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A SCIENTIFIC REVIEW OF FUNCTIONALLY GRADED NANO-REINFORCED PLATES: TYPES, FABRICATION METHODS, APPLICATIONS, AND VIBRATION BEHAVIOR

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ABSTRACT

Functionally graded materials (FGM) are advanced composite systems characterized by a continuous variation in material composition and properties, allowing for improved mechanical performance and resistance to thermal and structural stresses. Their unique gradation structure minimizes interfacial failures and makes them suitable for demanding applications in aerospace, biomedical devices, defence, and energy systems. With the advent of nanotechnology, incorporating nanomaterials such as carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs) has significantly enhanced the mechanical strength, thermal conductivity, and damping characteristics of FGM. This review provides a comprehensive overview of the recent advances in FGM reinforced with nanomaterials, emphasizing their types, fabrication techniques, and functional performance. Special attention is given to the vibrational behavior of these materials under various conditions, including different volume fraction distributions, porosity levels, and loading scenarios. Moreover, the impact of environmental factors—such as temperature fluctuations, humidity, and chemical exposure—on the long-term stability and functionality of FGM is thoroughly discussed. The review aims to offer a consolidated understanding of current research trends and identify key challenges and opportunities for the future development of nano-reinforced FGM in engineering applications.

1. Introduction

Functionally graded materials have received significant attention from researchers in engineering

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sciences. They possess multifunctional properties within a single part through a gradual change in composition. Consequently, FGM plates can avoid stress concentration and layer separation, which often occur in composite structures. Nanomaterials and functionally graded materials are part of recent developments in materials science, as both contribute to improved performance and properties. Nanomaterials, such as carbon and graphene tubes, have exceptional nanoscale properties, making them ideal for use in diverse applications. Functionally graded materials, on the other hand, allow the design of structures with characteristics that gradually change as needed, enhancing functionality. By combining these materials, compounds with superior mechanical and chemical properties can be achieved, opening new horizons in fields such as electronics, energy, and medicine[1].Therefore, materials play an important role in human life, as man use various materials to make multiple compounds used in various engineering applications. Therefore, composite materials have received considerable attention from researchers due to their wide range of uses. Composite materials are lighter, stronger, and more flexible in design [2].High-performance and cost-effective body component designs are of the highest standards that cannot be ignored in the aerospace, automotive, civil, and other energy industries. These critical requirements for industries have led engineers to give great importance to the design of high-strength materials while reducing weight [3] .The first international conference on functionally graded materials was launched in Japan in 1990. The first polymeric material (FGM) was patented in 2000. FGM have a variety of applications, including carbon nanotubes and electronics. These materials have great importance in improving performance by modifying their mechanical, thermal, and chemical properties, as shown in Figure 1[4]

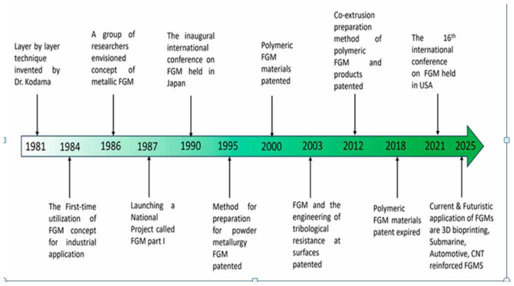

Figure 1. Timeline of FGM technology[4]

Composite materials is defined as a mixture of two or more substances in specified proportions[5]. Functionally graded composite materials are distinguished from conventional materials by a smooth transition in their properties through the composite material, which enhances their strength and reduces the likelihood of their failure, as shown in Figure 2, making them an excellent choice in many fields.[6].

