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REVIEW ARTICLE

Computational Modelling and Experimental Challenges of Linear and Nonlinear Analysis of Porous Graded Structure: A Comprehensive Review

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Abstract

This research reviewed the functionally graded (FG) structures exposed to mechanical/thermomechanical loading, including the porosity effect. The review focuses on the modelling of FGM via different theoretical approaches adopted in the past and their responses (static, vibration, and transient) without indicating the detailed mathematical implications and the solution methodologies. The present review is majorly divided into three categories of the analysis reported in the published domain of the linear and nonlinear static, vibration, and transient deflection, including the stress parameters. Further, an effort has been made to discuss the articles from the last decade to show the significant improvements made by the different researchers, with a few exceptions. The main findings and subsequent lacunae are summarized to redefine the future course of action in graded structural modelling and the challenges related to the experimentation.

1 Introduction

Functionally graded material (FGM) originally invented by Japanese scientists in 1984 as an ultrahigh temperature-resistant material [1]. The FGMs are an advanced form of layered composite materials with smooth materials grading in one/more directions (Fig. 1) to achieve tailor-made properties. In general, metal and ceramic are combined to create FGMs. Because of poor thermal conductivity, the ceramic part of FGM provides resistance to high temperatures, whilst a ductile metal part helps in preventing fracture caused by thermal stresses [2]. The variation of ceramic and metal in the FG structures can be achieved using different grading techniques.

1.1 Type of Gradings in FGM

Different material grading approaches, such as power-law (P-FGM), exponential (E-FGM), and sigmoid (S-FGM), can be used to achieve the material property variation [3]. These grading techniques are capable of computing the unidirectional as well as multidirectional variation of FG counterparts. Through-thickness variation (unidirectional) of material properties using P-FGM (Fig. 2), S-FGM (Fig. 3), and E-FGM (Fig. 4) grading can be achieved using Eqs. (1), (2) and (3), respectively.

$$P(z) = (P^c - P^m)\left(\frac{1}{2} + \frac{z}{h}\right)^{nz} + P^m \tag{1}$$

where, $P(z)$ is material property of FGM. P^c and P^m are respective ceramic and metal properties, and nz is transverse power exponent.

$$P(z) = \begin{cases} (P^c - P^m)\left[1 - \frac{1}{2}\left(1 - \frac{2z}{h}\right)^{nz}\right] + P^m & \text{for } 0 \le z \le \frac{h}{2} \\ (P^c - P^m)\left[\frac{1}{2}\left(1 + \frac{2z}{h}\right)^{nz}\right] + P^m & \text{for } -\frac{h}{2} \le z \le 0 \end{cases} \tag{2}$$

$$P(z) = P^c \times e^{-\frac{1}{2}\ln\left(\frac{P^c}{P^m}\right)\left(1 - \frac{2z}{h}\right)} \tag{3}$$

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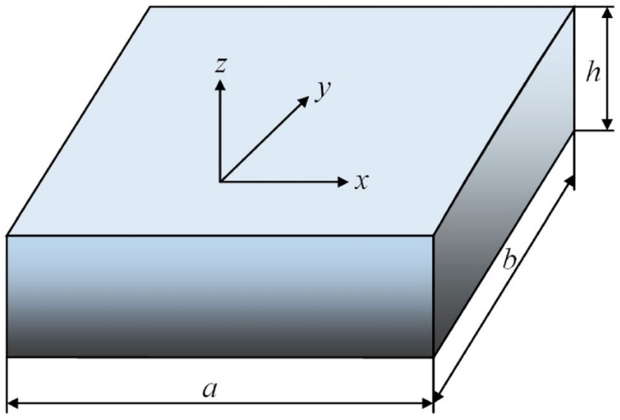


