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REVIEW PAPER

A review on functionally graded porous structures reinforced by graphene platelets

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Abstract

Nowadays, there is a high demand for great structural implementation and multifunctionality with excellent mechanical properties. The porous structures reinforced by graphene platelet (GPLs) having valuable properties, such as heat resistance, lightweight, and excellent energy absorption, have been considerably used in different engineering implementations. However, stiffness of porous structures reduces significantly, due to the internal cavities, by adding GPLs into porous medium, effective mechanical properties of porous structure considerably enhance. To boost the efficiency and capability of structures, functionally graded (FG) porous structures reinforced by GPLs have been suggested in the literature. Therefore, some researchers tried to figure out the fantastic characteristics of these structures and research activities in this emerging area have been rapidly increasing. The present paper (a) briefly reviews the mechanical properties of functionally graded porous composites reinforced by GPLs and discusses the existing micromechanics model for the prediction of effective mechanical properties; (b) presents a comprehensive review on the mechanical analyses of these structures; (c) discusses the challenges and possible future works.

Keywords: Functionally graded materials; Graphene platelets; Composite structures; Mechanical analyses; Porous.

1. Introduction

Recently, multifunctional structures with superior mechanical properties in engineering applications have been largely applied [1-18]. The porous cellular structures having excellent properties e.g. lightweight, heat resistance, great energy absorption, have been greatly used in various engineering applications [19-27]. However, stiffness of structure reduces significantly, due to the internal pores in metal matrix [28- 30]. For rectifying this limitation, Nano-fillers e.g. carbon nanotubes (CNTs) [31–34] or graphene Nano-platelets (GPLs) [35] into lightweight

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materials is employed as an effective and useful way to boost their mechanical properties. On the other hand, this Nano particle will lead to keep their excellent potential for lightweight structures, if they disperse in the metal or polymer matrix as well-even [36]; thus, it is prominent to prevent agglomeration in these reinforcements. Comparing with CNTs, GPLs have revealed major abilities to choose a proper reinforcement volunteer [37] due to they have great mechanical properties, a less expensive, a more special surface area and 2D geometry. To boost the efficiency and capability of structures, functionally graded (FG) porous structures with reinforced graphene platelets have been suggested in the literature to determine the eligible mechanical properties by controlling the density and size of porosities as well as porosity pattern and GPL distribution [38]. Based on numerical and analytical analyses, several researches have been performed to investigate the influence of porosity and graphene platelets pattern on structural behaviors subjected to different loading and boundary conditions. Due to the wide range of analysis and geometry which have been investigated, the literature review is classified based on shape of geometry and type of analysis including static, buckling, post-buckling, free and forced vibration, dynamic instability analyses. This review article is organized as follows. Section 2 reviews micromechanics based model for the determination of effective material properties of FG-GPL porous composite structures. Section 3-6 present a comprehensive review on the state-of-the-art on the mechanical analyses of FG-GPL porous structures such as beams, arches, plates, shells subjected to various loading conditions, followed by Section 7 in which key technical challenges and future research directions in this emerging area are discussed and identified.

2. *Material properties of functionally graded porous nanocomposite structures reinforced by graphene platelets:*

The literature review denotes that there is only one procedure reported for estimation of material properties of functionally graded porous structures reinforced by GPLs reported here. In this manner, researchers generally consider two kinds of non-uniform symmetric distribution of porosity and a uniform porosity distribution across the thickness direction of structure which are shown in Fig. 1. In distribution 1, the porosity is a symmetrical parabolic curve, which its value in the mid-plane is higher than the upper and lower surfaces (i.e. for a plate). In distribution 2, a non-uniform symmetric porosity distribution is considered, its value on the top and bottom surfaces are higher than the mid-plane. The functions of Non-uniform symmetric porosity distributions 1 and 2 are shown in Eqs. (1) and (2), respectively. The function of the uniform porosity distribution is shown in Eq. (3). Simultaneously, three GPL distribution patterns along the thickness direction of structure are described in Fig. 1 and given in Eq. (15).

