A Critical Review of Recent Research of Free Vibration and Stability of Functionally Graded Materials of Sandwich Plate

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Abstract. In the past few decades, due to the unique material properties of functionally graded materials (FGM’s), they have been used in various engineering industries. This article aims to introduce an overview of the existing literature on the area of application, stability, and free vibration analysis of FGM structures conducted by some recent research studies and to provide a comprehensive overview of the development, application, different numerical representation of materials, demonstrating procedures and arrangement technique and solution method of FGM rectangular plate. It focuses on the influence of many parameters on natural frequencies and buckling loads, such as aspect ratio, power-law index, porosity distribution throughout the thickness of the plate, and face sheet thickness. This research also involves various analyses and numerical techniques for vibration and buckling analysis of the FGM sandwich plate. Furthermore, some important notes and suggestions are put forward for future work trails in this field. It is found that there is an exceptionally restricted path to investigate the same above analysis for the FGM sandwich plate with the porous metal dependent on various parameters such as gradient index, aspect ratio, face sheet thickness, porous factor, FGM layers thickness, and the number of layers.

Keywords. Applications of FGM, Free vibration, Buckling, Power-law index, FGM Plates, analytical techniques, FEA.

1. Introduction
In the progress of science and innovation, materials have undertaken significant work. The engineering of modern composite materials has had a significant impact on design and construction technology. The special engineering application of raw materials in various inorganic and organic compounds has played an essential role in developing polymers, alloys, structural parts, etc. [1]. Functionally graded materials (FGM) are a class of advanced materials whose material properties (such as mechanical and thermal properties) change continuously from one surface to another, thereby eliminating stress concentration in laminated composites. Changes in phase distribution can be transformed into their volume or weight fraction, configuration, and geometry. The change in volume fraction may occur directly over the entire thickness of the part or in any other direction (such as the coordinates of the plate or beam). The ceramic area has good heat resistance due to its low expansion capability. The ductile metal parts can avoid failure due to stress due to rapid temperature changes in a short time [2,3].
1.1. History of FGMs plate

In 1972, Shen and Bever [4] first proposed the concept of gradual material composition for composite and polymer materials. In order to maintain mechanical properties and reduce the effects of thermal stress, most of these materials are used as coating materials. Functionally graded materials (FGMs) were developed in Japan in the 1980s for thermal insulation purposes [5]. Since then, FGMs have received extensive attention in various engineering applications and manufacturing industries as high-grade structural materials for heat insulation such as aerospace, nuclear reactors, automobiles, airplanes, spacecraft biomedicine, and steel industries. FGM was initially designed as a thermal insulation material for aerospace structures and fusion reactors [6]. At present, the focus of the material development activities of composite materials and FGM includes improving material performance, supporting optimized structural design, reducing manufacturing costs continuously, and the ability to operate reliably [7]. According to the composition stages’ distribution, FGM can be divided into continuous or discontinuous gradual composition changes. Similarly, it can be divided into thin and overall FGM according to manufacturing technology [8, 9].

1.2. Areas of application of FGMs

The essential characteristics of FGM make it the first choice for almost engineering applications. Also, they are artificially produced. The original form of FGM exists in nature; bones, teeth, human skin, and bamboo trees can be considered organic forms of FGM. Due to its excellent thermal and mechanical properties, functionally graded materials (FGMs) are widely used in various fields and are likely to be used for other purposes. The most important applications include energy, aerospace, automobile, biomedical, defense, electrical/electronics, marine, Opto-Electronics, sport, thermoelectrics, and bioengineering [10]. Figure 1 shows the different types of FGMs and their application areas [11].

![Figure 1. Areas of applications for the three types of FGM]([12](image))

2. Mathematical Idealization of FGMs

Although FGM is very non-uniform, it is beneficial to idealize it as a continuum so that its mechanical properties change smoothly in spatial coordinates. In order to analyze FGMS effectively, a homogenization scheme must be adopted to simplify its complex heterogeneous microstructure. Through this idealization, mathematical model representation to identify some problems can be acquired, which will also help include and improve numerical techniques of FGM structures. It is vital that the conveyance of materials in the FG structure can be intended for different spatial particulars. A typical FGM represents a modern composite material with a recommended conveyance of the volume portion of the constituent stages. It is commonly expected that the material properties follow the progressive change in thickness in a nonstop way. Two sorts of varieties are usually used in the literature, and they include the vast majority of the current analysis models in the fabrication work.
2.1. The power law

Material properties and volume content vary along the thickness direction. FGM is usually designed to assume that one of the outermost layers is treated as metal and the other layer is ceramic. The combination of FGM defines the characteristics of plates and beams. Assuming that the FG plate follows a power law change, it can be defined as follows [13],

$$V_c(z) = \left(\frac{z + \frac{h}{2}}{h}\right)^k$$  \hspace{1cm} (1)

The constituent volume fraction of the FGM plate is supposed to change continually along the thickness direction and obey power-law distribution in the following,

$$\phi(z) = \left(\phi_c - \phi_m\right)\left(\frac{z + \frac{h}{2}}{h}\right)^k + \phi_m$$  \hspace{1cm} (2)

In equation (2), $\phi_c$ & $\phi_m$ are the corresponding material characteristic values of the ceramic and metal components of the FG plate, respectively. The total volume fraction of constituents are expressed as: $V_m(z) + V_c(z) = 1$, where $V_m$ and $V_c$ are the volume fractions of metals and ceramics respectively, and $k$ is the power-law exponent, which is a non-negative variable parameter, where $k \in [0, \infty)$. The value of $k$ equal to zero represents a fully ceramic plate, whereas infinite $k$ indicates a fully metallic plate. The variations may be seen in Figure 2, which reveals that material properties with exponential gradation usually lie between those obtained with power-law exponents, $k = 0.2, 0.5, 1, 2,$ and $5$. For our current formulation, the material properties (such as Young's modulus and mass density) vary along with the thickness, but it is assumed that the Poisson’s ratio is constant.