Fig. 1 FG plate with gradual material variation

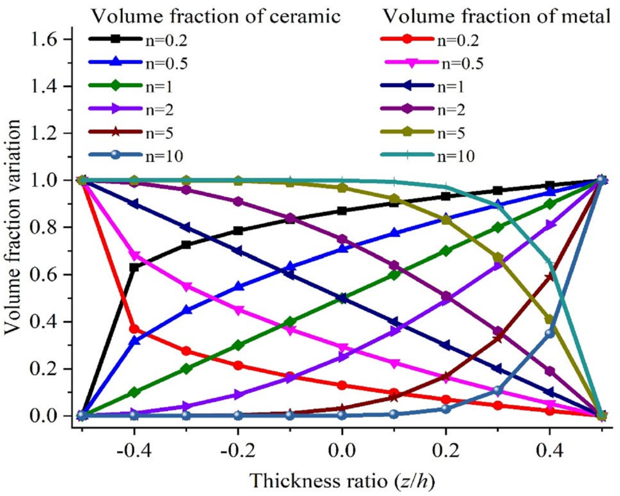


Fig. 2 Material grading in P-FGM

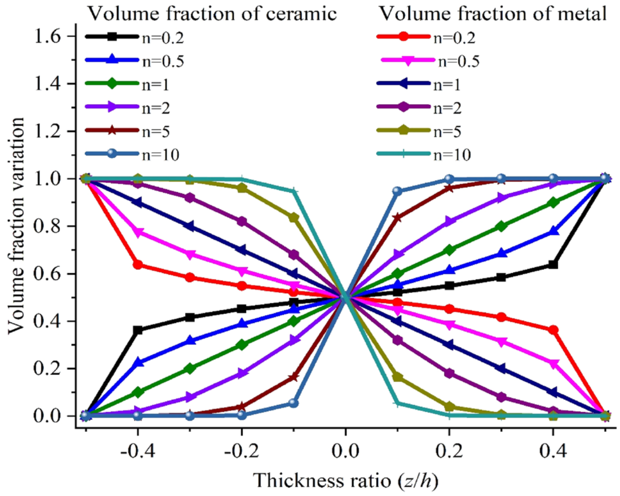


Fig. 3 Material grading in S-FGM

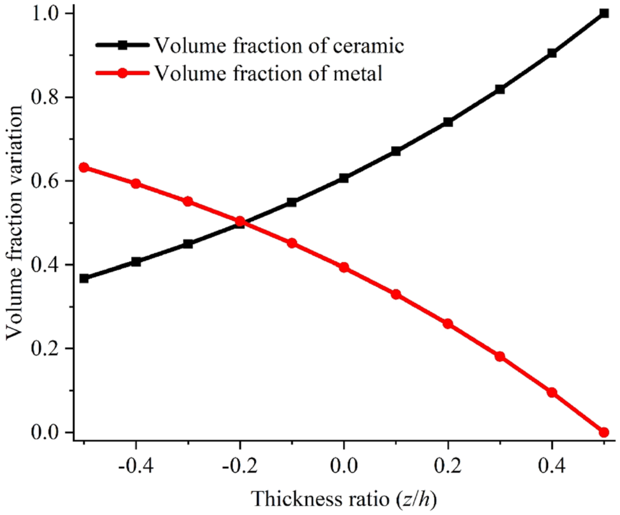


Fig. 4 Material grading in E-FGM

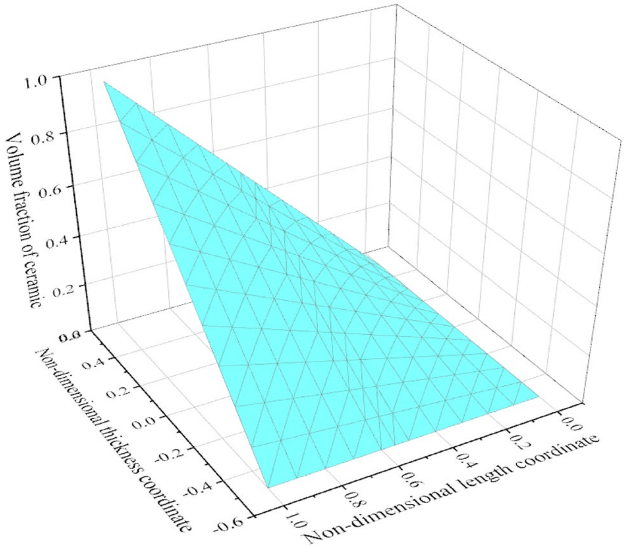


Fig. 5 Bidirectional ceramic volume fraction variation in P-FGM ($nx = nz = 1$)

Similarly, the bidirectional material property variation [4, 5] in the FG (P-FGM) structure (Fig. 5) can be computed using Eq. (4).

$$P(z,x) = (P^c - P^m)\left(\frac{1}{2}+\frac{z}{h}\right)^{nz}\left(\frac{x}{l}\right)^{nx} + P^m \tag{4}$$

where, nx is longitudinal power exponent.

1.2 Porosity in FGMs

During fabrication, porosity defects may be induced into the FG structures. In general, even and uneven [6–9] porosities are considered through the panel thickness, as shown in Fig. 6. The modified equations for calculating properties of the FG panel (P-FGM) introducing even and uneven porosity are given in Eqs. (5) and (6), respectively.

$$P(z) = (P^c - P^m)\left(\frac{1}{2} + \frac{z}{h}\right)^n + P^m - \frac{\beta}{2}(P^c + P^m) \tag{5}$$

$$P(z) = (P^c - P^m)\left(\frac{1}{2} + \frac{z}{h}\right)^n + P^m - \frac{\beta}{2}(P^c + P^m)\left(1 - \frac{2|z|}{h}\right) \tag{6}$$

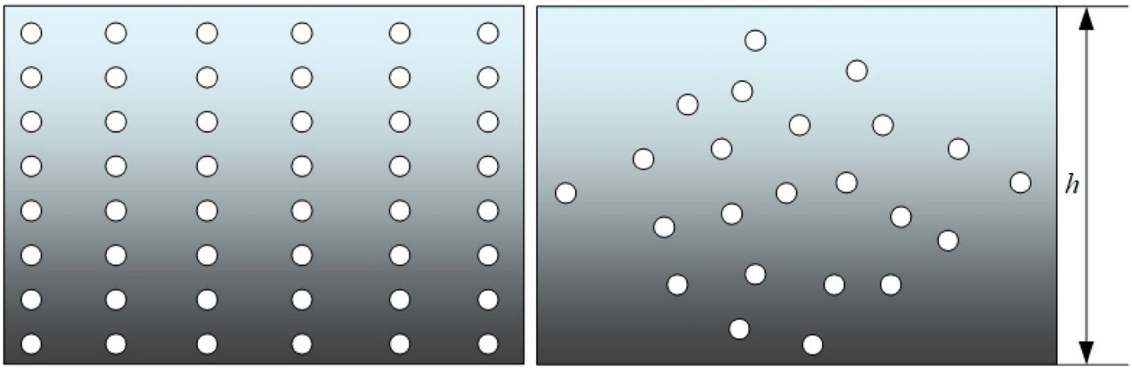
Based on the grading direction, pattern and porosity distribution, the classification of the FGMs is shown in Fig. 7.