Porosity distribution 1 (Non-uniform symmetric I):

$$\begin{cases} E(z) = E^*\left[1-e_0\cos\left(\pi z / h\right)\right] \\ G(z) = G^*\left[1-e_0\cos\left(\pi z / h\right)\right] \\ \rho(z) = \rho^*\left[1-e_m\cos\left(\pi z / h\right)\right] \end{cases} \tag{1}$$

Porosity distribution 2 (Non-uniform symmetric II):

$$\begin{cases} E(z) = E^*\left[1 - e_0^*\left(1 - \cos\left(\pi z / h\right)\right)\right] \\ G(z) = G^*\left[1 - e_0^*\left(1 - \cos\left(\pi z / h\right)\right)\right] \\ \rho(z) = \rho^*\left[1 - e_m^*\left(1 - \cos\left(\pi z / h\right)\right)\right] \end{cases} \quad (2)$$

Uniform porosity distribution:

$$\begin{cases} E(z) = E^*\alpha \\ G(z) = G^*\alpha \\ \rho(z) = \rho^*\alpha' \end{cases} \quad (3)$$

where z, h $E(z)$, $G(z)$ and $\rho(z)$ are thickness direction, thickness, modulus of elasticity, rigidity modulus and mass density of porous nanocomposite structure. E^*, $G^*$and $\rho^*$are the same properties of GPL structure without interior cavities. Also, e_0 and e_0^*($0 \le e_0(e_0^*) < 1$) are the coefficients of porosity for distribution 1 and 2, respectively. e_m and e_m^* are the corresponding coefficients of mass density for distribution 1 and 2, respectively. α and α' are the variables for uniform porosity distribution.

The material properties of open-cell foams in Eq. (4) apply to derive relationship between the porosity coefficients and mass density coefficients for porosity patterns in Eq. (5).

$$\frac{E(z)}{E^*} = \left(\frac{\rho(z)}{\rho^*}\right)^2 \quad (4)$$

$$\begin{cases} 1 - e_m\cos(\pi z/h) = \sqrt{1 - e_0 cos(\pi z/h)} \\ 1 - e_m^*(1 - cos(\pi z/h)) = \sqrt{1 - e_0^*(1 - cos(\pi z/h))} \\ \alpha' = \sqrt{\alpha} \end{cases} \quad (5)$$

The mass of structure with different porosities and GPL dispersions are assumed to be known, therefore, we have:

$$\begin{cases} \int_0^{h/2} \sqrt{1 - e_0^*(1 - cos(\pi z/h))}dz = \int_0^{h/2} \sqrt{1 - e_0 cos(\pi z/h)}dz \\ \int_0^{h/2} \sqrt{\alpha}dz = \int_0^{h/2} \sqrt{1 - e_0 cos(\pi z/h)}dz \end{cases} \quad (6)$$

which should be applied to estimate e_0^* and α with a known value of e_0, as given in Table 1. It is obtained that e_0^* enhances by increasing e_0. When e_0 is 0.6,e_0^* (=0.9612) is near to the upper bound. Thus, $e_0 \in [0,0.6]$ is applied in the present analyses.

Modulus of elasticity of the nanocomposite without interior cavities E^* is estimated based on the Halpin-Tsai micromechanics model as:

$$E^* = \frac{3}{8}\left(\frac{1 + \varepsilon_L^{GPL}\eta_L^{GPL}V_{GPL}}{1 - \eta_L^{GPL}V_{GPL}}\right)E_m + \frac{5}{8}\left(\frac{1 + \varepsilon_W^{GPL}\eta_W^{GPL}V_{GPL}}{1 - \eta_W^{GPL}V_{GPL}}\right) \quad (7)$$

$$\varepsilon_L^{GPL} = \frac{2l_{GPL}}{t_{GPL}} \quad (8)$$

$$\varepsilon_W^{GPL} = \frac{2w_{GPL}}{t_{GPL}} \tag{9}$$

$$\eta_L^{GPL} = \frac{E_{GPL} - E_m}{E_{GPL} + \varepsilon_L^{GPL} E_m} \tag{10}$$