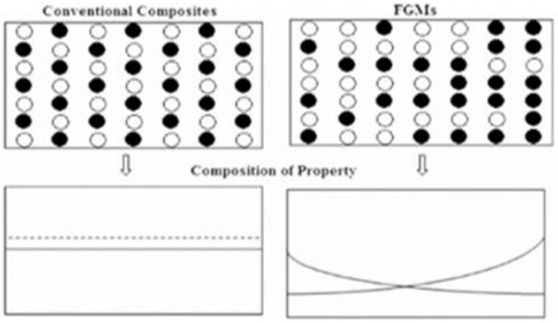

Figure 2. Variation of properties in conventional composites and FGM [6]

Pointed out that functionally graded materials are characterized by several positive aspects, including improving thermal properties, increasing the strength of the material, and improving the distribution of residual stress. It also has a high modulus of elasticity and high fracture toughness, low modulus of stress intensity, increased wear resistance, as well as reduced planar and transverse stresses[7]. The concept of gradient materials was initially designed for high-temperature resistant materials; however, over time, these materials have been used to control deformation, pressure, and wear, as well as to reduce stress concentration through a smooth, gradual transition between the layers of the material[8] .Usually made of metals and ceramics, Functionally Graded ingredients (FGM) are produced using different ratios of ingredients. Stress-induced fractures are prevented by the metallic component of FGM, while the ceramic component is resistant to heat [9]. In contrast to conventional composite materials, FGM sheets' altered material characteristics contribute to a continuous pressure distribution by lowering residual stresses and stress concentration factors[10] **.** This study presents a brief overview of nano-reinforced functionally graded plates, highlighting the influence of weight and volume fractions on their vibration behavior. It summarizes various types and fabrication methods of FG plates, explores their applications across sectors such as defense, aerospace, biomedical, energy, and automotive industries, and examines environmental impacts on structural performance. The review also integrates recent research findings to guide future advancements in structural design.

2.Types of Functionally Graded Materials

Functionally graded materials can be classified into two main categories: those based on the pattern of material gradation and those based on the structural configuration of the graded material itself. [11].

٢.1. Based on material gradient forms: Functionally graded materials are divided into four types in terms of gradation:

(a) In volume fraction.
(b) In particle size.
(c) In an angle of arrangement.
(d) shape.

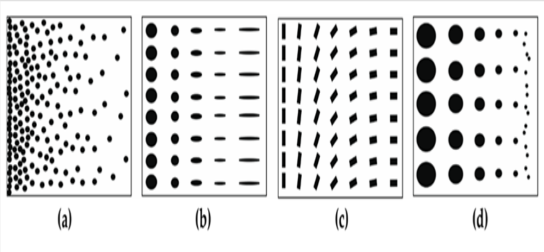

Figure.3. Functionally Graded Materials type based on gradient [11]

2.2. Based on the structure of the tool, there are two types: (a) continuous, and (b) discontinuous

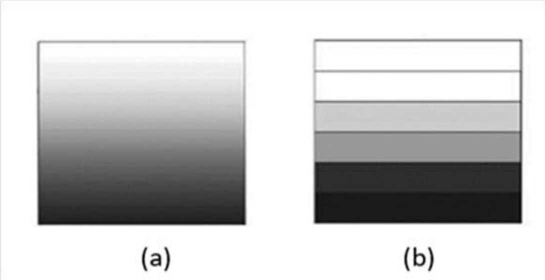

Figure.4. FGM type based on Structure[12]

3. Applications of functionally graded materials

Most industrial applications, such as aerospace, automotive, biomedical, and defense fields, need specific features that require a gradual change in the composition and structure of the material in a certain direction. The advanced class of heterogeneous composite materials known as functionally graded materials (FGM) is characterized by multifunctional characteristics on the one hand, through a gradual change in their composition or structure. They are very suitable for engineering applications that require conflicting properties in one component. Therefore, the graded materials differ in their mechanical, thermal, and frictional properties in specific fields, allowing them to be used in many applications, including [13] as shown in Figure (5).

1. Energy: It is used in the development of solar energy systems and withstands high temperatures.
2. Aviation and space: Used as barriers in spacecraft to withstand high temperatures when they enter the atmosphere.
3. Medicine: Used in the design of artificial limbs and human tissues, and used in dentistry and bone grafts.
4. Defence: It is used in the manufacture of military armour to withstand shocks and high temperatures, and it is also used in the manufacture of weapons.
5. Optoelectronics: It enters the field of manufacturing lenses and optical devices that require optical characteristics.
6. Civil engineering: Used in the development of building materials with mechanical properties to withstand different loads.
7. Engines: Used in the design of car engines, specifically in combustion chambers, to withstand high temperatures.