1.3 Theories Used for Analysis of FG Structures

A number of theories, including the classical theory (CLT) [10, 11], the first-order shear deformation theory (FSDT) [12, 13], and the higher-order shear deformation theory (HSDT) [14, 15], are utilized for analysis of FGM panels. The CLT only applies to thin structures since it assumes that the transverse normal is inextensible and ignores shear deformation [16]. The FSDT holds all the CLT's assumptions, excluding the condition of normality and needs a shear correction factor (SCF) [17]. According to earlier research [16, 18], the HSDT offers a precise approximation of the transverse shear stresses and strains with no SCF considering fewer assumptions. Apart from the theories mentioned above, zigzag theory [19], Carrera's unified formulation (CUF) [20, 21] etc., are also adopted by a few researchers to study the structural characteristics of FGMs.

1.4 Solution Techniques for Structural Analysis

A variety of benchmark solution techniques, i.e. 3D elasticity [22–24], exact [25], analytical method [26], a meshless method [27, 28] etc., are adopted to study the structural behaviour of the FGMs considering all the real-life



(a) Even porosity (b) Uneven porosity

Fig. 6 Porosity distribution in the FG panel

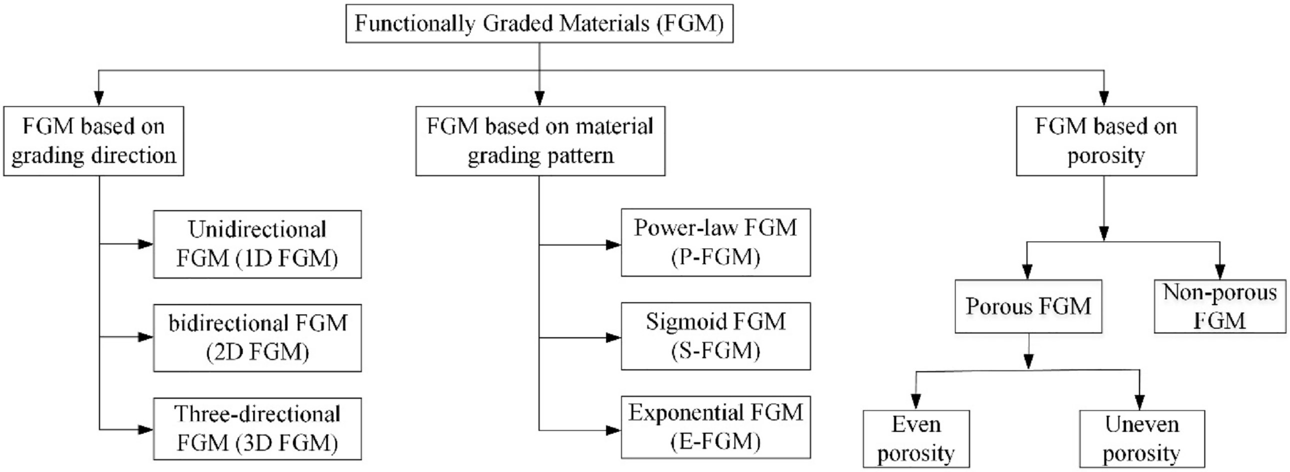


Fig. 7 Classification of FGM

situations. However, the above-mentioned techniques are capable of analyzing the global responses only, not local ones. Therefore, the FE approach is used by most of the researchers [9, 12, 29–32], as it is capable of computing local as well as global responses.

1.5 Temperature Distribution (TD) in FGM

Let T_c and T_m be the temperature of ceramic (top) and metal (bottom) layers, respectively, and T_0 is the ambient temperature. The temperature variation through graded panel's thickness can be considered in three different ways as uniform TD [33] as expressed in Eq. (7), linear TD [34] as in Eq. (8) and nonlinear TD. The nonlinear TD in the lateral direction of FG panel is achieved by utilizing a one-dimensional (1D) heat conduction equation [35] given by Eq. (9).

$$T(z) = T_0 + T_{cm} \tag{7}$$

where, T_0 is ambient temperature and $T_{cm} = T_c - T_m$.

$$T(z) = T_m + T_{cm}\left(\frac{1}{2} + \frac{z}{h}\right) \tag{8}$$

$$-\frac{d}{dz}\left(k(z)\frac{dT}{dz}\right) = 0 \tag{9}$$

$$\text{where, } z = \begin{cases} -\dfrac{h}{2} & \text{at } T = T_m \\ \dfrac{h}{2} & \text{at } T = T_c \end{cases}$$

The temperature in Eq. (9) is computed analytically and expressed as:

$$T(z) = T_c - \frac{T_{cm}}{\int_{-h/2}^{h/2} \frac{1}{k(z)} dz} \int_{-h/2}^{z} \frac{1}{k(z)} dz \tag{10}$$

where, $k(z)$ is thermal conductivity.