$$\eta_L^{GPL} = \frac{E_{GPL} - E_m}{E_{GPL} + \varepsilon_W^{GPL} E_m} \tag{11}$$

where E_{GPL} and E_m are modulus of elasticity of GPLs and the matrix. l_{GPL}, W_{GPL} and t_{GPL} are length, width and thickness of nanofiller platelets, and V_{GPL} is the volume content of GPLs. The rule of mixture applies to estimate the mass density and Poisson's ratio of the nanocomposite:

$$\rho^* = \rho_{GPL} V_{GPL} + \rho_m \left(1 - V_{GPL}\right) \tag{12}$$

$$v^* = v_{GPL} V_{GPL} + v_m \left(1 - V_{GPL}\right) \tag{13}$$

where ρ_{GPL} and v_{GPL} are the mass density and Poisson's ratio of GPLs. ρ_m and υ_m are the same material properties of the matrix. Poisson's ratio is assumed to be constant for open-cell foams. The rigidity modulus G^* of the nanocomposite is estimated as:

$$G^* = \frac{E^*}{2\left(1 + v^*\right)} \tag{14}$$

V_{GPL} is the volume content of GPLs that varies across the thickness direction of structure according to the Eq. (15) for various dispersion patterns.

$$V_{GPL}(z) = \begin{cases} S_{i1}[1 - \cos(\pi z/h)] & GPL\ Pattern\ A \\ S_{i2}\cos(\pi z/h) & GPL\ Pattern\ B \\ S_{i3} & GPL\ Pattern\ C \end{cases} \tag{15}$$

where s_{i1}, s_{i2} and s_{i3} are the upper limit of the V_{GPL}, and i =1, 2, 3 related to different porosity distributions 1, 2 and uniform distribution. The total volume content of GPLs (V_{GPL}^T) is obtained by using the nanofiller weight fraction Δ_{GPL} in Eq.(16), and then is applied to find s_{i1}, s_{i2} and s_{i3} by Eq. (17) .

$$V_{GPL}^T = \frac{\Delta_{GPL}\rho_m}{\Delta_{GPL}\rho_m + \rho_{GPL} - \Delta_{GPL}\rho_{GPL}} \tag{16}$$

$$V_{GPL}^{T}\int_{-h/2}^{h/2}\frac{\rho(z)}{\rho_c}dz=\begin{cases} s_{i1}\int_{-h/2}^{h/2}[1-\cos(\pi z/h)]\frac{\rho(z)}{\rho_c}dz \\ s_{i2}\int_{-h/2}^{h/2}[\cos(\pi z/h)]\frac{\rho(z)}{\rho_c}dz \\ s_{i3}\int_{-h/2}^{h/2}\frac{\rho(z)}{\rho_c}dz \end{cases} \quad (17)$$

