-0.0000847	-0.0000847	-0.0000848	-0.0000848	-0.0000848	-0.0000848
0.000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
0.001	0.0000847	0.0000847	0.0000848	0.0000848	0.0000848	0.0000848
0.002	0.0001694	0.0001695	0.0001695	0.0001696	0.0001696	0.0001696
0.003	0.0002542	0.0002543	0.0002543	0.0002544	0.0002544	0.0002545
0.004	0.0003389	0.0003390	0.0003391	0.0003392	0.0003393	0.0003393
0.005	0.0004237	0.0004238	0.0004240	0.0004241	0.0004242	0.0004242
0.006	0.0005085	0.0005087	0.0005088	0.0005089	0.0005090	0.0005091
0.007	0.0005933	0.0005935	0.0005937	0.0005939	0.0005940	0.0005941
0.008	0.0006782	0.0006784	0.0006786	0.0006788	0.0006790	0.0006791
0.009	0.0007632	0.0007634	0.0007636	0.0007638	0.0007640	0.0007641
0.010	0.0008481	0.0008484	0.0008487	0.0008489	0.0008491	0.0008492
0.011	0.0009332	0.0009335	0.0009337	0.0009340	0.0009342	0.0009344
0.012	0.0010183	0.0010186	0.0010189	0.0010192	0.0010194	0.0010196
0.013	0.0011035	0.0011038	0.0011041	0.0011044	0.0011046	0.0011049
0.014	0.0011887	0.0011891	0.0011894	0.0011897	0.0011900	0.0011902
0.015	0.0012740	0.0012744	0.0012748	0.0012751	0.0012754	0.0012756
0.016	0.0013594	0.0013598	0.0013602	0.0013606	0.0013609	0.0013611
0.017	0.0014449	0.0014453	0.0014458	0.0014461	0.0014465	0.0014467
0.018	0.0015305	0.0015309	0.0015314	0.0015318	0.0015321	0.0015324
0.019	0.0016161	0.0016166	0.0016171	0.0016175	0.0016179	0.0016182
0.020	0.0017018	0.0017024	0.0017029	0.0017033	0.0017037	0.0017040

Table 3 Continued

Z	T=315	T=320	T=325	T=330	T=335	T=340
0.021	0.0017877	0.0017882	0.0017888	0.0017892	0.0017896	0.0017900
0.022	0.0018736	0.0018742	0.0018747	0.0018752	0.0018757	0.0018760
0.023	0.0019596	0.0019603	0.0019608	0.0019613	0.0019618	0.0019622
0.024	0.0020458	0.0020464	0.0020470	0.0020475	0.0020480	0.0020484
0.025	0.0021320	0.0021327	0.0021333	0.0021338	0.0021343	0.0021348

Table 4 variation in out of plane shear strain γ_{xz} component along the thickness direction with variation in thermal load