![Figure 2](image-url)  

**Figure 2.** Material properties representation of the FG plate using the power-law index [14].

2.2. The exponential law

It has been found many research articles that used the exponential function to express the material properties variation with the thickness of the FG plate as follows [15],

$$E(z) = E_2 e^{\frac{k_z}{k_m}(\frac{z}{h} + \frac{h}{2})}$$

$$k_z = k_m e^{\frac{k_z}{k_m} \left(\frac{z}{h}\right)} , \quad \alpha_z = \alpha_m e^{\left(\frac{z}{h}\right) \left(\frac{\alpha_c}{\alpha_m}\right)}$$  \hspace{1cm} (3)

Where $E(z)$ is the modulus of elasticity, $\alpha_z$ indicates the value of the coefficient of thermal expansion and $k_z$ denotes the property of thermal conductivity of the FGM plate or beam with a thickness of $h$. 
The representation of Young’s modulus in the direction of the EFGM plate's thickness is plotted in Figure 3.

![Figure 3](image)

**Figure 3.** Young modulus variation along with the thickness of the FG plate using exponential function [16].

### 2.3. Sigmoid law

Sometimes, it is unwise to use low power functions to express FG beams and plates' characteristics and thickness changes. When ensuring the continuity of material properties over the entire thickness range, stress concentration appears in the beam's interface layer, but the change is not smooth [17]. To solve this type of problem, two power indices are used. In a study done by Chung and Chi [18], two power functions were used to express the change in volume fraction to prevent rapid stress changes through the interface. The following equations represent the variation of volume fraction using two power-law indices [19],

\[
g_1(z) = 1 - \frac{1}{2} \left( \frac{h - z}{h/2} \right)^p \text{ for } 0 \leq z \leq \frac{h}{2} \\
g_2(z) = \frac{1}{2} \left( \frac{z + h/2}{h/2} \right)^p \text{ for } -\frac{h}{2} \leq z \leq 0
\]  

(4)

By using the rule of mixture, Young's modulus of the Sigmoid FGM can be calculated by,

\[
E(z) = g_1(z)E_1 + [1 - g_1(z)]E_2 \text{ for } 0 \leq z \leq \frac{w}{2} \\
E(z) = g_2(z)E_1 + [1 - g_2(z)]E_2 \text{ for } -\frac{h}{2} \leq z \leq 0
\]  

(5)

Figure 4 shows the variation of FGM volume for different values of \(p\) by employing the sigmoid function.

![Figure 4](image)

**Figure 4.** Variation of Young’s modulus and the thickness of the FG plate using the sigmoid function [20].
2.4. Mori-Tanaka scheme

This method is suitable for composite materials with a well-defined continuous matrix and gradually discontinuous particle-phase microstructure regions. Similarly, this method also considers the influence of the elastic field between adjacent inclusions and their interaction with the components. The effective bulk modulus $K_z$ and shear modulus $G_z$ are calculated according to the following formula [21].

\[
\frac{K_z-K_m}{K_c-K_m} = \frac{V_f \Pi}{1+(1-V_f)\left(\frac{K_c-K_m}{K_m+2G_m}\right)}
\]

(6)

\[
\frac{G_z-G_m}{G_c-G_m} = \frac{V_f \Pi}{1+(1-V_f)\left(\frac{G_c-G_m}{G_m+G_m}\right)}
\]

(7)

\[
f_m = \frac{G_m(9K_m+8G_m)}{6(K_m+2G_m)}
\]

(8)

The modulus of elasticity $E_z$ and Poisson’s ratio $v$ are evaluated using the Bulk modulus $K_z$ and the modulus of shear $G_z$ as indicated below, [22],

\[
E_z = \frac{9K_zG_z}{3K_m+G_z}
\]

(9)

\[
v = \frac{3K_z-2G_z}{2(3K_m+G_z)}
\]

(10)

The heat conductivity $K_z$ and thermal expansion parameter $\alpha_z$ are as follows,

\[
\frac{K_z-K_m}{K_c-K_m} = \frac{V_f \Pi}{1+(1-V_f)\left(\frac{K_c-K_m}{3K_m}\right)}
\]

(11)

\[
\frac{\alpha_z-\alpha_m}{\alpha_c-\alpha_m} = \frac{\frac{1}{K_z} - \frac{1}{K_m}}{\frac{1}{K_c} - \frac{1}{K_m}}
\]

(12)

3. Literature review on the free vibration of functionally graded rectangular plates

Rectangular plates are widely used in many engineering applications due to their ability to deal with the various loads' conditions (mechanical and thermal). The instability of the plate is caused by the in-plane compressive stress caused by these loads. For FGM plates, the stability problem is susceptible to boundary type conditions and material thickness variations [23]. When studying the vibration of FGM plates and beams, many researchers used frequent parameters that affect the fundamental natural frequency, Batra and Vel [24] provided an accurate solution for free vibration analysis of 3D of FGM plates. They assumed that the plate is made of an isotropic material with material properties varying in the thickness direction only. Farajollah Zare Jouneghani et al. [25] used the first-order shear deformation theory to study an FG porous shell's free vibration problem. Vyacheslav N. et al. [26] provided 3D modeling of free vibration and static response of functionally graded materials (FGM) sandwich plates. J. Woo [27] studied the dynamic response of an FGM thin plate using nonlinear analysis. The thin rectangular plate has an impact force locally distributed and has no or no elastic foundation. Prapot and Nuttawit [28] described the flexural vibration analysis of a functionally graded sandwich plate resting on an elastic foundation under arbitrary boundary conditions: Chebyshev collocation technology, the governing equation of free vibration problem is derived, and some of the crucial influences on the relationship between shear deformation and rotational inertia are given. Nuttawit Wattanasakulpong et al. [29], based on the improved coupling stress theory, the vibration state of dimension-dependent functionally graded sandwich microbeams with different boundary conditions was studied. Tran Van Liena et al. [30] used the dynamic stiffness method to study the free and forced vibration analysis of the multi-crack FGM multi-span continuous beam and explained the crack's influence on the vibration of the functionally graded beam. A.W. Leissa [31] used combinations of boundary conditions to investigate FGM rectangular plates' free vibration problems.
A. F. Mota et al. [32] studied the mechanical behavior of porous functionally graded nanocomposite materials and analyzed nanocomposite functionally graded materials with different porosity distributions. Hassen Ait Atmane et al. [33] conducted a free vibration analysis on a porous functionally graded material beam resting on an elastic foundation. Mechab et al. [34] proved the effects of pores on the dynamic analysis of functionally graded materials nanoplates depend on Winkler–Pasternak foundation. Adda Hadj Mostefa and Merdaci Slimane [35] studied the influence of material property distribution and porosity on the natural frequency of FGM sandwich panels and explained different boundary conditions. Mesut Simsek [36], the free vibration frequency of rectangular plates has been evaluated in research and modern fields under different possible combinations of classical boundary conditions. Baferani et al. [37] described a mathematical model of free vibration of FG thick rectangular plates placed on an elastic foundation. Senthil S.Vela and R.C. Batrab [24] used Mori–Tanaka and self-consistent methods to study the accurate three-dimensional solutions of free vibration and forced vibration of a simply supported functionally graded rectangular plate. Also, Malekzadeh [38] combined 3D shear theory to study the dynamic response of thick functionally graded plates resting on elastic foundation. Liu et al. [39, 40] explained the influence of in-plane material inhomogeneity on the fundamental frequency of the FGM plate. In the mathematical model representation, the kinematic relations relying on the classical plate theory (CPT) were considered, and the analysis of rectangular plates using the (Rayleigh–Ritz) method was mentioned in [41–43]. According to different combinations of classical boundary conditions, rectangular plates' free vibration frequency is described in [44–46]. Reddy [47] proposed a general formula for FG plates using the 3D shear deformation theory. F. Liu and Liew [40] the free vibration of a medium-thickness rectangular plate is studied by the differential orthogonal parameter technique. Matsunaga [48] estimated the natural frequency and buckling stress of FG plates based on the two-dimensional high-order shear deformation theory. Hosseini Hashemi et al. [49] introduced the precise structural arrangement of 3D elasticity theory to study the free vibration of FG simply supported rectangular plates.