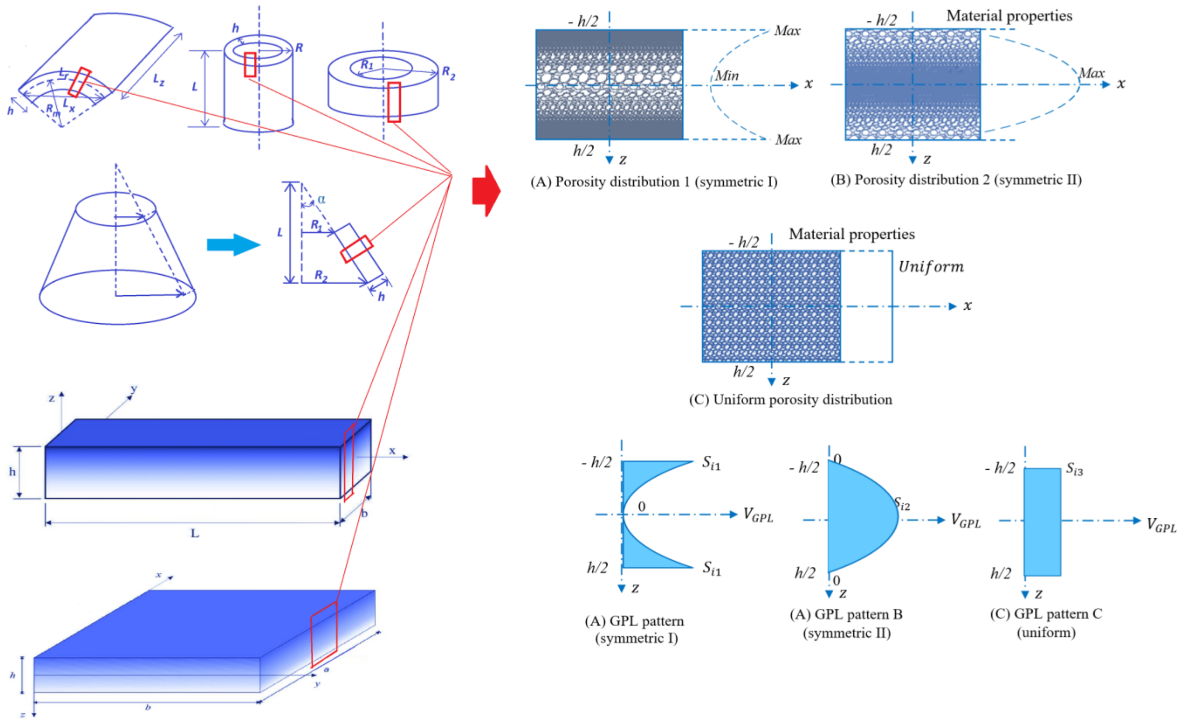

Figure 1: Porosity distributions and GPL dispersion patterns.

Table 1: Coefficients of porosity for different distributions

e_0	e_0^*	α
0.1	0.1738	0.9361
0.2	0.3442	0.8716
0.3	0.5103	0.8064
0.4	0.6708	0.7404
0.5	0.8231	0.6733
0.6	0.9612	0.6047

3. Static response and buckling analysis

In this section, researches on static and buckling analyses of FG-GPL porous beams, plate- and shell-type structures are reviewed.

a) **Beams:** Hung et al. [39] investigated nonlinear bending analysis of FG porous beam reinforced by GPLs under different boundary conditions based on the trigonometric shear deformation beam theory and the von Kárman type of geometrical nonlinearity strains and by applying the Ritz method. Anirudh et al. [40] performed a comprehensive investigation about buckling, bending and vibration of FG porous curved beam reinforced by GPLs by developing finite element formulation based on the trigonometric shear deformation theory. The results denote that the type of weight distribution of GPLs influences the beam stiffness considerably while comparing with the pores distribution pattern in the metal matrix. Sahmani et al. [41] investigated nonlinear static bending of FG-GPLs porous nanobeams based on nonlocal strain gradient theory and third-order shear deformation beam theory (TSDT). Polit et al. [42] presented an analytical solution based on Navier's solution for bending and elastic stability using a higher-order FG porous curved beam reinforced by GPLs. The results denote that the weight dispersion pattern of GPLs affects the stiffness of the beam significantly while relating with the distribution of porosity in the metal foam. Yas and Rahimi [43] investigated thermal buckling analysis of FG-GPL porous beams based on Timoshenko beam theory and by applying the generalized differential quadrature method (GDQM). The results denote that either GPLs dispersion pattern or porosity distribution is effective on studied beam behavior but the effect of nanofiller pattern is predominant. Gao et al. [44] studied probabilistic stability analysis of functionally graded graphene reinforced porous beams based on Timoshenko beam theory and by using a non-inclusive Chebyshev metamodel (CMM). Liu et al. [45] presented an analytical solution for nonlinear behavior and stability of FG porous arches with GPLs reinforcements based on the Euler-Bernoulli hypothesis.