1.6 Temperature-Dependent Material Properties

The FG structures are exposed to the combined thermomechanical loading in real-time applications. To achieve realistic structural responses under thermal environmental conditions, the material properties need to be considered as TD [2, 36–38] as expressed in Eq. (11). Also, dynamic loading is necessary to consider instead of static when these structures are exposed to such unlike conditions for a longer time. In view of such loading conditions, the deformation characteristics may follow nonlinear behaviour rather than linear. The linear model cannot accurately predict the responses of such nonlinear problems and thus needs a technique considering nonlinear effects. Therefore, researchers have developed several solution techniques to estimate the nonlinear structural responses with great accuracy, considering thermal environmental conditions. A brief review of the recently published literature on linear/nonlinear static, frequency and transient analysis of the FG panels with/without porosity under ambient/thermal environment is presented in this article. The review of the literature is divided into three major sections, i.e. static, vibration, and transient analysis of FG structures.

$$P(T) = P_0\left(\frac{P_{-1}}{T} + 1 + P_1T + P_2T^2 + P_3T^3\right) \tag{11}$$

2 Static Deflection and Stress Analysis of FG Structures

The study of the flexural behaviour of the FG structures is important from the design perspective. The deformation behaviour is associated with the load-bearing capacity of the structures. The structure deformed due to variety of loads, i.e. mechanical, thermal, or combined thermomechanical load. In this regard, the subsections below present the review on the graded panels' static bending and stress analysis under the mechanical/thermomechanical load with/without considering porosity.

2.1 Static Deflection and Stress Analysis Under Ambient Conditions

2.1.1 Linear Analysis of Unidirectional FGM

The bending and stress analyses of FG flat panels exposed to mechanical load are addressed [20, 21] using Carrera's unified formulation (CUF) and principle of virtual displacements. A 3D elasticity solution is presented [22] for the bending and stress analysis of FG plates. A closed-form solution was obtained via the extended Kantorovich method and CPT [39] for flexural analysis of FGM plates (annular). The static analysis of FG shells and plates is performed using HSDT [40]. A mathematical model is developed based on the FSDT to study static and dynamic investigation of FG shells [41, 42] and FG carbon nanotube-reinforced composites (CNTRC) [43]. Similarly, static and dynamic characteristics of the FG elliptical plates are investigated using a 3D elasticity theory [23]. A non-uniform rotational B-spline (NURBS) based FE technique in conjunction with FSDT is used to examine the static and dynamic behaviour of FG plates [12]. The static bending analysis of FG CNTRC cylinders is performed [28] using a mesh-free method. A third-order shear deformation theory (TSDT) is employed [44] for bending analysis of FG shell panels. A bending and vibration analysis of FG composite doubly-curved shells is carried out by utilizing HSDT kinematic model [45]. Using a higher-order beam theory, the bending and frequency behaviour of FG layer coated nanobeam is studied [46]. Also, the review is presented on the efficiency of nanomaterials for solar energy storage systems [47] and machine learning applications in additive manufacturing [48].

2.1.2 Linear Analysis of Bidirectional FGM

The Euler-Bernoulli beam theory (EBBT) has been adopted in [49] to compute the flexural responses and the stress values of 2D FGB. The 2D FGM plates are analyzed in [50] using the FEM formulation based on the TSDT kinematics to compute flexural deflections and the corresponding stresses. A NURBS essential function and isogeometric analysis (IGA) are used to study the optimum material distribution for the 2D FGB under static load [51]. Mechanical bending and frequency analyses of FG doubly-curved shells are performed using 2D and quasi-3D HSDTs [52]. Third-order beam theory is adopted [27] for the flexural analysis of 2D FGB. The effect of moving load on the deflection parameters (static and dynamic cases) is performed in [53] for the 2D FGB via the FSDT types of deformation kinematics. Similarly, Timoshenko beam theory (TBT) in association with nonlocal strain gradient theory (SGT) has been adopted in [54] for the evaluation of deflection values under the influence of transverse and axial loading to count the static bending and buckling responses of the 2D-FG beam.

2.1.3 Nonlinear Analysis

Nonlinear bending and frequency responses of FG piezoelectric plates are analyzed using Mindlin-Reissner plate theory/FSDT and Green-Lagrange nonlinear strains (GLNS) [55, 56]. A similar analysis is carried out for the FGB using TBT and EBBT in the framework of SGT and considering a closed-form solution [57]. A differential quadrature method (DQM) combined with EBBT and von-Karman nonlinear strain terms (VKNS) are utilized in [58] to compute deflections (nonlinear) and dynamic responses of the exponentially graded 2D-FGB. Similarly, the HSDT kinematics in conjunction with VKNS is adopted in [59] to evaluate nonlinear deflections of the FGM plate using the modified radial point interpolation technique. A nonlocal SGT in the exponential shear deformation beam theory framework is utilized in [60] to establish the 2D-FGB model for nonlinear flexural and post-buckling analysis.