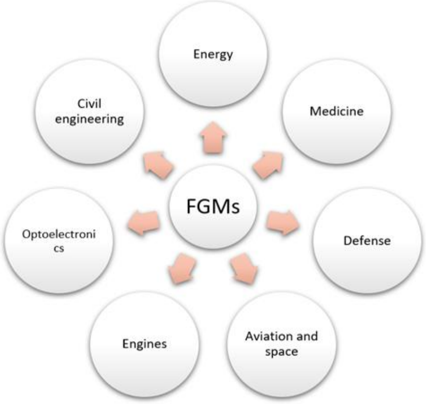

Figure 5. Applications of FGM.

4. Limitations and Challenges in Manufacturing Functionally Graded Materials

While functionally graded materials (FGM) offer significant potential in advanced engineering applications due to their tailored material properties, the process of manufacturing such materials with precise and reliable gradation remains technically challenging. One major difficulty lies in controlling the smooth transition of material composition across the thickness or volume of the component. Conventional methods such as powder metallurgy and centrifugal casting often struggle to achieve a truly continuous gradient, resulting instead in stepped or segmented structures that may not meet the performance expectations in critical applications [14], [15] . Additionally, the geometric limitations of these fabrication techniques restrict the production of complex or non-symmetrical components. For instance, centrifugal casting is largely applicable to cylindrical shapes, and techniques like powder pressing may fall short in maintaining dimensional precision and structural uniformity [15]. Additive manufacturing methods, though promising, introduce their own issues, including thermal stress, porosity, incomplete fusion, and cracking, all of which affect the integrity and mechanical behavior of the final part[16]

In nano-reinforced FGM, another level of complexity arises from the tendency of nano-fillers such as carbon nanotubes and graphene to agglomerate. Non-uniform dispersion leads to poor interfacial bonding and creates localized weak zones, which can significantly impair mechanical performance [17]. Furthermore, inconsistencies in melt pool behavior during layer-by-layer fabrication can result in undesirable microstructures and bonding defects between layers[18]

Finally, the high cost, energy consumption, and scalability limitations of most FGM production methods continue to be major barriers to industrial adoption. The need for specialized equipment and long processing times restricts large-scale manufacturing, especially for complex or hybrid nano-structured FGM [19]

5. Environmental Effects on the Structural Performance of Functionally Graded Materials

- Environmental conditions such as temperature, humidity, and chemical exposure have a significant impact on the performance of functionally graded materials (FGM). Due to the heterogeneous and gradual nature of their composition, FGM respond differently to environmental stimuli compared to conventional homogeneous materials.
- Temperature plays a crucial role, especially in high-performance applications. Variations in temperature can alter the material’s stiffness, induce thermal stresses due to mismatched thermal expansion coefficients across layers, and, in some cases, lead to micro-cracking or delamination. FGM designed for high-temperature environments—such as in aerospace or energy systems—must be carefully engineered to maintain structural integrity under thermal gradients.
- Humidity and moisture absorption primarily affect FGM with polymeric or organic matrices. These conditions may degrade the matrix, reduce interfacial bonding between phases, and ultimately weaken the mechanical properties, such as strength, toughness, and damping capacity.[20]A bibliometric review of 3D-printed functionally graded materials, focusing on mechanical properties[21]

In summary, the performance and reliability of FGM are highly dependent on their exposure environment. Therefore, environmental effects must be thoroughly considered during the design and selection process, especially for long-term or mission-critical applications.

6. Composite and nano materials

Composite materials are divided into two categories based on the type of matrix (plastics, ceramics) and the type of reinforcement (fibers or particles). Thermoplastic polymer compounds have superior mechanical properties, making them desirable in engineering fields. Figure (6) shows the main classification of composite materials.