b) **Plate-type structures:** Yang et al. [46] presented an investigation about buckling behavior and natural frequency analyses of FG graphene reinforced porous nanocomposite plates by applying Chebyshev-Ritz method and first order shear deformation theory (FSDT). The results denote that the uniaxial, biaxial and shear buckling loads, as well as the fundamental natural frequencies of the proposed plates, decrease with the increase of porosity coefficient, while growing evidently with the addition of GPL weight fraction, highlighting the weakening effect of internal pores and the impressive reinforcement effect of GPLs. Nguyen et al. [47] employed high order shear deformation theory (HSDT) to investigate free vibration, buckling and instability analysis of FG porous plates reinforced by GPLs by applying isogeometric approach. Winkle and Pitchaimani [48] investigated the impact of various porosity distribution and GPL patterns on buckling loads and natural frequencies of FG porous cylindrical panels reinforced by GPLs based on HSDT. The results denote that the bucking and free vibration behaviors are influenced by grading pattern of porosity and GPL. Better free vibration and buckling performance are observed when both GPL dispersion pattern and porosity distribution are non-uniform but symmetric. Based on FSDT, free vibration and buckling behavior of FG porous plates reinforced by GPLs using spectral Chebyshev approach were presented by Rafiei Anamagh and Bediz [49]. Lieu and Hung [50] employed isogeometric analysis (IGA) to investigate static response of piezoelectric functionally graded porous plates reinforced by GPLs based on HSDT. Arefi et al. [51] presented an analytical solution for deflection analysis of porous micro-plates reinforced with FG-GNPs based on Reddy plate theory. Arshid et al. [52] studied thermal buckling analysis of FG graphene nanoplatelets reinforced porous nanocomposite annular/circular microplates based on modified couple stress theory and using GDQM method.

c) **Shell-type structures:** Based on FSDT and employing Rayleigh-Ritz procedure, buckling [53] and torsional buckling responses [54] of FG-GPL porous cylindrical shells were performed by Shahgholian et al. Dong et al. [55] obtained an analytical solution to show buckling response of FG –GPL porous cylindrical shells based on FSDT. Zhou et al. [56] studied nonlinear buckling response of FG porous reinforced GPL cylindrical shells according to classical thin shell theory and the HSDT. Ebrahimi et al. [57] presented an analytical solution based on modified couple stress theory to analyze thermal buckling and forced vibration of a porous GNP reinforced nanocomposite cylindrical shell. Li and Zheng [58] presented an analytical solution for buckling analysis of FG porous cylinder consolidated by graphene platelet subjected to uniform radial loading based on Sanders' thin-walled shell theory. Twinkle et al. [59] studied the impact of grading, porosity and non-uniform edge loads on buckling and natural frequency analyses of FG porous cylindrical panel reinforced by GPLs based on HSDT and applying Galerkin method. Shahgholian et al. [60] presented an analytical solution for buckling analyses of FG-GPL porous cylindrical shell using the Rayleigh–Ritz method based on FSDT. Rahimi et al. [61] performed an analytical solution for static and free vibration analysis of graphene platelet–reinforced porous composite cylindrical shell based on 3D elasticity of theory.

4. Post-buckling analyses

In this section, investigations on post-buckling analyses of FG-GPL porous beams, plate- and shell-type structures are reviewed. In contrast to other analyses, post-buckling of FG-GPL porous structures due to nonlinearity of analyses are limited in number.

a) **Beam:** Based on Timoshenko beam theory and von Kármán type nonlinearity, Chen et al. [62] investigated nonlinear vibration and post-buckling behavior of FG-GPL porous nanocomposite beams by applying the Ritz method and a direct iterative algorithm. Barati and Zenkour [63] employed Euler theory to study post-buckling of FG porous beams reinforced by GPLs by applying the Galerkin method

b) **Plate-type structures:** Ansari et al. [64] investigated buckling and post -buckling of FG porous plates reinforced by GPLs with various shapes and boundary conditions based on HSDT and by employing VDQ-FEM. Yaghoobi and Taheri [65] presented an analytical solution for buckling of sandwich plates with uniform and non-uniform porous core reinforced with graphene nanoplatelets based on refined HSDT.

c) **Shell-type structures:** Salmani et al. [66] presented an analytical solution for nonlinear post-buckling of functionally graded porous cylindrical shells reinforced with GPLs based on the classical sell theory and by utilizing Ritz method and Airy function.

