

Thermo-foldable bending analysis of tunable shells using a higher-order modeling

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Abstract

This article investigates the effect of higher-order kinematic modeling on the elasto-static bending behavior of doubly-curved shells. Graphene origami is introduced as a novel nanofiller, synthesized through a chemical process to achieve a controllable material. A copper matrix serves as the primary constituent, reinforced with folded graphene origami. The principle of virtual work is employed to derive the governing equations for the thickness-stretchable shell. Following the derivation of the governing equations, formulas from established sources are utilized to determine the effective material properties of the shell. A verification test is conducted prior to investigating the influence of the primary parameters of the graphene origami and environmental conditions on the bending behavior. The findings of this study may be applied to the analysis of structures with controllable responses.

Full Text

Preamble

This article investigates the effect of higher-order kinematic modeling on the elasto-static bending behavior of tunable shells reinforced with folded graphene origami nanofillers. A copper matrix reinforced with folded graphene origami serves as the primary constituent material. The virtual work principle is employed to derive the governing equations for the thickness-stretchable shell. After deriving the governing equations, empirical formulas from validated sources are used to determine the effective material properties. A verification test is presented before exploring the effects of key parameters related to graphene origami and thermal environment on the bending results. The findings of this work may be applied to the analysis of structures with controllable responses.

1. Introduction

The development of novel and advanced materials using nanomaterials in various formats has become a major research interest for scientists in materials science, civil engineering, mechanical engineering, and chemistry. Following the introduction of carbon nanotubes in both single- and double-walled configurations, researchers proposed graphene sheets and nanoplatelets, which exhibit superior properties compared to their predecessors. Experimental studies have demonstrated that adding small amounts of graphene can lead to significant improvements in mechanical and thermal properties [?]. Material scientists have proposed new processes to control material properties and corresponding responses [?, ?], with hydrogenation emerging as a novel method for producing controllable materials.

The intelligent and hybrid applications of novel materials for robotic systems and structures as actuators and sensors have been described [?]. Neural and fuzzy systems, along with networks, have been organized and explained for characterization, modeling, and simulation of effective material properties of nanocomposite structures and polymer-based composite materials [?]. Durability and enhanced performance applications of novel composite materials and structures with multi-field effects have been discussed in recent works [?]. Fan et al. [?] provided experimental analysis on the thermal behavior of graphene-reinforced polyurethane structures, including composite fibers with high sensitivity. Temperature sensitivity of the materials was explained for biomaterial applications in skin-core structures. Fan et al. [?] developed characteristics of a new fabrication method for producing 3D nanomaterials and fiber reinforcement, demonstrating significant improvements in mechanical and thermal properties through the proposed manufacturing approach.

Waste materials can be utilized for fiber reinforcement production and in composite structures reinforced with fibers. For instance, Wang et al. [?] organized a novel study on the production of nano-reinforced composites. Using recycled fibers in nanocomposite structure production yields materials bonded through hydrogen bonding. In a similar work, Zhang et al. [?] developed applications of hydrophobic carbon fibers in composite structures to achieve optimal conductivity, mechanical strength, and weather resistance. A low-cost composite was manufactured using the proposed material. Sun et al. [?] studied the effects of various fiber types, such as carbon, aramid, and silk, on the mechanical properties and inter-laminar shear strength of 3D composite structures under thermal environments. Bai et al. [?] investigated temperature-dependent behaviors of metal unsaturated soils using solutions of coupled nonlinear contaminant-heat-moisture equations, examining the effects of various moisture environment and thermal ambient parameters on hybrid coupled responses.

Intelligent nonlinear characteristics of novel systems have been described by researchers [?] for application as sensors and actuators. Hua et al. [?] developed a novel experimental setup for investigating the frictional properties of graphene-

reinforced epoxy matrix composites. Heat capacities and molecular dynamics results of carbon nanotube-based composites were described by Li et al. [?] and Tomioka et al. [?]. Bai et al. [?] studied temperature effects on the mechanical properties of geopolymers enriched with alkali activator across an extended ambient temperature range. Bai et al. [?] investigated fluid velocity effects on penetration characteristics of porous materials and their impact on absorption capacity, developing a general solution for particle migration in porous media. Ge et al. [?] introduced a new method for producing bio-composite structures composed of bamboo biomass fibers using hot-pressing to achieve low-energy consumption without adhesive properties, describing improved material properties through biomass foldability. Yue et al. [?] presented review works on adsorption and photocatalytic applications of nano and carbon active particles. Ge et al. [?] illustrated details of a pyrolysis operation for bio-energy production using activation through a sodium-potassium hydroxide mixture, with experimental results demonstrating efficiency and importance. Foong et al. [?] developed thermo-mechanical operations to produce more efficient nanocomposite materials with enhanced properties and energy absorption capacity. Lam et al. [?] developed a novel efficient thermo-mechanical operation for producing microporous materials with high absorption capacity using a higher-order kinetic model. Huang et al. [?] developed an efficient production experimental method for a new material with negative transfer for transmission systems.