4. Functionally graded sandwich plates

The wide application of sandwich structures in automotive, marine development, transportation, and aviation companies has attracted many considerations, and specific researchers have performed continuous static and dynamic inspections on them. Due to the outstanding performance of high strength-to-weight ratio, the use of sandwich structures in the field of micro auxiliary frames is constantly developing [50]. Therefore, in a wide range of FGM material types and uses, it is crucial to explore the static and dynamic behavior of auxiliary personnel with FGM, such as beams and plates [51, 52]. Consider the plate comprised of homogeneous hardcore and FGM face sheets [53–58]. The material non-uniformity of the FGMs is assumed as follows [59],

\[
V_m = \begin{cases} 
\left(\frac{2z+h}{2h_f}\right)^k & -\frac{1}{2}h \leq z \leq -\frac{1}{2}h_H \\
1 & -\frac{1}{2}h_H \leq z \leq \frac{1}{2}h_H \\
\left(\frac{2z+h}{2h_f}\right)^k & \frac{1}{2}h_H \leq z \leq \frac{1}{2}h 
\end{cases}
\]  

(13)

Where \(h_H\) and \(h_f\) are the thickness of the plate core and each FG sheet, respectively. The material heterogeneity of the whole FG structure can be evaluated by using the Voigt rule. Therefore, the material inhomogeneity of the sandwich plate \(P\) varies with the thickness coordinates as,

\[
P(z) = \begin{cases} 
P_c + P_{mc}\left(\frac{2z+h}{2h_f}\right)^k & -\frac{1}{2}h \leq z \leq -\frac{1}{2}h_H \\
P_m & -\frac{1}{2}h_H \leq z \leq \frac{1}{2}h_H \\
P_c + P_{mc}\left(\frac{2z+h}{2h_f}\right)^k & \frac{1}{2}h_H \leq z \leq \frac{1}{2}h 
\end{cases}
\]  

(14)
5. Research on vibration of FGM structures with porosities

Because of technical issues during the manufacture, porosities and microvoids can be made inside the FGM plate, which may essentially decrease the quality of materials. The assembling strategies for FGMs are a creating region; the sintering strategy is the most utilized because of its cost-saving advantage proportion. In any case, the sintering cycle empowers the development of microvoids or porosities [9]. Despite the critical improvement observed recently here, porosity stays an incessant imperfection in FGMs. As related above, porosities are outcomes of the assembling cycle and decrease the material's quality. Henceforth, the effect of this type of imperfection is necessary to consider the porosity effect on unique attributes of FGM structures conveying porosities [60]. Yan Qing Wang and Jean W. Zu contemplated vibration practices of practically evaluated rectangular plates with porosities and moving in a warm domain [61]. Saidi Hayat and Sahla Meriem [62] utilized vibration analysis of functionally graded plates with porosity made out of a mixture of Aluminum (Al) and Alumina (Al2O3) installed in an elastic medium.

Xiang-Yu Zhang et al. [63] altered the topological design, porousness, and mechanical conduct of additively fabricated functionally graded porous metallic biomaterials. Free vibration of Timoshenko beams with porosities was carried out by Wattanasakulpong and Chaiikittratana, who thought about unevenly conveyed porosities in the model [29]. Y.H Dang et al. [64] additionally gave the conversation on free vibration attributes inferable from porosities occurring inside FGM tests of the graphene fortified permeable nanocomposite barrel-shaped shell with a spinning motion. Concerning porosity distributions, Nguyen et al. [65] studied the mechanical conduct of porous FGP. For this reason, they considered two diverse porosity appropriations, shifting both through the thickness direction (to be specific, the even and uneven distributions). Zhang and Wang [66] created eight different porous material structures with deferent pore appropriations, including gradient distributions, and exposed them to some mechanical tests to assess significant materials properties like Young's modulus. Functionally graded porous materials join the qualities of both FGMs and porous materials. Beyond the great rigidity–weight ratio, the exceptional mechanical properties they present to clarify why these particular materials are broadly utilized in a broad scope of various fields [67].

Notwithstanding incredible advancements in assembling measures, the arrangement of micro-voids or porosities is as yet a reality [68], and in some particular applications, this can be even alluring and intended for. Notwithstanding the particular case, the material's strength will become lower as a result of these pores, which should be remembered for mechanical conduct contemplates [69]. Three types of porosity distributions through the thickness proposed by Kim et al. [70] and applied in numerous studies, along with the ones evolved by using Coskun et al. [71] and by Zhao et al. [72]. The closing was inspired inside the uniform distribution referred to Merdaci [73], whose studies recognize the case of a typical functionally graded ceramic/metal square plates considering deferent porosity distributions through the thickness. Moreover, Chakraverty and Pradhan [14, 74] have studied the free vibration of thin FG rectangular plates in the presence of complicated environments. Nuttawit and Variddhi [75] investigated the porosity parameter that influences the frequency parameter of FGM restrained ends beams using a combination of linear and nonlinear analysis.