5. Vibration and dynamic analysis

This section reviews the studies on free vibration and dynamic analyses of FG-GPL porous beams, plate- and shell-type structures.

a) **Beam:** Kitipornchai et al. [67] performed an investigation about natural frequency and elastic buckling of FG porous beams reinforced by GPLs based on Timoshenko beam theory and by employing the Ritz method. Yang et al. [68] studied thermo-mechanical vibration of FG curved nanobeam contained porosities and reinforced by GPLs based on curved refined shear deformation beam theory associated with nonlocal strain gradient size scale effect. Zhang et al. [69] studied dynamic analysis of FG graphene platelet-reinforced porous beams on elastic foundation under a moving load based on the Timoshenko beam theory and by employing DSC regularized Dirac-delta method. Priyanka et al. [70] studied the influence of graded porosity, graphene platelets, and axially varying loads on the stability and dynamic response of FG-GPL porous beam. Binh et al. [71] studied free vibration of rotating functionally graded porous beams reinforced by GPLs based on Timoshenko beam theory and applying GDQM. Xu et al. [72] investigated free vibration of functionally graded graphene platelet-reinforced porous beams based on Euler–Bernoulli beam theory with spinning movement and by applying the differential transformation method. In another analytical analysis, Ganapathi et al. [73] presented dynamic characteristics of FG-GPL porous nanocomposite curved beams based on trigonometric shear deformation theory with thickness stretch effect. Yas and Rahimi [74] studied the thermal vibration of FG porous beam reinforced by GPLs based on Timoshenko beam theory and applying GDQM.

b) **Plate-type structures:** Safarpour et al. [75] performed a parametric 3D study for bending and free vibration of FG-GPL porous circular and annular plates for various boundary conditions by applying GDQM. Nguyen et al. [76] presented a novel computational approach to investigate free vibration and static bending analysis of FG-GPL porous plates based on FSDT theory and using Polygonal mesh with Serendipity shape functions. Gao et al. [77] analyzed nonlinear free vibration of FG-GPLs as for a porous nanocomposite plate resting on elastic foundation based on classical plate theory (CPT) with the consideration of von Kármán assumptions. The governing equations were solved by employing DQM. Based on FSDT, an analytical investigation about vibration and stability analysis of FG-GPL porous plates under aerodynamical loading was performed by Saidi et al. [78]. Asemi et al. [79] comprehensively investigated the static, free and forced vibration of FG porous annular sector plate reinforced by GPLs based on the FSDT. Rayleigh-Ritz energy formulation was applied to achieve the governing equations of motion, and FEM was employed to solve the governing equations. Phan [80] presented isogeometric analysis for free and forced vibration analysis of FG-GPL porous nanocomposite plates using a refined plate theory via employing the non-uniform rational B-splines (NURBS). Gao et al. [81] investigated wave propagation in FG porous plates reinforced with GPLs. The governing equations of wave propagation are derived by Hamilton's principle as well as other different plate theories. Zhou et al. [82] investigated free vibration of FG-GPL porous plates applying 3D theory of elasticity and generalized DQM to derive the governing motion equations. Teng and Wang [83] employed the multiple scale and Galerkin methods to analyze the nonlinear forced vibration of FG porous nanocomposite thin rectangular plates reinforced with GPLs based on the von Kármán nonlinear plate theory. Based on the FSDT and Chebyshev polynomials, a novel quadrilateral element for analyzing FG porous plates/shells reinforced by GPLs was presented by Ton-That et al. [84]. Ansari et al. [85] presented a novel solution according to variational differential quadrature (VDQ) for free vibration analysis of postbuckled arbitrary-shaped FG-GPL-reinforced porous nanocomposite plates based upon the TSDT. Gao et al. [86] studied wave propagation in FG porous plates reinforced with GPLs based on different plate theories and by applying semi- analytical solution.

