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A comprehensive analysis of porous graphene-reinforced curved beams by finite element approach using higher-order structural theory: bending, vibration and buckling

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Running title: Bending, vibration, buckling of porous graphene-reinforced curved beams

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Highlights

- Static and dynamic study GPL reinforced curved beam by trigonometric shear deformation theory
- Inclusion of various form distributions for the pores and GPLs presence in the beam.
- Provided the results for different radii of curvature of beams and different boundary conditions.
- Conducted a thorough study considering various geometry and material parameters.
- Generated new results for benchmarking the solutions from other numerical/analytical approach.

A comprehensive analysis of porous graphene-reinforced curved beams by finite element approach using higher-order structural theory: bending, vibration and buckling

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Summary

In this paper, the bending, vibration and buckling characteristics of functionally graded porous graphene-reinforced nanocomposite curved beams are studied based on a trigonometric shear deformation theory. The effect of various theories deduced from the proposed formulation on the static and dynamic behavior of curved nanocomposite beams is also studied. The governing equilibrium equations are formed by applying Lagrangian equations of motion coupled with the finite element approach employing a 3-noded C¹ continuous curved beam element. The methodology developed here is tested for problems having known solutions in the open literature. A detailed investigation involving various parameters such as coefficient of porosity, type of distribution pattern for the porosity and graphene platelets, radius of curvature of curved beam, length-to-thickness ratio, the platelet geometry, and boundary conditions on the static bending, free vibration and elastic stability behavior of nanocomposite curved beams is conducted. New results for certain boundary conditions of graphene reinforced curved beams are presented. Participation of various types of in-plane and transverse bending modes responsible for yielding the lowest critical buckling loads/natural frequencies are also highlighted.

Keywords: Higher-order theory; Finite element; Bending; Free vibration; Buckling; Porous curved beams; Graphene reinforcement.

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1. Introduction

Advancements in manufacturing and material characterization techniques aid designers to create efficient designs by tailoring material properties. Advanced composites like porous composite materials and in particular, metal foams, are gaining prominence in the electronics and aerospace industries especially because of their lightweight, impact resistant and thermal resistant properties [1-4]. Metal foams can fall under the category of Functionally Graded Materials (FGM) as the size and density of porosity in metal foams can be varied directionally and have been realized in laboratories [5]. Since porous composite materials are lightweight and have low structural stiffness, the prediction of the mechanical behavior under different situations including the boundary conditions, loads and the reinforced-material inclusions like graphene platelets are warranted. The available appropriate studies are discussed in the subsequent paragraph.

Functionally graded porous straight beams and plates subjected to different environments were analyzed both theoretically and experimentally to characterize different mechanical behaviors [6-10]. To improve the structural stiffness, micro/nanofillers like Graphene Platelets (GPLs) can be introduced in the matrix. The global properties of the materials like strength and stiffness are governed by weight fraction and dispersion form of GPLs in the matrix given in Refs. [11-13]. The advantages of using GPLs or Carbon Nanotubes (CNTs) reinforcements to improve the vibrational and buckling behavior of beams, plates, and shells were dealt in Refs. [14-17]. Furthermore, the nonlinear vibrational characteristics of functionally graded CNT reinforced laminates were treated in Refs. [18-20]. Sandwich panels with CNT reinforced face sheets were analyzed for flutter study using a higher-order theory by Sankar et al. [21] and CNT reinforced shells were analyzed for post-buckling by Shen [22, 23].

The flexibility in making differently sized graphene platelets by using the lay-up of 2D form of graphite nano-crystals [24, 25] and the recent studies outlining the favorable characteristics of graphene platelet reinforce composites has led to an increase in their usage in many critical technologies. Buckling, post-buckling, bending and, stability analyses of GPL reinforced straight beams were carried out in [26,

27] and [28], respectively. An optimization study was also attempted in Ref. [29] discretely changing GPLs dispersion in the direction of thickness. The influence of GPLs on parametric instabilities and vibrational properties of beams were studied in Refs. [30, 31] and their impact on bending, vibration, dynamic impact response and thermal buckling of such plates were examined in [32-39]. Similar studies on GPL reinforced shells were also highlighted in Refs. [40-46].

A combination of porosity and GPLs in a metal matrix can help in achieving the desired strength and stiffness for a given weight of the structure. Work pertaining to such kind of composite structures available in the literature are discussed here. References [47-50] dealt with the vibrational behavior of porous GPL reinforced beams and Ref. [50], in particular, accounted for different distribution patterns as well. Some work done in literature pertaining to plate and shell structures were detailed in [51-53] where Yang et al. [51] employed the Chebyshev-Ritz discretization method to solve for free vibrational and buckling properties of plates, and finite element method was employed in Refs. [52,53] to solve the similar problems of shells.

Based on an extensive literature survey, it is evident that a large body of available research work on graphene-reinforced structures is limited to straight beams without the inclusion of pores in the metal/polymer matrix. Furthermore, all analyses have been carried out using the first-order or classic theory. Also, such studies pertaining to the curved beam are not commonly available in the literature, except the recent work of Polit et al. [54] which was focused on analytical approach considering bending analysis of simply supported case. [Comprehensive static and dynamic analyses of graphene reinforced curved beam considering different boundary conditions are scarce in the literature.](#) The present paper concerns itself with static, stability and free vibration behavior of GPL reinforced porous curved beams based on finite element approach introducing a trigonometric refined beam theory proposed by Polit et al. [55] and Touratier [56]. [Since the trigonometric refined theory used here is a class of higher-order theory, it can accurately predict the structural behavior for various types of nanocomposite curved beam with graphene reinforcement.](#) Lagrangian equations of motion are employed to develop the governing equations that are solved introducing the finite element procedure. [The formulation is validated against](#)

the available analytical methods. A detailed numerical experimentation is made varying the design parameters such as beam angle, geometry of GPL, beam thickness ratio, dispersion form of porosity and GPLs, and boundary conditions. Some new results are provided for various boundary conditions that can form benchmark solutions while applying other numerical or analytical approach to study such problems.

The structure of the paper is outlined as follows: Material part of porosity dispersion and GPL form are given in section 2, curved beam theory and governing equations in section 3, results and discussion in section 4, and followed by a conclusion.

2. Formulation of effective properties

The material considered here is a porous curved beam involving metal foam which is reinforced with graphene nanoplatelets. The porosity is presumed as closed-cells in nature and is distributed through the thickness in different patterns. The graphene platelet properties are governed by their geometric parameters and are also distributed through the thickness in different forms. The evaluation of the effective properties is briefly outlined here [54, 57-61].

2.1. Distribution of porosity

The material properties of a closed cell porous structure are presumed to change in the thickness plane as a function of z coordinate as indicated in Fig. 1. The effective mass density and Young's modulus are written as follows [6,50,53]

$$\begin{aligned}\rho(z) &= \hat{\rho}[1 - c_m\lambda(z)] \\ E(z) &= \hat{E}[1 - c_p\lambda(z)]\end{aligned}\tag{1}$$

where $\hat{\rho}$ & \hat{E} are the density and Young's modulus of nanocomposite curved beam, respectively, without having any defects like pores/porosity; c_m & c_p are porosity coefficients pertaining to density and stiffness functions, respectively. $\lambda(z)$ refers the porosity dispersion patterns that are selected here as uniform, symmetric and unsymmetric variations [6], as represented in Fig. 1a and is shown below as

$$\lambda(z) = \begin{cases} \lambda_0 \\ \cos\left(\frac{\pi z}{h}\right) \\ \cos\left(\frac{\pi z}{2h} + \pi/4\right) \end{cases} \quad (2)$$

The coefficient c_p related to the stiffness function given in Eq. (1) is treated as

$$c_p = 1 - \bar{E}_2/\bar{E}_1 \quad (3)$$

where \bar{E}_1 & \bar{E}_2 are the high and low values of Young's moduli of GPL reinforced curved beams with the presence of non-uniform porous dispersion, respectively. The constant c_p is considered to be one of the primary parameters for the design of such structures.

The relationship between the porosity coefficients c_p and c_m involved in Eq. (1) can be obtained using the curve fitting equation developed for $(E(z)/\hat{E})$ from the data generated by Gaussian Random Field model [62, 63] as

$$c_m = \frac{1.121 \left[1 - (1 - c_p \lambda(z))^{\frac{1}{2.3}} \right]}{\lambda(z)} \quad (4)$$

Similarly, the fitting data formed for the effective Poisson's ratio [63] is given as

$$\nu(z) = 0.221c_m\lambda(z) + \hat{\nu}(0.342 [c_m\lambda(z)]^2 - 1.21c_m\lambda(z) + 1) \quad (5)$$

To compute the λ_0 value of the uniform porosity distribution case, Eq. (2), it is assumed that the total weight of the beam is constant, irrespective of the variation in the porosity distribution. This allows one to find the value of λ_0 using a reference distribution such as the symmetric case, and by using Eq. (4) in the density equation Eq. (1) as

$$\lambda_0 = \frac{1}{c_p} \left[1 - \left(\frac{1/h \int_{-h/2}^{h/2} \rho(z)/\hat{\rho} dz + 0.121}{1.121} \right)^{2.3} \right] \quad (6)$$

With the above details, the equivalent material properties of the GPL reinforced matrix, considering the introduction of porosity in a GPL reinforced composite, can be found. To evaluate this, the beam can be first considered to be reinforced with GPLs, thus forming as pure nano-composites. The elastic modulus \bar{E} of such beam is estimated from the expression of the Halpin-Tsai data model [59] while the density $\hat{\rho}$ and Poisson's ratio $\hat{\nu}$ for the same case are found by using rule of mixtures as shown below.

$$\hat{E} = \frac{3}{8} \left(\frac{1 + \alpha_{gpl}^l \beta_{gpl}^l V_{gpl}}{1 - \beta_{gpl}^l V_{gpl}} \right) E_m + \frac{5}{8} \left(\frac{1 + \alpha_{gpl}^w \beta_{gpl}^w V_{gpl}}{1 - \beta_{gpl}^w V_{gpl}} \right) E_m \quad (7)$$

$$\hat{\rho} = \rho_{gpl} V_{gpl} + \rho_m V_m \quad (8)$$

$$\hat{\nu} = \nu_{gpl} V_{gpl} + \nu_m V_m \quad (9)$$

where $V_m = 1 - V_{gpl}$.