2.1.4 Analysis of Porous Structures

The effect of porosity on FGB's static bending and buckling responses is highlighted in [61] using the TBT kinematics. A 3D elasticity theory and DQM are utilized [62] for the bending and stress analysis of FG auxetic-porous circular plates subjected to mechanical load. The porous FG plate bending, stress and eigenvalue buckling load parameters are investigated through the Chebyshev-Ritz method and FSDT framework [63]. A nonlocal SGT is utilized to model the FG porous nanotube to investigate nonlinear bending responses [64]. The FSDT type of deformation polynomial is adopted in [4] to compute the static and eigenvalue characteristics (frequency and buckling) for the 2D FG plate type of structure in association with the IGA concept. Later, a four-unknown type of HSDT kinematic model is developed [65] to examine the porous FG nanoshell structural responses (bending, frequency and buckling load parameter). Similar analyses of porous FG nanoplates are performed in [66] using nonlocal elasticity and Reissner-Mindlin theory. The vibration and/or static bending analysis of FG porous plates is performed [67, 68] by employing FEM. The nonlinear bending and stability analysis of FGM porous arches is performed using the potential energy method based on EBBT [69]. Nonlinear buckling and post-buckling behaviour of FG porous panels exposed to axial load are studied [70] using Donnell shell theory and VKNS.

2.2 Static Deflection and Stress Analysis Under Thermal Environment

2.2.1 Linear Analysis of Unidirectional FGM

The thermoelastic bending responses of FG cylindrical shells are analyzed [71] using CLT. The bending and stress analysis of 3D FG plates under a thermal environment is carried out using DQM and 3D elasticity theory [24]. The IGA and modified SGT are adopted in [72] to study the bending and buckling characteristics of the FG microplates under thermomechanical loads. Bending and vibrational analyses of 3D FGM plates under a thermal environment are carried out [73] utilizing 3D elasticity theory and IGA. The FSDT is applied [74] for flexural analysis of FG cylindrical nanoshells in a thermal environment. The IGA-FSDT approach is adopted [75] for bending and frequency analyses of FGM plates with cutout and exposed to a hostile environment.

2.2.2 Nonlinear Analysis

An analytical approach is presented for the nonlinear bending analysis of tapered FGB exposed to thermomechanical load [26]. Nonlinear static bending and dynamic characteristics of FG composite beams under hygrothermal [76] and thermal [77] environments are investigated using HSDT and VKNS. A similar kinematic model, along with nonlinear strains, is adopted for flexural analysis of FG composite plates [78] and curved tubes [79] subjected to the thermal environment. An analytical approach following the two-step perturbation technique is adopted in [79] to obtain the closed-form solutions for the nonlinear behaviour of the FGM tubes. Further, the HSDT, combined with Green's strain, is utilized to investigate the nonlinear bending and buckling behaviour of FG plates under thermomechanical loading [37]. The static analysis (nonlinear) of FGM shells/plates under thermomechanical loading is performed [80] using CPT. A modified SGT in association with VKNS is adopted [81] to examine the nonlinear thermal deformation of FG microplates.

2.2.3 Analysis of Porous Structures

The nonlinear static bending responses of the FG beam with porosity under thermal environment are examined [82] using Lagrangian FEM and 2D continuum model. The effect of porosity on bending and frequency analysis of FG plates exposed to a thermal environment is presented [83] by employing higher-order shear and normal deformation theory (HSNDT). A cell-vertex FEM is developed [84] for the thermoelastic bending and stress analysis of FG porous structure with TD properties. Nonlinear structural analysis of porous FG shallow shell panel with variable grading patterns, subjected to hygro-thermo-mechanical load, is presented using FSDT and GLNS [85]. Similarly, the nonlinear flexural behaviour of FG porous microplates [30] and micro-tubes [86] under a thermal environment is analyzed using HSDT and VKNS. The effect of porosity on the FGB's nonlinear deflection is presented [87] using FSDT and nonlinear Green's strains. Nonlinear buckling and post-buckling characteristics of porous FG shells/plates in a thermal environment are studied in [88, 89] using classical theory/HSDT and VKNS.

It can be observed from the majority of the articles that the static deflection/stress analysis of unidirectional FG flat panels is performed majorly using lower-order kinematics (CPT/FSDT) under ambient conditions. In contrast, the analysis of curved structures is limited in number. Also, the nonlinearity in most of the published work is introduced via von-Karman nonlinear strains. Further, the articles relevant to the flexural analysis are considered GT-I grading to compute the effective material properties without considering porosity kind of defects.

3 Vibration Analysis

A brief review on the linear/nonlinear eigenfrequency analysis of FGM panels under ambient and thermal environments with and without porosity is presented in this section. Additionally, the following subsections have analysed and presented numerous mathematical models that were previously developed to study the aforementioned characteristics in the elevated environmental conditions.

3.1 Vibration Analysis Under Ambient Conditions

3.1.1 Linear Analysis of Unidirectional FGM

Free vibration characteristics of the FG plate with in-plane material grading are examined using CPT [90]. A DQM is adopted to examine the vibrational responses of FG circular/annular plates [91]. Likewise, vibration analysis of the 3D FGM Euler-Bernoulli beam is presented using a nonlocal SGT [92]. A material optimization of 3D FG plates is performed for vibration and buckling analysis using generalized shear deformation theory (GSDT) and IGA [93]. HSDT and IGA-based numerical analysis is performed to examine the vibrational behaviour of multidirectional plates with variable thickness [14]. Free and forced vibration of the FG plate in contact with a turbulent fluid is investigated using TSDT [94]. An EBBT is applied for vibrational analysis of sandwich FGB [95]. The free vibrational behaviour of 3D FG plates and shells (doubly-curved) is studied [96] using Eringen's nonlocal theory (ENT). A damage index based on the closed-form of modal flexibility sensitivity is derived in [97] for damage identification of FG beams. The vibrational behaviour of the sandwich beam is investigated [98] using a simulation tool (ANSYS).