Enhanced resonance capacity of hybrid and intelligent materials was developed by Deng et al. [?] and Huang et al. [?], with theoretical approaches extended for analysis. Semi-exact and numerical methods were employed for hybrid analysis of smart piezoelectric structures with imperfections in recent works [?]. Kinematic relations for double-curved shells and higher-order analysis are available in references [?], with potential extensions for future works based on comprehensive literature studies [?]. Hadji et al. [?] studied the effect of multi-directional material property gradation on thermal buckling analysis of functionally graded shear-deformable plates assumed to be made of porous materials with various distributions, exploring parametric effects of porosity coefficient and distributions on thermal buckling results. Dahmane et al. [?] investigated bidirectional variation effects of material properties on dynamic responses of graded beams through higher-order modeling, presenting wave propagation results using Hamilton's principle with eigenvalue problem solutions.

Novel materials and structures find applications in materials science [?], with production methods for nanocomposite structures explained in recent works [?]. Nanocomposite structures can be utilized in various situations [?], with functionally graded material analysis using energy-based methods and small-scale dependence studied recently [?]. Numerical methods such as the differential quadrature method have been applied to vibrational and stability analyses of advanced materials and structures [?, ?], with novel kinematic and constitutive relations extending governing equations to new materials and compositions [?, ?, ?].

This article examines the foldability and controllability of material properties of novel nanomaterials in new configurations using chemical processes. A review of graphene origami structure analysis and effective material properties confirms that considering shaped nanomaterials and nanofillers through folding processes and their application in new structures represents an important subject in mechanical engineering. The goal of this work is to provide a higher-order framework for stress, deformation, and strain analyses of stretchable shells in double-curved form composed of a copper-based matrix reinforced with folded nanofillers in a thermal environment. An extended parametric analysis investigates the impact of geometric and material characteristics of folded nanomaterials on static results and elastic stress, strain, and deformation responses of the graphene origami reinforced double-curved shell. A new, more accurate kinematic model is developed for shell analysis.

2. Mathematical Modeling

A thickness-stretchable model is developed for deformation, strain, and stress analyses of a graphene origami auxetic metamaterial reinforced doubly curved shell. The shell is assumed shear-deformable and fabricated from copper reinforced with auxetic metamaterial. The kinematic relations based on the thickness-stretchable model are developed as:

$$w_Z = w_b + w_s + g(Z)\chi$$

where the coordinates are depicted in Figure 1 [Figure 1: see original paper]. In this figure, the three coordinate directions are assumed as ξ , ζ , Z , the radii of curvature are R_ξ , R_ζ , and the lengths of middle surfaces are L_ξ , L_ζ . The shape functions used to satisfy more accurate changes of shear strain along the thickness are assumed as:

$$f(Z) = Z - \frac{h}{\pi} \sin\left(\frac{\pi Z}{h}\right)$$

$$g(Z) = 1 - f'(Z) = \cos\left(\frac{\pi Z}{h}\right)$$

The strain components are:

$$\varepsilon_\xi = \frac{1}{L_\xi} \left[u_{,\xi} - Z w_{b,\xi\xi} - f(Z) w_{s,\xi\xi} + \frac{w_b}{R_\xi} + \frac{w_s}{R_\xi} + \frac{g(Z)\chi}{R_\xi} \right]$$

$$\varepsilon_\zeta = \frac{1}{L_\zeta} \left[v_{,\zeta} - Z w_{b,\zeta\zeta} - f(Z) w_{s,\zeta\zeta} + \frac{w_b}{R_\zeta} + \frac{w_s}{R_\zeta} + \frac{g(Z)\chi}{R_\zeta} \right]$$

$$\varepsilon_Z = g'(Z)\chi$$

$$\gamma_{\xi\zeta} = \frac{1}{L_\xi}v_{,\xi} + \frac{1}{L_\zeta}u_{,\zeta} - \left\{ \frac{1}{L_\xi} + \frac{1}{L_\zeta} \right\}$$

$$\gamma_{\xi Z} = -\frac{L_\xi u}{R_\xi} + \{-f'(Z) + 1\}Zw_{b,\xi\zeta} + f(Z)w_{s,\xi\zeta} + w_{s,\xi} + g(Z)L_\xi\chi_{,\xi}$$

$$\gamma_{\zeta Z} = -\frac{L_\zeta v}{R_\zeta} + \{-f'(Z) + 1\}Zw_{b,\xi\zeta} + f(Z)w_{s,\xi\zeta} + w_{s,\zeta} + g(Z)L_\zeta\chi_{,\zeta}$$

The constitutive relations are:

$$\begin{bmatrix} \sigma_\xi \\ \sigma_\zeta \\ \sigma_Z \\ \sigma_{\xi\zeta} \\ \sigma_{\xi Z} \\ \sigma_{\zeta Z} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{66} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{44} \end{bmatrix} \begin{bmatrix} \varepsilon_\xi - \alpha_{\text{eff}}T \\ \varepsilon_\zeta - \alpha_{\text{eff}}T \\ \varepsilon_Z - \alpha_{\text{eff}}T \\ \gamma_{\xi\zeta} \\ \gamma_{\xi Z} \\ \gamma_{\zeta Z} \end{bmatrix}$$

where C_{ij} , α_{eff} , T , σ_{ij} , ε_ξ , $\gamma_{\zeta Z}$ are stiffness coefficients, effective thermal expansion, thermal loading, stress components, normal strain components, and shear strain components, respectively.