Z	T=315	T=320	T=325	T=330	T=335	T=340
-0.025	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000
-0.024	-0.0000198	-0.0000198	-0.0000199	-0.0000199	-0.0000200	-0.0000200
-0.023	-0.0000395	-0.0000396	-0.0000397	-0.0000398	-0.0000399	-0.0000400
-0.022	-0.0000591	-0.0000592	-0.0000594	-0.0000595	-0.0000597	-0.0000598
-0.021	-0.0000784	-0.0000786	-0.0000788	-0.0000790	-0.0000792	-0.0000794
-0.020	-0.0000974	-0.0000977	-0.0000979	-0.0000982	-0.0000984	-0.0000987
-0.019	-0.0001161	-0.0001164	-0.0001167	-0.0001170	-0.0001172	-0.0001175
-0.018	-0.0001342	-0.0001346	-0.0001349	-0.0001353	-0.0001356	-0.0001359
-0.017	-0.0001519	-0.0001523	-0.0001527	-0.0001530	-0.0001534	-0.0001538
-0.016	-0.0001689	-0.0001694	-0.0001698	-0.0001702	-0.0001707	-0.0001711
-0.015	-0.0001853	-0.0001858	-0.0001863	-0.0001867	-0.0001872	-0.0001877
-0.014	-0.0002010	-0.0002015	-0.0002020	-0.0002025	-0.0002030	-0.0002035
-0.013	-0.0002158	-0.0002164	-0.0002169	-0.0002175	-0.0002180	-0.0002186
-0.012	-0.0002298	-0.0002304	-0.0002310	-0.0002316	-0.0002322	-0.0002327
-0.011	-0.0002429	-0.0002436	-0.0002442	-0.0002448	-0.0002454	-0.0002460
-0.010	-0.0002551	-0.0002557	-0.0002564	-0.0002570	-0.0002577	-0.0002583
-0.009	-0.0002662	-0.0002669	-0.0002676	-0.0002682	-0.0002689	-0.0002696
-0.008	-0.0002763	-0.0002770	-0.0002777	-0.0002784	-0.0002791	-0.0002798
-0.007	-0.0002853	-0.0002860	-0.0002867	-0.0002875	-0.0002882	-0.0002889
-0.006	-0.0002932	-0.0002939	-0.0002946	-0.0002954	-0.0002961	-0.0002969
-0.005	-0.0002999	-0.0003006	-0.0003014	-0.0003021	-0.0003029	-0.0003036
-0.004	-0.0003054	-0.0003062	-0.0003069	-0.0003077	-0.0003085	-0.0003092
-0.003	-0.0003097	-0.0003105	-0.0003113	-0.0003121	-0.0003128	-0.0003136
-0.002	-0.0003128	-0.0003136	-0.0003144	-0.0003152	-0.0003160	-0.0003168
-0.001	-0.0003147	-0.0003155	-0.0003163	-0.0003171	-0.0003179	-0.0003186
0.000	-0.0003153	-0.0003161	-0.0003169	-0.0003177	-0.0003185	-0.0003193
0.001	-0.0003147	-0.0003155	-0.0003163	-0.0003171	-0.0003179	-0.0003186
0.002	-0.0003128	-0.0003136	-0.0003144	-0.0003152	-0.0003160	-0.0003168
0.003	-0.0003097	-0.0003105	-0.0003113	-0.0003121	-0.0003128	-0.0003136
0.004	-0.0003054	-0.0003062	-0.0003069	-0.0003077	-0.0003085	-0.0003092
0.005	-0.0002999	-0.0003006	-0.0003014	-0.0003021	-0.0003029	-0.0003036
0.006	-0.0002932	-0.0002939	-0.0002946	-0.0002954	-0.0002961	-0.0002969
0.007	-0.0002853	-0.0002860	-0.0002867	-0.0002875	-0.0002882	-0.0002889
0.008	-0.0002763	-0.0002770	-0.0002777	-0.0002784	-0.0002791	-0.0002798
0.009	-0.0002662	-0.0002669	-0.0002676	-0.0002682	-0.0002689	-0.0002696
0.010	-0.0002551	-0.0002557	-0.0002564	-0.0002570	-0.0002577	-0.0002583
0.011	-0.0002429	-0.0002436	-0.0002442	-0.0002448	-0.0002454	-0.0002460
0.012	-0.0002298	-0.0002304	-0.0002310	-0.0002316	-0.0002322	-0.0002327

Table 4 Continued

Z	T=315	T=320	T=325	T=330	T=335	T=340
0.013	-0.0002158	-0.0002164	-0.0002169	-0.0002175	-0.0002180	-0.0002186
0.014	-0.0002010	-0.0002015	-0.0002020	-0.0002025	-0.0002030	-0.0002035
0.015	-0.0001853	-0.0001858	-0.0001863	-0.0001867	-0.0001872	-0.0001877
0.016	-0.0001689	-0.0001694	-0.0001698	-0.0001702	-0.0001707	-0.0001711
0.017	-0.0001519	-0.0001523	-0.0001527	-0.0001530	-0.0001534	-0.0001538
0.018	-0.0001342	-0.0001346	-0.0001349	-0.0001353	-0.0001356	-0.0001359
0.019	-0.0001161	-0.0001164	-0.0001167	-0.0001170	-0.0001172	-0.0001175
0.020	-0.0000974	-0.0000977	-0.0000979	-0.0000982	-0.0000984	-0.0000987
0.021	-0.0000784	-0.0000786	-0.0000788	-0.0000790	-0.0000792	-0.0000794
0.022	-0.0000591	-0.0000592	-0.0000594	-0.0000595	-0.0000597	-0.0000598
0.023	-0.0000395	-0.0000396	-0.0000397	-0.0000398	-0.0000399	-0.0000400
0.024	-0.0000198	-0.0000198	-0.0000199	-0.0000199	-0.0000200	-0.0000200
0.025	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000	0.0000000

Table 5 variation in in-plane normal component σ_x along the thickness direction with variation in thermal load

