Journal of Computational Applied Mechanics 2022, 53(2): 297-308

DOI: 10.22059/jcamech.2022.342710.719

REVIEW PAPER

Functionally graded saturated porous structures: A review

Masoud Babaei[1], Faraz Kiarasi[1], Kamran Asemi [2,*], Mohammad Hosseini[3]

[1]*Department of Mechanical Engineering, University of Eyvanekey, Eyvanekey, Semnan, Iran,*
[2]*Department of Mechanical Engineering, Islamic Azad University, North Tehran Branch, Tehran, Iran,*
[3]*Department of Mechanical Engineering, University of Hormozgan, Bandar Abbas, Iran.*

Abstract

Functionally graded porous materials are porous structures with porosity gradient distributed over volume. The porous structures having valuable properties, such as lightweight and excellent energy absorption, have been considerably used in different engineering implementations such as aerospace, biomedical, and other industries. Two limit cases are usually considered for the porous structures: 1- The fluid pressure of pores is zero and 2- The pores fill by incompressible fluid and is in saturated condition. Many investigations have been reported on the behavior of functionally graded porous structures. But, most of them are concerned on the drained conditions. However, the investigations into saturated porous structures are limited in number. The present paper (a) specially reviews the mechanical properties of functionally graded saturated porous structures; (b) presents a comprehensive review on the mechanical analyses of these structures in saturated condition; (c) discusses the challenges and possible future works.

Keywords: Functionally graded porous; Saturated; Mechanical analyses; Biot.

Nomenclature:

e_0 **:** Porosity coefficient

e_m: Porosity coefficient for mass density

$\bar{M}$: Biot's modulus

ν_u: Undrained Poisson's ratio

ν: Poisson's ratio

β : Skempton coefficient

G: Shear modulus

α: Biot coefficient of effective stress

ε_{kk} : Volumetric strain

Ψ : Variation of fluid volume content

K_u : Bulk modulus in the undrained state

K: Bulk modulus in the drained state

C_p: Fluid Compressibility in the pores

C_s: Solid Compressibility

δ_{ij} : Kronecker delta

p: Pore fluid pressure

* Corresponding author: *k.asemi@iau-tnb.ac.ir*

1. Introduction

Porous material is a material containing pores filled by a fluid. There are lots of examples for porous materials in the nature and industries (Figure 1). The skeletal part of the material is called matrix or frame and is usually a solid. The porosity is the main characteristics of a porous material. Permeability, tensile strength and electrical conductivity depend on the properties of the matrix and those of the fluid within the pores. If the fluid pressure of pores be zero, the porous structure is called foam. Metallic or polymeric foam depends on the material of skeletal part. Porous structures are widely applied in many industries such as: aerospace, marine, civil, etc. By introducing functionally graded materials (FGMs) [1-28] in which the mechanical properties vary continuously through the structure, functionally graded porous materials (FGPMs) have received much attention by researchers, recently. These are materials with porosity gradually changing throughout their volume. The pores are distributed in the base material with variation in porosity. The variation of porosity may be due to changes in density or size of the pores. Based on the cell structure, FGPMs can be open- or closed-cell structures. In open-cell structures, the pores are interconnected; while in closed-cell structures, each cell is enclosed and isolated by the base material. The gradual change of porosity can impart desirable properties. Examples of nature FGPMs include bamboo with density gradients along the radial direction in its cross section [29], human cancellous bone which is sponge-like cellular structure [30], banana peel [31], and elk antler [32], etc. Artificial FGPMs, such as biomedical implants [32, 33], cushioning materials [34], filtration materials, drug delivery devices [35], and permeable interlocking pavement, etc. are also widely used in industries and daily lives.

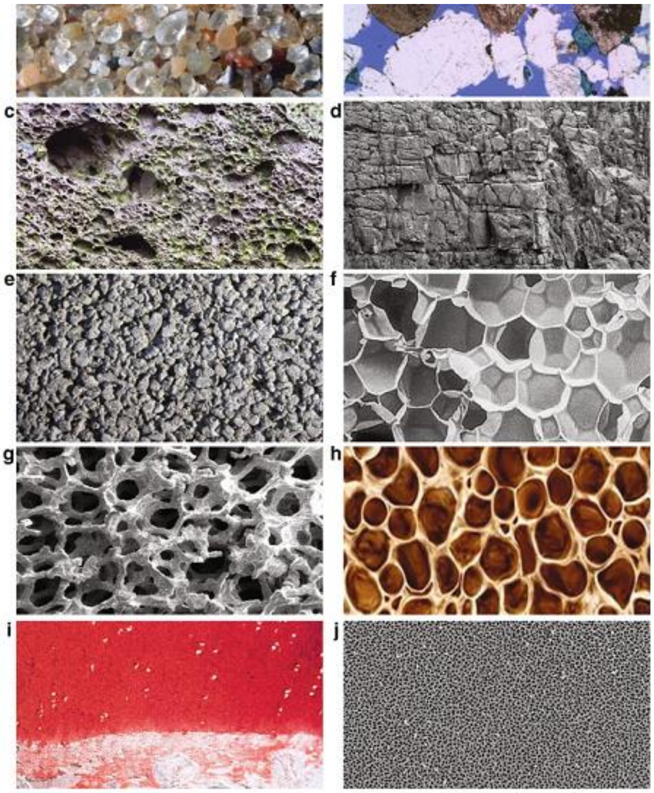

Fig. 1. Various porous materials. (a) Sand. (b) Sandstone. (c) Volcanic rock. (d) Fractured rock. (e) Pervious concrete. (f) Polyurethane foam. (g) Metal foam. (h) Bone with osteoporosis. (i) Articular cartilage. (j) Nanoporous alumina [32].

The extraction of law for description of these materials is a big challenge due to the fluid solid interactions. Two limit states are usually considered for these structures because of their practical application. First state is when the fluid pressure of pores is zero and the second state is when the pores fill by incompressible fluid and is in saturated condition. By this way the fluid be trapped in the pores and the pressure of pores are in the maximum level. Therefore, the stiffness of structures considerably increases. Biot [36] is the pioneer who has studied the behavior of porous structures in saturated condition. Actually, Biot derived the stress- strain relationship of these structures for the first time. After that many researchers have been conducted a lot of investigation about structural behavior of various shapes of these structures such as beam, plate and shells structures. They considered the arrangement of pores, called porosity distribution, and the size of pores, called porosity coefficient, as a design variable. The kind of fluid which fills the pores can be modeled by Biot modulus. Biot modulus describes the ratio of average pressure of local pores to global pressure which is applied to structure. The details of Biot constitutive law is described in Section 2.