6. Analytical solution of free vibration of fg rectangular plate

The static and dynamic response of FG plates had been studied by many researchers based on specific plate theories defined below. Generally, in vibration problems, the displacement fields of the deformed beam (or plate) can be decided via shear deformation beam (or plate) theories. Instead of classical beam (or plate) theory, exceptional varieties of deformation theories may also be observed in the open literature. It might also occur because of the reality that the classical plate (or beam) idea neglects transverse shear deformation outcomes. To have a look at the vibration characteristics, the displacement fields of deformed FG beams and plates are considered with recognition to transverse displacement. Higher-order deformation beam theories of various forms are assumed by taking transverse shear deformations in the case of FG beams, whereas the classical plate theory (CPT) is taken into consideration within the case of FG plates with different geometries. A new quasi-three dimensional high shear deformation theory for the vibration of the functionally graded plate was considered by [76].
Baferani et al. [77] have analyzed the dynamic response of functionally graded thin plates. The governing equations of motion are obtained based on the classical plate theory, and the effects of aspect ratio, thickness, length ratio, power-law index, and boundary conditions on the vibration characteristics of functionally graded rectangular plates are discussed in detail. The nonlinear bending analysis is presented by Shen [78] for a simply supported functionally graded plate subjected to a transverse uniform or sinusoidal loads in thermal environments. Yang and Shen [79] have offered free and forced vibration analyses for initially stressed functionally graded plates in thermal surroundings.

6.1. Classical plate theory (CPT)

The two-dimensional plate theories can be categorized into two types: (1) classical plate theory, in which the transverse shear deformation consequences are neglected, and (2) shear deformation plate theories. In the two-dimensional theory, the free vibration, thermal, and stability problems of the FGM structures, the displacement is represented in terms of thickness, while the lateral displacement is independent of the lateral (or thickness) coordinates. The results of the mathematical model in the coupled governing equation are independent of lateral displacement. Therefore, the analytical solution of this type of equation may be simpler than the solution procedure of three-dimensional elasticity theory [80]

The easiest method concept is the Classical Plate Theory (CPT), which is an extension of the Kirchhoff (classical) plate theory to laminated composite plates. The conventional Kirchhoff model is no longer regarded as the effect of shear deformation; consequently, it is solely relevant for thin plate analysis. The classical plate principle was once at the beginning developed for homogeneous isotropic plates and was later extended to laminated composite and FGM plates. Most researchers hire CPT in the analysis alongside with the solution of FG plates of various shapes, viz. rectangular, elliptic, and triangular alongside with specific complicating results (elastic foundation, thermal environment, and piezoelectricity). Based on the physical neutral surface property, Zhang and Zhou [81] used classical plate theory to analyze FG thin plates neglecting the tension-bending coupling effect in the mathematical formulation for deflection problems. Liu et al. [39] studied the analysis of CPT-based FGM plates, especially when the material properties changed through the thickness, the effect of this configuration on the panel's natural frequency. Generally, the classical or Kirchhoff’s plate theory is based on the following assumptions [82, 83],

- The thickness of the plate is small in contrast to different dimensions.
- The normal stresses in the route transverse to the plate are taken to be negligibly small.
- The effect of rotatory inertia is negligible. The normal to the undeformed middle surface remains straight, and the normal to the deformed middle surface remains unstretched in length.

Using the CPT, the displacement fields of FG plates across the plate thickness at a distance $z$ away from the middle surface are [84, 85],

$$
\begin{align*}
    u_x(x, y, z) &= -z \frac{\partial w}{\partial x} \\
    u_y(x, y, z) &= -z \frac{\partial w}{\partial y} \\
    u_z(x, y, z) &= w(x, y)
\end{align*}
$$

Where, $u_x, u_y$ and $u_z$ are the displacement of a point on the reference plane in the $x$, $y$, and $z$ directions, respectively, and $w$ represents the lateral deflection of the points on the mid-plane ($x$-$y$ plane). The Kirchoff model is not considered the effect of shear deformation due to bending and plane elongation.

6.2. First-order shear deformation theory

When a shear correction component is needed to compensate for the difference between the proper stress state and the assumed normal stress state, the first-order shear deformation theory (FSDT) is used. It was developed by Mindlin [86], and Reissner [87] accounts for the effect of shear deformation, but it violates the traction-free boundary conditions at the ends of the desired surface [88,
Aghdam et al. [90] combined the iterative technique with the Kantorovich method and based on the theory of first-order shear deformation to investigate a static analysis of the bending of medium-thickness FG plate. Therefore, shear correction parameters are needed to compensate for the difference between the actual stress and the assumed normal stress state. Hosseini-Hashemi et al. [49] introduced the FOST, to study the free vibration of FGM plates based on the kinematics and constitutive equations for the proposed model to calculate the natural frequency, assuming that the properties of FG plate vary through the thickness and have a gradient index along with the part thickness orientation. M. Karami Khorraramabadi et al. [91] used both FOST and TSDT to investigate the free vibration problem of simply supported FG plates and discussed the differences between the two theories on the dynamic response of FG plates. Nguyen et al. [92] developed a new model of free vibration for FGM plates employing the assumptions of FOST in the closed-form solution. According to fundamentals of the first-order shear deformation plate theory [49], the displacement field can be expressed as,

\[
\begin{align*}
    u(x, y, z) &= u_0(x, y) + z\phi_x(x, y) \\
    v(x, y, z) &= v_0(x, y) + z\phi_y(x, y) \\
    w(x, y, z) &= w_0(x, y)
\end{align*}
\]

Where, \(u_0\), \(v_0\), and \(w_0\) denote the displacements at the mid-plane of the plate along the \(x\), \(y\), and \(z\) directions, and \(\phi_x\) and \(\phi_y\) represent the normal transverse rotations about the \(y\) and \(x\)-axes, respectively.