Z	T=315	T=320	T=325	T=330	T=335	T=340
-0.025	-2.636E+08	-2.732E+08	-2.832E+08	-2.935E+08	-3.042E+08	-3.154E+08
-0.024	-2.653E+08	-2.749E+08	-2.849E+08	-2.952E+08	-3.060E+08	-3.172E+08
-0.023	-2.669E+08	-2.765E+08	-2.865E+08	-2.969E+08	-3.077E+08	-3.188E+08
-0.022	-2.683E+08	-2.780E+08	-2.880E+08	-2.984E+08	-3.092E+08	-3.204E+08
-0.021	-2.697E+08	-2.794E+08	-2.894E+08	-2.999E+08	-3.107E+08	-3.219E+08
-0.020	-2.710E+08	-2.807E+08	-2.908E+08	-3.012E+08	-3.120E+08	-3.233E+08
-0.019	-2.722E+08	-2.819E+08	-2.920E+08	-3.024E+08	-3.133E+08	-3.246E+08
-0.018	-2.733E+08	-2.830E+08	-2.931E+08	-3.036E+08	-3.144E+08	-3.257E+08
-0.017	-2.743E+08	-2.840E+08	-2.941E+08	-3.046E+08	-3.155E+08	-3.268E+08
-0.016	-2.752E+08	-2.850E+08	-2.951E+08	-3.056E+08	-3.165E+08	-3.278E+08
-0.015	-2.761E+08	-2.858E+08	-2.960E+08	-3.065E+08	-3.174E+08	-3.287E+08
-0.014	-2.769E+08	-2.866E+08	-2.967E+08	-3.072E+08	-3.182E+08	-3.295E+08
-0.013	-2.775E+08	-2.873E+08	-2.975E+08	-3.080E+08	-3.189E+08	-3.302E+08
-0.012	-2.782E+08	-2.880E+08	-2.981E+08	-3.086E+08	-3.195E+08	-3.308E+08
-0.011	-2.787E+08	-2.885E+08	-2.986E+08	-3.092E+08	-3.201E+08	-3.314E+08
-0.010	-2.792E+08	-2.890E+08	-2.991E+08	-3.097E+08	-3.206E+08	-3.319E+08
-0.009	-2.797E+08	-2.895E+08	-2.996E+08	-3.101E+08	-3.210E+08	-3.323E+08
-0.008	-2.801E+08	-2.898E+08	-3.000E+08	-3.105E+08	-3.214E+08	-3.327E+08
-0.007	-2.804E+08	-2.902E+08	-3.003E+08	-3.108E+08	-3.217E+08	-3.331E+08
-0.006	-2.807E+08	-2.905E+08	-3.006E+08	-3.111E+08	-3.220E+08	-3.333E+08
-0.005	-2.810E+08	-2.908E+08	-3.009E+08	-3.114E+08	-3.223E+08	-3.336E+08
-0.004	-2.812E+08	-2.910E+08	-3.011E+08	-3.116E+08	-3.225E+08	-3.338E+08
-0.003	-2.815E+08	-2.912E+08	-3.013E+08	-3.118E+08	-3.227E+08	-3.340E+08
-0.002	-2.817E+08	-2.914E+08	-3.015E+08	-3.120E+08	-3.228E+08	-3.341E+08
-0.001	-2.818E+08	-2.916E+08	-3.017E+08	-3.121E+08	-3.230E+08	-3.343E+08
0.000	-2.820E+08	-2.917E+08	-3.018E+08	-3.123E+08	-3.231E+08	-3.344E+08
0.001	-2.822E+08	-2.919E+08	-3.020E+08	-3.124E+08	-3.233E+08	-3.346E+08
0.002	-2.824E+08	-2.921E+08	-3.022E+08	-3.126E+08	-3.234E+08	-3.347E+08
0.003	-2.826E+08	-2.923E+08	-3.023E+08	-3.128E+08	-3.236E+08	-3.349E+08
0.004	-2.828E+08	-2.925E+08	-3.025E+08	-3.130E+08	-3.238E+08	-3.350E+08