Many investigations have been reported on the behavior of functionally graded porous structures. But, most of which are concerned on the drained conditions [37-49]. In a drained condition, the fluid compressibility inside the cavities is in maximum level, and the structure's behavior represents that of without fluid. In this case, the simple Hooke's law applies for modeling the stress-strain relationships of porous structure [50]. However, the investigations on saturated porous structures are limited in number which is reviewed here in details.

This review article is organized as follows. Section 1 reviews the investigations into FG saturated structures. Section 2 reviews assumption of Biot theory and constitutive law for saturated porous materials followed by Section 3 in which key technical challenges and future research directions in this emerging area are discussed and identified.

There are a lot of investigations on saturated porous structures. In details, Theodorakopoulos and Beskos have extended the classical theory of thin rectangular plates to porous materials including Biot's stress-strain relations in porous media. They have established two coupled governing equations and have given the solutions for a simply supported plate by extending Navier's algebraic solution to the porous case. Leclaire *et al.* [51] presented the vibrations of a rectangular saturated porous plate described by two coupled equations involving the time and space derivatives of the deflection and of the relative fluid-solid motion. By using Galerkin's variational method and classical theory of plates, the equations were solved. Buckling of porous beams with varying properties was described by Magnucki and Stasiewicz [52]. They used shear deformation theory for solving the critical load, and also they have investigated the effect of porosity on the strength and buckling load of the beam. Magnucka-Blandzi [53] investigated the problem of axi-symmetrical deflection and buckling of circular porous–cellular plate with the geometric model of nonlinear hypothesis. Magnucka-Blandzi and Magnucki [54] performed an effective design of a sandwich beam with an FG metal foam core and calculated the optimal dimensionless parameters to maximize the critical force and minimize the beam mass. Debowski and Magnucki [55] explored the dynamic stability of a porous rectangular plate to study an axial compressed porous-cellular rectangular plate which is a generalization of sandwich or multilayer plates. Jabbari *et al.* [56] presented an analytical solution for buckling analysis of thin circular FG plates made of saturated porous-soft ferromagnetic materials in transverse magnetic field based on classical plate theory (CLPT). Jabbari *et al.* [57] investigated thermal buckling analysis of functionally graded thin circular plate made of saturated porous materials based on Love–Kirchhoff hypothesis sense and utilizing analytical solution. Based on classical plate theory and shooting method, axisymmetric post-buckling behavior of saturated porous circular plates was presented by Feyzi and Khorshidvand [58]. Rezaei and Saidi [59] presented an analytical solution bases on Navier method for the influence of coupled solid-fluid deformation on natural frequencies of fluid saturated porous plates based on Mindilin plate theory. Analytical solution for deflection and vibration analysis of higher-order shear deformable compositionally graded porous plate were presented by Ebrahimi and Habibi [60]. Panah *et al.* [61] investigated pore pressure and porosity effects on bending and thermal postbuckling behavior of FG saturated porous circular plates based on Love–Kirchhoff theory and by using GDQM. Mojahedin *et al.* [62] performed an investigation about free vibration of functionally graded thin beams made of saturated porous materials based on Euler-Bernoulli theory and by employing analytical solution. A closed form solution for axisymmetric buckling of saturated circular porous-cellular plate based on first-order shear deformation theory was presented by Mojahedin *et al.* [63]. Abjadi *et al.* [64] presented an analytical solution for axisymmetric elasticity solution for an undrained saturated poro-piezoelastic thick disk. Mojahedin *et al.* [65] presented an analytical solution for buckling analysis of functionally graded circular plates made of saturated porous materials based on higher order shear deformation theory. Panah *et al.* [66] investigated axisymmetric nonlinear behavior of functionally graded saturated poroelastic circular plates under thermo-mechanical loading based on CLPT and by employing GDQM in conjunction with Newton–Raphson iterative algorithm. Babaei *et al.* [67] studied the influences of porosity on elastic stability of toroidal shell segments made of saturated porous functionally graded materials on the basis of classical thin shell theory and by applying analytical solution. By employing analytical method, mechanical buckling analysis of saturated porous functionally graded elliptical plates subjected to in-plane force resting on two parameters elastic foundation based on HSDT was presented by Sharifan and Jabbari [68]. Jabbari *et al.* presented an analytical solution for Mechanical buckling of FG saturated porous rectangular plate with piezoelectric actuators [69] and mechanical buckling of FG saturated porous rectangular plate under temperature field [70] based on CLPT. Exact solution for free vibration of thick rectangular plates made of porous materials based on Reddy's third-order shear deformation plate theory was presented by Rezaei and Saidi [71]. Rezaei and Saidi [72] presented an analytical solution for buckling response of moderately thick fluid-infiltrated porous annular sector plates based on Mindlin plate theory. Askari *et al*. [73] presented an analytical solution based on Navier-type for free vibration analysis of porous smart plates based on reddy's plate theory. An analytical study on the free vibration of moderately thick fluid-infiltrated porous annular sector plates based on Mindlin plate theory was presented by Rezaei and Saidi [74]. Rad *et al*. [75] presented an analytical solution for elastic buckling of fluid-infiltrated porous plates based on shear deformation theories. Akbari *et al*. [76] investigated free vibration analysis of thick sandwich cylindrical panels with saturated FG-porous core based on the third order shear deformation theory (TSDT) by using GDQ procedure. Arshid and khorshidvand [77] applied GDQM to study natural frequencies of saturated porous FG circular plates integrated with piezoelectric actuators based on CLPT. On the higher-order thermal vibrations of FG saturated porous cylindrical micro-shells integrated with nanocomposite skins in viscoelastic medium based on sinusoidal theory was presented by Soleimani-Javid *et al*. [78]. Size-dependent magneto-electro-elastic vibration analysis of FG saturated porous annular/circular micro sandwich plates embedded with nano-composite face sheets subjected to multi-physical pre loads via GDQ approach based on Modified couple stress theory in conjunction with FSDT was presented by Amir *et al*. [79]. Natural frequency and dynamic analyses of functionally graded saturated porous annular sector plate and cylindrical panel based on 3D elasticity via FEM approach was presented by Babaei *et al*. [80]. Kiarasi *et al*. [81] applied a novel computational solution (mixed of FE and GDQ approach) to investigate three-dimensional buckling analysis of functionally graded saturated porous rectangular plates under combined loading conditions. Babaei *et al*. applied finite element method to investigated buckling, static [82] and dynamic [83] analyses of functionally graded saturated porous thick beam resting on foundation based on higher order beam theory. Babaei and Asemi [84] employed FEM based on Rayleigh –Ritz approach to investigate static response of saturated FG porous rotating cone based on 2D axisymmetric elasticity. Babaei *et al*. [85] performed an investigation about dynamic analysis of functionally graded rotating thick truncated cone made of saturated porous materials based on 2D axisymmetric elasticity via finite element method. Static response and free-vibration analysis of a functionally graded annular elliptical sector plate made of saturated porous material based on 3D finite element method was presented by Babaei *et al*. [86]. Flexural vibrations analysis of saturated porous circular plates using differential quadrature method based on CLPT was presented by Arshid and Khorshidvand [87]. Alhaifi *et al*. [88] studied large deflection analysis of functionally graded saturated porous rectangular plates on nonlinear elastic foundation via GDQM based on FSDT. Wu *et al*. [89] presented a review investigation on mechanical analysis of functionally graded porous structures with open cell pores. Mojahedin *et al*. [90] presented an exact solution for thermos-elastic analysis of saturated functionally graded porous beam based on the Timoshenko beam theory. Static behavior of functionally graded sandwich beam with fluid-infiltrated porous core based on various beam theories and using Navier's solution was presented by Hung *et al*. [91]. Vibration behavior of poroelastic thick curved panels with graded open-cell and saturated closed-cell porosities based on 3D elasticity theory and using the GDQ prcedure was presented by Heshmati *et al*. [92]. Free vibration of saturated FG porous plate using GDQM in conjunction with third-order shear deformation and poroelasticity theories was presented by Ghorbanpour Arani *et al*. [93]. Arshid *et al*. [94] applied GDQ procedure to investigate the bending and buckling behaviors of heterogeneous temperature-dependent micro annular/circular porous sandwich plates integrated by FGPEM nano-Composite layers based on modified couple stress theory (MCST) in conjunction with FSDT. Quasi-3D tangential shear deformation theory for size-dependent free vibration analysis of three-layered FG porous micro rectangular plate integrated by nano-composite faces in hygrothermal environment was presented by Amir *et al*. [94]. Analytical solution for longitudinal vibration of a floating pile in saturated porous media based on a fictitious saturated soil pile model was presented by Cui *et al*. [95]. Sharifian and Jabbari [68] applied Ritz method to investigate mechanical buckling analysis of saturated porous functionally graded elliptical plates subjected to in-plane force resting on two parameters elastic foundation based on HSDT. Thermal and mechanical stability of a circular porous plate with piezoelectric actuators based on CLPT and using analytical procedure was presented by Mojahedin *et al*. [96]. Mojahedin *et al*. [57] presented an analytical solution for buckling analysis of a functionally graded thin circular plate made of saturated porous materials based on Love-Kirchhoff hypothesis.