The material parameters V_{gpl} & V_m , respectively, denote the volume fractions of GPLs and matrix material presented in the resultant composite, respectively; ν_{gpl} & ν_m , ρ_{gpl} & ρ_m are the mass densities, Poisson's ratios of GPLs and matrix, respectively; E_m is the elastic modulus of the matrix. The geometry parameters of graphene platelet ($\alpha_{gpl}^l, \alpha_{gpl}^w$) can be written in terms of GPL thickness and aspect ratios; $\beta_{gpl}^l, \beta_{gpl}^w$ are related to the elastic modulus ratio of GPL and matrix, and GPL geometric parameters, respectively as

$$\alpha_{gpl}^l = \frac{2l_{gpl}}{t_{gpl}}; \alpha_{gpl}^w = \frac{2w_{gpl}}{t_{gpl}} \quad (10a)$$

$$\beta_{gpl}^l = \frac{(E_{gpl}/E_m)^{-1}}{(E_{gpl}/E_m)^{-1} - \alpha_{gpl}^l}; \beta_{gpl}^w = \frac{(E_{gpl}/E_m)^{-1}}{(E_{gpl}/E_m)^{-1} + \alpha_{gpl}^w} \quad (10b)$$

Here, t_{gpl}, w_{gpl} & l_{gpl} are the GPL thickness, breath, and length, respectively; E_{gpl} is the elastic modulus of the GPL fillers.

2.2. GPL distribution

The volume fraction V_{gpl} in Eq. (11) is changed in the thickness direction assuming various dispersion forms (uniform, symmetric and unsymmetric cases) as shown in Fig. 1b and can be stated as

$$V_{gpl} = \begin{cases} V_1^j \\ V_2^j [1 - \cos(\pi z/h)] \\ V_3^j \left[1 - \cos\left(\frac{\pi z}{2h} + \pi/4\right) \right] \end{cases} \quad (11)$$

where the superscript j indicates the dispersion pattern of porosity.

The volume fraction V_{gpl} , in general, can be linked with the GPL weight fraction (W_{gpl}) as

$$V_{gpl} = \frac{W_{gpl}}{W_{gpl} + \rho_{gpl}/\rho_m(1 - W_{gpl})} \quad (12)$$

The maximum value V_i in Eq. (11) can be computed using Eqs. (11), (12) in conjunction with the relative weights calculated from Eq. (1) for the selected porosity and GPL distributions as

$$\int_{-h/2}^{h/2} V_{gpl} [1 - e_m \chi(z)] dz = \frac{W_{gpl}}{[W_{gpl} + (\rho_{gpl}/\rho_m)(1 - W_{gpl})]} \int_{-h/2}^{h/2} [1 - e_m \chi(z)] dz \quad (13)$$

3. Structural Formulation

The beam model considered here is based on a curved one with length L , thickness h , unit width, and radius of curvature R having beam included angle ϕ , as illustrated in Fig. 2a. The structural behavior is defined following a trigonometric shear deformation theory that utilizes a sinusoidal function in representing the deformation of the beam cross-section, referred as the SIN model [54-56]. The displacements in the x direction along the length and $z \in (-\frac{h}{2}, \frac{h}{2})$ direction i.e the thickness direction, are represented by u and w respectively and are related to the field variables as follows

$$\begin{cases} u_1(x, z, t) = \left(1 + \frac{z}{R}\right) u_0(x, t) - z w'_0(x, t) + \Gamma(z) \gamma_0(x, t) \\ u_3(x, z, t) = w_0(x, t) \end{cases} \quad (14)$$

where t is the time, and the transverse shear strain contribution γ_0 can be given as

$$\gamma_0(x, t) = \theta(x, t) + w'_0(x, t) - \frac{1}{R} v_0(x, t) \quad (15)$$

The kinematics assumed here has three field variables as functions of x and t , independent of the thickness direction; u_0 is the curvilinear axial displacement; w_0 is the transverse displacement along the beam neural axis; θ is the rotation of the cross-section. Derivatives are denoted by $(\cdot)' = \partial/\partial x$ and $(\cdot)^\cdot = \partial/\partial t$. The function $\Gamma(z)$ in Eq. (14) is used to deduce different theories, for instance, the classical Euler Bernoulli theory by $\Gamma(z) = 0$, Timoshenko theory by $\Gamma(z) = z$, and or the SIN theory by $\Gamma(z) = \frac{h}{\pi} \sin \frac{\pi z}{h}$.

The strains obtained from kinematic equations and the relation between these strains with stresses by the constitutive law are stated as follows

$$\begin{Bmatrix} \varepsilon_{11} \\ \varepsilon_{33} \\ \gamma_{13} \end{Bmatrix} = \begin{Bmatrix} v_0' + \frac{w_0}{R} + z \left(\frac{v_0'}{R} - w_0'' \right) + \Gamma(z) \gamma_0' \\ 0 \\ \Gamma'(z) \gamma_0 \end{Bmatrix} \quad (16)$$

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{13} \end{Bmatrix} = \begin{Bmatrix} C_{11} \varepsilon_{11} \\ C_{66} \gamma_{13} \end{Bmatrix} \quad (17)$$

where $C_{11} = \frac{E}{1-\nu^2}$; $C_{66} = G$

For the material model considered here, the shear modulus G can be connected to the Young's modulus E by $E = 2G(1 + \nu)$.

The porous GPL curved beam is supposed to be under an externally distributed force $P_3(x, t)$ acting on the top of the beam ($z = h/2$) whereas the in-plane compressive force $P_0(x, t)$ is assumed to be present in the tangent direction along the mid-line of the beam *i.e.* such in-plane load may form when the curved beam is under uniform pressure [66, 67]. The equations of motion are in general developed through the Lagrangian equations of motion by

$$\frac{d}{dt} \left[\frac{\partial(T-U_T)}{\partial \delta_i} \right] - \left[\frac{\partial(T-U_T)}{\partial \delta_i} \right] = 0, i = 1, 2, \dots, n \quad (18)$$

where, δ_i is the vector of global degrees of freedom; U_T is the total energy consisting of strain energy (U_s), the potential energy by the compressive axial force $P_0(V)$ and work done by the externally applied pressure load $P_3(W)$; T is the kinetic energy. All these energy contributions can be expressed as

$$U_s(\delta) = \int_0^L \int_{-\frac{h}{2}}^{\frac{h}{2}} (\delta \varepsilon^T \sigma) dz dx = \frac{1}{2} [\delta]^T [K] [\delta] \quad (19a)$$

$$W(\delta) = - \int_0^L P_3 w dx \quad (19b)$$

$$V(\delta) = - \frac{1}{2} \int_0^L \int_{-h/2}^{h/2} P_0 \left(\frac{\partial w}{\partial x} - \frac{u_0}{R} \right)^2 = \frac{1}{2} \{\delta\}^T [K_G] \{\delta\} \quad (19c)$$

$$T(\delta) = \frac{1}{2} \int_0^L \int_{-\frac{h}{2}}^{\frac{h}{2}} \rho \{\dot{u} \dot{w}\} \{\dot{u} \dot{w}\}^T dx dz = \frac{1}{2} [\dot{\delta}]^T [M] [\dot{\delta}] \quad (19d)$$

where $[M]$ & $[K]$ are the matrices of global mass and stiffness, respectively. $[K_G]$ is the matrix of global geometric stiffness.

Substituting Eqs (19) in Lagrange's equation of motion (18), the following governing equations for various problems such as bending, vibration, and buckling identified are outlined as

$$\begin{aligned}
 [K]\{\delta\} &= \{F\} && \text{(bending)} \\
 ([K] - \omega^2[M])\{\delta\} &= \{0\} && \text{(free vibration)} \\
 ([K] - P_0[K_G])\{\delta\} &= \{0\} && \text{(buckling)} \tag{20}
 \end{aligned}$$

The different matrices involved in the above governing equations can be developed using finite element procedure. In the present work, a C^1 continuous 3-noded beam element with Hermite shape function for the transverse displacement function, w_0 and a quadratic function for axial displacement u_0 and cross-sectional rotation θ is proposed to study the problems [55]. The end nodes have 4 degrees of freedom (DoF) i.e. u_0 , w_0 , $w_{0,x}$ and θ , while the mid-node has 2 DoFs i.e. u_0 and θ , as depicted in Fig. 2b. The interpolation functions selected here interpolate the membrane/ shear strain energy term in a field-consistency way to avoid the membrane/shear locking syndrome. All the energy terms were numerically calculated adopting full integration. This element performs very well for thick/thin curved beam case. It has no artificial mode and produces the correct rigid body modes. The convergence characteristics of the element are good.

4. Numerical results and Discussion

4.1 The problems detailed

Here, the ability of the developed finite element formulation based on the trigonometric shear deformation theory using sine function as outlined in the previous section is tested for the known problems available in the open literature. A comprehensive study is carried out assuming parameters like

length-to-thickness ratio i.e. $S = L/h$, radius of curvature of curved beam R and beam angle ϕ , GPLs distribution and pores dispersion in the thickness direction, and GPL's geometry on the bending, buckling and vibration characteristics of GPL reinforced porous curved composite beams.

The beam geometry considered here consists of various types of curved beams including the straight one and fixing the length $L = 10\text{m}$. The curved beam angle $\phi = \{15^\circ, 60^\circ, 120^\circ\}$ is varied to represent the shallow/deep curved beam cases. The radius of curvature R can be computed from the relation, $L = R \times \phi$. For thin and thick beams, different values for $S = \{5, 10, 20\}$ are presumed.

Boundary Conditions: The following boundary conditions have been employed for the purpose of this study:

- movable simply supported (HH-movable): $w_0 = 0$ at $x = 0, L$
- immovable simply supported (HH-immovable): $u_0 = w_0 = 0$ at $x = 0, L$
- fully clamped support (CC): $u_0 = \theta = w_0 = w_0' = 0$ at $x = 0, L$
- clamped-hinged support (CH): $u_0 = \theta = w_0 = w_0' = 0$ at $x = 0$; $u_0 = w_0 = 0$ at $x = L$

The properties of GPLs and metal matrix are taken as [64,65]

- material: Young's modulus, $E_{gpl}=1.01$ TPa; density, $\rho_{gpl}= 1062.5$ kg/m³; Poisson's ratio, $\nu_{gpl}=0.186$
- geometry: width, $w_{gpl}=1.5$ μm , length, $l_{gpl}=2.5$ μm , thickness, $t_{gpl}=1.5$ nm,
- metal matrix: Copper based metal- Young's modulus $E_m=130$ GPa; density, $\rho_m= 8960$ kg/m³; Poisson's ratio, $\nu_m=0.34$

Results: All results presented here, unless mentioned otherwise, the following non-dimensional forms are introduced as

- bending: $\bar{w} = w \frac{100E_m I}{p_3 L^4}$; $\bar{\sigma}_{11} = 10 \sigma_{11} \frac{h^2}{p_3 L^2}$; $\bar{\sigma}_{13} = 100 \sigma_{13} \frac{h^2}{p_3 L^2}$
- buckling: $P_{cr} = P_0 \frac{L^2}{E_m I}$

- vibration: $\bar{\omega} = \omega L^2 \sqrt{\frac{m}{E_m I}}$; where $m = \rho h$ and $I = h^3/12$

4.2 Assessment of present model

Based on the progressive mesh refinement, a 32-elements discretization model was found to yield the required converged solutions for different boundary conditions and for all the analyses focused in the present study as seen from Table 1. Before conducting in-depth analyses, the performance of the model was assessed by comparing against existing results in the tabular or graphical form for isotropic curved beams, and graphene-reinforced straight beam cases. Tables 2-4 highlight the comparison of the present results with those of analytical solutions for the static bending/buckling/ free vibrations of hinged-hinged isotropic curved beams. They are found to be in very good agreement. As there is no work seen in the literature related to static/dynamic study of graphene-reinforced metal or polymer beams, the available analytical solutions for straight beam with such reinforcement are compared with the obtained results using the present model in Figs. 3-5, respectively for the static, buckling and free vibration cases. It is noticed from Figs. 3-5 that the present numerical solutions are in excellent agreement with those of the available analytical methods.