Table 5 Continued

Z	T=315	T=320	T=325	T=330	T=335	T=340
0.005	-2.830E+08	-2.927E+08	-3.028E+08	-3.132E+08	-3.240E+08	-3.352E+08
0.006	-2.833E+08	-2.930E+08	-3.030E+08	-3.134E+08	-3.243E+08	-3.355E+08
0.007	-2.836E+08	-2.933E+08	-3.033E+08	-3.137E+08	-3.245E+08	-3.358E+08
0.008	-2.840E+08	-2.936E+08	-3.037E+08	-3.141E+08	-3.249E+08	-3.361E+08
0.009	-2.844E+08	-2.940E+08	-3.041E+08	-3.145E+08	-3.253E+08	-3.365E+08
0.010	-2.848E+08	-2.945E+08	-3.045E+08	-3.149E+08	-3.257E+08	-3.369E+08
0.011	-2.853E+08	-2.950E+08	-3.050E+08	-3.154E+08	-3.262E+08	-3.374E+08
0.012	-2.859E+08	-2.955E+08	-3.056E+08	-3.160E+08	-3.268E+08	-3.380E+08
0.013	-2.865E+08	-2.962E+08	-3.062E+08	-3.166E+08	-3.274E+08	-3.386E+08
0.014	-2.872E+08	-2.969E+08	-3.069E+08	-3.173E+08	-3.281E+08	-3.393E+08
0.015	-2.880E+08	-2.976E+08	-3.077E+08	-3.181E+08	-3.289E+08	-3.401E+08
0.016	-2.888E+08	-2.985E+08	-3.085E+08	-3.190E+08	-3.298E+08	-3.410E+08
0.017	-2.897E+08	-2.994E+08	-3.095E+08	-3.199E+08	-3.308E+08	-3.420E+08
0.018	-2.908E+08	-3.005E+08	-3.105E+08	-3.210E+08	-3.318E+08	-3.431E+08
0.019	-2.919E+08	-3.016E+08	-3.117E+08	-3.221E+08	-3.330E+08	-3.443E+08
0.020	-2.930E+08	-3.028E+08	-3.129E+08	-3.234E+08	-3.342E+08	-3.455E+08
0.021	-2.943E+08	-3.041E+08	-3.142E+08	-3.247E+08	-3.356E+08	-3.469E+08
0.022	-2.957E+08	-3.055E+08	-3.156E+08	-3.261E+08	-3.371E+08	-3.484E+08
0.023	-2.972E+08	-3.070E+08	-3.171E+08	-3.277E+08	-3.386E+08	-3.500E+08
0.024	-2.987E+08	-3.086E+08	-3.187E+08	-3.293E+08	-3.403E+08	-3.517E+08
0.025	-3.004E+08	-3.102E+08	-3.205E+08	-3.311E+08	-3.420E+08	-3.535E+08

Table 6 Variation in out of plane normal component σ_z along the thickness direction with variation in thermal load

Z	T=315	T=320	T=325	T=330	T=335	T=340
-0.025	-2.748E+08	-2.844E+08	-2.943E+08	-3.046E+08	-3.154E+08	-3.265E+09
-0.024	-2.762E+08	-2.859E+08	-2.958E+08	-3.062E+08	-3.169E+08	-3.281E+09
-0.023	-2.776E+08	-2.872E+08	-2.972E+08	-3.076E+08	-3.184E+08	-3.295E+09
-0.022	-2.788E+08	-2.884E+08	-2.985E+08	-3.089E+08	-3.197E+08	-3.309E+09
-0.021	-2.799E+08	-2.896E+08	-2.996E+08	-3.100E+08	-3.208E+08	-3.321E+09
-0.020	-2.808E+08	-2.906E+08	-3.006E+08	-3.110E+08	-3.219E+08	-3.331E+09
-0.019	-2.817E+08	-2.914E+08	-3.015E+08	-3.120E+08	-3.228E+08	-3.341E+09
-0.018	-2.825E+08	-2.922E+08	-3.023E+08	-3.127E+08	-3.236E+08	-3.349E+09
-0.017	-2.831E+08	-2.928E+08	-3.029E+08	-3.134E+08	-3.243E+08	-3.356E+09
-0.016	-2.836E+08	-2.934E+08	-3.035E+08	-3.140E+08	-3.249E+08	-3.362E+09
-0.015	-2.841E+08	-2.938E+08	-3.039E+08	-3.144E+08	-3.253E+08	-3.367E+09
-0.014	-2.844E+08	-2.942E+08	-3.043E+08	-3.148E+08	-3.257E+08	-3.370E+09
-0.013	-2.846E+08	-2.944E+08	-3.045E+08	-3.151E+08	-3.260E+08	-3.373E+09
-0.012	-2.848E+08	-2.946E+08	-3.047E+08	-3.152E+08	-3.261E+08	-3.375E+09
-0.011	-2.849E+08	-2.946E+08	-3.048E+08	-3.153E+08	-3.262E+08	-3.375E+09
-0.010	-2.849E+08	-2.946E+08	-3.048E+08	-3.153E+08	-3.262E+08	-3.375E+09
-0.009	-2.848E+08	-2.946E+08	-3.047E+08	-3.152E+08	-3.261E+08	-3.375E+09
-0.008	-2.846E+08	-2.944E+08	-3.045E+08	-3.151E+08	-3.260E+08	-3.373E+09
-0.007	-2.844E+08	-2.942E+08	-3.043E+08	-3.148E+08	-3.258E+08	-3.371E+09
-0.006	-2.842E+08	-2.940E+08	-3.041E+08	-3.146E+08	-3.255E+08	-3.368E+09
-0.005	-2.839E+08	-2.937E+08	-3.038E+08	-3.143E+08	-3.252E+08	-3.365E+09
-0.004	-2.836E+08	-2.933E+08	-3.034E+08	-3.139E+08	-3.248E+08	-3.361E+09