2. Porosity distribution and constitutive law of saturated porous material

The literature review denotes that there are many mathematical functions reported for estimation of material properties of functionally graded saturated porous structures. In this manner, researchers generally consider three different patterns for porosity distribution along with the thickness of structure ($0 \leq z \leq h$; i.e for a plate), which are (See Fig.2): a) porous material with nonlinear non-symmetric distribution (PNND) and b) nonlinear symmetric distribution (PNSD) and c) uniform distribution (PUD). In PNSD, 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 PNND, a non-uniform non-symmetric porosity distribution is considered; its value on the bottom surface is higher. Except for uniform porosities, the mechanical properties of the material in terms of shear modulus, Young's modulus and mass density, for a PNND and PNSD, are defined as [84-86]:

$$E = E_1\left[1-e_0 Q\right]$$
$$G = G_1\left[1-e_0 Q\right] \tag{1}$$
$$\rho = \rho_1\left[1-e_m Q\right]$$

in which

$$Q(z) = \begin{cases} (a) PNND & cos\left(\dfrac{\pi.z}{2.h}\right) \\ \text{(b)-PNSD} & cos\left(\dfrac{\pi}{2}-(\dfrac{\pi.z}{h})\right) \end{cases} \tag{2}$$

and $0 \le e_0 \le 1$ is the porosity coefficient. Moreover, E_1, G_1 and ρ_1 denote the Young's modulus, the shear modulus and the mass density at $z=h$ (for a PNND) and at $z=0$ (for a PNSD), whereby $E_j = 2G_j\left(1+\nu\right)$, $j=0,1$, and the Poisson's ratio ν is assumed to be constant in the $z-$ direction (thickness direction).

Shear modulus, Young's modulus and density for Porous material with uniform distribution are as following [64-66]:

$$G = G_1\left[1-e_0\right]$$
$$E = E_1\left[1-e_0\right] \tag{3}$$
$$\rho = \rho_1\left[1-e_m\right]$$

The porosity coefficient e_0 and the porosity coefficient for mass density e_m are described by:

$$e_0 = 1-\frac{G_0}{G_1} = 1-\frac{E_0}{E_1} \tag{4}$$
$$e_m = 1-\sqrt{1-e_0}$$

Constitutive equations of FG saturated porous structure are based on Biot theory [11]. Biot theory deals with the displacements of the skeleton and the pore fluid movement, as well as their interactions due to the applied loads. The main assumptions of this theory are:

1. Infinitesimal transformations occur between the reference and current states of deformation. Displacements, strains and particle velocities are small. Consequently, the Eulerian and Lagrangian formulations coincide up to the first-order. The constitutive equations, dissipation forces, and kinetic momentum are linear (The strain energy, dissipation potential, and kinetic energies are quadratic forms in the field variables).

2. The principles of continuum mechanics can be applied to measurable macroscopic values. The macroscopic quantities used in Biot theory are volume averages of the corresponding microscopic quantities of the constituents.

3. The wavelength is large compared with the dimensions of a macroscopic elementary volume. This volume has well-defined properties, such as porosity, permeability and elastic modules, which are representative of the medium. Scattering effects are thus neglected.

4. The liquid phase is continuous. The matrix consists of the solid phase and disconnected pores, which do not contribute to the porosity.