The effective properties E_{eff} , ν_{eff} , α_{eff} of the shell are assumed as follows [?, ?]:

$$E_{\text{eff}} = E_{\text{Cu}}f_E(H_{\text{GOFD}}, V_{\text{GOAM}}, T)$$

$$\nu_{\text{eff}} = (\nu_{\text{Gr}}V_{\text{GOAM}} + \nu_{\text{Cu}}V_{\text{Cu}})f_\nu(H_{\text{GOFD}}, V_{\text{GOAM}}, T)$$

$$\alpha_{\text{eff}} = (\alpha_{\text{Gr}}V_{\text{GOAM}} + \alpha_{\text{Cu}}V_{\text{Cu}})f_\alpha(H_{\text{GOFD}}, V_{\text{GOAM}}, T)$$

where modification functions $f_E(H_{\text{GOFD}}, V_{\text{GOAM}}, T)$, $f_\nu(H_{\text{GOFD}}, V_{\text{GOAM}}, T)$, $f_\alpha(H_{\text{GOFD}}, V_{\text{GOAM}}, T)$ are used for correction. The relation between V_{GOAM} and V_{Cu} is obtained as follows:

$$V_{\text{GOAM}} = V_{\text{Gr}}, \quad V_{\text{Cu}} = 1 - V_{\text{Gr}}$$

The non-dimensional parameters defined in effective modulus of elasticity are obtained in terms of geometric and material properties of the Cu matrix reinforced with graphene origami nanomaterials.

The stress components yield:

$$\sigma_{\xi} = C_{11} \left[u_{,\xi} - Z w_{b,\xi\xi} - f(Z) w_{s,\xi\xi} + \frac{w_b}{R_{\xi}} + \frac{w_s}{R_{\xi}} + \frac{g(Z)\chi}{R_{\xi}} \right]$$

$$\sigma_{\zeta} = C_{12} \left[u_{,\xi} - Z w_{b,\xi\xi} - f(Z) w_{s,\xi\xi} + \frac{w_b}{R_{\xi}} + \frac{w_s}{R_{\xi}} + \frac{g(Z)\chi}{R_{\xi}} \right] + C_{13} \left[v_{,\zeta} - Z w_{b,\zeta\zeta} - f(Z) w_{s,\zeta\zeta} + \frac{w_b}{R_{\zeta}} + \frac{w_s}{R_{\zeta}} + \frac{g(Z)\chi}{R_{\zeta}} \right]$$

$$\sigma_Z = C_{13} \left[u_{,\xi} - Z w_{b,\xi\xi} - f(Z) w_{s,\xi\xi} + \frac{w_b}{R_{\xi}} + \frac{w_s}{R_{\xi}} + \frac{g(Z)\chi}{R_{\xi}} \right] + C_{23} \left[v_{,\zeta} - Z w_{b,\zeta\zeta} - f(Z) w_{s,\zeta\zeta} + \frac{w_b}{R_{\zeta}} + \frac{w_s}{R_{\zeta}} + \frac{g(Z)\chi}{R_{\zeta}} \right]$$

$$\sigma_{\xi\zeta} = C_{66} \left[\frac{1}{L_{\xi}} v_{,\xi} + \frac{1}{L_{\zeta}} u_{,\zeta} - \left\{ \frac{1}{L_{\xi}} + \frac{1}{L_{\zeta}} \right\} \right]$$

$$\sigma_{\xi Z} = C_{55} \left[-\frac{L_{\xi} u}{R_{\xi}} + \{-f'(Z) + 1\} Z w_{b,\xi,\zeta} + f(Z) w_{s,\xi,\zeta} + w_{s,\xi} + g(Z) L_{\xi} \chi_{,\xi} \right]$$

$$\sigma_{\zeta Z} = C_{44} \left[-\frac{L_{\zeta} v}{R_{\zeta}} + \{-f'(Z) + 1\} Z w_{b,\xi,\zeta} + f(Z) w_{s,\xi,\zeta} + w_{s,\zeta} + g(Z) L_{\zeta} \chi_{,\zeta} \right]$$

The strain energy is [?]:

$$\delta U = \int_V [\sigma_{\xi} \varepsilon_{\xi} + \sigma_{\zeta} \varepsilon_{\zeta} + \sigma_{\zeta Z} \gamma_{\zeta Z} + \sigma_{\xi Z} \gamma_{\xi Z} + \sigma_{\xi\zeta} \gamma_{\xi\zeta}] dV$$

The work is expressed as follows:

$$\delta W = \int_{\xi} \int_{\zeta} [-q + (N_{0x}^{\xi} + N_{T0x}^{\xi})] \delta(w_b + w_s) R_{\xi} R_{\zeta} d\xi d\zeta$$

Finally, the equilibrium equations are derived as follows:

$$\delta u : -N_{\xi,\xi} - N_{\xi\zeta,\zeta} - N_{\xi Z} = 0$$

$$\delta v : -N_{\xi\zeta,\xi} - N_{\zeta,\zeta} - N_{\zeta Z} = 0$$

$$\delta w_b : -M_{\xi,\xi\xi} + \frac{N_{\xi}}{R_{\xi}} - M_{\zeta,\zeta\zeta} + \frac{N_{\zeta}}{R_{\zeta}} - M_{\xi\zeta,\xi\zeta} - (N_{0x}^{\xi} + N_{T0x}^{\xi}) (w_{b,\xi\xi} + w_{s,\xi\xi}) - (N_{0x}^{\zeta} + N_{T0x}^{\zeta}) (w_{b,\zeta\zeta} + w_{s,\zeta\zeta}) = 0$$