Table 6 Continued

Z	T=315	T=320	T=325	T=330	T=335	T=340
-0.003	-2.832E+08	-2.930E+08	-3.031E+08	-3.135E+08	-3.244E+08	-3.357E+09
-0.002	-2.828E+08	-2.926E+08	-3.027E+08	-3.131E+08	-3.240E+08	-3.353E+09
-0.001	-2.824E+08	-2.922E+08	-3.022E+08	-3.127E+08	-3.236E+08	-3.349E+09
0.000	-2.820E+08	-2.917E+08	-3.018E+08	-3.123E+08	-3.231E+08	-3.344E+09
0.001	-2.816E+08	-2.913E+08	-3.014E+08	-3.118E+08	-3.227E+08	-3.340E+09
0.002	-2.812E+08	-2.909E+08	-3.010E+08	-3.114E+08	-3.223E+08	-3.335E+09
0.003	-2.808E+08	-2.905E+08	-3.006E+08	-3.110E+08	-3.219E+08	-3.331E+09
0.004	-2.805E+08	-2.902E+08	-3.002E+08	-3.106E+08	-3.215E+08	-3.327E+09
0.005	-2.801E+08	-2.898E+08	-2.999E+08	-3.103E+08	-3.211E+08	-3.323E+09
0.006	-2.798E+08	-2.895E+08	-2.996E+08	-3.100E+08	-3.208E+08	-3.320E+09
0.007	-2.796E+08	-2.893E+08	-2.993E+08	-3.097E+08	-3.205E+08	-3.317E+09
0.008	-2.794E+08	-2.891E+08	-2.991E+08	-3.095E+08	-3.203E+08	-3.315E+09
0.009	-2.792E+08	-2.889E+08	-2.989E+08	-3.094E+08	-3.202E+08	-3.314E+09
0.010	-2.792E+08	-2.888E+08	-2.989E+08	-3.093E+08	-3.201E+08	-3.313E+09
0.011	-2.792E+08	-2.888E+08	-2.989E+08	-3.093E+08	-3.201E+08	-3.313E+09
0.012	-2.792E+08	-2.889E+08	-2.989E+08	-3.093E+08	-3.201E+08	-3.314E+09
0.013	-2.794E+08	-2.891E+08	-2.991E+08	-3.095E+08	-3.203E+08	-3.315E+09
0.014	-2.796E+08	-2.893E+08	-2.993E+08	-3.098E+08	-3.206E+08	-3.318E+09
0.015	-2.800E+08	-2.897E+08	-2.997E+08	-3.101E+08	-3.209E+08	-3.322E+09
0.016	-2.804E+08	-2.901E+08	-3.001E+08	-3.106E+08	-3.214E+08	-3.326E+09
0.017	-2.809E+08	-2.906E+08	-3.007E+08	-3.111E+08	-3.220E+08	-3.332E+09
0.018	-2.816E+08	-2.913E+08	-3.014E+08	-3.118E+08	-3.227E+08	-3.339E+09
0.019	-2.823E+08	-2.921E+08	-3.021E+08	-3.126E+08	-3.235E+08	-3.347E+09
0.020	-2.832E+08	-2.929E+08	-3.030E+08	-3.135E+08	-3.244E+08	-3.357E+09
0.021	-2.842E+08	-2.939E+08	-3.040E+08	-3.145E+08	-3.254E+08	-3.368E+09
0.022	-2.853E+08	-2.950E+08	-3.052E+08	-3.157E+08	-3.266E+08	-3.380E+09
0.023	-2.865E+08	-2.963E+08	-3.064E+08	-3.170E+08	-3.279E+08	-3.393E+09
0.024	-2.878E+08	-2.976E+08	-3.078E+08	-3.184E+08	-3.293E+08	-3.407E+09
0.025	-2.892E+08	-2.991E+08	-3.093E+08	-3.199E+08	-3.309E+08	-3.423E+09

Table 7 Variation in in- plane shear stress component τ_{xy} along the thickness direction with variation in thermal load