3.1.2 Linear Analysis of Bidirectional FGM

HSNDT and a Petrov-Galerkin method utilized to design a 2D FG plate to find the optimal natural frequencies [99]. A 3D elasticity solution is provided for the frequency and modal displacement analysis of 2D FG curved panels [100]. Free and forced vibrations of 2D-FGB with different end-supports are investigated by utilizing TBT and EBBT [101]. A 3D exact shell model and 2D models (FEM and DQM) are used to analyze the cylindrical bending in the vibration analysis of FG shells and plates [25]. A higher-order Timoshenko beam element is established to study the vibrational analysis of 2D FGB [102]. Reissner's theorem has been adopted in [103] to analyze the eigenfrequencies of 2D FG plates. An eigenfrequency analysis of 1D/2D FGB is performed using TBT and EBBT in the framework of FEA [104]. An IGA is proposed in [105] for the 2D FG plates in the fluid medium to investigate the eigenvalues.

3.1.3 Nonlinear Analysis

A CPT and VKNS used [106] to compute the nonlinear eigenfrequencies of the FG plates. A FE model is developed using FSDT and GLNS for computation of nonlinear frequency responses (NFR) of FG plates integrated with piezoelectric patches [29]. Nonlinear frequency and static analyses of FG plates are carried out using FSDT and GLNS [55]. A Sanders–Koiter theory applied to examine the NFR of FG cylindrical shells [107]. A Homotopy perturbation method in association with VKNS is adopted for the nonlinear vibration analysis of FG plates [108] and nanobeam [109]. Nonlinear vibrations of FG cylindrical shells are analyzed by employing Donnell's nonlinear theory [110]. A generalized DQM in conjunction with EBBT is adopted for the nonlinear vibration analysis of 2D FGB [111]. Nonlinear vibration of in-plane 2D FG plates with geometrical imperfection is investigated [112] using the classic Kirchhoff hypothesis and VKNS. A higher-order cubic-quintic model is employed to analyze the NFR of 2D FGB [113]. The frequency response of FG plates is studied [114]numerically using FSDT and VKNS.

3.1.4 Analysis of Porous Structures

A TBT in conjunction with nonlinear strain, i.e. VKNS adopted in [115] for the nonlinear frequency and post-buckling analysis of FG beams with porosity. Similar theories, as discussed earlier, along with the modified couple stress theory (MCST), are adopted in [116] to compute the nonlinear vibration analysis of porous 2D FGB. Vibration analysis (free and transient) of FG porous annular plates and cylindrical panels is performed [117] using a 3D elasticity theory. FSDT and HSDT, along with VKNS employed [118] for the investigation of NFR of porous cylindrical panels. The imperfection sensitivity in the NFR of 2D porous FGB [119] is analyzed using FSDT and VKNS. A sinusoidal shear deformation theory is applied to examine the vibrational and buckling behaviour of 2D FG sandwich plates [120]. FSDT is adopted in [121] for the vibrational analysis of FG porous plates. Geometrical nonlinear analysis of porous FG plates is performed [122, 123] using GSDT/refined shear deformation theory and VKNS. The classical and shear deformation shell theories employed in [124] for vibration analysis of porous FG shells. An analytical approach was proposed through a closed-form solution to study the vibration characteristics. A layerwise shear deformation theory/FSDT is applied [125, 126] for free vibration analysis of the FG porous plates.

3.2 Vibration Analysis Under Thermal Environment

3.2.1 Linear Analysis

Vibrational analysis of FGM plates with circular/non-circular cutouts under a thermal environment is carried out using a simulation tool (ANSYS) [127]. A similar analysis is performed for FG sandwich plates exposed to a thermal environment considering TD properties and using higher-order theory, and establishing the closed-form solutions [128]. Further, thermal vibration and buckling analysis of thick FG panels are studied [13] using FSDT. The frequency characteristics of the FGB with material property variation along the longitudinal and lateral directions are investigated [129] using the CLT considering closed-form characteristic equations. A higher-order layerwise theory is adopted to investigate thermally induced vibrations of FG flat/shell panels [130]. ENT is applied [131] for the vibrational analysis of rotary tapered FGB in a thermal environment considering TD material properties. The thermal vibration and buckling behaviour of 2D FGB investigated by utilizing EBBT [132]. The effect of multidirectional temperature distribution on frequency characteristics of the 2D FG microplates is presented [133] using TSDT. A 1D-heat conduction equation and Kirchhoff's plate theory are employed to investigate the frequency responses of FGM plates with thermoelastic coupling effect [134]. FSDT kinematics is applied for stability and vibrational analysis of initially stressed FGM plates under a thermal environment [135].