5. In most cases, the material of the frame is isotropic. Anisotropy occurs by a preferential alignment of the pores (or cracks).

The linear poroelasticity theory of Biot has two characteristics [11]:

1. An increase of pore pressure induces a dilation of the pore.

2. The compression of the pore causes a rise of pore pressure. Particularly when the fluid cannot move freely within the network of pores. These coupled mechanisms display the time -dependent character of the mechanical behavior of the porous structures.

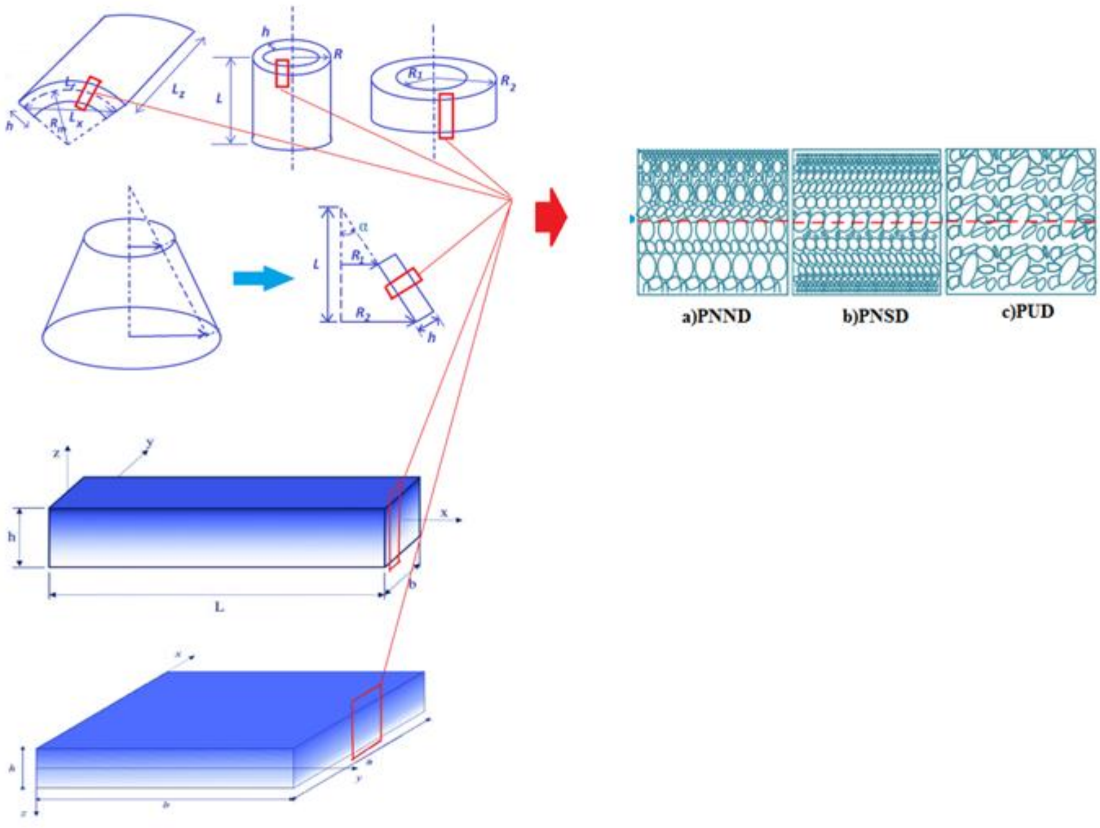

Fig. 2. Porosity distributions [60].

According to the Biot theory, the constitutive law is as [11]:

$$
\begin{aligned}
&\sigma_{ij} = 2G\varepsilon_{ij} + \lambda\varepsilon_{kk}\delta_{ij} - p\alpha\delta_{ij} \\
&p = \bar{M}\left(\Psi - \alpha\varepsilon_{kk}\right) \\
&\bar{M} = \frac{2G\left(v_u - v\right)}{\alpha^2\left(1-2v_u\right)\left(1-2v\right)} \\
&v_u = \frac{v + \alpha\beta\left(1-2v\right)/3}{1-\alpha\beta\left(1-2v\right)/3} \\
&v = \frac{\varepsilon_{jj}}{\varepsilon_{ii}}\Big|_{\sigma_{ii}=0}, p = 0, i \neq \mathrm{j} \\
&v_u = \frac{\varepsilon_{jj}}{\varepsilon_{ii}}\Big|_{\sigma_{ii}=0}, \Psi = 0, i \neq \mathrm{j}
\end{aligned} \tag{5}
$$

$$\alpha = 1 - \frac{K}{K_S}$$

$$K = \frac{2(1+\nu)}{3(1-2\nu)}G$$

$$K_u = \frac{2(1+\nu_u)}{3(1-2\nu_u)}G$$

where *p* denotes pore fluid pressure, for p=0, the Biot law reduces to conventional Hook's law or drained condition. λ is Lame constant, δ_{ij} is Kronecker delta, and α is the Biot coefficient of effective stress (0<α<1). The porosity effect on the behaviour of the porous material without fluid is indicated by this coefficient, and also states that due to porosity, the resistance of the body varies a few percents. $\bar{M}$ is Biot's modulus, G is shear modulus, ν_u is undrained Poisson's ratio (ν< ν_u<0/5), ε_{kk} is the volumetric strain, Ψ is variation of fluid volume content, K_s is the bulk modulus of a homogeneous material. β is the Skempton coefficient introducing the pore fluid property. It is an important dimensionless parameter for describing the effect of the fluid inside the cavities on the behavior of the porous material in the undrained state ($\Psi = 0$), and is the ratio of the cavity pressure to the total body stress.

$$\beta = \frac{dp}{d\sigma}\Big|_{\Psi=0} = \frac{1}{1+e_0 \, C_P/C_s} = \frac{K_u - K}{\alpha K_u} \tag{6}$$

where K_u is the bulk modulus in the undrained state, K is the bulk modulus in the drained state, C_p is the fluid Compressibility in the pores and C_s is solid Compressibility, And also Skempton coefficient can show the effect of fluid Compressibility on the elastic modulus and the compressibility of the entire porous material.

3. Challenges and future work

Functionally graded porous structures 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.