Z	T=315	T=320	T=325	T=330	T=335	T=340
-0.025	-4.896E+07	-4.882E+07	-4.869E+07	-4.856E+07	-4.842E+07	-4.828E+07
-0.024	-4.698E+07	-4.685E+07	-4.672E+07	-4.659E+07	-4.646E+07	-4.633E+07
-0.023	-4.500E+07	-4.488E+07	-4.475E+07	-4.463E+07	-4.451E+07	-4.438E+07
-0.022	-4.302E+07	-4.291E+07	-4.279E+07	-4.267E+07	-4.255E+07	-4.243E+07
-0.021	-4.105E+07	-4.094E+07	-4.083E+07	-4.071E+07	-4.060E+07	-4.049E+07
-0.020	-3.908E+07	-3.897E+07	-3.887E+07	-3.876E+07	-3.865E+07	-3.854E+07
-0.019	-3.711E+07	-3.701E+07	-3.691E+07	-3.681E+07	-3.670E+07	-3.660E+07
-0.018	-3.514E+07	-3.505E+07	-3.495E+07	-3.486E+07	-3.476E+07	-3.466E+07
-0.017	-3.318E+07	-3.309E+07	-3.300E+07	-3.291E+07	-3.282E+07	-3.272E+07
-0.016	-3.122E+07	-3.113E+07	-3.105E+07	-3.096E+07	-3.087E+07	-3.079E+07
-0.015	-2.925E+07	-2.918E+07	-2.910E+07	-2.902E+07	-2.893E+07	-2.885E+07
-0.014	-2.730E+07	-2.722E+07	-2.715E+07	-2.707E+07	-2.700E+07	-2.692E+07
-0.013	-2.534E+07	-2.527E+07	-2.520E+07	-2.513E+07	-2.506E+07	-2.499E+07

Table 7 Continued

Z	T=315	T=320	T=325	T=330	T=335	T=340
-0.012	-2.338E+07	-2.332E+07	-2.326E+07	-2.319E+07	-2.313E+07	-2.306E+07
-0.011	-2.143E+07	-2.137E+07	-2.131E+07	-2.125E+07	-2.119E+07	-2.113E+07
-0.010	-1.948E+07	-1.942E+07	-1.937E+07	-1.932E+07	-1.926E+07	-1.921E+07
-0.009	-1.752E+07	-1.748E+07	-1.743E+07	-1.738E+07	-1.733E+07	-1.728E+07
-0.008	-1.557E+07	-1.553E+07	-1.549E+07	-1.545E+07	-1.540E+07	-1.536E+07
-0.007	-1.362E+07	-1.359E+07	-1.355E+07	-1.351E+07	-1.348E+07	-1.344E+07
-0.006	-1.168E+07	-1.165E+07	-1.161E+07	-1.158E+07	-1.155E+07	-1.152E+07
-0.005	-9.729E+06	-9.703E+06	-9.676E+06	-9.650E+06	-9.623E+06	-9.595E+06
-0.004	-7.783E+06	-7.762E+06	-7.740E+06	-7.719E+06	-7.697E+06	-7.675E+06
-0.003	-5.836E+06	-5.821E+06	-5.805E+06	-5.789E+06	-5.772E+06	-5.756E+06
-0.002	-3.891E+06	-3.880E+06	-3.870E+06	-3.859E+06	-3.848E+06	-3.837E+06
-0.001	-1.945E+06	-1.940E+06	-1.935E+06	-1.929E+06	-1.924E+06	-1.918E+06
0.000	2.700E-08	2.692E-08	2.685E-08	2.677E-08	2.670E-08	2.662E-08
0.001	1.945E+06	1.940E+06	1.935E+06	1.929E+06	1.924E+06	1.918E+06
0.002	3.891E+06	3.880E+06	3.870E+06	3.859E+06	3.848E+06	3.837E+06
0.003	5.836E+06	5.821E+06	5.805E+06	5.789E+06	5.772E+06	5.756E+06
0.004	7.783E+06	7.762E+06	7.740E+06	7.719E+06	7.697E+06	7.675E+06
0.005	9.729E+06	9.703E+06	9.676E+06	9.650E+06	9.623E+06	9.595E+06
0.006	1.168E+07	1.165E+07	1.161E+07	1.158E+07	1.155E+07	1.152E+07
0.007	1.362E+07	1.359E+07	1.355E+07	1.351E+07	1.348E+07	1.344E+07
0.008	1.557E+07	1.553E+07	1.549E+07	1.545E+07	1.540E+07	1.536E+07
0.009	1.752E+07	1.748E+07	1.743E+07	1.738E+07	1.733E+07	1.728E+07
0.010	1.948E+07	1.942E+07	1.937E+07	1.932E+07	1.926E+07	1.921E+07
0.011	2.143E+07	2.137E+07	2.131E+07	2.125E+07	2.119E+07	2.113E+07
0.012	2.338E+07	2.332E+07	2.326E+07	2.319E+07	2.313E+07	2.306E+07
0.013	2.534E+07	2.527E+07	2.520E+07	2.513E+07	2.506E+07	2.499E+07
0.014	2.730E+07	2.722E+07	2.715E+07	2.707E+07	2.700E+07	2.692E+07
0.015	2.925E+07	2.918E+07	2.910E+07	2.902E+07	2.893E+07	2.885E+07
0.016	3.122E+07	3.113E+07	3.105E+07	3.096E+07	3.087E+07	3.079E+07
0.017	3.318E+07	3.309E+07	3.300E+07	3.291E+07	3.282E+07	3.272E+07
0.018	3.514E+07	3.505E+07	3.495E+07	3.486E+07	3.476E+07	3.466E+07
0.019	3.711E+07	3.701E+07	3.691E+07	3.681E+07	3.670E+07	3.660E+07
0.020	3.908E+07	3.897E+07	3.887E+07	3.876E+07	3.865E+07	3.854E+07
0.021	4.105E+07	4.094E+07	4.083E+07	4.071E+07	4.060E+07	4.049E+07
0.022	4.302E+07	4.291E+07	4.279E+07	4.267E+07	4.255E+07	4.243E+07
0.023	4.500E+07	4.488E+07	4.475E+07	4.463E+07	4.451E+07	4.438E+07
0.024	4.698E+07	4.685E+07	4.672E+07	4.659E+07	4.646E+07	4.633E+07
0.025	4.896E+07	4.882E+07	4.869E+07	4.856E+07	4.842E+07	4.828E+07