4.3. Bending analysis

The curved beams with ($L/h = 5, 10$ & $\phi = 45^\circ$) are subjected to uniformly distributed load of magnitude $P_3 \left(x, z = \frac{h}{2} \right) = p_3 \sin \frac{\pi x}{L}$ in the transverse direction. The GPL weight fraction and the porosity coefficient are assumed as $W_{gpl} = 1\%$ and $c_p = 0.5$. Considering three different types of dispersion for porosity and GPLs in the beam as shown in Fig. 1, the maximum nondimensional displacements of beams evaluated for different boundary conditions are shown in Table 5 along with those of straight beam cases. It is seen that, in general, the combination of a symmetric GPL and symmetric porosity distribution yields the lowest deflection values, thus exhibiting maximum stiffness, next followed by the uniform and unsymmetric distribution cases, respectively. The high bending stiffness in symmetric distribution case is attributed to the high concentration of GPL and less pores near the upper and lower surfaces of the beam

compared to those of around midplane values. It is further viewed that the influence of GPL distribution shows significant change in the stiffness for all cases in comparison with those of porosity distributions. Also, the effect of radius of curvature of the beam is observed to noticeably reduce the nondimensional deflection, irrespective of material and geometric parameters because of the presence of coupling between bending and stretching in the curved beam. The clamped case gives lower deflection compared to all other supports, as expected. The deflection clamped-hinged beam falls in between the clamped-clamped and hinged-hinged case as expected. The detailed investigations, unless otherwise mentioned, are conducted by assuming symmetric distributions for the porosity and GPLs in the curved beams.

Next, the influence of the graphene platelets in the porous nanocomposite curved beam under uniform load on the bending deflection while varying the beam included angle $\phi = \{15^\circ, 60^\circ, 120^\circ\}$, the length-to-thickness ratio, $S \{5, 10, 20\}$ and boundary conditions is investigated and the results are depicted in Fig. 6. It can be opined from this figure that the beam bending stiffness increases significantly by dispersing the GPLs and, an addition of 1% weight fraction of GPLs results in about 45% decrease in maximum beam deflection for all boundary conditions considered here. Furthermore, the resistance of the beam against transverse load increases while increasing the beam included angle, and the boundary condition significantly affects the deflection. A gradual decrease in deflection is also noticed when increasing the percentage of weight fraction of GPL.

The through-thickness plots of shear and normal stresses (σ_{13} , σ_{11}) of porous GPL-reinforced curved beam having $\phi = 60^\circ$ & $S=5$ are presented in Fig. 7 for different boundary conditions assuming some values for GPL weight fraction and porosity coefficient ($c_p = 0.5$; $W_{gpl}=1\%$). The effect of different types of distributions for GPLs and porosity are also considered. It is noticed from this figure that the present model exhibits zero transverse shear stress values at the extreme surfaces of the curved beam as required. It is also observed that the variation of pores through the thickness has less effect compared to the influence of GPLs dispersion. Furthermore, the location of maximum shear stress value in the thickness direction can be different from the physical neutral axis and it is highly dependent on the GPLs

dispersion and pores distribution. This is due to the stiffness variation in the thickness direction. Also, it is seen that, for the clamped case, the transverse shear stress variation in the thickness direction is noticeably high when comparing with those of other boundary conditions. The variation of normal stress σ_{11} in direction of the thickness is nonlinear and the degree of nonlinearity is significantly influenced by the distribution of GPLs and pores. The location of zero normal stress σ_{11} value can be different from neutral axis as seen in the case of the location of the maximum shear stress in the thickness direction. However, the influence of boundary conditions on variation of normal stress through the thickness is less.

Next, the influence of aspect and thickness ratios (ℓ/w , ℓ/t) of graphene platelets on the bending behavior is examined assuming the curved porous beam with $\phi = 90^\circ$ & $L/h=5$, and symmetric dispersion for both GPLs and pores. The numerical results obtained are plotted in Fig.8 and it is evident that beams with graphene platelets with low aspect ratio and high thickness ratio have predominantly high beam stiffness, irrespective of the boundary conditions.

4.4. Buckling analysis

The elastic buckling study of porous graphene-reinforced curved beam ($c_p=0.5$ & $W_{gpl}=1\%$) is investigated by various types of dispersion of porosity/GPL in the reinforced metal matrix. The minimum critical buckling compressive load is presented in Table 6 for thick curved beams ($L/h = 5, 10$ & $\phi = 45^\circ$) including the straight beam case. Similar to the static bending study, it is seen that the symmetric pattern for both GPLs and porosity offers the maximum stiffness, thus yielding in high critical values. It is also seen that the critical buckling load increases significantly while increasing in thickness ratio of the beam and this is due to the involvement of higher mode corresponding to the lowest critical load.

Next, the buckling loads corresponding to the lowest buckling modes are evaluated for various thickness ratio values ($L/h=5, 10, 20$) and curved beam angle ($\phi = 15^\circ, 60^\circ, 120^\circ$) are detailed in Figs. 9. This Figure also brings out the effect of various boundary types on the buckling loads. The buckling mode plots with reference to transverse displacement and in-plane displacements (w , u_0) for hinged-

hinged and clamped are described in Fig. 10. From Fig. 9, it is observed that, for the shallow beam case, the critical buckling value is less compared to the cases of fairly deep and very deep beams. It is possibly due to the low membrane energy contribution to the total potential energy which increases with the beam included angle cases. However, for the hinged-hinged case, the total potential energy for the intermediate curved beam case $\phi = 60^\circ$ appears to be more compared to the case of deep beam ($\phi = 120^\circ$). Accordingly, the critical buckling value is somewhat more for fairly deep beam case ($\phi = 60^\circ$), irrespective of thickness ratio. But this trend is reversed in the case of clamped beam case, thus yielding higher buckling load for deep beam $\phi = 120^\circ$. This is attributed to the energy contribution due to the membrane and bending deformations. It is also viewed from Fig. 10 that, for the shallow curved beam, the lowest mode w for buckling mode matches the first symmetric mode whereas the first anti-symmetric mode w dominates the lowest critical load for the deep cases. It is also inferred that the enhancement in the compressive resisting load is noticeable while adding 1% GPLs in the metal matrix. It is further opined that the increase in the minimum critical compressive value is about 80% depending on the thickness ratio of the beam. It can be in general opined that the lowest buckling value for the selected curved beam depends on the participation of the type mode, symmetric or anti-symmetric mode, and also the boundary conditions.

4.5. Free vibration analyses

The free vibration study of the GPLs reinforced nanocomposite porous curved beams is investigated assuming symmetric dispersion for GPL and pores in the thickness direction based on the bending and buckling analyses. The detailed parametric investigation is made considering nanocomposite beams with $S=5, 10, 20$ and beam angle $\phi = 15^\circ, 60^\circ, 120^\circ$. The results for the fundamental frequency are plotted in Figs. 11. It is noticed from Fig. 11 that the fundamental frequency value for very deep beam case is higher for thick beam compared to the cases of shallow and fairly deep cases but it may change with the increase in thickness ratio and boundary condition as seen in Fig. 11. This behavior is qualitatively similar to those of buckling case. The vibration mode shapes with respect to transverse and

in-plane displacements (w, u_0) for hinged-hinged and clamped are shown in Fig. 12. It is viewed from this figure that the in-plane vibration modes are in general different from the buckling modes (Fig.10).

5. Conclusion

The application of finite element approach coupled with higher-order SIN model is carried out for bending, buckling and free vibration of graphene platelets reinforced porous curved beams. The performance of the numerical model is compared with the analytical method. A comprehensive analysis is done to highlight the effect of different design parameters like length-to-thickness ratio and boundary conditions, included angle of curved beam on the static and dynamic behavior of curved beams. From the present investigation, certain observations made are as follows:

- (i) The type of weight distribution of GPLs influences the beam stiffness considerably while comparing with the pores distribution pattern in the metal matrix.
- (ii) The increase in beam included angle decreases the deflection of the curved beam.
- (iii) The transverse shear stress variation in the thickness direction is noticeably high for the clamped case.
- (iv) The change in the normal stress in the thickness direction is nonlinear and the degree of nonlinearity depends on the distribution of GPLs and pores.
- (v) The occurrence of the maximum shear stress values and zero normal stress in the thickness direction is dependent on the dispersion type of pores and GPLs in the matrix.
- (vi) Graphene platelet geometric parameters significantly affect the structural design of the nanocomposite curved beam.
- (vii) Significant enhancement in the buckling value is observed while increasing GPLs weight fraction in comparison with the reduction level of static bending deflection of the beam.
- (viii) The buckling value of a curved beam significantly depends on the beam included angle.

- (ix) The increment in frequency value highly depends on the shallowness and thickness ratio of the reinforced porous curved beam.
- (x) The in-plane mode significantly affects the critical buckling and fundamental frequency values depending on the curved beam included angle.
- (xi) The results provided for certain boundary conditions can thus form as benchmark solutions while dealing with different theories/solution approaches.

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Legends for Tables

Table 1. Mesh convergence table for different loading and boundary conditions, C - C and H - H-movable ($L/h=5$, $\phi = 60^\circ$, $c_p = 0.5$, $W_{gpl} = 1\%$).

Table 2. Comparison of nondimensional deflections (\bar{u}_3) for different L/h , beam angles (ϕ), and theories ($c_p = 0$, $W_{gpl} = 0\%$).