$$\delta w_s : -S_{\xi,\xi\xi} + \frac{N_{\xi}}{R_{\xi}} - S_{\zeta,\zeta\zeta} + \frac{N_{\zeta}}{R_{\zeta}} - S_{\xi\zeta,\xi\zeta} - (N_{0x}^{\xi} + N_{T0x}^{\xi}) (w_{b,\xi\xi} + w_{s,\xi\xi}) - (N_{0x}^{\zeta} + N_{T0x}^{\zeta}) (w_{b,\zeta\zeta} + w_{s,\zeta\zeta}) = 0$$

$$\delta\chi : \frac{P_{\xi}}{R_{\xi}} + \frac{P_{\zeta}}{R_{\zeta}} + G_Z - S_{\zeta Z,\zeta} - S_{\xi Z,\xi} = 0$$

where the resultant components are defined as:

$$\{N_{\xi}, M_{\xi}, S_{\xi}, P_{\xi}\} = \int_{-h/2}^{h/2} \sigma_{\xi} L_{\xi} \{1, Z, f(Z), g(Z)\} dZ$$

$$\{N_{\zeta}, M_{\zeta}, S_{\zeta}, P_{\zeta}\} = \int_{-h/2}^{h/2} \sigma_{\zeta} L_{\zeta} \{1, Z, f(Z), g(Z)\} dZ$$

$$\{N_{\xi Z}, M_{\xi Z}, S_{\xi Z}\} = \int_{-h/2}^{h/2} \sigma_{\xi Z} L_{\xi} \{1/R_{\xi}, Z - f'(Z) + 1, g(Z) L_{\xi}\} dZ$$

$$\{N_{\zeta Z}, M_{\zeta Z}, S_{\zeta Z}\} = \int_{-h/2}^{h/2} \sigma_{\zeta Z} L_{\zeta} \{1/R_{\zeta}, Z - f'(Z) + 1, g(Z) L_{\zeta}\} dZ$$

$$\{N_{\xi\zeta}, N_{\zeta\xi}, M_{\xi\zeta}, S_{\xi\zeta}\} = \int_{-h/2}^{h/2} \sigma_{\xi\zeta} \{L_{\xi}, L_{\zeta}, Z \{L_{\xi} + L_{\zeta}\}, f(Z) \{L_{\xi} + L_{\zeta}\}\} dZ$$

$$\{G_Z\} = \int_{-h/2}^{h/2} \sigma_Z g'(Z) dZ$$

In which the integration constants are presented in Appendix A.

3. Solution Procedure

The displacements are assumed as [?]:

$$w_s = U \cos(\lambda_m \xi) \sin(\mu_n \zeta)$$

$$v = V \sin(\lambda_m \xi) \cos(\mu_n \zeta)$$

$$w_b = W_b \sin(\lambda_m \xi) \sin(\mu_n \zeta)$$

$$w_s = W_s \sin(\lambda_m \xi) \sin(\mu_n \zeta)$$

$$\chi = \chi \sin(\lambda_m \xi) \sin(\mu_n \zeta)$$

in which $\{Y\} = \{U, V, W_b, W_s, \chi\}^T$ are unknown amplitudes and $\lambda_m = \frac{m\pi}{L_\xi}$, $\mu_n = \frac{n\pi}{L_\zeta}$. Substitution leads to:

$$[K]\{Y\} = \{F\}$$

where the elements of stiffness matrix $[K]$ and force vector $\{F\}$ are obtained as follows:

$$K_{1,1} = -\lambda_m^2 \delta_1 - \mu_n^2 \delta_{167} - \frac{\delta_{82}}{R_\xi}$$

$$K_{1,2} = -(\delta_{166} + \delta_5) \lambda_m \mu_n$$

$$K_{1,3} = \delta_2 \lambda_m^3 + (\delta_6 + \delta_{168}) \lambda_m^2 \mu_n + \frac{\delta_1}{R_\xi} + \frac{\delta_5}{R_\zeta}$$

$$K_{1,4} = \delta_3 \mu_n^3 - (\delta_{169} + \delta_7) \lambda_m^2 \mu_n + \frac{\delta_4}{R_\xi} + \frac{\delta_8}{R_\zeta} + \delta_9 + \delta_{84}$$

$$K_{1,5} = \frac{\delta_1}{R_\xi} + \frac{\delta_5}{R_\zeta} + \delta_{83}$$

$$K_{2,1} = -(\delta_{165} + \delta_{37}) \lambda_m \mu_n$$

$$K_{2,2} = -\delta_{73}\lambda_m^2 - \delta_{41}\mu_n^2 - \frac{\delta_{98}}{R_\zeta}$$

$$K_{2,3} = \delta_{42}\lambda_m^3 + (\delta_{74} + \delta_{38})\lambda_m^2\mu_n + \frac{\delta_{41}}{R_\zeta} + \frac{\delta_{37}}{R_\xi}$$

$$K_{2,4} = \delta_{43}\mu_n^3 - (\delta_{75} + \delta_{39})\lambda_m^2\mu_n + \frac{\delta_{41}}{R_\zeta} + \delta_{99} + \frac{\delta_{37}}{R_\xi}$$

$$K_{2,5} = \frac{\delta_{44}}{R_\zeta} + \delta_{45} + \frac{\delta_{40}}{R_\xi} + \delta_{101}$$