6.3. A simple higher-order shear deformation theory

To avoid using the shear correction thing and obtain a higher prediction of the transverse shear deformation and regular strains in FG plates, Higher-order shear deformation plate theories (HSDTs) have been proposed. In general, HSDTs can be developed based totally on higher-order variants of the in-plane displacements [93-95] or each in-plane and transverse displacements [96, 97] (i.e., quasi-3D theories). Using the simple and complete theory of trigonometric high-order, the bending and vibration of FG parts are discussed to study the influence of normal transverse strain on deflection and stress [98]. Fakhari et al. [99] used thermal, electrical, and mechanical loads to propose a new nonlinear mathematical model based on high-order shear deformation theory to evaluate FG plates' natural frequency and stability with piezoelectric layers bonded through the part surface. However, HSDTs are enormously computational due to many unknowns (e.g., theories employing Neves et al. [100] with nine unknowns). Among different HSDT, Whitney and Sun [101] introduced the second-order shear deformation formulation and the TSDT of Lo et al. [102] with (11 unknowns), Kant [103] with six unknowns, Bhimaraddi and Stevens [104] with five unknowns, and Hanna and Leissa [57] with four unknowns, furthermore the TSDT proposed by Chen and Reddy [105] with five unknowns is the most generally utilized model in the investigation of FG vessels due to its acceptable results. Reddy [106] with (eleven unknowns) while Jha et al., [107] with (12 unknowns), Talha and Singh [108], and Natarajan and Manickam [109] with (13 unknowns). Many modifications are performed on this concept, such as a quasi-3D (hyperbolic, sinusoidal, simple, and higher-order shear deformation theory). Khalili and Mohammadi [110] used an improved high-order sandwich plate theory to analyze sandwich plates' free vibration with FGM face sheets in various thermal environments. According to fundamentals of the shear deformation theory, both the axial and lateral displacement \(u_x\) & \(u_z\) at any point of the plate or beam can be represented as [111],

\[
\begin{align*}
    u_x(x, z) &= u(x, t) - zw_x(x, t) + f(z)v(x, t) \\
    u_z(x, z) &= w(x, t)
\end{align*}
\]

Where, \(u\) and \(w\) represent the axial and lateral displacement of any point on the neutral axis, and \(v\) is a special function, which depends on the actual value of the shear strain on the symmetry axis, \(f(z)\) represents the geometric function to be calculated with assistance both of strain and stress resulting from transverse action across the plate thickness, and the derivative of the lateral displacement concerning \(x\) is the component \(w_x\). By selecting the correct form of the structural characteristic function \(f(z)\), the various mathematical formulation can be obtained, classical plate theory (CBT),
first-order shear deformation theory FSDT, higher-order shear deformation theory HSDT, exponential shear deformation plate theory (ESDT, sinusoidal shear deformation plate theory SSDT, as mentioned in Simsek, \(f(z)\) for these, are given below [36],

\[
\begin{align*}
\text{BT: } f(z) &= 0, \quad \text{FSDT: } f(z) = z \\
\text{HSDT: } f(z) &= \left(1 - \frac{4z^2}{3h^2}\right), \quad \text{ESDT: } f(z) = ze^{-2(z/h)^2} \\
\text{SSDT: } f(z) &= \frac{h}{n} \sin\left(\frac{\pi z}{h}\right)
\end{align*}
\] (18)

6.4. Zeroth-order shear deformation theory

To predict actual results for the free vibration and buckling load problems associated with FGM structures, a Zeroth-order shear deformation principle was utilized. This concept was first explored through Shimpi [112] for isotropic plates and later stretched out by Ray [113] for laminated composite plates. They affect the use of shear forces used to be taken into accounts in the Zeroth-order as an alternative of rotational displacements of transverse shear deformation as in present shear deformation theories. The zeroth-order shear deformation theory contains the equal five unknowns in the first-order shear deformation theory; however, it satisfies the traction-free boundary conditions on the plate's top and bottom surfaces besides requiring any shear correction factor. Using the zero-order shear deformation theory, equations of motions and the analytical solutions are derived. The frequency parameter of the free vibration analysis of functionally graded plates treated with nanoparticles mounting on elastic foundations was carried out [114,115]. Based on the CPT, the linear constitutive relations of an FG plate such as the bending and twisting moments \(M_{xx}, M_{yy}, \) and \(M_{xy}\) respectively on a plate element in the pure bending case can be written as [116],

\[
\begin{align*}
M_{xx} &= \frac{1}{2} \int_{-h/2}^{h/2} \sigma_{xx} z dz = \frac{E}{(1-v^2)} \int_{-h/2}^{h/2} \left(\varepsilon_{xx} + v\varepsilon_{yy}\right) dz = -D \left(\frac{\partial^2 w}{\partial x^2} + v \frac{\partial^2 w}{\partial y^2}\right) \\
M_{yy} &= \frac{1}{2} \int_{-h/2}^{h/2} \sigma_{yy} z dz = \frac{E}{(1-v^2)} \int_{-h/2}^{h/2} \left(\varepsilon_{yy} + v\varepsilon_{xx}\right) dz = -D \left(\frac{\partial^2 w}{\partial y^2} + v \frac{\partial^2 w}{\partial x^2}\right) \\
M_{xy} &= \frac{1}{2} \int_{-h/2}^{h/2} \sigma_{xy} z dz = G \int_{-h/2}^{h/2} \gamma_{xy} z dz = -(1 - v)D \frac{\partial^2 w}{\partial x \partial y}
\end{align*}
\] (19)

Then,

\[
\begin{align*}
\frac{\partial^2 M_{xx}}{\partial x^2} - 2 \frac{\partial^2 M_{yy}}{\partial x \partial y} + \frac{\partial^2 M_{xy}}{\partial y^2} &= I_0 \frac{\partial^2 w}{\partial t^2} \\
D_{FG} &= \int_{-h/2}^{h/2} \frac{z^2}{(1-v_f^2)} E(z) dz \\
D_{FG} &= \frac{(E_c-E_m)h^3}{(1-v_f^2)} \left(1 - \frac{1}{k+3} - \frac{k+1}{4(k+1)}\right) \frac{E_m h^3}{12(1-v_f^2)}
\end{align*}
\] (20)

where, \(D_{FG}\) is the stiffness coefficient of the functionally graded plate. And,

\[
I_0 = \int_{-h/2}^{h/2} \rho(z) dz
\]