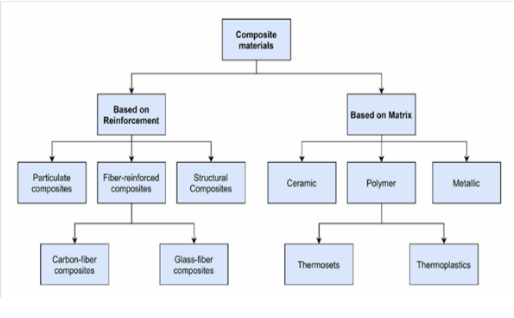

Figure 6. Classification of composite materials based on matrix and reinforcement type [22].

Nanomaterials, typically ranging in size from 1 to 100 nanometers, have emerged as one of the most significant innovations in modern engineering. Due to their unique scale and structure, they play a central role in the advancement of nanotechnology. Among these materials, carbon nanotubes (CNTs) and graphene nanoparticles (GNPs) stand out for their exceptional mechanical, electrical, and thermal properties, making them highly effective as reinforcing agents in polymer-based nanocomposites[23], [24].

7. Free vibration of metal–ceramic FG plate

A plate is a three-dimensional structural element whose very small thickness, when compared with other dimensions (length and width). The mechanical behavior of a functionally graded (FG) plate under a transverse load is investigated by [25]. [26] Studied the vibration of the FG plate that is exposed to moving loads as shown in Figure (7). Hamilton's principle was used to derive the governing equations, taking into account the effect of high deformations. The free vibration behavior of functionally graded ceramic metal sandwich flat panels is investigated by [27] as shown in Figure (8).

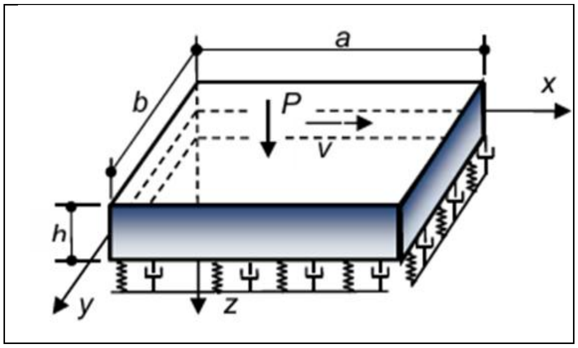

Figure7. The Geometry of FG plates [26].

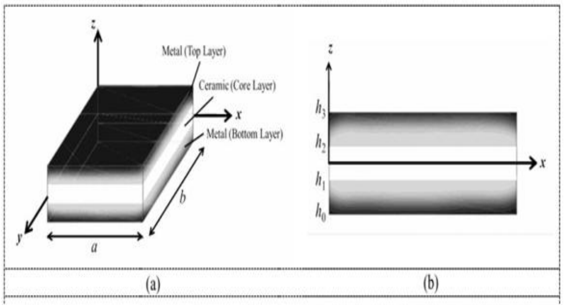

Figure 8. (a)Geometry, (b) lay-up scheme of FG sandwich flat plate[27].

[28] used an innovative mixed-layer model for the static evaluation of graded material sheets, and functionally, including embedded FGM as either surface layer or axial layers.[29] studied the free vibration behavior of plates made of graded materials and functionally.[30] studied free vibration of non-local plates with gradient ratios under different boundary conditions. Rayleigh-Ritz and classical plate theory were used to calculate the natural frequencies of nanoplates with graded ratios. [31] Analyzed the forced nonlinear dynamic behavior of a functionally graded plate (FGM) under external dynamic loads high-order implicit algorithm. The finite elements are discretized using a four-node quadrilateral element with seven degrees of freedom per node, as shown in Figure (9).

Figure 9. Quadrilateral element with four nodes and seven degrees of freedom per node [31].