c) **Shell-type structures:** Safarpour et al. [87] investigated three-dimensional static and free vibration analysis of FG-GPLRC truncated conical shells, cylindrical shells and annular plates with various boundary conditions within the framework of elasticity theory. Saidi [88] presented an analytical solution for free vibration of FG-GPL porous truncated conical shell based on Love's first approximation theory. The effect of porosity coefficient, the geometry, and size and weight fraction of GPLs on the natural frequencies have been examined. Ye and Wang [87] investigated the internal resonance of FG- GPL-reinforced metal foam cylindrical shells based on Donnell's nonlinear shell theory and by using Galerkin method. Wang et al. [88] employed Galerkin method to study the nonlinear vibration of metal foam cylindrical shells reinforced with GPLs based on improved Donnell nonlinear shell theory. Moradi Dastjerdi and Behdinan [89] studied stress waves in thick porous graphene-reinforced cylinders under thermal gradient environments by applying a meshless solution based on an axisymmetric model and moving least squares (MLSs) interpolation functions. Salehi et al. [90] presented an analytical solution for nonlinear vibration of shear deformable imperfect FG-GPL porous nanocomposite cylindrical shells based on FSDT. Nejadi et al. [91] employed GDQM approach to investigate the natural frequencies of sandwich pipe by considering porosity and graphene platelet effects on conveying fluid flow based on FSDT. Zhou et al. [92] studied vibration and flutter characteristics of GPL-reinforced functionally graded porous cylindrical panels subjected to supersonic flow based on Reddy's TSDT and by applying the standard Lagrange procedure. Ye and Wang [93] studied nonlinear forced vibration of functionally graded graphene platelet-reinforced metal foam cylindrical shells based on Donnell's nonlinear shell theory and by applying Galerkin method. Ebrahimi et al. [94] studied vibration analysis of FG porous shells reinforced by GPLs based on the FSDT of the shells and by utilizing analytical solution. Pourjabari et al. [95] performed an investigation about the effect of porosity on free and forced vibration characteristics of the GPL reinforcement composite cylindrical shell based on modified strain gradient theory (MSGT) and by applying analytical method. Bahaadini et al. [96] studied vibration analysis of FG porous truncated conical shells reinforced by GPLs based on Love's first approximation theory and by using analytical solution. Pourjabari et al. [97] investigated nonlinear dynamic analysis of porous graphene platelet-reinforced composite sandwich shallow spherical shells based on FSDT and by applying analytical solution. Baghlani [98] studied the free vibration of functionally graded graphene-reinforced porous nanocomposite shells of revolution based on the HSDT and by using Fourier Differential Quadrature (FDQ) technique. In another investigation, based on the same solution, they [99] studied nonlinear dynamic responses of smart sandwich FG porous cylindrical shells reinforced by GPLs under rectangular, sine, and exponential loads based on the HSDT and Sanders' nonlinear theory.

d) **Other geometries:** Sobhani et al. [100] presented semi-analytical solution method for free vibration analysis of sandwich composite coupled conical-cylindrical – conical shells made of FG-CNT and FG-GPL based on FSDT. In another investigation, Sobhani et al. [101] applied FSDT theory and GDQ procedure to investigate the free vibration analysis of hybrid porous nanocomposite joined hemispherical–cylindrical–conical shells. Three phases, including a matrix of epoxy, macroscale carbon fiber and nanoscale 3D graphene foams (3GFs) are considered for the hybrid porous nanocomposite. Kiarasi et al. [102] investigated the free vibration analysis of FG porous joined conical-cylindrical shells based on 2D axisymmetric elasticity theory and by employing FEM in conjunction with Rayleigh-Ritz method. Zhao et al. [103] performed an investigation about vibration characteristics of functionally graded porous nanocomposite blade-disk-shaft rotor system reinforced with GPLs by using the finite element method. Zhao et al. [104] performed an investigation about natural frequency analysis of a spinning porous nanocomposite blade reinforced with graphene nanoplatelets, according to the Kirchhoff's plate theory and by employing a finite element approach. Cai et al. [105] performed an investigation about parameter interval uncertainty analysis of internal resonance of rotating porous Shaft–Disk–Blade assemblies reinforced by GPLs by applying the Chebyshev polynomial approximation method and FEM. Zhao et al. [106] studied free vibration analysis of a functionally graded graphene nanoplatelet reinforced disk-shaft assembly with whirl motion based on Timoshenko beam theory for the shaft and Kirchhoff plate theory for the disk, and by applying Galerkin method. Chai et al. [107] investigated the wave propagation analysis of graphene platelet reinforced porous joined conical-cylindrical shells in a spinning motion based on Donnell's shell theory and by utilizing power the series method. Babaei et al. [108] employed graded finite element method to investigate the natural frequencies of FG porous joined conical-cylindrical-conical shells reinforced by graphene platelet based on 2D elasticity approach