Table 3. Comparison of non-dimensional first, second and third fundamental frequencies of curved isotropic beam (H - H-movable boundary condition, $\phi = 60^\circ$).

Table 4. Critical buckling load, \bar{P}_{cr} , of an isotropic curved beam (H - H-movable)

Table 5. Non-dimensional deflection (\bar{u}_3) of curved beams of different porosity and GPLs weight distribution types for different boundary conditions ($c_p = 0.5$, $W_{gpl} = 1\%$).

Table 6. Non-dimensional buckling load, \bar{P}_{cr} of different porosity and GPLs weight distribution types for different boundary conditions ($c_p = 0.5$, $W_{gpl} = 1\%$).

Legends for Figures

Figure 1. Distribution of porosity and GPLs in the thickness direction: (a) Porosity; (b) GPLs.

Figure 2. a) Geometrical parameters of curved beam; b) Beam element with the degrees of freedom.

Figure 3. Comparison of non - dimensional deflections against porosity coefficient for the straight nanocomposite beam under uniform load for different boundary conditions ($L/h = 20$, $W_{gpl} = 0\%$).

Figure 4. Comparison of critical buckling load increment of straight GPL reinforced beam against weight fraction of GPL for different values for porosity coefficient and different GPL distributions (CC boundary condition, $L/h=20$, symmetric porosity distribution).

Figure 5. Comparison of fundamental frequency increment of straight GPL reinforced beam against GPL weight fraction of GPLs for different GPL distributions and boundary conditions ($c_p = 0.5$, $L/h = 20$, symmetric porosity distribution).

Figure 6. Non - dimensional deflections of curved beams with different beam angles (ϕ) against GPL weight fraction (W_{gpl}) for different thickness ratios and different boundary conditions ($c_p = 0.5$, symmetric distribution type for porosity and GPLs).

Figure 7. Comparison stress plots through the thickness for different porosity and graphene platelet distribution types and boundary conditions ($\phi = 60^\circ$ and $L/h = 5$; $c_p = 0.5$; $W_{gpl} = 1\%$): (a) shear stress, (b) normal stress.

Figure 8. Non - dimensional deflections of curved beam ($\phi = 90^\circ$) against GPLs weight fraction (W_{gpl}) for different values of GPL geometry, $(\ell/w)_{gpl}$ & $(\ell/t)_{gpl}$ and boundary conditions ($L/h=5$, $c_p = 0.5$; symmetric distribution type for Porosity and GPLs).

Figure 9. Non - dimensional critical buckling loads of curved beams with different beam angles (ϕ) against GPL weight fraction (W_{gpl}) for different thickness ratios and boundary conditions ($c_p = 0.5$, symmetric distribution type for porosity and GPLs).

Figure 10. Mode shapes (u_0 and w_0) corresponding to the first buckling mode for different beam angles ($c_p = 0.5$, $W_{gpl}=1\%$, symmetric distribution type for porosity and GPLs). a) H – H boundary condition; b) C – C boundary condition

Figure 11. Fundamental frequencies of curved beams with different beam angles (ϕ) against GPL weight fractions (W_{gpl}) for different thickness ratios and boundary conditions ($c_p = 0.5$, symmetric distribution type for porosity and GPLs).

Figure 12. Mode shape (u_0 and w_0) corresponding to the fundamental free vibration mode for different beam angles ($c_p = 0.5$, $W_{gpl}=1\%$, symmetric distribution type for porosity and GPLs). a) H – H boundary condition; b) C – C boundary condition

Table 1. Mesh convergence table for different loading and boundary conditions, C - C and H - H-movable ($L/h=5$, $\phi = 60^\circ$, $c_p = 0.5$, $W_{gpl} = 1\%$).

| No. of elements | \bar{u}_3 | | $\bar{\omega}_1$ | | P_{cr} | |
|-----------------|-------------|--------|------------------|---------|----------|---------|
| | C - C | H - H | C - C | H - H | C - C | H - H |
| 2 | 0.1741 | 0.2540 | 28.9013 | 22.7054 | 53.5886 | 38.9586 |
| 4 | 0.1701 | 0.2534 | 28.5536 | 22.6451 | 46.2255 | 33.9416 |
| 8 | 0.1706 | 0.2534 | 28.4374 | 22.6361 | 45.7590 | 33.7491 |
| 16 | 0.1708 | 0.2534 | 28.4055 | 22.6354 | 45.7070 | 33.7357 |
| 32 | 0.1709 | 0.2534 | 28.3989 | 22.6354 | 45.7022 | 33.7348 |
| 64 | 0.1709 | 0.2534 | 28.3981 | 22.6354 | 45.7018 | 33.7347 |

Table 2. Comparison of nondimensional deflections (\bar{u}_3) for different L/h , beam angles (ϕ), and theories ($c_p = 0$, $W_{gpl} = 0\%$).

| L/h | ϕ | (\bar{u}_3) REF. [67] | | | (\bar{u}_3) Present | | |
|-------|--------|-------------------------|--------|--------|-----------------------|--------|--------|
| | | CLT | FSDT | SIN | CLT | FSDT | SIN |
| 5 | 30° | 1.0871 | 1.1800 | 1.1982 | 1.0871 | 1.1800 | 1.1982 |
| | 60° | 1.3040 | 1.4152 | 1.4370 | 1.3040 | 1.4152 | 1.4370 |
| | 90° | 1.8401 | 1.9962 | 2.0269 | 1.8401 | 1.9962 | 2.0268 |
| 10 | 30° | 1.0863 | 1.1096 | 1.1142 | 1.0863 | 1.1096 | 1.1142 |
| | 60° | 1.3005 | 1.3283 | 1.3338 | 1.3005 | 1.3283 | 1.3338 |
| | 90° | 1.8288 | 1.8678 | 1.8756 | 1.8288 | 1.8678 | 1.8756 |
| 20 | 30° | 1.0862 | 1.0920 | 1.0931 | 1.0862 | 1.0920 | 1.0920 |
| | 60° | 1.2996 | 1.3065 | 1.3079 | 1.2996 | 1.3065 | 1.3079 |
| | 90° | 1.8260 | 1.8358 | 1.8377 | 1.8260 | 1.8357 | 1.8376 |

Table 3. Comparison of non-dimensional first, second and third fundamental frequencies of curved isotropic beam (H - H-movable boundary condition, $\phi = 60^\circ$).

| L/h | Mode | Present | | | Hosseini <i>et al.</i> [66] | |
|-------|------------------|---------|---------|---------|-----------------------------|---------------------|
| | | CLT | FSDT | SIN | Sol ⁿ I | Sol ⁿ II |
| 10 | $\bar{\omega}_1$ | 8.2864 | 8.2004 | 8.1837 | 8.1991 | 8.2152 |
| | $\bar{\omega}_2$ | 37.2371 | 35.8230 | 35.5630 | 35.7451 | 35.8144 |
| | $\bar{\omega}_3$ | 84.1010 | 77.7885 | 76.7076 | 77.3993 | 77.5359 |
| 50 | $\bar{\omega}_1$ | 8.3213 | 8.3178 | 8.3171 | 8.3177 | 8.3184 |
| | $\bar{\omega}_2$ | 37.8341 | 37.7697 | 37.7569 | 37.7658 | 37.7690 |
| | $\bar{\omega}_3$ | 87.0629 | 86.7317 | 86.6665 | 86.7084 | 86.7158 |

Table 4. Critical buckling load, \bar{P}_{cr} , of an isotropic curved beam (H - H-movable)

| Critical buckling load (\bar{P}_{cr}) | Method | Value |
|-------------------------------------------|--------|-------|
| Present | FEA | 37.37 |
| Luu et al. [64] | IGA | 39.40 |
| Timoshenko and Gere [65] | Exact | 38.38 |
| Kang et al. [68] | DQM | 38.49 |

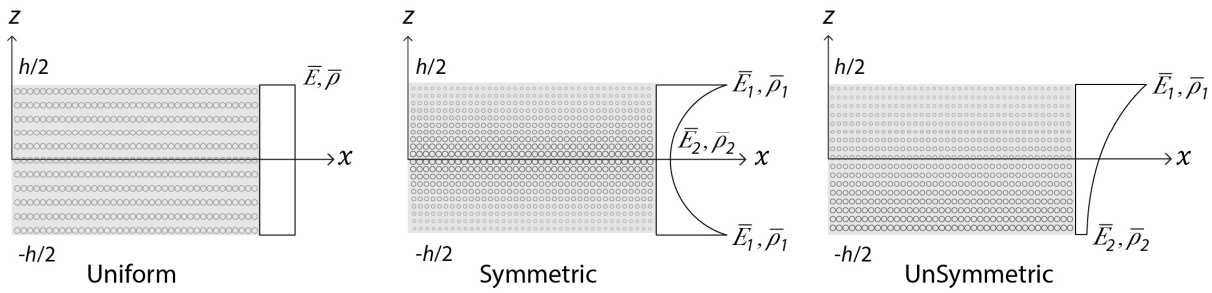
Table 5. Non-dimensional deflection (\bar{u}_3) of curved beams of different porosity and GPLs weight distribution types for different boundary conditions ($c_p = 0.5$, $W_{gpl} = 1\%$).

| L/h | ϕ | Porosity Dist. Type | \bar{u}_3 (H – H) | | | \bar{u}_3 (C – H) | | | \bar{u}_3 (C – C) | | |
|-------|----------|---------------------|---------------------|--------|---------|---------------------|--------|---------|---------------------|--------|---------|
| | | | GPL Dist. Type | | | GPL Dist. Type | | | GPL Dist. Type | | |
| | | | Sym. | Unsym. | Uniform | Sym. | Unsym. | Uniform | Sym. | Unsym. | Uniform |
| 5 | Straight | Sym. | 0.7946 | 0.9117 | 0.9334 | 0.4235 | 0.4815 | 0.4688 | 0.2706 | 0.2955 | 0.2849 |
| | | Unsym. | 0.8824 | 0.9982 | 1.0587 | 0.4647 | 0.5467 | 0.5273 | 0.2881 | 0.3292 | 0.3117 |
| | | Uniform | 0.9134 | 1.0703 | 1.1004 | 0.4656 | 0.5423 | 0.5321 | 0.2866 | 0.3215 | 0.3124 |
| | 45° | Sym. | 0.3579 | 0.3208 | 0.3894 | 0.2656 | 0.2676 | 0.2869 | 0.2031 | 0.2219 | 0.2135 |
| | | Unsym. | 0.3257 | 0.3098 | 0.3559 | 0.2658 | 0.2738 | 0.2893 | 0.2169 | 0.2407 | 0.2308 |
| | | Uniform | 0.3893 | 0.3492 | 0.4185 | 0.2871 | 0.2907 | 0.3116 | 0.2150 | 0.2376 | 0.2298 |
| 10 | Straight | Sym. | 0.6924 | 0.8234 | 0.8478 | 0.3155 | 0.3883 | 0.3776 | 0.1745 | 0.2120 | 0.2037 |
| | | Unsym. | 0.7898 | 0.9191 | 0.9815 | 0.3668 | 0.4640 | 0.4449 | 0.2007 | 0.2544 | 0.2381 |
| | | Uniform | 0.8216 | 0.9915 | 1.0238 | 0.3679 | 0.4586 | 0.4500 | 0.1997 | 0.2464 | 0.2392 |
| | 45° | Sym. | 0.1316 | 0.1233 | 0.1400 | 0.1139 | 0.1146 | 0.1238 | 0.0942 | 0.1065 | 0.1040 |
| | | Unsym. | 0.1240 | 0.1219 | 0.1320 | 0.1139 | 0.1156 | 0.1229 | 0.1033 | 0.1152 | 0.1130 |
| | | Uniform | 0.1409 | 0.1316 | 0.1463 | 0.1238 | 0.1234 | 0.1322 | 0.1036 | 0.1159 | 0.1136 |