[32] studied and analyzed the mechanical behavior of FG sheets under the influence of various loads. Two types of combined materials have been used, ceramic materials, such as alumina Al_2O_3 and zirconia ZrO_2 and metal materials, such as aluminum (Al). [33] developed an analytical solution to the behavior of the free vibration analysis of porous functionally graded sandwich plates consisting of an FGM core and two skins. [34] analyzed the natural frequency of conical FG plates with variable thickness, which is based on Pasternak's principle. Manufactured (FGM) is made from materials such as zirconia (ZrO_2) and alumina (Al_2O_3) in the form of multiple layers. [35] analyzed the dynamic behavior of plates made from functionally graded materials using an implicit algorithm approach. The sigmoid law (S-FGM), the exponential law (E-FGM), and the power law (P-FGM) are shown in Figure (10**).** [36] Investigated of the vibrational properties of functional gradient (FG) supported plates based on a Winkler-Pasternak, using 3D shear theory. Table 1 presented the summary of different methods used to study the free vibration FG plate.

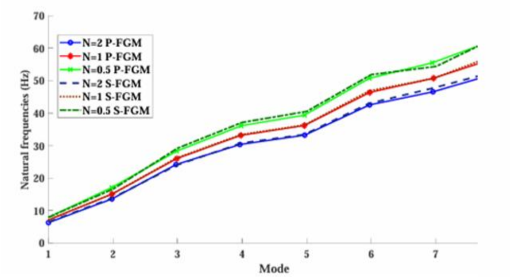

Figure 10. Comparison of natural frequencies between P-FGM and S-FGM [35].

Table 1 The summary of the different methods

Authors	Type	In study	Compute
[25]	Analytically	improve its high-temperature performance in different environments	Mechanical behavior under transverse load
[26]	Analytically	Effect of stresses and damping coefficients on displacement	vibration of the FG plate that exposed to moving loads
[27]	Numerically	Effect of the power index on the non.	free vibration behavior of FG.
[28]	Analytically	mixed-layer model for the static evaluation of	Mechanical and thermal behavior.
[29]	Analytically	Effects of the plate length to thickness ratio	Free vibration behavior of panels made of FGM.
[30]	Analytically	Vibration and buckling behavior analysis of FGM-based nanocomposites	vibration frequencies and buckling pressures
[31]	Analytically	Comparison between natural vibration frequency and dynamic response of FGM	Analysis of nonlinear dynamic behavior
[32]	Analytically and experimentally	Effect of volume ratio, stresses, and mechanical properties	Mechanical behavior analysis for different loads
[33]	Analytically	Effect of porosity on natural frequency	Development of a new solution for free vibration analysis behavior
[34]	Analytically	Effect of porosity on FG sheets.	Analysis of the natural frequency of conical FG plates
[35]	Analytically	Properties of the material constantly change across the thickness of the plate.	Dynamic behavior of an FGM plate.
[36]	Analytically	Vibrational properties of functional gradient (FG) supported plates	affect the natural frequencies

8. Graphene nanoplate–Epoxy FG plate

The nonlinear vibration behavior of graphene-reinforced composite FG in thermal environments is studied by[37]. The Reddy theory of third-order bending was adopted. Halpin-Tsai model is used to estimate the properties and the gradient of graphene in the layers. [38] presented the effect of graphene sheets on the properties of composite materials used in aerospace applications, especially in high combustion conditions. Equations were used to calculate combustion rates and percentages. Different weight fractions of graphene were used (0,0.3,0.5, and 1%) wt, and the thermal conductivity was measured according to ASTM standards. [39]developed the effect of graphene nanoplate concentration on the tensile properties of graphene nanoplate/epoxy composites. Four samples with different weight concentrations (0, 0.25, 0.5, 1, and 2%) of graphene nanoplates are simulated. The results showed that for ductile epoxy with 1% of nanoparticles, there was a 41% increase in tensile strength and a 19% increase in Young's modulus, as shown in Figure (11). [40] analyzed the bending and vibration of FG polymer nanocomposite reinforced with graphene nanosheets under distributed load.

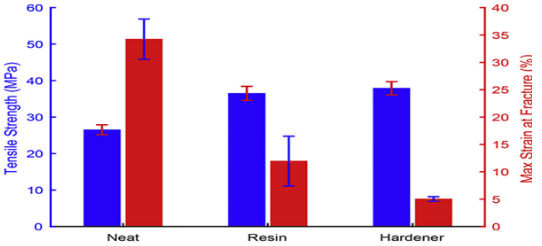

Figure .11 Mean tensile strength and fracture strain values of GNP /Epoxy with and 1% GNPs [39].