$$K_{3,1} = \delta_{10}\lambda_m^3 + (\delta_{170} + \delta_{46})\lambda_m\mu_n^2 + \frac{\delta_1}{R_\xi} + \frac{\delta_{37}}{R_\zeta}$$

$$K_{3,2} = \delta_{50}\mu_n^3 + \frac{\delta_5}{R_\xi} + \frac{\delta_{41}}{R_\zeta}\mu_n + (\delta_{14} + \delta_{76})\lambda_m^2\mu_n$$

$$K_{3,3} = -\delta_{11}\lambda_m^4 - \delta_{51}\mu_n^4 - (\delta_{15} + \delta_{77} + \delta_{47})\lambda_m^2\mu_n^2 + \frac{\delta_{14}}{R_\zeta} + \frac{\delta_{38}}{R_\zeta} + \frac{\delta_2}{R_\xi} + \frac{\delta_{10}}{R_\xi} + \frac{\delta_{50}}{R_\zeta} + \frac{\delta_6}{R_\xi} + \frac{\delta_{46}}{R_\xi} + \frac{\delta_{42}}{R_\zeta} + \frac{\delta_{41}}{R_\zeta R_\zeta} + \frac{\delta_5}{R_\xi R_\zeta} + \frac{\delta_{37}}{R_\zeta R_\xi}$$

$$K_{3,4} = -\delta_{12}\lambda_m^4 - \delta_{52}\mu_n^4 - (\delta_{78} + \delta_{48} + \delta_{16})\lambda_m^2\mu_n^2 + \frac{\delta_{10}}{R_\xi} + \frac{\delta_{14}}{R_\zeta} + \frac{\delta_{39}}{R_\zeta} + \frac{\delta_3}{R_\xi} + \frac{\delta_7}{R_\xi} + \frac{\delta_{43}}{R_\zeta} + \frac{\delta_{50}}{R_\zeta} + \frac{\delta_{46}}{R_\xi} + \frac{\delta_{37}}{R_\zeta R_\xi} + \frac{\delta_{41}}{R_\zeta R_\zeta} + \frac{\delta_1}{R_\xi R_\zeta}$$

$$K_{3,5} = \frac{\delta_{17}}{R_\zeta} + \delta_{18} + \frac{\delta_{13}}{R_\xi} + \frac{\delta_{49}}{R_\xi} + \frac{\delta_{53}}{R_\zeta} + \delta_{54} + \frac{\delta_{45}}{R_\zeta} + \frac{\delta_9}{R_\xi} + \frac{\delta_4}{R_\xi R_\xi} + \frac{\delta_8}{R_\xi R_\zeta} + \frac{\delta_{40}}{R_\zeta R_\xi} + \frac{\delta_{44}}{R_\zeta R_\zeta}$$

$$F_3 = +q$$

$$K_{4,1} = \delta_{19}\lambda_m^3 + (\delta_{55} + \delta_{171})\lambda_m\mu_n^2 + \frac{\delta_1}{R_\xi} + \frac{\delta_{37}}{R_\zeta} + \frac{\delta_{86}}{R_\xi}$$

$$K_{4,2} = +\delta_{59}\mu_n^3 + (\delta_{23} + \delta_{79})\lambda_m^2\mu_n + \frac{\delta_5}{R_\xi} + \frac{\delta_{41}}{R_\zeta} + \frac{\delta_{102}}{R_\zeta}$$

$$K_{4,3} = -\delta_{20}\lambda_m^4 - \delta_{60}\mu_n^4 - (\delta_{24} + \delta_{56} + \delta_{80})\lambda_m^2\mu_n^2 + \frac{\delta_{19}}{R_\xi} + \frac{\delta_{23}}{R_\zeta} + \frac{\delta_{38}}{R_\zeta} + \frac{\delta_2}{R_\xi} + \frac{\delta_{55}}{R_\xi} + \frac{\delta_{42}}{R_\zeta} + \frac{\delta_6}{R_\xi} + \frac{\delta_{59}}{R_\zeta} + \frac{\delta_1}{R_\xi R_\xi} + \frac{\delta_5}{R_\xi R_\zeta} + \frac{\delta_{41}}{R_\zeta R_\zeta}$$

$$K_{4,4} = -\delta_{21}\lambda_m^4 - \delta_{61}\mu_n^4 - (\delta_{25} + \delta_{57} + \delta_{81})\lambda_m^2\mu_n^2 + \frac{\delta_{19}}{R_\xi} + \frac{\delta_{87}}{R_\xi} + \frac{\delta_{23}}{R_\zeta} + \frac{\delta_3}{R_\xi} + \frac{\delta_{39}}{R_\zeta} + \frac{\delta_{43}}{R_\zeta} + \frac{\delta_{103}}{R_\zeta} + \frac{\delta_7}{R_\xi} + \frac{\delta_{59}}{R_\zeta} + \frac{\delta_{55}}{R_\xi} + \frac{\delta_1}{R_\xi R_\zeta} + \frac{\delta}{R_\xi}$$

$$F_4 = +q \left(1 + \frac{h}{2R_\xi} \right) \left(1 + \frac{h}{2R_\zeta} \right)$$

$$K_{5,1} = -\frac{\delta_{28}}{R_\xi} + \frac{\delta_{64}}{R_\zeta} + \delta_{114} + \frac{\delta_{90}}{R_\xi}$$