6. Dynamic instability

In this section, dynamic instability analyses of FG-GPL porous beams, plate type structures and shell-type structures are reviewed. Compared with other analyses, the dynamic instability of FG-GPL structures is very limited.

a) **Beam:** Zhao et al. [109] investigated dynamic instability of functionally graded porous arches reinforced by graphene platelets based on classical Euler-Bernoulli theory and Galerkin method. Yang et al. [110] presented an analytical solution for dynamic buckling of rotationally restrained FG porous arches reinforced with graphene platelets under a uniform step load based on Euler-Bernoulli theory.

b) **Plate-type structures:** Li et al. [111] investigated nonlinear vibration and dynamic buckling analyses of sandwich functionally graded porous plate with graphene platelet reinforcement resting on Winkler–Pasternak elastic foundation based on CLPT and by applying Galerkin and the fourth-order Runge–Kutta methods

c) **Shell-type structures:** Khayat et al. [112] employed HSDT and Newton–Raphson in conjunction with Newmark methods to study the probabilistic dynamic stability analysis of fluid-filled porous cylindrical shells reinforced with graphene platelets

7. Challenges and future work

Functionally graded porous structures reinforced by GPLs have excellent potentials to enhance lightweight structures that have great importance in aerospace, automotive, marine, mechanical, and other engineering applications. However, many initial research studies have been developed on this subject; there are still many problems yet to be discussed.

Agglomeration, weak dispersion of GPLs in the matrix and poor bonding between GPL and the matrix are the main problems in manufacturing of GPL nanocomposites. To the best of the authors' knowledge there is no work reported for fabrication process of FG-GPL porous structures. Stir casting method can be used to fabricate porous metal based-nanocomposites, in which the porosity creates when the oxygen gas enters into the melt. The size of the pores can be controlled by controlling the oxygen gas entering the melt. Also, nanoparticles can be distributed uniformly in the melt by using a stir casting machine, in which an ultrasonic agitator is used. However, the main challenge during this procedure is the functionally graded dispersing of nanoparticles. The manufacturing techniques for the micro-/nano FG-GPL porous structures have also not investigated yet. Moreover, to estimate the effective mechanical properties of FG-GPL porous structure, only the Halpin-Tsai micromechanics model was reported in the previous works, presented in Section 2. Therefore, it is necessary to introduce other models capable of considering the effects of thermal conditions, atom vacancy defects, uncertainty in GPL shape, size, and vacancy distribution. In addition, the majority of the reported analyses of FG-GPL porous nanocomposite structures are concentrated on elastic analyses, including bending, buckling, post-buckling, natural frequency and dynamic analyses and dynamic instability of FG-GPL porous beams, plates and shells type structures. There is no research reported about plasticity, failure, fracture and fatigue analyses of these structures so far. Furthermore, there is no study about the optimization of these structures. The multi-objective optimization process with different design variables such as distribution of porosity, GPL dispersion pattern, coefficient of porosity and volume weight fraction of GPL nanofillers seems to be useful for the practical design of these structures.

8. Concluding remarks

Functionally graded porous composite structures reinforced with graphene sheets or GPLs have been proved to be very promising in many engineering applications where lightweight structures are of great importance. This paper has comprehensively discussed and summarised the state-of-the-art of these structures. The review covers all of the important aspects in this emerging and fast-growing area, including the micromechanics based model for determining the effective material properties, analytical and numerical analyses of mechanical and structural behaviors of FG-GPL porous beam, plate, and shell structures under various loading conditions. The key technical challenges and future research directions have also been identified and highlighted.

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