3.2.2 Nonlinear Analysis

HSDT and VKNS are utilized for the investigation of NFR of FG doubly-curved panels [38, 136], FG CNTRC cylindrical shells [137], FGB [138] and FG graphene-reinforced composite (GRC) plates [139] under thermal environment. Large amplitude frequency and dynamic responses of FG doubly-curved shells exposed to a thermal environment are investigated using Reddy's TSDT [140]. Reddy's HSDT and VKNS are employed [141] for the investigation of NFR of FG doubly-curved shells in a thermal environment, taking into account TD properties. The effect of hygro-thermal load on the NFR of 2D FGB is presented [142] by employing EBBT and VKNS.

3.2.3 Analysis of Porous Structures

Author's	Year	Contributions
Wang and Zu [10]	2017	Geometrical nonlinear vibrational characteristics of FG plates with porosity under a thermal environment are studied.

Author's	Year	Contributions
Zhou et al. [143]	2018	Vibrational and flutter analysis of FG plates in a thermal environment, including the effect of porosity, is performed using FSDT kinematics.
Ibnorachid et al. [144]	2019	Vibrational responses of porous FGB in a thermal environment are examined using HSDT.
Ebrahimi et al. [145]	2020	The porous FG cylindrical shell's thermal vibration and buckling behaviour are examined using FSDT kinematics.
Ahmed et al. [146]	2021	The dynamic responses of porous FG plates in an elevated temperature are computed using higher-order refined plate theory.
Fang, Yin, and Zhang [147]	2022	Vibrational analysis of porous FGM plates exposed to a thermal environment is carried out using FSDT and MCST.
Pham et al. [148]	2022	Bending and hygro-thermo-mechanical vibration analysis of an FG porous sandwich shell is performed.

The published articles in the field of the eigenvalue (linear/nonlinear) analysis of the graded structure have already been established in many folds. However, it can also be observed that the majority of research focuses on numerical modelling and effort made to reduce the mathematical calculation. Hence, the available studies are approximated nonlinear strain in the framework lower-order displacement field considering the rotational nonlinearity effect. Additionally, the influences of porosity, grading and curvature have not been addressed to achieve the final accomplishment of graded structural analysis.

4 Transient Deflection and Stress Analysis

As discussed earlier, the FG panels are exposed to dynamic loading when subjected to a hostile environment. The past literature for transient analysis of the FG structures with/without porosity under ambient/thermal environments is reviewed and addressed in the following lines to better understand the structural analysis.

4.1 Transient Deflection and Stress Analysis Under Ambient Conditions

4.1.1 Linear Analysis

Transient dynamic and frequency analysis of conical FG shells subjected to mechanical shock loading is performed using displacement-based layerwise theory and DQM [149]. An FE-based model was developed using FSDT for transient analysis of conical FG shells subjected to moving load [150]. A DQM, state space method, and Laplace transforms numerical inversion method adopted to examine the transient characteristics of FG annular plates with different end supports [151]. The transient deflection and stresses of FG shells are computed using FSDT kinematics [152]. Similarly, transient responses of FG annular and sector plates exposed to circumferentially distributed load are computed using FSDT [153]. A quasi-3D theory is applied to investigate the dynamic characteristics of the sandwich 2D FGB under a moving load [154]. The scaled boundary FEM utilized for the dynamic analysis of sandwich FGB [32].

4.1.2 Nonlinear Analysis

A CLT and von Karman-Donnell nonlinearity (VKDN) applied [11] for the nonlinear dynamic analysis of cylindrical FG panels. NT responses of FG doubly-curved shells are computed by employing CLT [155]. FSDT and GLNS utilized for the large deformation-induced static and transient analysis of curved FGB [156]. A VKNS utilized for NT analysis of FG plates exposed to blast loading [157]. The nonlinear dynamic behaviour of FG shells is examined by employing HSDT in association with GLNS [158]. Similarly, VKNS, in conjunction with HSDT [159] and FSDT [160] adopted for NT analysis of flat panels made of FGMs.

4.1.3 Analysis of Porous Structures

Porosity-dependent NT responses of FG plates are illustrated using HSDT and VKNS [161]. The FSDT and VKNS are adopted in [162] to study the dynamic characteristics of porous 2D-FGM plates under moving load. Similarly, the FSDT and VKNS used to examine the porosity effect on nonlinear dynamic and frequency responses of FG shells with double curvature [163] and FG skew plates [164]. Dynamic analysis (linear and nonlinear) of FG conical panels made of porous materials is performed using 2D elasticity theory [165] and DQM in association with FSDT and GLNS [166]. Dynamic analysis of FG Porous plates is performed in [167] using FSDT.

4.2 Transient Deflection and Stress Analysis Under Thermal Environment

4.2.1 Linear Analysis

Transient analysis of FG shells in a thermal environment is presented using elasticity theory [168]. A CLT and DQM utilized [169] to compute the transient deflections of FG cylindrical shells under dynamic thermal loading. Differential and Laplace transform methods are adopted to study the dynamic responses of the FG spherical shell subjected to thermomechanical shock [170]. Assumptions of three plate bending theories (Kirchhoff love theory, FSDT and TSDT) are incorporated into CLT and non-CLT to study the flexural behaviour of FGM plates under transient thermal loading [171]. A cell-based smooth FEM is proposed in [31] to evaluate the deflection parameters under the dynamic loading for graded structure. The thermomechanical deflections of graded structures are reported in [172], and the structure is modelled via HSDT type of polynomial kinematics. Frequency and transient deflection responses of FGB in a thermal environment are investigated using TBT [173].