Many investigations have been reported on the behavior of functionally graded porous structures. But, most of them are concerned on the drained conditions. However, the investigations into saturated porous structures are limited in number. Although significant efforts have been devoted to the fabrication of these structures, existing manufacturing processes exhibit limitations on either the fabrication of closed-cell structures or the exact controlling of pore geometry and porosity gradient. The manufacturing techniques for the micro-/nano FG saturated porous structures have also not investigated yet. In addition, the majority of the reported analyses of FG saturated porous structures are concentrated on elastic analyses, including bending, buckling, natural frequency and dynamic analyses of FG saturated 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 and coefficient of porosity seems to be useful for the practical design of these structures.

4. Concluding remarks

Functionally graded saturated porous structures 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 mechanics based model for determining the effective material properties, analytical and numerical analyses of mechanical and structural behaviors of FG saturated porous beam, plate, and shell structures under various loading conditions. The key technical challenges and future research directions have also been identified and highlighted.

References:

[1] A. Hadi, M. Z. Nejad, A. Rastgoo, M. Hosseini, Buckling analysis of FGM Euler-Bernoulli nano-beams with 3D-varying properties based on consistent couple-stress theory, *Steel and Composite Structures, An International Journal,* Vol. 26, No. 6, pp. 663-672, 2018.

[2] M. M. Khoram, M. Hosseini, A. Hadi, M. Shishehsaz, Bending analysis of bidirectional FGM Timoshenko nanobeam subjected to mechanical and magnetic forces and resting on Winkler–Pasternak foundation, *International Journal of Applied Mechanics,* Vol. 12, No. 08, pp. 2050093, 2020.

[3] M. Z. Nejad, N. Alamzadeh, A. Hadi, Thermoelastoplastic analysis of FGM rotating thick cylindrical pressure vessels in linear elastic-fully plastic condition, *Composites Part B: Engineering,* Vol. 154, pp. 410-422, 2018.

[4] M. Mohammadi, M. Hosseini, M. Shishesaz, A. Hadi, A. Rastgoo, Primary and secondary resonance analysis of porous functionally graded nanobeam resting on a nonlinear foundation subjected to mechanical and electrical loads, *European Journal of Mechanics-A/Solids,* Vol. 77, pp. 103793, 2019.

[5] H. Asemi, S. Asemi, A. Farajpour, M. Mohammadi, Nanoscale mass detection based on vibrating piezoelectric ultrathin films under thermo-electro-mechanical loads, *Physica E: Low-dimensional Systems and Nanostructures,* Vol. 68, pp. 112-122, 2015.

[6] S. Asemi, A. Farajpour, H. Asemi, M. Mohammadi, Influence of initial stress on the vibration of double-piezoelectric-nanoplate systems with various boundary conditions using DQM, *Physica E: Low-dimensional Systems and Nanostructures,* Vol. 63, pp. 169-179, 2014.

[7] S. Asemi, A. Farajpour, M. Mohammadi, Nonlinear vibration analysis of piezoelectric nanoelectromechanical resonators based on nonlocal elasticity theory, *Composite Structures,* Vol. 116, pp. 703-712, 2014.

[8] S. R. Asemi, M. Mohammadi, A. Farajpour, A study on the nonlinear stability of orthotropic single-layered graphene sheet based on nonlocal elasticity theory, *Latin American Journal of Solids and Structures,* Vol. 11, pp. 1541-1546, 2014.

[9] M. Baghani, M. Mohammadi, A. Farajpour, Dynamic and stability analysis of the rotating nanobeam in a nonuniform magnetic field considering the surface energy, *International Journal of Applied Mechanics,* Vol. 8, No. 04, pp. 1650048, 2016.

[10] M. Danesh, A. Farajpour, M. Mohammadi, Axial vibration analysis of a tapered nanorod based on nonlocal elasticity theory and differential quadrature method, *Mechanics Research Communications,* Vol. 39, No. 1, pp. 23-27, 2012.

[11] A. Farajpour, M. Danesh, M. Mohammadi, Buckling analysis of variable thickness nanoplates using nonlocal continuum mechanics, *Physica E: Low-dimensional Systems and Nanostructures,* Vol. 44, No. 3, pp. 719-727, 2011.

[12] M. Hosseini, M. Shishesaz, K. N. Tahan, A. Hadi, Stress analysis of rotating nano-disks of variable thickness made of functionally graded materials, *International Journal of Engineering Science,* Vol. 109, pp. 29-53, 2016.

[13] M. Hosseini, M. Shishesaz, A. Hadi, Thermoelastic analysis of rotating functionally graded micro/nanodisks of variable thickness, *Thin-Walled Structures,* Vol. 134, pp. 508-523, 2019.

[14] M. Shishesaz, M. Hosseini, K. Naderan Tahan, A. Hadi, Analysis of functionally graded nanodisks under thermoelastic loading based on the strain gradient theory, *Acta Mechanica,* Vol. 228, No. 12, pp. 4141-4168, 2017.

[15] H. Nazari, M. Babaei, F. Kiarasi, K. Asemi, Geometrically nonlinear dynamic analysis of functionally graded material plate excited by a moving load applying first-order shear deformation theory via generalized differential quadrature method, *SN Applied Sciences*, Vol. 3, No. 11, pp. 1-32, 2021.

[16] M. Shahsavari, K. Asemi, M. Babaei, F. Kiarasi, Numerical investigation on thermal post-buckling of annular sector plates made of FGM via 3D finite element method, *Mechanics of Advanced Composite Structures,* Vol. 8, No. 2, pp. 309-320, 2021.

[17] F. Kiarasi, M. Babaei, R. Dimitri, F. Tornabene, Hygrothermal modeling of the buckling behavior of sandwich plates with nanocomposite face sheets resting on a Pasternak foundation, *Continuum Mechanics and Thermodynamics,* Vol. 33, No. 4, pp. 911-932, 2021.

[18] A. Farajpour, M. H. Yazdi, A. Rastgoo, M. Loghmani, M. Mohammadi, Nonlocal nonlinear plate model for large amplitude vibration of magneto-electro-elastic nanoplates, *Composite Structures,* Vol. 140, pp. 323-336, 2016.