$$K_{5,2} = -\frac{\delta_{32}}{R_\xi} + \frac{\delta_{68}}{R_\zeta} + \delta_{118} + \frac{\delta_{106}}{R_\zeta}$$

$$K_{5,3} = \delta_{115} + \frac{\delta_{29}}{R_\xi} + \frac{\delta_{65}}{R_\zeta} + \frac{\delta_{69}}{R_\zeta} + \frac{\delta_{33}}{R_\xi} + \delta_{119} + \frac{\delta_{114}}{R_\xi} + \frac{\delta_{28}}{R_\xi R_\zeta} + \frac{\delta_{68}}{R_\zeta R_\zeta} + \frac{\delta_{32}}{R_\xi R_\zeta} + \frac{\delta_{118}}{R_\zeta} + \frac{\delta_{64}}{R_\zeta R_\xi}$$

$$K_{5,4} = \frac{\delta_{70}}{R_\zeta} + \frac{\delta_{34}}{R_\xi} + \delta_{120} + \delta_{107} + \frac{\delta_{28}}{R_\xi R_\xi} + \frac{\delta_{114}}{R_\xi} + \frac{\delta_{32}}{R_\xi R_\zeta} + \frac{\delta_{68}}{R_\zeta R_\zeta} + \frac{\delta_{118}}{R_\zeta} + \frac{\delta_{64}}{R_\zeta R_\xi}$$

$$K_{5,5} = \delta_{92}\lambda_m^2 + \delta_{109}\mu_n^2 + \left(\frac{\delta_{67}}{R_\zeta R_\xi} + \frac{\delta_{71}}{R_\zeta R_\zeta} + \frac{\delta_{72}}{R_\zeta} + \frac{\delta_{31}}{R_\xi R_\xi} + \frac{\delta_{117}}{R_\xi} + \delta_{121} + \delta_{122} + \frac{\delta_{35}}{R_\zeta} + \frac{\delta_{36}}{R_\xi} \right)$$

$$F_5 = -q \left(1 + \frac{h}{2R_\xi} \right) \left(1 + \frac{h}{2R_\zeta} \right)$$

4. Numerical Results and Discussion

To validate the formulation procedure, governing equations, and solution methodology, results are compared with available literature data.

Table 1 presents a comparative study with results from Kiani et al. [?]. The results are shown for various geometric parameters of the doubly curved shell, demonstrating acceptable agreement between the present results and those of Kiani et al. [?]. The input parameters are assumed as: $E_{Cu} = 65.79$ GPa, $E_{Gr} = 929.57$ GPa, $\theta_{Cu} = 0.387$, $\theta_{Gr} = 0.22$.

Table 2 lists the impact of folding degree H_{GOFD} and thermal loading T on the variation in middle surface deformation u . The deformation is presented for different uniform temperature rises $T = 320, 330, 340$, and 350 . A significant enhancement in middle surface deformation u is observed with increasing foldability parameter H_{GOFD} and thermal loading T .

Table 3 lists the impact of origami content V_{GOAM} and thermal loading T on the variation in middle surface deformation u . The deformation is presented for different uniform temperature rises $T = 320, 330, 340$, and 350 . A decreasing trend in middle surface deformation u is observed with increasing origami content V_{GOAM} due to enhanced structural stiffness.

Table 4 lists the impact of folding degree H_{GOFD} and thermal loading T on the variation in bending transverse deflection w_b . The deformation is presented for different uniform temperature rises $T = 320, 330, 340$, and 350 . An enhancement in bending transverse deflection w_b is observed with increasing foldability parameter H_{GOFD} and thermal loading T .

Table 5 lists the impact of folding degree H_{GOFD} and thermal loading T on the variation in shear transverse deflection w_s . This table reflects an enhancement in shear transverse deflection w_s with increasing foldability parameter H_{GOFD} and thermal loading T . One can conclude that the stiffness is significantly decreased with increasing foldability parameter H_{GOFD} .

Table 6 lists the impact of origami content V_{GOAM} and thermal loading T on the variation in shear transverse deflection w_s . A significant decreasing behavior in shear transverse deflection w_s is observed with increasing origami content V_{GOAM} due to enhanced structural stiffness.

Table 7 lists the impact of folding degree H_{GOFD} and thermal loading T on the variation in stretching transverse deflection χ . Unlike other displacement and deflection components, the stretching transverse deflection χ is significantly decreased with increasing foldability parameter H_{GOFD} .

Table 8 lists the impact of origami content V_{GOAM} and thermal loading T on the variation in stretching transverse deflection χ . A significant decreasing behavior in stretching transverse deflection χ is observed with increasing origami content V_{GOAM} due to enhanced structural stiffness.

Table 9 lists the impact of folding degree H_{GOFD} and thermal loading T on the variation in normal in-plane strain ε_ξ . An enhancement in normal in-plane strain ε_ξ is observed with increasing foldability parameter H_{GOFD} and thermal loading T .

Table 10 lists the impact of folding degree H_{GOFD} and thermal loading T on the variation in normal out-of-plane strain ε_Z . Unlike other displacement and deflection components, the normal out-of-plane strain ε_Z is significantly decreased with increasing foldability parameter H_{GOFD} .

Table 11 lists the impact of origami content V_{GOAM} and thermal loading T on the variation in normal out-of-plane strain ε_Z . A significant decreasing behavior in normal out-of-plane strain ε_Z is observed with increasing origami content V_{GOAM} due to enhanced structural stiffness.