The free vibration and instability of FG porous laminates reinforced with graphene sheets (GPLs) is presented by (Nguyen et al., 2020) as shown in Figure (12).

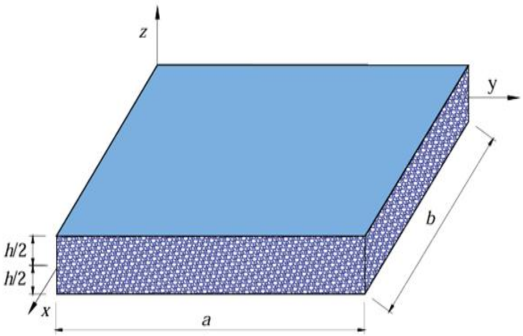

Figure 12. A model of a rectangular FGP-GPLs plate[41]

Under axial load, the dynamic responce of FG sheets reinforced with graphene nanoplates is developed by [42]. While [43] investigated the influence of Graphene on the tensile properties and surface adhesion between flax fibers and epoxy resin. The results showed that the addition of graphene oxide (GO) to the surfaces of flax fibers enhanced the adhesion between the fibers and the matrix.

The free vibration of an FG plate reinforced with graphene nanoplate (GNPs) is presented by [44]. The modified strain gradient theory (MSGT) is investigated to analyses the vibration response. The results showed that the elastic young's modulus increases with 31% and 62% when the weight fraction of GNPs is 0.1% and 0.7%, respectively.[45] developed the mechanical properties of FG porous structures supported by graphene plate (GPLs). Different weight ratios of graphene ranging from 0.1% to 6%, with the porosity controlled between 10% and 30%, are studied to find the optimal performance. The results indicate that the graphene plates lead to a significant increase in the stiffness of the structures and that the efficient distribution of graphene significantly affects the behavior of the structures under loading, making them ideal for engineering applications.[46] presented the dynamic behavior of panels under the influence of graphene distribution and density, as shown in Figure (13). The first-order deformation theory was used to derive the equations of motion using the Halpin-Tsai model. The results showed that this model improves the dynamic performance of advanced materials in engineering.

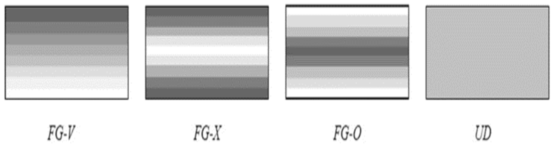

Figure 13. Different GPL distribution patterns[46] .

The free vibration analysis of sandwich plates reinforced with graphene nanoparticles, focusing on the effects of porosity distribution and graphene on the vibration behavior is presented by [47]**.** The results showed that the plates reinforced with graphene nanoparticles exhibit enhanced vibration behavior.[48] studied the effect of adding graphene particles on the flexural properties of the epoxy matrix experimentally. The effect of six different graphene weight concentrations (0, 0.5, 1, 2.5, 5, and 10) % is studied. Their results showed that adding graphene enhanced the flexural modulus.[49] created FG nanocomposites from graphene nanoparticles and a polyester matrix, and calculated the mechanical properties. The results showed that the addition of 4% graphene nanoparticles lead to an increase in the elastic modulus and tensile strength of 44.5% and 79.2%, respectively.[50] studied the effect of temperature on the dynamic response of a three-layer microplate, a composite core of epoxy-based (FG) reinforced with graphene nanosheets. Sinusoidal shear deformation plate theory (SSDPT) is used to predict the mechanical properties of the nanocomposite. The results indicate that the temperature has a significant effect on the stiffness and frequencies of the composite plates. An increase in temperature results in a decrease in frequency due to stiffness.[51] developed the effect of nanographene on the hardness, impact strength, and density of glass-epoxy composites. The effect of different concentration is studied. The results showed that the addition of 2% graphene leads to an increase in the hardness values from 60 to 74.

Table 2. The summary of the different methods used to study the graphene nanoplates.