[19] M. Shariyat, K. Asemi, Three-dimensional non-linear elasticity-based 3D cubic B-spline finite element shear buckling analysis of rectangular orthotropic FGM plates surrounded by elastic foundations, *Composites Part B: Engineering,* Vol. 56, pp. 934-947, 2014.
[20] A. Hadi, M. Z. Nejad, M. Hosseini, Vibrations of three-dimensionally graded nanobeams, *International Journal of Engineering Science,* Vol. 128, pp. 12-23, 2018/07/01/, 2018.
[21] M. Hosseini, A. Hadi, A. Malekshahi, M. Shishesaz, A review of size-dependent elasticity for nanostructures, *Journal of Computational Applied Mechanics,* Vol. 49, No. 1, pp. 197-211, 2018.
[22] H. Haghshenas Gorgani, M. Mahdavi Adeli, M. Hosseini, Pull-in behavior of functionally graded micro/nano-beams for MEMS and NEMS switches, *Microsystem Technologies,* Vol. 25, No. 8, pp. 3165-3173, 2019/08/01, 2019.
[23] M. Shishesaz, M. Hosseini, Mechanical Behavior of Functionally Graded Nano-Cylinders Under Radial Pressure Based on Strain Gradient Theory, *Journal of Mechanics,* Vol. 35, No. 4, pp. 441-454, 2018.
[24] M. Shishesaz, M. Hosseini, Effects of joint geometry and material on stress distribution, strength and failure of bonded composite joints: an overview, *The Journal of Adhesion,* Vol. 96, No. 12, pp. 1053-1121, 2020/09/09, 2020.
[25] M. Mousavi Khoram, M. Hosseini, M. Shishesaz, A concise review of nano-plates, *Journal of Computational Applied Mechanics,* Vol. 50, No. 2, pp. 420-429, 2019.
[26] M. Shariati, M. Shishesaz, H. Sahbafar, M. Pourabdy, M. Hosseini, A review on stress-driven nonlocal elasticity theory, *Journal of Computational Applied Mechanics,* Vol. 52, No. 3, pp. 535-552, 2021.
[27] M. Shishesaz, M. Shariati, M. Hosseini, Size-Effect Analysis on Vibrational Response of Functionally Graded Annular Nano-Plate Based on Nonlocal Stress-Driven Method, *International Journal of Structural Stability and Dynamics,* Vol. 0, No. 0, pp. 2250098.
[28] F. Kiarasi, A. Asadi, M. Babaei, K. Asemi, M. Hosseini, Dynamic analysis of functionally graded carbon nanotube (FGCNT) reinforced composite beam resting on viscoelastic foundation subjected to impulsive loading, *Journal of Computational Applied Mechanics,* Vol. 53, No. 1, pp. 1-23, 2022.
[29] E. C. N. Silva, M. C. Walters, G. H. Paulino, Modeling bamboo as a functionally graded material: lessons for the analysis of affordable materials, *Journal of Materials Science,* Vol. 41, No. 21, pp. 6991-7004, 2006.
[30] N. Oxman, S. Keating, E. Tsai, Functionally graded rapid prototyping, *Innovative developments in virtual and physical prototyping*, pp. 483-489, 2011.
[31] M. Ali, A. Qamhiyah, D. Flugrad, M. Shakoor, Theoretical and finite element study of a compact energy absorber, *Advances in Engineering Software,* Vol. 39, No. 2, pp. 95-106, 2008.
[32] P.-Y. Chen, A. Lin, Y.-S. Lin, Y. Seki, A. Stokes, J. Peyras, E. Olevsky, M. A. Meyers, J. McKittrick, Structure and mechanical properties of selected biological materials, *Journal of the mechanical behavior of biomedical materials,* Vol. 1, No. 3, pp. 208-226, 2008.
[33] S. J. Kalita, S. Bose, H. L. Hosick, A. Bandyopadhyay, Development of controlled porosity polymer-ceramic composite scaffolds via fused deposition modeling, *Materials Science and Engineering: C,* Vol. 23, No. 5, pp. 611-620, 2003.
[34] L. Cui, S. Kiernan, M. D. Gilchrist, Designing the energy absorption capacity of functionally graded foam materials, *Materials Science and Engineering: A,* Vol. 507, No. 1-2, pp. 215-225, 2009.
[35] K. Leong, K. Phua, C. Chua, Z. Du, K. Teo, Fabrication of porous polymeric matrix drug delivery devices using the selective laser sintering technique, *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine,* Vol. 215, No. 2, pp. 191-192, 2001.
[36] M. A. Biot, Theory of elasticity and consolidation for a porous anisotropic solid, *Journal of applied physics,* Vol. 26, No. 2, pp. 182-185, 1955.
[37] M. Babaei, F. Kiarasi, S. M. Hossaeini Marashi, M. Ebadati, F. Masoumi, K. Asemi, Stress wave propagation and natural frequency analysis of functionally graded graphene platelet-reinforced porous joined conical–cylindrical–conical shell, *Waves in Random and Complex Media*, pp. 1-33, 2021.
[38] F. Kiarasi, M. Babaei, P. Sarvi, K. Asemi, M. Hosseini, M. Omidi Bidgoli, A review on functionally graded porous structures reinforced by graphene platelets, *Journal of Computational Applied Mechanics,* Vol. 52, No. 4, pp. 731-750, 2021.
[39] F. Kiarasi, M. Babaei, S. Mollaei, M. Mohammadi, K. Asemi, Free vibration analysis of FG porous joined truncated conical-cylindrical shell reinforced by graphene platelets, *Advances in nano research,* Vol. 11, No. 4, pp. 361-380, 2021.
[40] R. Mahmoudi, A. Barati, M. Hosseini, A. Hadi, Torsional Vibration of Functionally Porous Nanotube Based on Nonlocal Couple Stress Theory, *International Journal of Applied Mechanics,* Vol. 13, No. 10, pp. 2150122, 2021.

[41] D. Chen, J. Yang, S. Kitipornchai, Free and forced vibrations of shear deformable functionally graded porous beams, *International journal of mechanical sciences,* Vol. 108, pp. 14-22, 2016.

[42] D. Chen, J. Yang, S. Kitipornchai, Elastic buckling and static bending of shear deformable functionally graded porous beam, *Composite Structures,* Vol. 133, pp. 54-61, 2015.

[43] J. Parthasarathy, B. Starly, S. Raman, A design for the additive manufacture of functionally graded porous structures with tailored mechanical properties for biomedical applications, *Journal of Manufacturing Processes*, Vol. 13, No. 2, pp. 160-170, 2011.

[44] D. Wu, A. Liu, Y. Huang, Y. Huang, Y. Pi, W. Gao, Dynamic analysis of functionally graded porous structures through finite element analysis, *Engineering Structures,* Vol. 165, pp. 287-301, 2018.