Table 6. Non-dimensional buckling load, \bar{P}_{cr} of different porosity and GPLs weight distribution types for different boundary conditions ($c_p = 0.5$, $W_{gpl} = 1\%$).

| L/h | ϕ | Porosity Dist. Type | $\bar{P}_{cr} (H - H)$ | | | $\bar{P}_{cr} (C - H)$ | | | $\bar{P}_{cr} (C - C)$ | | |
|-------|----------|---------------------|------------------------|---------|---------|------------------------|---------|---------|------------------------|---------|---------|
| | | | GPL Dist. Type | | | GPL Dist. Type | | | GPL Dist. Type | | |
| | | | Sym. | Unsym. | Uniform | Sym. | Unsym. | Uniform | Sym. | Unsym. | Uniform |
| 5 | Straight | Sym. | 12.7509 | 11.1354 | 10.8551 | 21.5291 | 18.7961 | 19.2864 | 33.7904 | 30.6660 | 31.8268 |
| | | Unsym. | 11.4974 | 10.2003 | 9.5803 | 19.5156 | 16.4880 | 17.0643 | 31.5406 | 27.3215 | 28.9035 |
| | | Uniform | 11.0922 | 9.4837 | 9.2077 | 19.4633 | 16.5927 | 16.8921 | 31.7123 | 28.0159 | 28.8442 |
| | 45° | Sym. | 29.2827 | 30.6251 | 26.9201 | 32.0643 | 31.8196 | 29.6735 | 42.2129 | 39.4165 | 40.4182 |
| | | Unsym. | 31.5053 | 27.2662 | 28.8727 | 32.0253 | 30.8646 | 29.3272 | 40.1783 | 36.5079 | 37.7502 |
| | | Uniform | 26.9290 | 27.9801 | 25.0513 | 29.6730 | 29.1803 | 27.1097 | 40.0895 | 36.7652 | 37.4818 |
| 10 | Straight | Sym. | 14.6324 | 12.3327 | 11.9513 | 28.2040 | 22.8551 | 23.4641 | 51.0039 | 41.7201 | 43.4204 |
| | | Unsym. | 12.8465 | 11.0829 | 10.3351 | 24.2030 | 19.1255 | 19.8820 | 44.1466 | 34.6224 | 37.0038 |
| | | Uniform | 12.3324 | 10.2395 | 9.8967 | 24.1082 | 19.2999 | 19.6352 | 44.3690 | 35.7556 | 36.8310 |
| | 45° | Sym. | 50.9782 | 41.6773 | 43.3986 | 60.3205 | 54.5715 | 53.2042 | 83.4023 | 73.7898 | 75.3282 |
| | | Unsym. | 44.1065 | 34.5757 | 36.9728 | 56.5342 | 47.5889 | 48.7154 | 76.2413 | 64.3994 | 68.4848 |
| | | Uniform | 44.3467 | 35.7215 | 36.8124 | 53.8630 | 47.6591 | 46.6072 | 75.7490 | 66.2759 | 67.9921 |

a) Porosity Distribution types



b) GPL Distribution types

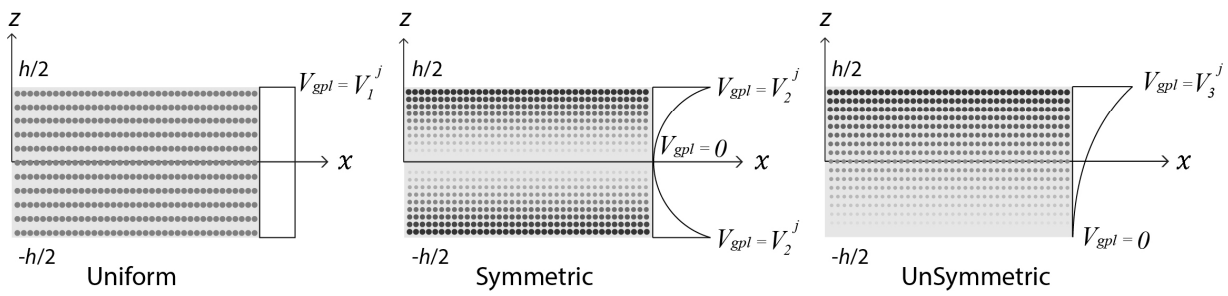


Figure 1. Distribution of porosity and GPLs in the thickness direction: (a) Porosity; (b) GPLs.

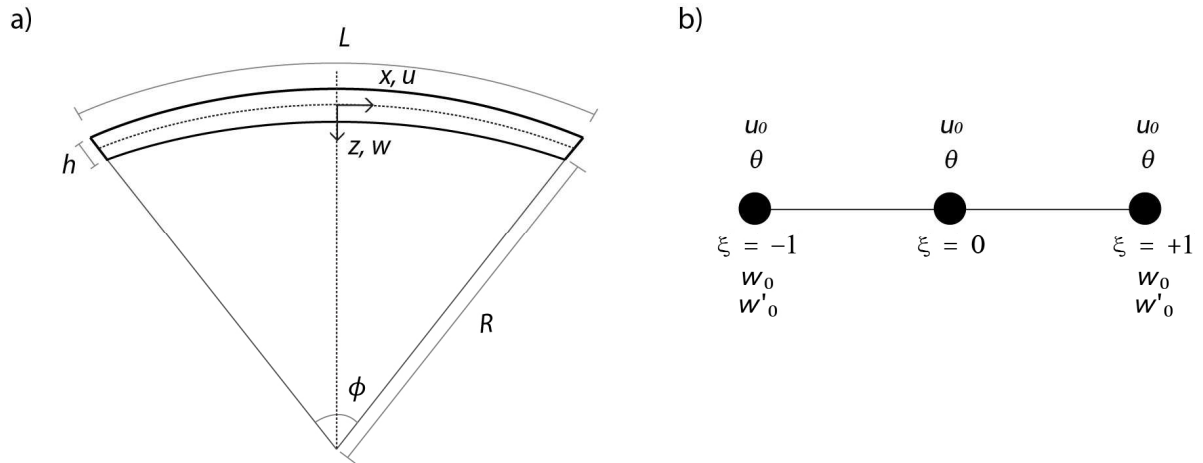


Figure 2. a) Geometrical parameters of curved beam & b) Beam element with the degrees of freedom.

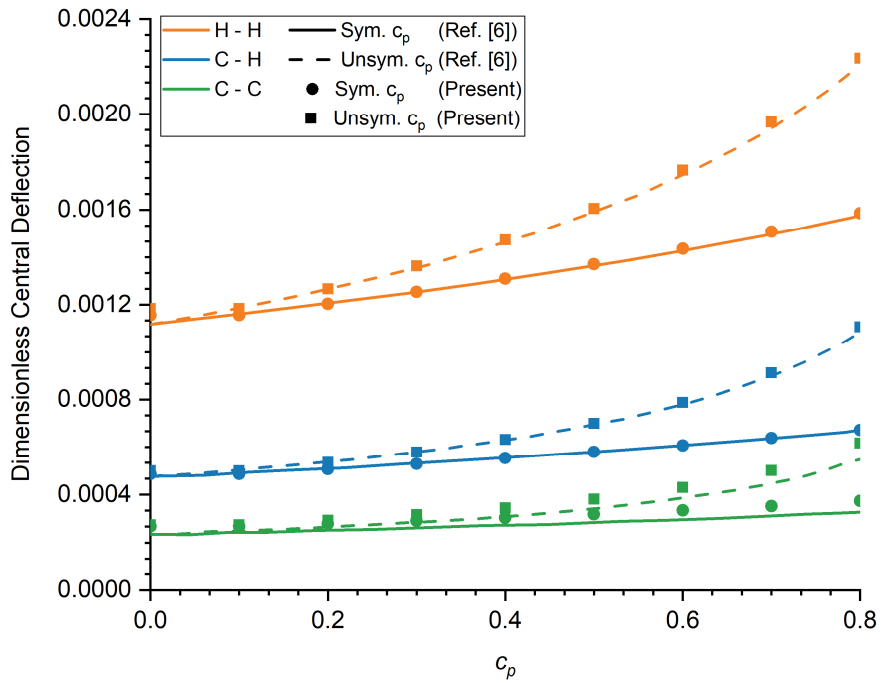


Figure 3. Comparison of non - dimensional deflections against porosity coefficient for the straight nanocomposite beam under uniform load for different boundary conditions ($L/h = 20$, $W_{gpl} = 0\%$).