Table 12 lists the impact of folding degree H_{GOFD} and thermal loading T on the variation in in-plane shear strain $\gamma_{\xi\zeta}$. An enhancement in in-plane shear

strain $\gamma_{\xi\zeta}$ is observed with increasing foldability parameter H_{GOFD} and thermal loading T .

Table 13 lists the impact of origami content V_{GOAM} and thermal loading T on the variation in in-plane shear strain $\gamma_{\xi\zeta}$. A significant decreasing behavior in in-plane shear strain $\gamma_{\xi\zeta}$ is observed with increasing origami content V_{GOAM} due to enhanced structural stiffness.

Table 14 lists the impact of folding degree H_{GOFD} and thermal loading T on the variation in out-of-plane shear strain $\gamma_{\xi Z}$. A slight decrease in out-of-plane shear strain $\gamma_{\xi Z}$ is observed with increasing foldability parameter H_{GOFD} and thermal loading T .

Table 15 lists the impact of origami content V_{GOAM} and thermal loading T on the variation in out-of-plane shear strain $\gamma_{\xi Z}$. A significant decreasing behavior in out-of-plane shear strain $\gamma_{\xi Z}$ is observed with increasing origami content V_{GOAM} due to enhanced structural stiffness.

5. Conclusion

A more accurate kinematic relation and a new nanocomposite-reinforced material are suggested in this article to study bending and deformation results. The general formulation includes an out-of-plane stretchable kinematic model derived through variational principles, with behavioral relations extended through generalized Hooke's law and the virtual work principle. To compute resultant force and moment components in the governing equations, material property relations from validated sources derived using experimental, statistical, and molecular dynamics-based analyses are employed. An extended parametric analysis investigates the impact of folded nanofiller parameters on the elasto-static responses of composite double-curved shells. A verification test was presented before presenting complete numerical results. The main conclusions of this work are:

Investigating the effect of thermal loading T reveals increasing behavior in displacement, strain, and stress components with increasing T due to decreased material stiffness. The effective material properties were estimated as functions of graphene origami characteristics. A decrease in the bending deflection component is observed with increasing V_{GOAM} and decreasing H_{GOFD} of the graphene origami. Furthermore, the effect of thermal loading is significant for higher values of folding degree.

Investigating the variation of normal out-of-plane strain ε_Z indicates that this component is compressive, experiencing more negative values with increasing thermal loading, while it is reduced with increasing V_{GOAM} and H_{GOFD} .

Investigating the variation of in-plane strain ε_ξ indicates that although this strain component experiences significant changes through the thickness direction, its values change only slightly with variations in volume fraction V_{GOAM} and folding degree H_{GOFD} .

Investigating the variation of in-plane shear strain $\gamma_{\xi\zeta}$ indicates that this component experiences no changes with volume fraction V_{GOAM} and only small changes with folding degree H_{GOFD} .

Disclosure Statement

No potential conflict of interest was reported by the author(s).

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Appendix

$$\{\delta_1, \delta_2, \delta_3, \delta_4\} = \int_{-h/2}^{h/2} C_{11} L_\xi^2 \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_5, \delta_6, \delta_7, \delta_8\} = \int_{-h/2}^{h/2} C_{12} L_\xi L_\zeta \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_9\} = \int_{-h/2}^{h/2} C_{13} L_\xi g'(Z) dZ$$

$$\{\delta_{10}, \delta_{11}, \delta_{12}, \delta_{13}\} = \int_{-h/2}^{h/2} C_{13} Z L_\xi g'(Z) \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{14}, \delta_{15}, \delta_{16}, \delta_{17}\} = \int_{-h/2}^{h/2} C_{13} f(Z) L_\xi g'(Z) \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{18}\} = \int_{-h/2}^{h/2} C_{13} g(Z) L_\xi g'(Z) dZ$$

$$\{\delta_{19}, \delta_{20}, \delta_{21}, \delta_{22}\} = \int_{-h/2}^{h/2} C_{13} L_\zeta g'(Z) \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{23}, \delta_{24}, \delta_{25}, \delta_{26}\} = \int_{-h/2}^{h/2} C_{23} Z L_{\zeta} g'(Z) \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{27}\} = \int_{-h/2}^{h/2} C_{23} f(Z) L_{\zeta} g'(Z) dZ$$

$$\{\delta_{28}, \delta_{29}, \delta_{30}, \delta_{31}\} = \int_{-h/2}^{h/2} C_{23} g(Z) L_{\zeta} g'(Z) \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{32}, \delta_{33}, \delta_{34}, \delta_{35}\} = \int_{-h/2}^{h/2} C_{33} g'(Z) L_{\zeta} \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{36}\} = \int_{-h/2}^{h/2} C_{33} g'(Z) L_{\zeta} dZ$$

$$\{\delta_{37}, \delta_{38}, \delta_{39}, \delta_{40}\} = \int_{-h/2}^{h/2} C_{21} L_{\xi} L_{\zeta} \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{41}, \delta_{42}, \delta_{43}, \delta_{44}\} = \int_{-h/2}^{h/2} C_{22} L_{\zeta}^2 \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{45}\} = \int_{-h/2}^{h/2} C_{23} L_{\zeta} g'(Z) dZ$$