\(I_0\) is the moment of inertia of the FGM plate, which can be expressed in terms of the volume fraction index as,

\[
I_0 = \int_{-h/2}^{h/2} \left((\rho_c - \rho_m) \left(\frac{z}{h} + \frac{1}{2}\right)^k + \rho_m\right) dz
\]

\[
= \int_{-h/2}^{h/2} \left((\rho_c - \rho_m) \left(\frac{z}{h} + \frac{1}{2}\right)^k\right) dz + \int_{-h/2}^{h/2} \rho_m dz = \frac{(\rho_c-\rho_m)h}{(k+1)} + \rho_m h
\] (23)
Where, \( E_c \) and \( E_m \), are young modulus for ceramic and metal respectively; \( \rho_c \) and \( \rho_m \), are the mass density for ceramic and metal respectively; \( \nu_{FG} \) is Poisson’s ratio for the FGM plate, and \( h \) is the thickness of the FGM plate. Substituting Eqs. (7), (12) and (13) into Eq. (10), the solutions can be obtained from

\[
\left( \frac{(E_c-E_m)h^3}{(1-\nu_{FG}^2)} - \frac{1}{k+3} + \frac{1}{4(k+1)} \right) + \frac{E_{mh}h^3}{12(1-\nu_{FG}^2)} \left( \frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} \right) + \left( \frac{(\rho_c-\rho_m)h}{k+1} + \rho_m h \right) \frac{\partial^2 w}{\partial x^2} = 0
\]  

(24)

7. Stability analyses of FGM plates

The stability research of functionally graded material plates involves calculating the buckling loads under different boundary and load conditions. Generally, there are two types of solutions. The first is the three-dimensional (3D) elastic theory, used to determine stability status, and the eigenvalue problem needs to be calculated. However, there is no report on using three-dimensional elastic theory (a high-precision analysis technique) for buckling analysis of FGM plates so far. The second is the two-dimensional (2D) plate theory [117]. Rectangular plates are used as much as possible in industrial applications and tend to withstand various loading conditions, such as mechanical or thermal loads. These loads will generate in-plane compressive stresses, which will lead to instability of the plate. For isotropic and FG plates, the buckling problem is critical for boundary type conditions and material thickness variations [118]. This article covers various studies on the buckling of FGM structures, as follows: Ashraf Zenkour et al. [119] used third-order deformation theory and nanobeam resting on Pasternak’s foundation to study the influence of the shear deformation and the slenderness ratio on the buckling behavior of the functionally graded part.

Huang and Li [120] presented various beam theories to investigate functionally graded columns' stability according to more than a few types of load conditions. Wang et al. [121] explained that the classical plate theory (CPT) in which the transverse shear deformation consequence neglected; therefore, the classical plate theory usually underestimates deflection and overestimates the natural frequencies and buckling loads for thick plates. Samsam Shariat et al. [122] investigated the Buckling evaluation of functionally graded plates subjected to uniaxial loading. Birman [123] studied the buckling problem of functionally graded composite rectangular plates subjected to uniaxial compression. Lee et al. [124] studied Post-buckling analysis of functionally graded plates’ concern to compressive and thermal loads. Wu L. [125] developed a new model of a simply supported rectangular functionally graded plate and studied the effect of aspect ratio and temperature gradient on buckling analysis. Czechowski L. et al. The buckling and post-buckling studies of step-variable FGM boxes were carried out [126]. Javaheri [127] studied the buckling of functionally graded plates under plane gradient compressive loads. Bekir Akgöz and his co-authors used the strain gradient theory and introduced the exact solution of FG microbeam stability analysis [128]. Fekrar et al. [129] proposed a new refined theory using the Navier method and including four unknown functions with in-plane loading to study the mechanical buckling of FG simply supported hybrid plates. The correspondence relationship between the deflection, buckling load, and frequency of functionally graded thin materials and corresponding homogeneous plates has been studied by Li Shirong et al. [130].

Shi-Rong Li et al. have learned about correspondence relations between deflection, buckling load, and frequencies of thin functionally graded materials and those of corresponding homogeneous plates [130]. Soldatos [131] presented 2D deformation theory based on Hamilton’s principle and Lagrange multipliers to examine the stability of the homogeneous monoclinic plate. Oyekoya et al. [132] introduced a new analytical solution for the buckling of FG structures and used the finite element method to validate the analysis results. Also, a great deal of study has been performed by Bodaghi M et al. [133] to solve an analytical model with the assistance of higher-order shear deformation plate theory to find a solution for buckling analysis of thick FG rectangular plates. M.M. Najafizadeh and M.R. Eslamia evaluated the response of FG plates with various geometrical considerations subjected to compressive load [134]. B. Sidda Reddy et al. used the theory of high-order shear deformation to analyze the buckling of functionally graduated material plates [135]. Farzad Ebrahimi and Fateme Mahmood [136] presented a modified couple stress concept for buckling evaluation of higher-order inhomogeneous microbeams with porosities. The difficulty of the new
principle of shear deformation for various engineering parts, such as laminated composite plates, is studied with the aid of [137].

Zenkour [138] presented a complete evaluation of the buckling and free vibration of a simply supported FG sandwich panel consisting of a homogeneous core and FG upper and lower parts. Elias Y. Ali and Yared S. Bayleyegan [139] presented a detailed study that includes an analytical and numerical calculation for buckling analysis of FG rectangular plates subjected to compression load in one direction. Akhavan et al. [140] evaluated the buckling analysis of a rectangular Mindlin plate under uniform load resting on the Pasternak elastic foundation and explained the influence of parameters such as foundation stiffness coefficient, boundary conditions, and thickness ratio on the buckling behavior. Meiche et al. [141] modified the new mathematical model of the dynamic response for the FG sandwich plate based on the hyperbolic shear deformation theory. Shen et al. [142] studied the post-buckling of sandwich panels with FGM panels and temperature-dependent characteristics. Kiani et al. [51] studied the stability and dynamic characteristics of functionally graded sandwich panels placed on Pasternak elastic foundations using different boundary conditions. Nguyen and Tung [143] introduced CPT and derived a mathematical model from studying FG plates' buckling analysis using different loads and aspect ratios. Park and Kim [144] developed a numerical model based on FSDT to study FGM plates' post-buckling response under thermal loads. Lee and Kim [145] studied the post-buckling of FGM panels in response to thermal environments. As an application, Zhang and Zhou [146] studied sandwich plates' equilibrium behavior made of functionally graded materials. They proposed the free vibration, buckling, and deflection analysis of FG structures based on physically neutral surfaces.