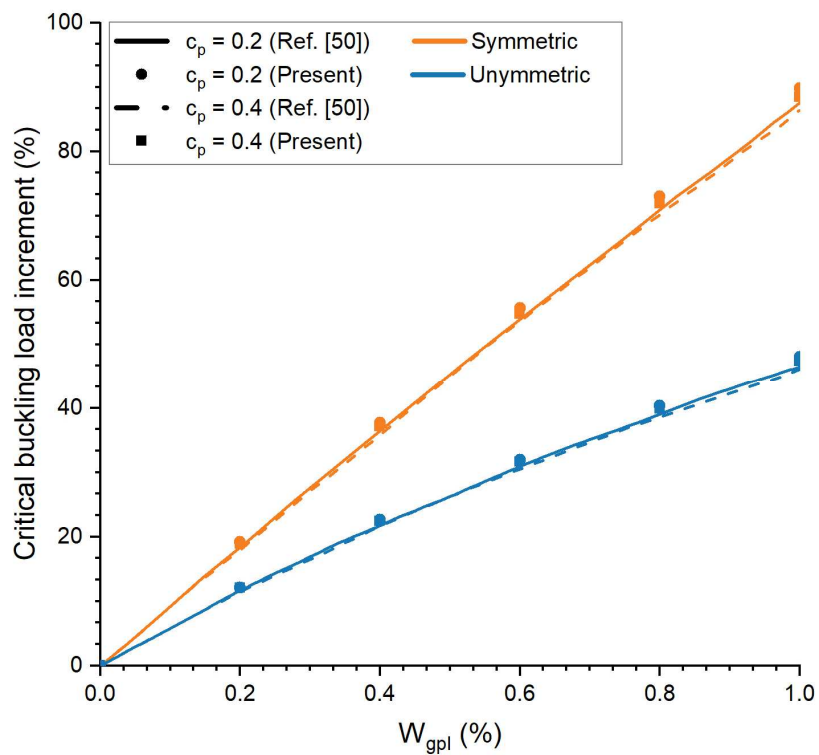


Figure 4. Comparison of critical buckling load increment of straight GPL reinforced beam against weight fraction of GPL for different values for porosity coefficient and different GPL distributions (C - C boundary condition, $L/h=20$, symmetric porosity distribution).

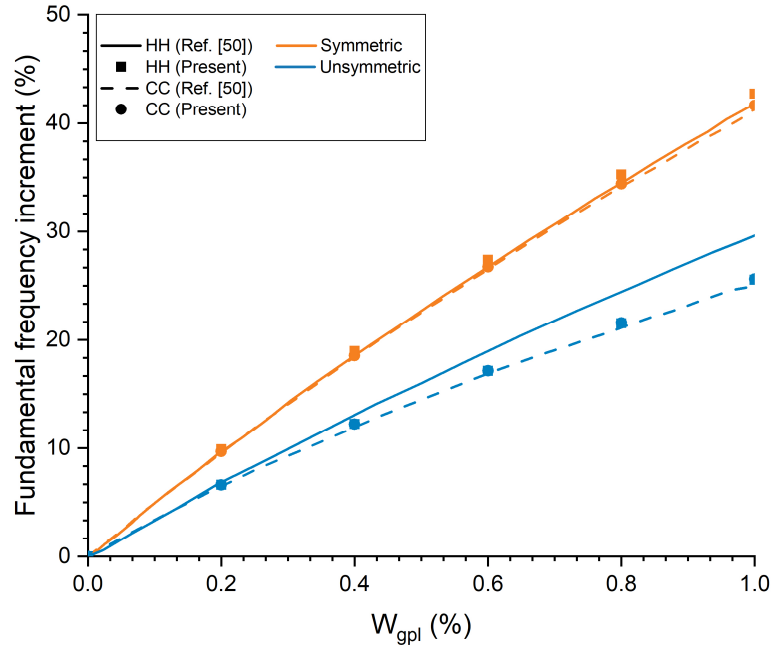


Figure 5. Comparison of fundamental frequency increment of straight GPL reinforced beam against weight fraction of GPLs for different GPL distributions and boundary conditions ($c_p = 0.5$, $L/h = 20$, symmetric porosity distribution).

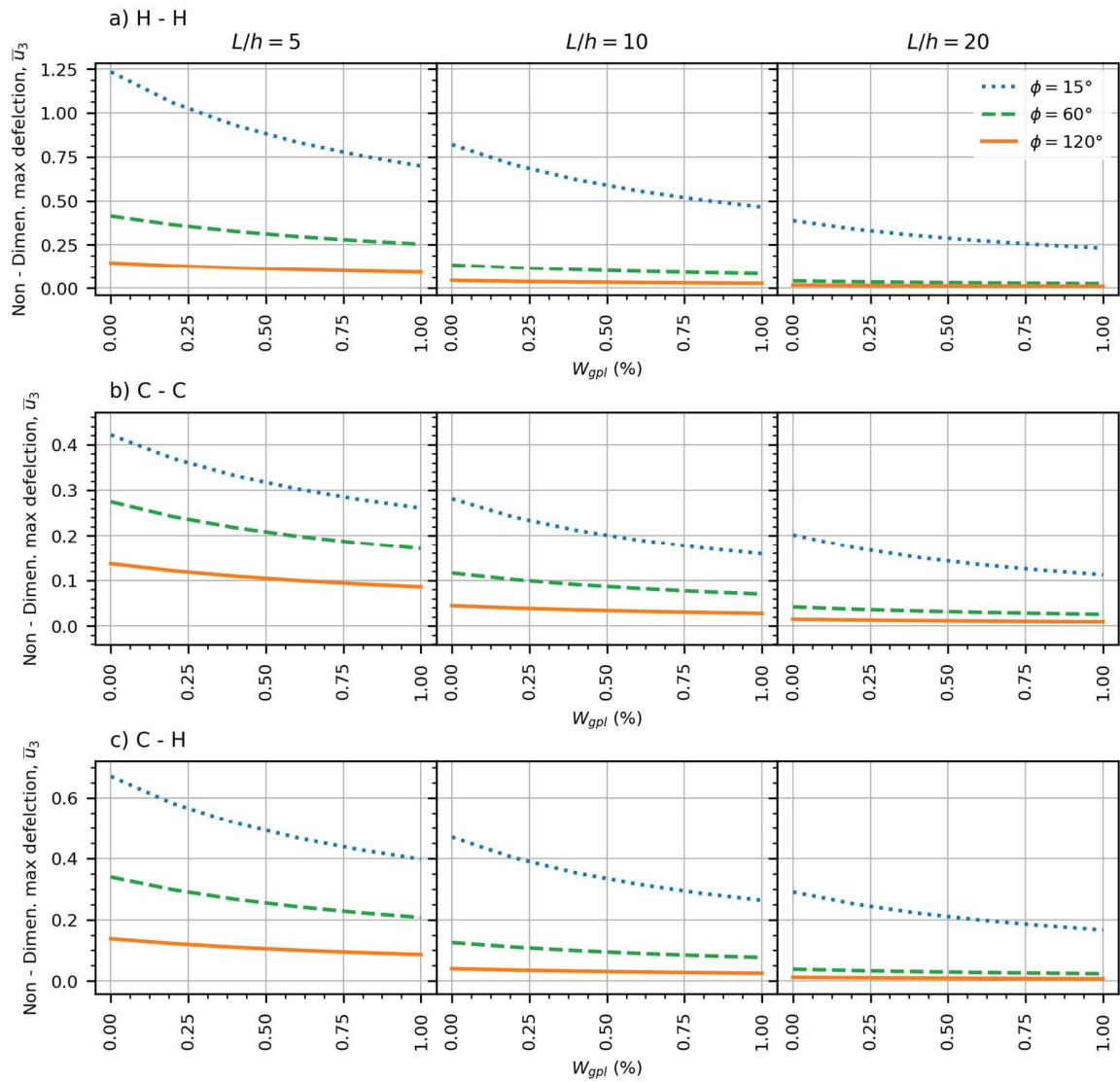


Figure 6. Non - dimensional deflections of curved beams with different beam angles (ϕ) against GPL weight fraction (W_{gpl}) for different thickness ratios and different boundary conditions ($c_p = 0.5$, symmetric distribution type for porosity and GPLs).

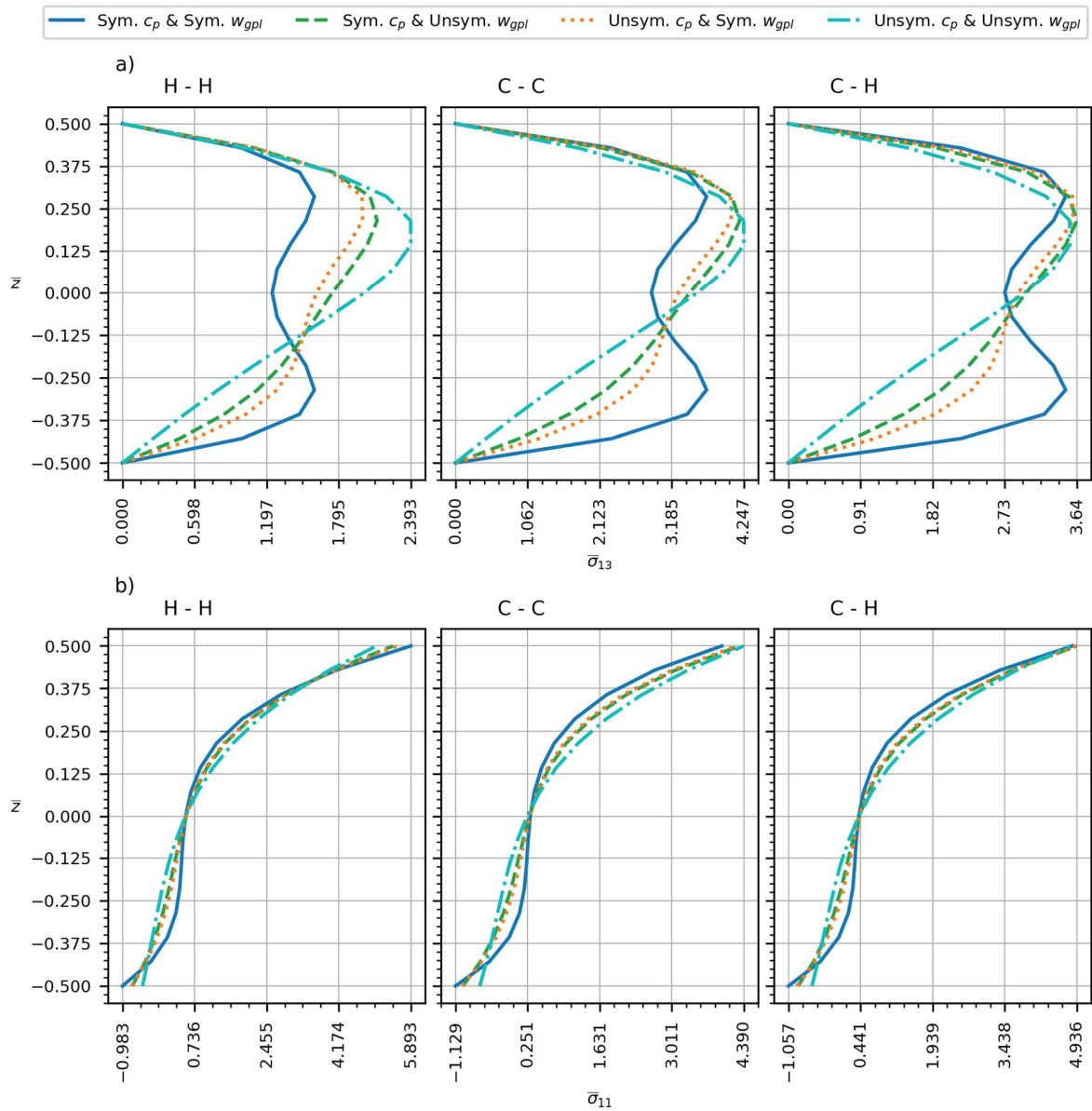


Figure 7. Comparison stress plots through the thickness for different porosity and graphene platelet distribution types and boundary conditions ($\phi = 60^\circ$ and $L/h = 5$; $c_p = 0.5$; $W_{gpl} = 1\%$): (a) shear stress, (b) normal stress.