Authors	In study	Computation
[37]	Non-linear vibration behavior of a graphene sheet-reinforced composite.	nonlinear vibration characteristics.
[38]	Effect of graphene in composite materials.	Improved thermal stability.

[39]	Effect of graphene nanoplate concentration on the tensile properties.	Behavior of graphene nanoparticles.
[40]	Analyzed the bending and vibration of the FG polymer nanocomposite.	gradient distribution of graphene sheets.
[41]	Developed a new model of high-order shear deformation theory	material properties, such as Young's modulus, density.
[42]	under axial mechanical load	Improvement in composite design.
[43]	Effect of Graphene oxide on the tensile properties and surface adhesion	Transverse bending and surface shearing.
[44]	free vibration of an FG plate reinforced with graphene nanoplates.	Young's elastic modulus.
[45]	Mechanical properties of FG porous structures supported by graphene plate	Behavior of mechanical properties.
[46]	Dynamic behavior of panels under the influence of graphene distribution and density.	dynamic performance.
[47]	Free vibration analysis of sandwich spiral plates reinforced with graphene nanoparticles.	vibration behavior.
[48]	Effect of adding graphene particles on the flexural properties of the epoxy matrix experimentally.	Behavior of mechanical properties.
[49]	Production of nanocomposites from graphene and polyester Matrix	mechanical properties.
[50]	Effect of temperature on the dynamic response of a three-layer microplate.	stiffness and frequencies of the composite plates
[51]	Effect of nanographene on the hardness, impact strength, and density.	Hardness

9. Carbon nanotube–epoxy FG plate

The effects of (MWCNTs) on the mechanical performance of epoxy matrix is studied by [52]. While [53] developed the effect of the carbon nanotubes and aluminium oxide with epoxy on the dynamic properties experimentally. [54] simulated the free vibration of the reinforced nanocomposite plates.(Saravanan et al., 2018) improved in mechanical properties of epoxy nanocomposites by different weight percentages of fillers (2, 4, and 6%).[56] presented the effect of MWCNT with the epoxy on tensile properties. The results showed that the adding of MWCNT improved the tensile strength by 11% and the tensile modulus by 68.7% compared to pure epoxy. [57] developed the effect of adding different sizes of MWCNT on the mechanical properties of the epoxy composite material. The results showed that the tensile strength was improved by 172% compared to pure epoxy. [58] investigated the dynamic behavior of cylindrical plates reinforced with single-walled carbon nanotubes. [59] improved the mechanical properties of epoxy-based nanocomposites by adding multi-walled carbon nanotubes (MWCNT), zirconium dioxide (ZrO_2), and yttrium oxide (Y_2O_3). Table 3 presented the summary of the different methods that used to study carbon nanotubes.

Table 3. The summary of the different methods used to study Carbon nanotubes.

Authors	In study	Computation
[52]	Effects of multi-walled carbon nanotubes and Nano diamonds on the mechanical performance of epoxy matrix.	mechanical properties.
[53]	Effect of mechanical and dynamic properties.	Ultimate tensile strength.
[54]	Vibration and bending behavior of the plates.	Increasing the volume fraction of CNTs.
[55]	Improvement in mechanical properties of epoxy nanocomposites.	Tensile strength and modulus of elasticity.
[56]	Effect of multi-walled carbon nanotubes with the epoxy on tensile and shear properties.	mechanical properties.
[57]	Effect of adding different sizes of multi-walled carbon nanotubes.	Tensile strength.
[58]	Vibrational behavior of cylindrical plates reinforced with single-walled carbon nanotubes.	dynamic response of the composite plates.
[59]	Improved the mechanical properties of epoxy-based nanocomposites.	Young's modulus and toughness.