Sobhy [147] analyzed the critical buckling load and free vibration of an exponential sandwich plate based on an elastic foundation under uniform shear under different boundary conditions. Hessameddin Yaghoobi and Pooria Yaghoobi [148] studied the buckling behavior of asymmetric FGM structure placed on an elastic foundation using the structural equation of FSDT and considered various boundary mechanics, thermodynamics, and thermodynamic analysis conditions. Based on the element-free Ritz procedure and FSDT, the buckling behavior of stable plates and plates with notches at the core was studied by Zhao et al. [149]; it was found that the influence of the volume fraction index affects the buckling temperature positively. Jalali et al. [150] used a new spectral method to study the effect of the volume fraction index on the stability degree and the results of thermal stresses owing to the buckling of sandwich round plates with variable thickness. It was concluded that the buckling load parameter would increase with a make bigger in volume fraction index and a decrease in the FG core to homogenous face sheet thickness ratio. Yu et al. [151] used an imperfect FGM plate, combined with the first-order shear deformation theory, and studied the buckling response using an extended isogeometric analysis method.

Latifi [85] used Fourier series expansion to analyze the stability analysis of rectangular FG plates under various boundary conditions. S. Sirinivas and A. K. Rao [152] conducted an investigation on bending, vibration, and buckling of simply supported thick orthotropic rectangular plates and laminates. Also, Na and Kim [153,154] investigated functionally graded composite rectangular plates subjected to uniaxial compression. The bending and buckled parts of FGM plates can be studied for various aspect ratios. Although the plate's buckled arrangement can be demonstrated in each load case, the shear and biaxial buckling styles of the linear gradient functionally graded plate at the aspect ratio = 1% have been obtained and given in [155]. In [156, 157], an alternative method of deriving the buckling analysis equilibrium equation based on virtual displacement is mentioned. Using the energy method, M. Mohammadi et al. [158] proposed a general analysis program for the stability analysis of a thick FG rectangular plate with two simply supported opposite edges in uniaxial compression .M. Darvizeh et al. [159] studied the buckling behavior of simply-supported composite plates subjected to compressive loading condition by using the total potential energy technique in conjunction with the Rayleigh-Ritz method. Javaheri and Esfami [160,161] introduced classical and higher-order plate theories to investigate FG rectangular plates' thermal and mechanical buckling. Wu et al. [125] using fast-converging finite double Chebyshev polynomials, the post-buckling response of FG plates is obtained by thermomechanical load analysis. The mathematical formula is based on FOST and von-Karman nonlinear kinematics. The stability equation of the thin plate can be obtained by the
variational approach. To identify the stability of the FG structural part, the buckling force can be found by solving the equilibrium equation in the form of a diaphragm, resulting in the following bending stress [162,163],

\[ M_{xx} = 2M_{xy} + M_{yy} = N_x w_{xx} \]  
\[ \frac{\partial^2 M_{xx}}{\partial x^2} - 2 \frac{\partial^2 M_{xy}}{\partial x \partial y} + \frac{\partial^2 M_{yy}}{\partial y^2} = -q_x \]  
\[ D_{R} \left( \frac{\partial^4 w}{\partial x^4} + 2 \frac{\partial^4 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} \right) = N_x \frac{\partial^2 w}{\partial x^2} \]  

8. Numerical investigation

To verify the accuracy of the analytical solutions, numerical methods are usually used. There are many mathematical methodologies utilized for problem-solving [164-177]; however, the most exact is Finite Element Analysis (FEA) and Meshless methods [178-191]. FEA is a versatile and necessary strategy for assessing most of the design problems permits the investigation of the different structures without improving and including complex relations [192,205]. Furthermore, hybrid numerical mathematical techniques include the Rayleigh-Ritz finite element method (FEM) [206-219], and the differential orthogonal method is used to solve free vibration and buckling problems exposed to dynamic and static problems [220-232]. The dynamic behavior of the FG plate has been studied by many researchers in the world utilizing analytical analysis and various numerical methods. Below, a summary of numerical techniques is used in most research studies.

Numerical results of Mantari et al. [233] were bound to the same layer of the functionally graded sandwich plate, while Zenkour and Sobhy [234,235] dealt with the same and different parts of the FGM sandwich plate. Many studies have been proposed to perform buckling analysis of FGM structures with general boundary conditions. The stability analysis in the thermal environment of Kiani and Eslami [236] depends on the details of the Galerkin procedure combining with the free KP-Ritz arrangement developed by Liew et al. [237] in this category. Chi and Chung used FEA to describe FGM plates’ dynamic response under various loads [238]. Pradyumna and Bandyopadhyay [239] developed a new mathematical model based on the principles of the higher-order formulation; to solve the buckling problem in FGM structures. Additionally, buckling analysis of FG simply-supported plates was carried out by Nguyen-Xuan et al. [240] using a higher-order finite element formulation. Khalili et al. [241] introduced Rayleigh-Ritz and differential orthogonal methods to study the dynamic response characteristics of functionally gradual structures under fluctuating loads. Jafari and Eftehari [242] proposed a new version of coupled finite element and differential orthogonal to study the dynamic characteristics of beams under dynamic loads.