4.2.2 Nonlinear Analysis

NT responses of FG plates and/or shell panels are computed using HSDT [15, 174] and FSDT [175, 176] in conjunction with VKNS considering thermal environmental conditions. A second-order formulation [177] and generalized thermoelasticity theory [178] utilized for NT thermal stress and wave propagation analysis of TD FG cylinders. A CLT and VKDN applied for NT deflection and vibration analysis of doubly-curved FG panel with TD properties [36], S-FGM spherical shell [179], and FG shell segments [180] under elevated temperature. The NT deflection behaviour of the S-FGM cylindrical panel under a thermal environment is examined using Reddy’s TSDT [181]. Thermo-elastic NT analysis of a hollow cylinder made of 2D FGM is investigated using FEM and higher-order Lagrange elements [182]. The nonlinear dynamic analysis of double-curved shells of FG CNTRC [141] and FG GRC [183] are evaluated under thermal loading using HSDT kind of deformation kinematics and VKNS. The nonlinear dynamics of 2D FGB exposed to time-dependent load are studied using TBT and VKNS [184]. The NT and buckling analysis of FG shells exposed to thermomechanical load considering TD properties are performed by utilizing GLNS [185].

4.2.3 Analysis of Porous Structures

The nonlinear dynamic behaviour of FG plates [161] and shells [186] with porosity exposed to thermal and mechanical loading are illustrated using FSDT and VKNS. An isogeometric analysis in association with TSDT and VKNS is applied to investigate the NT characteristics of the porous FG plates exposed to a hygro-thermo-mechanical loading [187]. The FG conical panel’s NT and vibrational responses in a thermal environment are computed utilizing FSDT and VKDN [188].

It is found from the literature presented in the above subsections that the transient analysis of the FGMs is limited to plate type of structures only. Also, most of the authors utilized CPT and FSDT to develop the numerical model considering von-Karman nonlinearity. Further, the materials are graded in the transverse direction (1D FGM) in a majority of the articles, and the effect of porosity, variable grading have not been addressed. It has been observed from all the reviews that no such attempt has been made in the past to evaluate the responses (static deflection/stress, frequency and transient deflection/stress) using any kind of experimental part for the flat/curved kind of FG structure.

5 Experimental Analysis of FGM

The bending and frequency parameters of the FG beams (FGB) are analyzed using third-order zigzag theory and validated experimentally [19]. The nonlinear transient (NT) experimental study for FG/fiber-metal laminated structures is reported in [189] under the influence of blast load and verified with a simulation model (ANSYS). Similarly, the eigenfrequencies of graded beam structures are investigated in [190] and compared with experimental values. The flexural behaviour FG beam made of concrete and high-volume fly-ash concrete is analyzed experimentally in [191] and found that there is a 12.86 and 3.56% increase in compressive and flexural strength. Experimental and numerical analysis of FGM is performed in [192] under static forces. The experimental and numerical investigation of process parameters on the residual stresses in the Al-Cu FG Materials is carried out in [193] and found that the number of residual stresses decreased by increasing the heat treatment temperature, increasing the uniformity between the layers and number of layers. Elastic properties of the thermoplastic composites with natural fibre (luffa and palm) are predicted in [194]. Numerical and experimental deflection (static ad dynamic) analysis has been performed in [195] for the 2D-FG structures considering the full-scale geometrical nonlinear strain.

6 Conclusion

A thorough review on static deflection and stress, vibration, and time-dependent flexural and stress analysis of the FG structures is presented in this article. Researchers utilize various theories and solution techniques to study the structural behaviour of FGMs. Based on the review of the published articles, a few shortcomings are highlighted and presented below in a pointwise manner.

- The structural analysis of 1D FGMs is presented in most of the published articles, whereas research relevant to 2D/3D types of grading is negligible in numbers.
- Furthermore, the majority of the authors computed the mechanical/elastic properties of the graded structures using the simplest grading rule, Voigt's model/power-law material grading. The FGM's structural analysis with sigmoid or exponential grading has received little attention.
- Numerous articles analyse the FG structures without taking porosity into account. The past focus on porous FGM structural analysis is limited to linear cases only.
- The majority of the research devoted to the structural analysis of FG flat panels or any specific geometric shape (cylindrical, elliptical etc.).
- The VKNS are used in the majority of small-strain large-deformation problems, and the use of GLNS is limited in number. Furthermore, it is well known that the VKNS are inadequate to compute the effect of large-deformation behaviour on the structural responses.
- The structural analysis of the FG materials is performed using CPT or FSDT, even though the CPT is limited to thin structures. SCF usage is required for the FSDT. These theories overpredict the structural stiffness and are less accurate in terms of shear deformation through the thickness. However, very few articles use HSDT in their mathematical models.
- The experimental analysis of the graded structure and the fabrication processes are received a few attention in the published domain.
- No study yet has been reported to analyse the doubly-curved FG panels under elevated environments with TD properties, considering variable porosity and grading patterns.

In order to fully utilize the capabilities of the FG structures for high-end engineering applications, there is a genuine need to develop an efficient mathematical model to predict the static and dynamic responses by considering porosity, thermal environment with TD material properties, and large deformation. If the aforementioned concerns are taken into account, the FG panel's design and analysis would probably be more reliable in practical applications.

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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