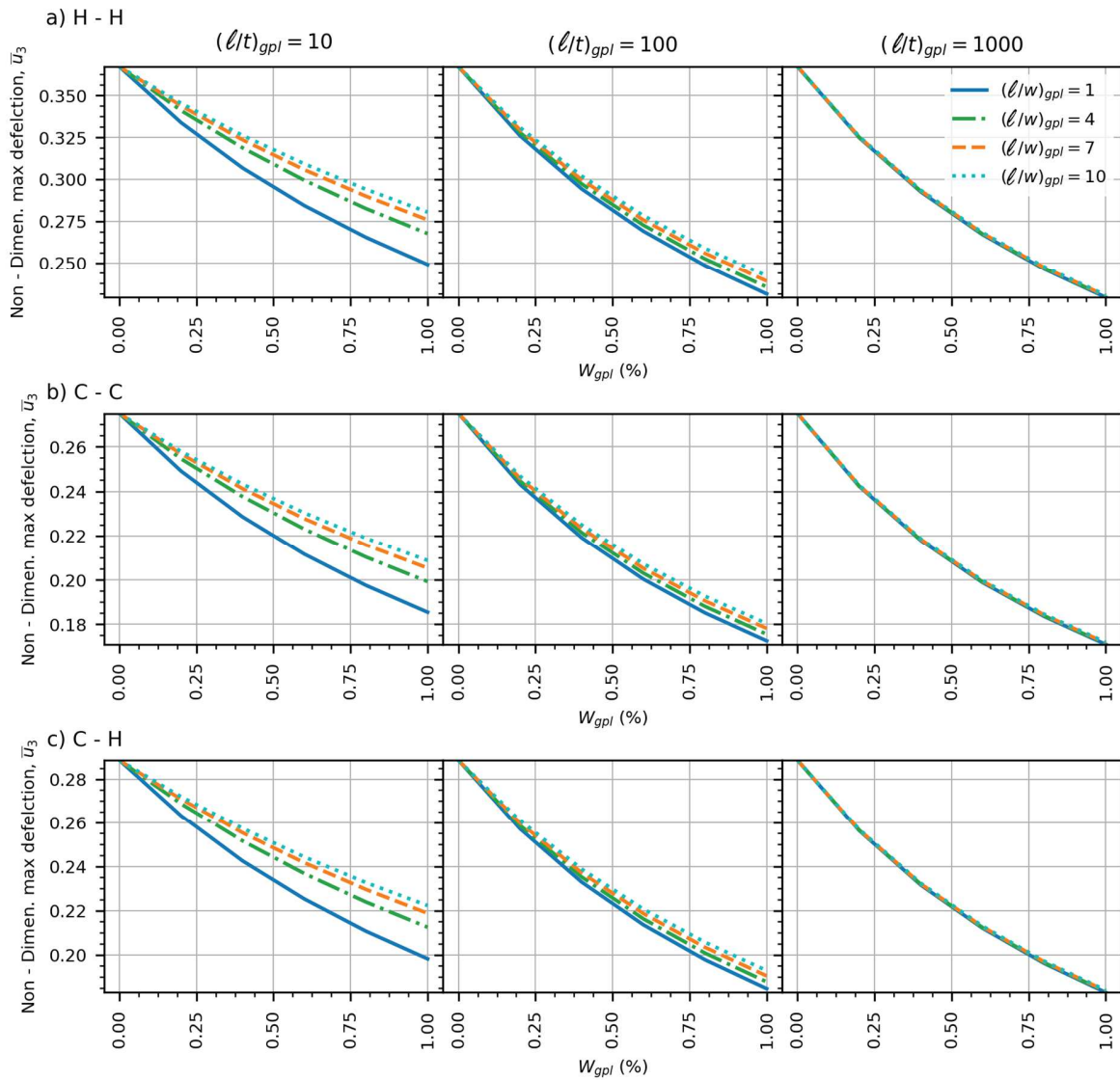


Figure 8. Non - dimensional deflections of curved beam ($\phi = 90^\circ$) against GPLs weight fraction (W_{gpl}) for different values of GPL geometry, $(\ell/w)_{gpl}$ & $(\ell/t)_{gpl}$ and boundary conditions ($L/h=5$, $c_p = 0.5$; symmetric distribution type for Porosity and GPLs).

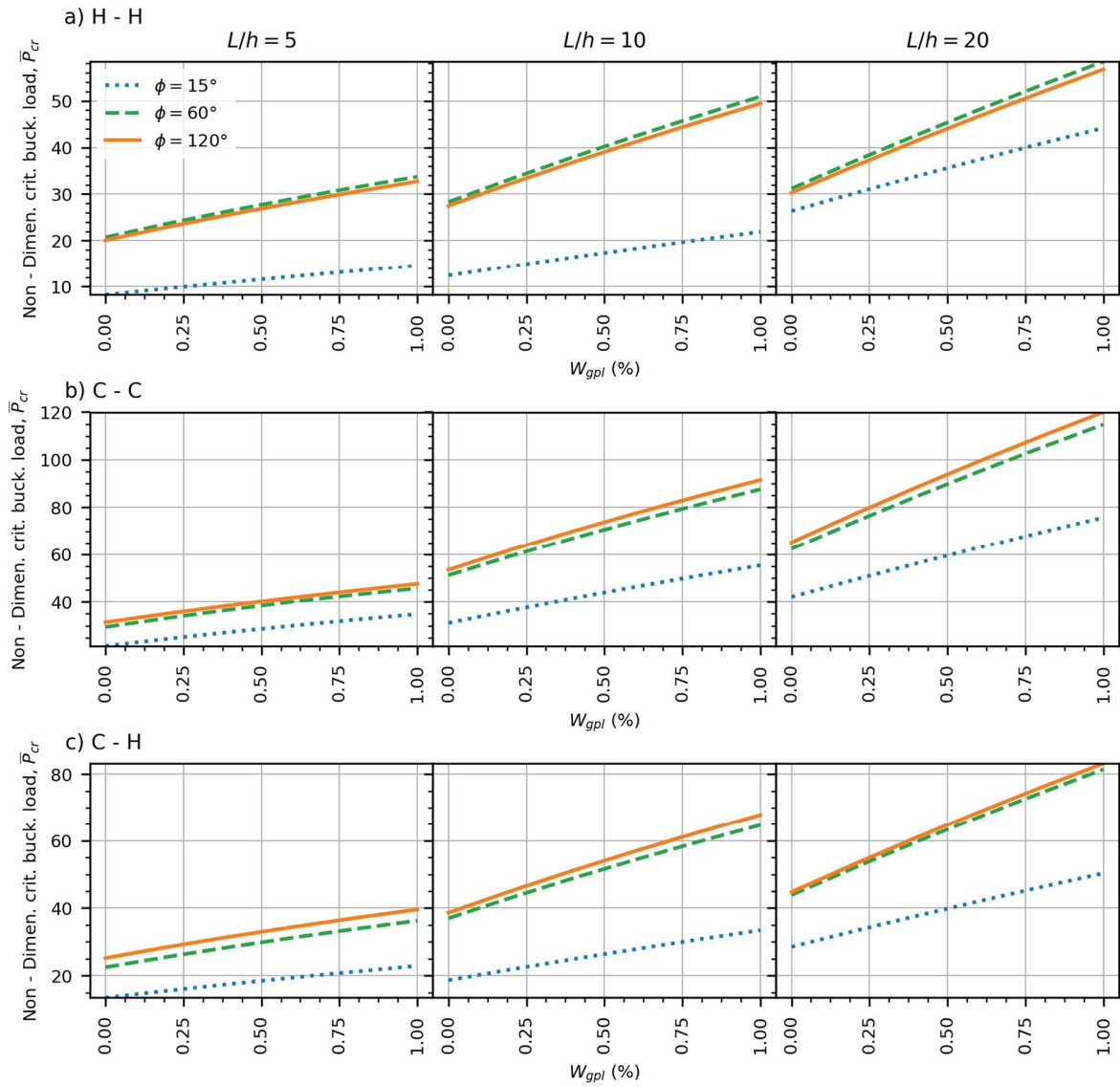


Figure 9. Non - dimensional critical buckling loads of curved beams with different beam angles (ϕ) against GPL weight fraction (W_{gpl}) for different thickness ratios and boundary conditions ($c_p = 0.5$, symmetric distribution type for porosity and GPLs).