[45] D. Chen, S. Kitipornchai, J. Yang, Dynamic response and energy absorption of functionally graded porous structures, *Materials & Design*, Vol. 140, pp. 473-487, 2018.

[46] P. Phung-Van, C. H. Thai, H. Nguyen-Xuan, M. A. Wahab, Porosity-dependent nonlinear transient responses of functionally graded nanoplates using isogeometric analysis, *Composites Part B: Engineering,* Vol. 164, pp. 215-225, 2019.

[47] Ş. D. Akbaş, Vibration and static analysis of functionally graded porous plates, *Journal of Applied and Computational Mechanics*, 2017.

[48] S. Kitipornchai, D. Chen, J. Yang, Free vibration and elastic buckling of functionally graded porous beams reinforced by graphene platelets, *Materials & Design,* Vol. 116, pp. 656-665, 2017.

[49] J. Kim, K. K. Żur, J. Reddy, Bending, free vibration, and buckling of modified couples stress-based functionally graded porous micro-plates, *Composite Structures,* Vol. 209, pp. 879-888, 2019.

[50] A. H.-D. Cheng, 2016, *Poroelasticity*, Springer,

[51] P. Leclaire, K. Horoshenkov, M. Swift, D. Hothersall, The vibrational response of a clamped rectangular porous plate, *Journal of Sound and Vibration,* Vol. 247, No. 1, pp. 19-31, 2001.

[52] K. Magnucki, P. Stasiewicz, Elastic buckling of a porous beam, *Journal of Theoretical and Applied Mechanics*, Vol. 42, No. 4, pp. 859-868, 2004.

[53] E. Magnucka-Blandzi, Axi-symmetrical deflection and buckling of circular porous-cellular plate, *Thin-walled structures,* Vol. 46, No. 3, pp. 333-337, 2008.

[54] E. Magnucka-Blandzi, K. Magnucki, Effective design of a sandwich beam with a metal foam core, *Thin-Walled Structures,* Vol. 45, No. 4, pp. 432-438, 2007.

[55] D. Debowski, K. Magnucki, Dynamic stability of a porous rectangular plate, in *Proceeding of,* Wiley Online Library, pp. 215-216.

[56] M. Jabbari, A. Mojahedin, M. Haghi, Buckling analysis of thin circular FG plates made of saturated porous-soft ferromagnetic materials in transverse magnetic field, *Thin-Walled Structures,* Vol. 85, pp. 50-56, 2014.

[57] M. Jabbari, M. Hashemitaheri, A. Mojahedin, M. Eslami, Thermal buckling analysis of functionally graded thin circular plate made of saturated porous materials, *Journal of thermal stresses,* Vol. 37, No. 2, pp. 202-220, 2014.

[58] M. Feyzi, A. Khorshidvand, Axisymmetric post-buckling behavior of saturated porous circular plates, *Thin-Walled Structures,* Vol. 112, pp. 149-158, 2017.

[59] A. Rezaei, A. Saidi, On the effect of coupled solid-fluid deformation on natural frequencies of fluid saturated porous plates, *European Journal of Mechanics-A/Solids,* Vol. 63, pp. 99-109, 2017.

[60] F. Ebrahimi, S. Habibi, Deflection and vibration analysis of higher-order shear deformable compositionally graded porous plate, *Steel Compos. Struct,* Vol. 20, No. 1, pp. 205-225, 2016.

[61] M. Panah, A. R. Khorshidvand, S. M. Khorsandijou, M. Jabbari, Pore pressure and porosity effects on bending and thermal postbuckling behavior of FG saturated porous circular plates, *Journal of Thermal Stresses*, Vol. 42, No. 9, pp. 1083-1109, 2019.

[62] M. Galeban1a, A. Mojahedin, Y. Taghavi, M. Jabbari, Free vibration of functionally graded thin beams made of saturated porous materials, *Steel and Composite Structures,* Vol. 21, No. 5, pp. 999-1016, 2016.

[63] A. Mojahedin, M. Jabbari, M. Salavati, Axisymmetric buckling of saturated circular porous-cellular plate based on first-order shear deformation theory, *International Journal of Hydromechatronics,* Vol. 2, No. 4, pp. 144-158, 2019.

[64] A. Abjadi, M. Jabbari, R. A. Khorshidvand, Axisymmetric elasticity solution for an undrained saturated poro-piezoelastic thick disk, *Theoretical and Applied Mechanics,* Vol. 46, No. 2, pp. 191-219, 2019.

[65] A. Mojahedin, M. Jabbari, A. Khorshidvand, M. Eslami, Buckling analysis of functionally graded circular plates made of saturated porous materials based on higher order shear deformation theory, *Thin-Walled Structures*, Vol. 99, pp. 83-90, 2016.

[66] M. Panah, A. Khorshidvand, S. Khorsandijou, M. Jabbari, Axisymmetric nonlinear behavior of functionally graded saturated poroelastic circular plates under thermo-mechanical loading, *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* Vol. 236, No. 8, pp. 4313-4335, 2022.

[67] H. Babaei, M. Jabbari, M. R. Eslami, The effect of porosity on elastic stability of toroidal shell segments made of saturated porous functionally graded materials, *Journal of Pressure Vessel Technology,* Vol. 143, No. 3, 2021.

[68] M. H. Sharifan, M. Jabbari, Mechanical buckling analysis of saturated porous functionally graded elliptical plates subjected to in-plane force resting on two parameters elastic foundation based on HSDT, *Journal of Pressure Vessel Technology,* Vol. 142, No. 4, pp. 041302, 2020.

[69] M. Jabbari, M. Rezaei, A. Mojahedin, Mechanical buckling of FG saturated porous rectangular plate with piezoelectric actuators, *Iranian Journal of Mechanical Engineering Transactions of the ISME,* Vol. 17, No. 2, pp. 46-66, 2016.

[70] M. Jabbari, M. Rezaei, A. Mojahedin, M. R. Eslami, Mechanical buckling of FG saturated porous rectangular plate under temperature field, *Iranian Journal of Mechanical Engineering Transactions of the ISME,* Vol. 17, No. 1, pp. 61-78, 2016.

[71] A. Rezaei, A. Saidi, Exact solution for free vibration of thick rectangular plates made of porous materials, *Composite Structures,* Vol. 134, pp. 1051-1060, 2015.