$$\{\delta_{46}, \delta_{47}, \delta_{48}, \delta_{49}\} = \int_{-h/2}^{h/2} C_{23} Z L_{\zeta} g'(Z) \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{50}, \delta_{51}, \delta_{52}, \delta_{53}\} = \int_{-h/2}^{h/2} C_{23} f(Z) L_{\zeta} g'(Z) \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{54}\} = \int_{-h/2}^{h/2} C_{23} g(Z) L_{\zeta} g'(Z) dZ$$

$$\{\delta_{55}, \delta_{56}, \delta_{57}, \delta_{58}\} = \int_{-h/2}^{h/2} C_{22} f(Z) L_{\zeta}^2 \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{59}, \delta_{60}, \delta_{61}, \delta_{62}\} = \int_{-h/2}^{h/2} C_{23} f(Z) L_{\zeta} g'(Z) \{1, Z, f(Z), g(Z)\} dZ$$

$$\{\delta_{63}\} = \int_{-h/2}^{h/2} C_{23}g(Z)L_{\zeta}g'(Z)dZ$$

$$\{\delta_{64}, \delta_{65}, \delta_{66}, \delta_{67}\} = \int_{-h/2}^{h/2} C_{13}g'(Z)L_{\xi}\{1, Z, f(Z), g(Z)\}dZ$$

$$\{\delta_{68}, \delta_{69}, \delta_{70}, \delta_{71}\} = \int_{-h/2}^{h/2} C_{23}g'(Z)L_{\zeta}\{1, Z, f(Z), g(Z)\}dZ$$

$$\{\delta_{72}\} = \int_{-h/2}^{h/2} C_{33}g'(Z)dZ$$

$$\{\delta_{73}, \delta_{165}, \delta_{74}, \delta_{75}\} = \int_{-h/2}^{h/2} C_{66}L_{\zeta}L_{\xi}\{L_{\xi}, L_{\zeta}, Z\{L_{\xi} + L_{\zeta}\}, f(Z)\{L_{\xi} + L_{\zeta}\}\}dZ$$

$$\{\delta_{76}, \delta_{170}, \delta_{77}, \delta_{78}\} = \int_{-h/2}^{h/2} C_{66}ZL_{\xi}\{L_{\xi}, L_{\zeta}, Z\{L_{\xi} + L_{\zeta}\}, f(Z)\{L_{\xi} + L_{\zeta}\}\}dZ$$

$$\{\delta_{79}, \delta_{171}, \delta_{80}, \delta_{81}\} = \int_{-h/2}^{h/2} C_{66}\{L_{\xi}, L_{\zeta}, Z\{L_{\xi} + L_{\zeta}\}, f(Z)\{L_{\xi} + L_{\zeta}\}\}dZ$$

$$\{\delta_{82}, \delta_{83}, \delta_{84}\} = \int_{-h/2}^{h/2} C_{55}L_{\xi}\{1/R_{\xi}, Z - f'(Z) + 1, g(Z)L_{\xi}\}dZ$$

$$\{\delta_{86}, \delta_{87}, \delta_{88}\} = \int_{-h/2}^{h/2} C_{55}ZL_{\xi}\{1/R_{\xi}, Z - f'(Z) + 1, g(Z)L_{\xi}\}dZ$$

$$\{\delta_{90}, \delta_{91}, \delta_{92}\} = \int_{-h/2}^{h/2} C_{55}g(Z)L_{\xi}\{1/R_{\xi}, Z - f'(Z) + 1, g(Z)L_{\xi}\}dZ$$

$$\{\delta_{98}, \delta_{99}, \delta_{101}\} = \int_{-h/2}^{h/2} C_{44}L_{\zeta}\{1/R_{\zeta}, Z - f'(Z) + 1, g(Z)L_{\zeta}\}dZ$$

$$\{\delta_{102}, \delta_{103}, \delta_{105}\} = \int_{-h/2}^{h/2} C_{44}ZL_{\zeta}\{1/R_{\zeta}, Z - f'(Z) + 1, g(Z)L_{\zeta}\}dZ$$

$$\{\delta_{106}, \delta_{107}, \delta_{109}\} = \int_{-h/2}^{h/2} C_{44}g(Z)L_{\zeta}\{1/R_{\zeta}, Z - f'(Z) + 1, g(Z)L_{\zeta}\}dZ$$

$$\{\delta_{114}, \delta_{115}, \delta_{116}, \delta_{117}\} = \int_{-h/2}^{h/2} C_{13}g'(Z)L_{\xi}\{1, Z, f(Z), g(Z)\}dZ$$

$$\{\delta_{118}, \delta_{119}, \delta_{120}, \delta_{121}\} = \int_{-h/2}^{h/2} C_{23}g'(Z)L_{\zeta}\{1, Z, f(Z), g(Z)\}dZ$$

$$\{\delta_{122}\} = \int_{-h/2}^{h/2} C_{33}g'(Z)dZ$$

$$\{\delta_{165}, \delta_{166}, \delta_{167}, \delta_{168}, \delta_{169}, \delta_{170}, \delta_{171}\} = \int_{-h/2}^{h/2} C_{66}\{L_{\xi}, L_{\zeta}, Z\{L_{\xi}+L_{\zeta}\}, f(Z)\{L_{\xi}+L_{\zeta}\}\}dZ$$

Note: Figure translations are in progress. See original paper for figures.

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