Table 8 Variation in out of plane shear stress component τ_{xz} along the thickness direction with variation in thermal load

Z	T=315	T=320	T=325	T=330	T=335	T=340
-0.025	-9.606E+00	-9.601E+00	-9.597E+00	-9.592E+00	-9.587E+00	-9.581E+00
-0.024	-4.546E+05	-4.544E+05	-4.542E+05	-4.539E+05	-4.537E+05	-2.658E+06
-0.023	-9.074E+05	-9.070E+05	-9.065E+05	-9.061E+05	-9.056E+05	-3.075E+06
-0.022	-1.357E+06	-1.356E+06	-1.355E+06	-1.355E+06	-1.354E+06	-3.479E+06

Table 8 Continued

Z	T=315	T=320	T=325	T=330	T=335	T=340
-0.021	-1.801E+06	-1.800E+06	-1.799E+06	-1.798E+06	-1.797E+06	-3.869E+06
-0.020	-2.237E+06	-2.236E+06	-2.235E+06	-2.234E+06	-2.233E+06	-4.245E+06
-0.019	-2.665E+06	-2.664E+06	-2.663E+06	-2.661E+06	-2.660E+06	-4.603E+06
-0.018	-3.083E+06	-3.081E+06	-3.080E+06	-3.078E+06	-3.076E+06	-4.943E+06
-0.017	-3.488E+06	-3.486E+06	-3.485E+06	-3.483E+06	-3.481E+06	-5.264E+06
-0.016	-3.879E+06	-3.878E+06	-3.876E+06	-3.874E+06	-3.872E+06	-5.564E+06
-0.015	-4.256E+06	-4.254E+06	-4.251E+06	-4.249E+06	-4.247E+06	-5.842E+06
-0.014	-4.615E+06	-4.613E+06	-4.610E+06	-4.608E+06	-4.606E+06	-6.097E+06
-0.013	-4.956E+06	-4.954E+06	-4.951E+06	-4.949E+06	-4.946E+06	-6.328E+06
-0.012	-5.278E+06	-5.275E+06	-5.273E+06	-5.270E+06	-5.267E+06	-6.534E+06
-0.011	-5.579E+06	-5.576E+06	-5.573E+06	-5.570E+06	-5.567E+06	-6.714E+06
-0.010	-5.857E+06	-5.854E+06	-5.852E+06	-5.849E+06	-5.845E+06	-6.868E+06
-0.009	-6.113E+06	-6.110E+06	-6.107E+06	-6.104E+06	-6.101E+06	-6.994E+06
-0.008	-6.344E+06	-6.341E+06	-6.338E+06	-6.335E+06	-6.332E+06	-7.093E+06
-0.007	-6.551E+06	-6.548E+06	-6.545E+06	-6.541E+06	-6.538E+06	-7.164E+06
-0.006	-6.732E+06	-6.728E+06	-6.725E+06	-6.722E+06	-6.718E+06	-7.207E+06
-0.005	-6.886E+06	-6.882E+06	-6.879E+06	-6.875E+06	-6.872E+06	-7.221E+06
-0.004	-7.013E+06	-7.009E+06	-7.006E+06	-7.002E+06	-6.998E+06	-7.207E+06
-0.003	-7.112E+06	-7.108E+06	-7.105E+06	-7.101E+06	-7.097E+06	-7.164E+06
-0.002	-7.183E+06	-7.179E+06	-7.176E+06	-7.172E+06	-7.168E+06	-7.093E+06
-0.001	-7.226E+06	-7.222E+06	-7.219E+06	-7.215E+06	-7.211E+06	-6.994E+06
0.000	-7.240E+06	-7.237E+06	-7.233E+06	-7.229E+06	-7.225E+06	-6.868E+06
0.001	-7.226E+06	-7.222E+06	-7.219E+06	-7.215E+06	-7.211E+06	-6.714E+06
0.002	-7.183E+06	-7.179E+06	-7.176E+06	-7.172E+06	-7.168E+06	-6.534E+06
0.003	-7.112E+06	-7.108E+06	-7.105E+06	-7.101E+06	-7.097E+06	-6.328E+06
0.004	-7.013E+06	-7.009E+06	-7.006E+06	-7.002E+06	-6.998E+06	-6.097E+06
0.005	-6.886E+06	-6.882E+06	-6.879E+06	-6.875E+06	-6.872E+06	-5.842E+06
0.006	-6.732E+06	-6.728E+06	-6.725E+06	-6.722E+06	-6.718E+06	-5.564E+06
0.007	-6.551E+06	-6.548E+06	-6.545E+06	-6.541E+06	-6.538E+06	-5.264E+06
0.008	-6.344E+06	-6.341E+06	-6.338E+06	-6.335E+06	-6.332E+06	-4.943E+06