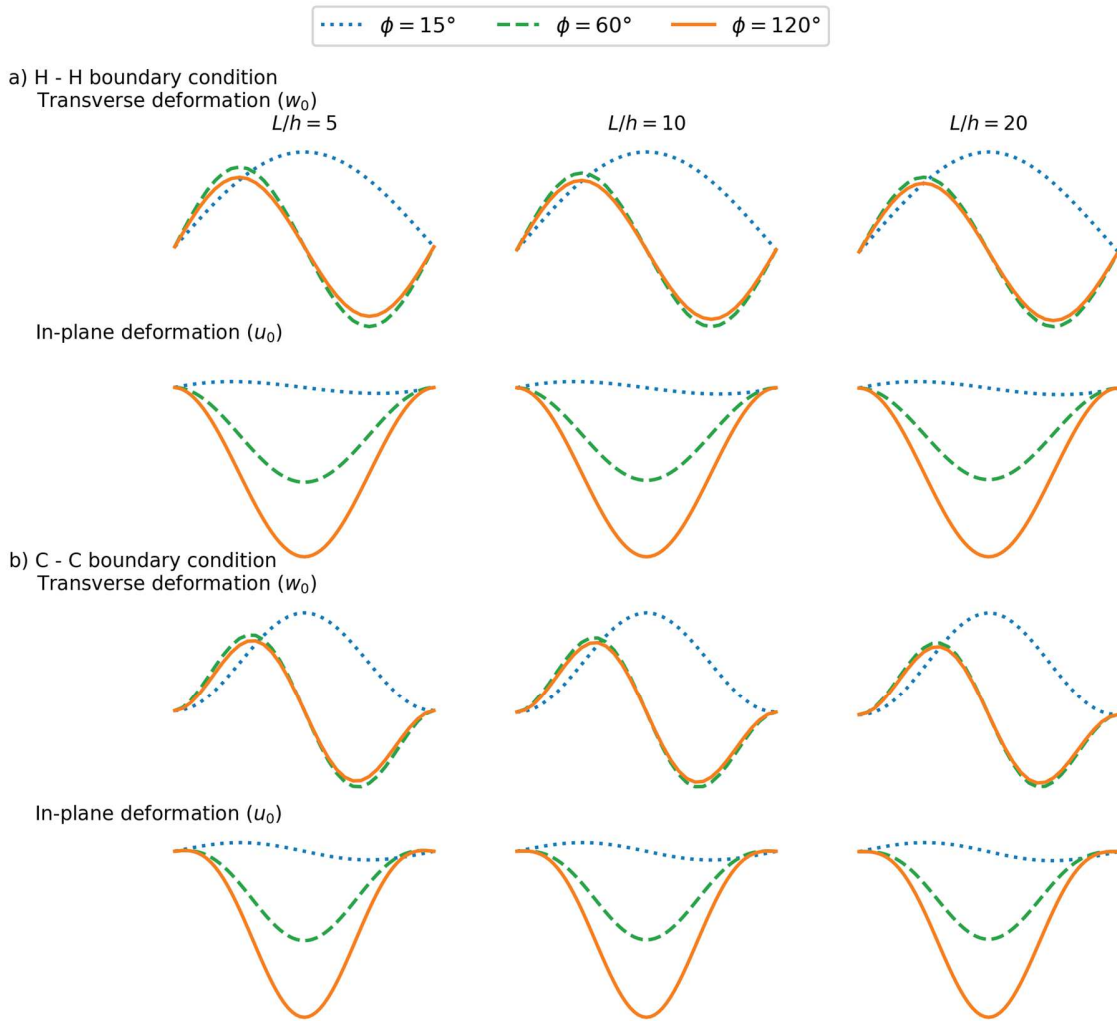


Figure 10. Mode shapes (u_0 and w_0) corresponding to the first buckling mode for different beam angles ($c_p = 0.5$, $W_{gp} = 1\%$, symmetric distribution type for porosity and GPLs). a) H – H boundary condition; b) C – C boundary condition

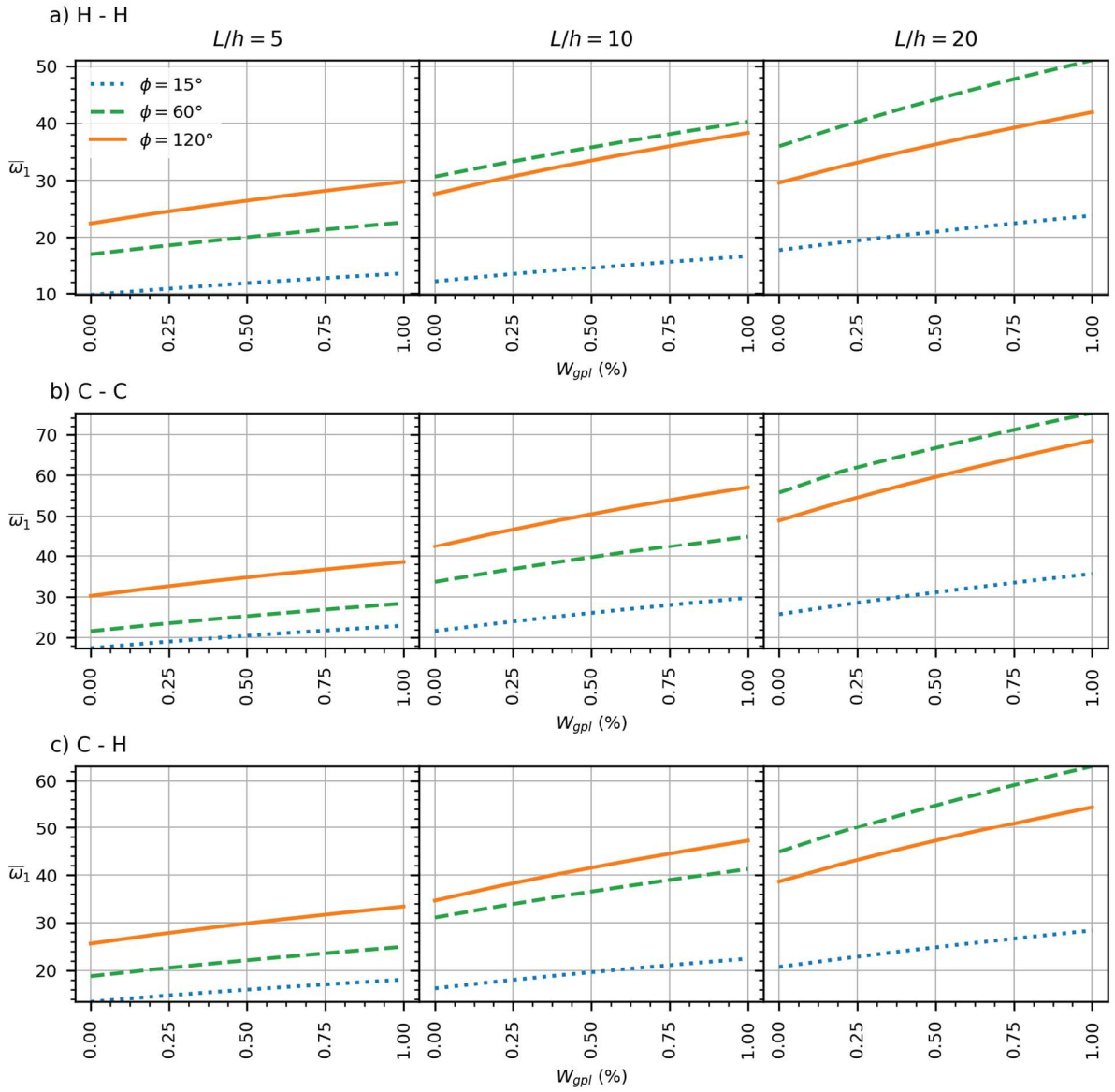


Figure 11. Fundamental frequencies of curved beams with different beam angles (ϕ) against GPL weight fractions (W_{gpl}) for different thickness ratios and boundary conditions ($c_p = 0.5$, symmetric distribution type for porosity and GPLs).

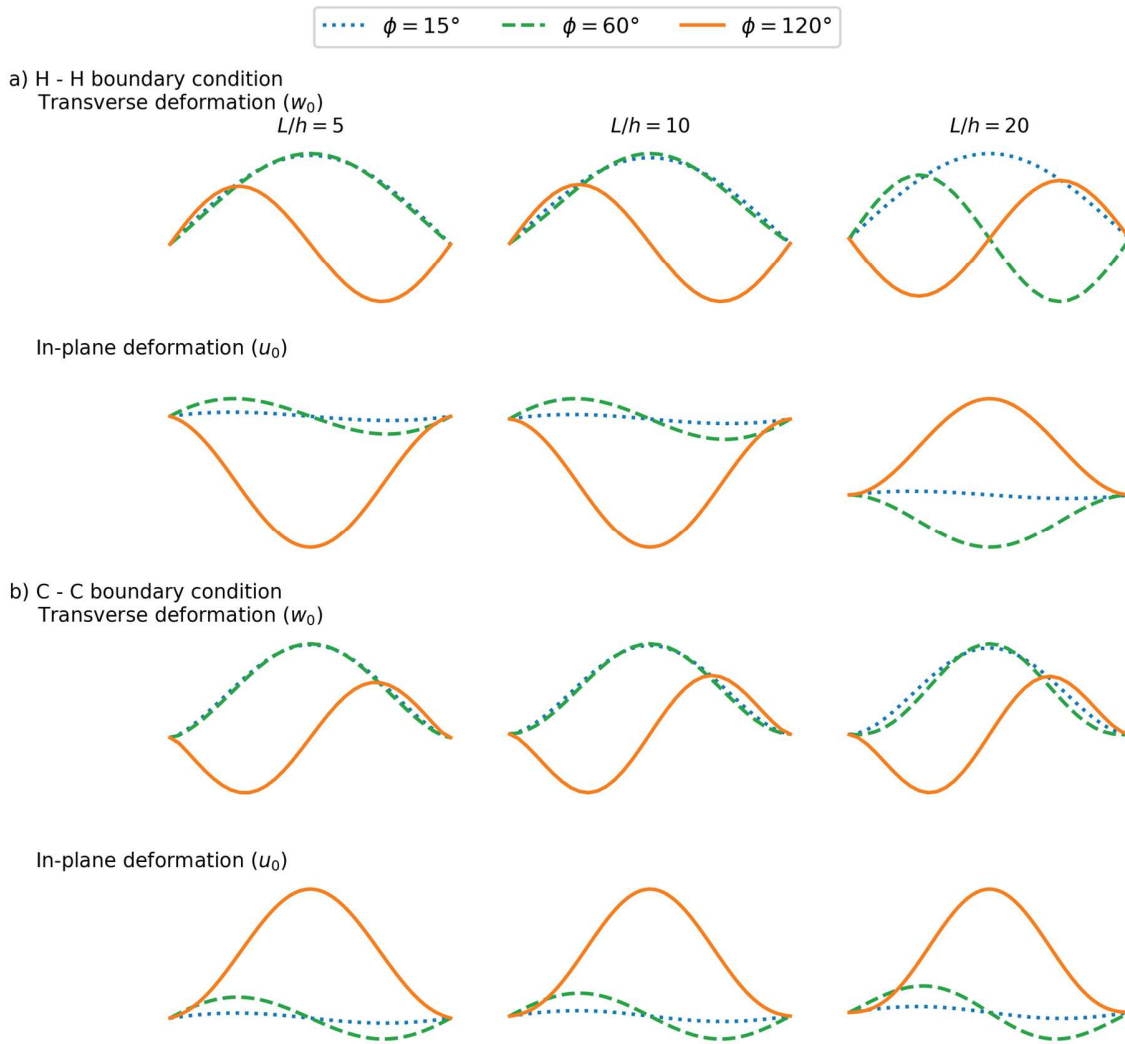


Figure 12. Mode shape (u_0 and w_0) corresponding to the fundamental free vibration mode for different beam angles ($c_p = 0.5$, $W_{GPL}=1\%$, symmetric distribution type for porosity and GPLs). a) H – H boundary condition; b) C – C boundary condition