Zhao et al. [243] proposed an element-free KP-Ritz method to analyze the free vibration of metal-ceramic FG plates whose material properties vary continuously throughout the thickness of the plate layers. Zhu and Liew [244] used the local Kriging meshless method to analyze metal and ceramic FG plates' free vibration. The comprehensive study includes the static and buckling analysis of the laterally loaded FG plate using the FEA formulation described in [245]. Dozio [246] presented 2-D Ritz models using FEA to study the dynamic behavior of FG sandwich plates with homogenous face sheet. A finite strip element for the analysis of variable thickness rectangular thick plates was investigated by [247]. K. M. Liew [248] presented an adequate solution for free vibration problems of multilayers plate using a mesh-free Galerkin method. Civalek [249] proposed static and dynamic numerical solutions for the rectangular thin plate problem. To analyze static and dynamic in two and three-dimensional elasticity problems of FG structure, a standard FEM technique method has been consolidated by Song et al. [250]. An investigation of FG beams and plates dependent on first-order shear deformation theory using the finite element method model is developed by Chakraborty and Pradhan. [251]. Kant and Khare [252] used high-order shear deformation theory to analyze free vibration and tested the good performance of thin and thick plates and shells. A mixed finite element formulation with a bilinear shape function is used to solve free vibration problems in FGM structures such as the analysis of thin plates resting on an elastic foundation that has been done by many
researches [253]. Given the first and third-order shear deformation plate theories, an analysis of free vibrations of FG plates has been introduced by Ferreira et al. [254]. Shufrin and Eisenberger used a new numerical technique to study the stability and vibration of shear-deformable FG plates based on first-order and high-order analysis [255]. Finite element models based on the third-order shear deformation theory were presented to analyze FG plates’ static and dynamic analysis by Reddy [256]. Navier arrangements acquired for a simply supported square plate under sinusoidally distributed load were presented, including the effect of shear deformation [257]. Kim and Hoa [258] experimentally determined the dynamic mechanical behavior of the composite plate under biaxial load and performed a numerical analysis. Sundararajan et al. [259] modified a combination of FSDT and correlation analysis with a high grade of node physical element representation conducting on a flexible quadrilateral plate made of FG to perform static and dynamic analysis. Malekzadeh and Shojaee [260] used eight-node physical elements and mathematical formula models to check the accuracy of FSDT on the dynamic response of printed FG parts subjected to heat movement. For static and vibration analysis of FGM structures recently, meshless technology has been widely used in different engineering analyses due to its flexibility [261]. Parandvar and Fārīd [262] proposed a new finite element modal technique that includes the development of system uniformity methods to deal with the free vibration of functionally graded plates. A modified Kirchhoff plate theory for free vibration analysis of FGM plates using the mesh-free method has been proposed by Vuong Nguyen Van Do [263]. Qian et al. [264,265] analyzed free and forced vibrations of both homogeneous and FG thick plates with the higher-order shear and normal deformable plate theory by using the meshless local Petrov–Galerkin method. Zhu and Liew [266] have developed a meshless method for FGM structure based on FSDT analysis using Kriging interpolation and von-Karman nonlinearity. Wang and Luo [267] used a meshless collocation and an element-free Galerkin method for the 3D free vibration of FGM sandwich plates. Yas and Aragh [268] used the generalized differential orthogonal method to analyze the four parameters and proposed a flexible solution for FGM cylindrical part. For the same arrangement, Pandey and Pradyumna [269] proposed commonly used numerical techniques to study the free vibration of FG sandwich plates installed in thermal surroundings. Hosseini Hashemi et al. [270] used both three-dimensional elasticity solutions and a finite element model to investigate two types of load (in-plane and out-of-plane) free vibrations for thick FGM simply supported rectangular plates, [271-273].

9. Discussion
Functionally graded material is a high-quality material that will revolutionize the manufacturing world in the 21st century. There are many roadblocks to understanding this target. Cost is a transcendent issue, with a tremendous section of the cost expended on the powder preparing and manufacturing strategy. In this work, a basic outline for study static and dynamic response of rectangular and sandwich plate with FGM core and metal face sheets for the selected models utilizing both the proposed analytical solution and numerical is completed to get the natural frequency and critical buckling load problem of sandwich structures. The FGM layers are graded throughout the thickness metal through changing more than a few parameters included but not restrained to gradient index, face sheet thickness, FGM thickness, aspect ratio, number of FGM platelayers, etc. The materials are assumed to be distributed to upper and lower plate parts and, the FGM part comprises various materials, for example, ceramic and aluminum.

10. Concluding remarks
It can be inferred from various applications that beams and plates' vibration research is a significant field. The dynamic response includes evaluating frequency parameters, mode shape, stability, and buckling load in various complex environments. Likewise, various analysis and calculation techniques can be used to evaluate vibration characteristics. Existing literature has reviewed various studies on the free vibration and buckling analysis of FG plates. People try their best to remember all the essential contributions in the current field of interest, focusing on the most relevant works available to research engineers studying FG plate structures. The general comments of the present writing overview are as follows:
1. Many researchers have made great efforts to study the free vibration and the buckling in beams, rectangular plates, and sandwich plates, but it should be noted that compared with the analysis mentioned above methods that there are limited trails to investigate same above analysis for FGM sandwich plate with the porous metal taking in account some important parameters such as power-law index, thickness ratio, face sheet thickness, porous ratio, FGM core thickness and the number of layers.

2. It is found that a three-dimensional analytical solution for FG plates can be utilized to check the accuracy of various 2D plate theories and finite element formulations, but in most cases, there is major trouble to distinguish the numerical the mathematical representation for the selected models and get results. By checking the 3-D elasticity solution results, the dynamic response due to the 2D shear deformation theory is verified and accurate. No correlation has been found between the accuracy of the results and verification with experimental work.

3. For CPT, the influence of transverse shear is eliminated. Therefore, it is only used for thin FG plates. In most 2D theories, the influence of transverse shear and normal transverse deformation is considered, so it is suitable for predicting dynamic response for both thin and thick FG plates.

4. For a fixed power-law exponent, the natural frequency of the FG plate increases with the increase of the aspect ratio, and for a fixed aspect ratio, the natural frequency of the FG plate decreases with the increase of the power-law exponent. Having assessed a large segment of the FGM research accessible, it is evident that virtually all the works conducted have been purely analytical or with numerical simulation, and there is an apparent lack in the experimental work.

5. Due to the wide application of FGM structures in engineering industries, subsequently, further work should be done to improve the process control for in general FGM manufacture improvement to suit execution which is connected with free vibration and the critical buckling load and investigate this subject in many types of research to distinguish and sufficient safe and bring down the cost of FGM.

6. For future work, it is found that a 3D thermoelastic solution has not been implemented. Few people consider the effect of temperature changes on the performance of FGM boards. To expand the thermal analysis of various structures, including nonlinear effects, detailed research must be conducted.

7. For free vibration and buckling load calculations, aspect ratio and various material distributions play a vital role in distinguishing the frequency and buckling load parameter values of FG rectangular plates. Also, maybe noticed in most studies of free vibration that as the aspect ratio increases, the FG rectangular plate's frequency parameters also increase. This fact is because as the aspect ratio increases, the plate stiffness becomes greater.

11. References

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