0.009	-6.113E+06	-6.110E+06	-6.107E+06	-6.104E+06	-6.101E+06	-4.603E+06
0.010	-5.857E+06	-5.854E+06	-5.852E+06	-5.849E+06	-5.845E+06	-4.245E+06
0.011	-5.579E+06	-5.576E+06	-5.573E+06	-5.570E+06	-5.567E+06	-3.869E+06
0.012	-5.278E+06	-5.275E+06	-5.273E+06	-5.270E+06	-5.267E+06	-3.479E+06
0.013	-4.956E+06	-4.954E+06	-4.951E+06	-4.949E+06	-4.946E+06	-3.075E+06
0.014	-4.615E+06	-4.613E+06	-4.610E+06	-4.608E+06	-4.606E+06	-2.658E+06
0.015	-4.256E+06	-4.254E+06	-4.251E+06	-4.249E+06	-4.247E+06	-2.232E+06
0.016	-3.879E+06	-3.878E+06	-3.876E+06	-3.874E+06	-3.872E+06	-1.796E+06
0.017	-3.488E+06	-3.486E+06	-3.485E+06	-3.483E+06	-3.481E+06	-1.353E+06
0.018	-3.083E+06	-3.081E+06	-3.080E+06	-3.078E+06	-3.076E+06	-9.051E+05
0.019	-2.665E+06	-2.664E+06	-2.663E+06	-2.661E+06	-2.660E+06	-4.534E+05
0.020	-2.237E+06	-2.236E+06	-2.235E+06	-2.234E+06	-2.233E+06	-9.581E+00
0.021	-1.801E+06	-1.800E+06	-1.799E+06	-1.798E+06	-1.797E+06	-7.221E+06
0.022	-1.357E+06	-1.356E+06	-1.355E+06	-1.355E+06	-1.354E+06	-7.221E+06
0.023	-9.074E+05	-9.070E+05	-9.065E+05	-9.061E+05	-9.056E+05	-7.221E+06
0.024	-4.546E+05	-4.544E+05	-4.542E+05	-4.539E+05	-4.537E+05	-7.221E+06
0.025	-9.606E+00	-9.601E+00	-9.597E+00	-9.592E+00	-9.587E+00	-7.221E+06

5. Conclusions

In this paper, authors provided a detailed shear deformable based kinematic modeling of a graphene origami reinforced nanocomposite plate subjected to thermal and mechanical loading. The analytical bending analysis was performed using the virtual work principle. The behavioral relations were extended using the overall material properties derived from the previously developed relations of the experimental and statistical studies. The numerical results were derived using the analytical works in terms of the significant import parameters. The main results of this work are expressed as follows:

The impact of thermal loads was studied on the responses. It is concluded that an enhancement in the thermal loads leads to a significant decrease in the structural stiffness of the constituent materials and consequently decrease in the strain components.

An increase in thermal loads has different effect on the stress variation because of simultaneous effect on the strain components and stiffness. While an increase in thermal loads leads to an increase in strain components. the stiffness parameter is decreased. Therefore, the stress component may be decreased or increased due to above mentioned fact.

Variation of the out of plane shear strain was examined along the thickness direction. The zero shear strain condition at top and bottom surfaces is satisfied based on the selection of the appropriate shape function.

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