[72] A. Rezaei, A. Saidi, Buckling response of moderately thick fluid-infiltrated porous annular sector plates, *Acta Mechanica,* Vol. 228, No. 11, pp. 3929-3945, 2017.

[73] M. Askari, A. R. Saidi, A. S. Rezaei, M. A. Badizi, Navier-type free vibration analysis of porous smart plates according to reddy's plate theory, in *Proceeding of,* 13.

[74] A. Rezaei, A. Saidi, An analytical study on the free vibration of moderately thick fluid-infiltrated porous annular sector plates, *Journal of Vibration and Control,* Vol. 24, No. 18, pp. 4130-4144, 2018.

[75] E. S. Rad, A. Saidi, A. Rezaei, M. Askari, Shear deformation theories for elastic buckling of fluid-infiltrated porous plates: an analytical approach, *Composite Structures,* Vol. 254, pp. 112829, 2020.

[76] H. Akbari, M. Azadi, H. Fahham, Free vibration analysis of thick sandwich cylindrical panels with saturated FG-porous core, *Mechanics Based Design of Structures and Machines,* Vol. 50, No. 4, pp. 1268-1286, 2022.

[77] E. Arshid, A. R. Khorshidvand, Free vibration analysis of saturated porous FG circular plates integrated with piezoelectric actuators via differential quadrature method, *Thin-Walled Structures,* Vol. 125, pp. 220-233, 2018.

[78] Z. Soleimani-Javid, E. Arshid, S. Amir, M. Bodaghi, On the higher-order thermal vibrations of FG saturated porous cylindrical micro-shells integrated with nanocomposite skins in viscoelastic medium, *Defence Technology*, 2021.

[79] S. Amir, E. Arshid, M. R. G. Arani, Size-dependent magneto-electro-elastic vibration analysis of FG saturated porous annular/circular micro sandwich plates embedded with nano-composite face sheets subjected to multi-physical pre loads, *Smart Structures and Systems, An International Journal,* Vol. 23, No. 5, pp. 429-447, 2019.

[80] M. Babaei, M. H. Hajmohammad, K. Asemi, Natural frequency and dynamic analyses of functionally graded saturated porous annular sector plate and cylindrical panel based on 3D elasticity, *Aerospace Science and Technology,* Vol. 96, pp. 105524, 2020.

[81] F. Kiarasi, M. Babaei, K. Asemi, R. Dimitri, F. Tornabene, Three-dimensional buckling analysis of functionally graded saturated porous rectangular plates under combined loading conditions, *Applied Sciences,* Vol. 11, No. 21, pp. 10434, 2021.

[82] M. Babaei, K. Asemi, P. Safarpour, Buckling and static analyses of functionally graded saturated porous thick beam resting on elastic foundation based on higher order beam theory, *Iranian Journal of Mechanical Engineering Transactions of the ISME,* Vol. 20, No. 1, pp. 94-112, 2019.

[83] M. Babaei, K. Asemi, P. Safarpour, Natural frequency and dynamic analyses of functionally graded saturated porous beam resting on viscoelastic foundation based on higher order beam theory, *Journal of Solid Mechanics,* Vol. 11, No. 3, pp. 615-634, 2019.

[84] M. Babaei, K. Asemi, Stress analysis of functionally graded saturated porous rotating thick truncated cone, *Mechanics Based Design of Structures and Machines,* Vol. 50, No. 5, pp. 1537-1564, 2022.

[85] M. Babaei, K. Asemi, F. Kiarasi, Dynamic analysis of functionally graded rotating thick truncated cone made of saturated porous materials, *Thin-Walled Structures,* Vol. 164, pp. 107852, 2021.

[86] M. Babaei, K. Asemi, F. Kiarasi, Static response and free-vibration analysis of a functionally graded annular elliptical sector plate made of saturated porous material based on 3D finite element method, *Mechanics Based Design of Structures and Machines*, pp. 1-25, 2020.

[87] E. ARSHID, A. KHORSHIDVAND, Flexural vibrations analysis of saturated porous circular plates using differential quadrature method, 2017.

[88] K. Alhaifi, E. Arshid, A. R. Khorshidvand, Large deflection analysis of functionally graded saturated porous rectangular plates on nonlinear elastic foundation via GDQM, *Steel and Composite Structures, An International Journal,* Vol. 39, No. 6, pp. 795-809, 2021.

[89] H. Wu, J. Yang, S. Kitipornchai, Mechanical analysis of functionally graded porous structures: A review, *International Journal of Structural Stability and Dynamics,* Vol. 20, No. 13, pp. 2041015, 2020.

[90] A. Mojahedin, M. Jabbari, T. Rabczuk, Thermoelastic analysis of functionally graded porous beam, *Journal of Thermal Stresses,* Vol. 41, No. 8, pp. 937-950, 2018.

[91] T. Q. Hung, D. M. Duc, T. M. Tu, *Static Behavior of Functionally Graded Sandwich Beam with Fluid-Infiltrated Porous Core,* in: *Modern Mechanics and Applications*, Eds., pp. 691-706: Springer, 2022.

[92] M. Heshmati, F. Daneshmand, Y. Amini, J. Adamowski, Vibration behavior of poroelastic thick curved panels with graded open-cell and saturated closed-cell porosities, *European Journal of Mechanics-A/Solids,* Vol. 77, pp. 103817, 2019.

[93] A. G. Arani, Z. Khoddami Maraghi, M. Khani, I. Alinaghian, Free vibration of embedded porous plate using third-order shear deformation and poroelasticity theories, *Journal of Engineering,* Vol. 2017, 2017.

[94] E. Arshid, S. Amir, A. Loghman, Bending and buckling behaviors of heterogeneous temperature-dependent micro annular/circular porous sandwich plates integrated by FGPEM nano-Composite layers, *Journal of Sandwich Structures & Materials,* Vol. 23, No. 8, pp. 3836-3877, 2021.

[95] C. Cui, K. Meng, C. Xu, Z. Liang, H. Li, H. Pei, Analytical solution for longitudinal vibration of a floating pile in saturated porous media based on a fictitious saturated soil pile model, *Computers and Geotechnics,* Vol. 131, pp. 103942, 2021.

[96] A. Mojahedin, E. F. Joubaneh, M. Jabbari, Thermal and mechanical stability of a circular porous plate with piezoelectric actuators, *Acta Mechanica,* Vol. 225, No. 12, pp. 3437-3452, 2014.