10. Graphene nanoplate - Carbon nanotube- Epoxy FG plate

The free vibrations of composite plate supported by CNT and graphene is investigated by [60]**.** [61] studied the effect of the shape arrangement of multi-walled carbon tubes and graphene nano-plate on the mechanical properties of epoxy-based nanocomposite materials. Halbin Cai Lee is used to estimate the elastic properties of the composite materials. [62] investigated the free vibration behavior of functionally inserted multilayer nanocomposite plates containing nanofillers (carbon nanotubes and graphene sheets). [63] studied the development of epoxy composites containing a mixture of graphene sheets and carbon nanotubes to improve their mechanical and thermal properties.[64] investigated the effect of adding multi-walled carbon nanotubes (MWCNT) and graphene nanoparticles (GNP) on the mechanical properties of glass-epoxy composites. The results found a significant improvement in the compressive strength and compressive modulus (80% and 74%), respectively, at a ratio of 0.2% of multi-walled carbon nanotubes and graphene nanoparticles. Their highest ratio (0.3%) led to a decrease in the mechanical properties due to the agglomeration of the materials. Table 4 presented the summary of the different methods used to study graphene nanoplate - carbon nanotube- epoxy FG plate

Table 4. The summary of the different methods used to stud graphene nanoplate - carbon nanotube- epoxy FG plate.

Authors	In study	Computation
[60]	Bending characteristics and free vibrations of composite panels.	dynamic behavior of the composite nanoplatelets
[61]	Effect of the shape arrangement of multi-walled carbon tubes and graphene nano-plate,	mechanical properties.
[62]	Free vibration behavior of functionally inserted multilayer nanocomposite plates	natural frequencies
[63]	development of epoxy composites containing a mixture of graphene sheets and carbon nanotubes.	mechanical properties.
[64]	Effect of adding (MWCNT) and (GNP) on the mechanical properties	compressive strength and compressive modulus.

11. Conclusions

Based on this study, the following conclusions can be drawn:

1. Functionally graded materials (FGM) have proven to be highly effective in addressing performance requirements in advanced engineering applications by enabling gradual transitions in mechanical and physical properties.
2. The integration of nanomaterials such as carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs) into composite systems has shown a marked improvement in stiffness, strength, and durability.
3. Studies based on higher-order shear deformation theories confirm that the distribution of material constituents significantly affects vibrational characteristics, particularly in enhancing natural frequencies.
4. Higher levels of porosity in functionally graded materials can significantly reduce their structural stiffness and diminish vibrational performance, highlighting the need for precise control of porosity during the manufacturing process.
5. Finite element analyses reveal that adjusting the spatial arrangement of reinforcing nanomaterials can enhance the mechanical performance of FGMs under both static and dynamic loading.
6. Changes in temperature have a notable effect on the dynamic characteristics of FGMs, as increased thermal conditions tend to lower their natural frequencies, emphasizing the importance of ensuring thermo-mechanical stability in their design.
7. Advancing the use of FGMs in fields such as aerospace, biomedical, and structural engineering depends on the continued refinement of accurate modeling tools and reliable fabrication techniques.

References

1. Alkunte, S., Fidan, I., Naikwadi, V., Gudavasov, S., Ali, M. A., Mahmudov, M., Hasanov, S., & Cheepu, M. (2024b). Advancements and Challenges in Additively Manufactured Functionally Graded Materials: A Comprehensive Review. In *Journal of Manufacturing and Materials Processing* (Vol. 8, Issue 1). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/jmmp8010023
2. Arani, A. G., Kiani, F., & Afshari, H. (2021). Free and forced vibration analysis of laminated functionally graded CNT-reinforced composite cylindrical panels. *Journal of Sandwich Structures*

and Materials, *23*(1), 255–278. https://doi.org/10.1177/1099636219830787

3. Badawy, A., & Khashaba, E. (2018). Fabrication and characterization of epoxy modified with 0.5% MWCNTs. *Journal of Engineering Science and Military Technologies*, *2*(3), 134–146. https://doi.org/10.21608/ejmtc.2018.4974.1089
4. Balguri, P. K., Samuel, D. G. H., & Thumu, U. (2021). A review on mechanical properties of epoxy nanocomposites. *Materials Today: Proceedings*, *44*, 346–355. https://doi.org/10.1016/j.matpr.2020.09.742
5. Belkhodja, Y., Ouinas, D., Zaoui, F. Z., & Fekirini, H. (2020). An exponential-trigonometric higher order shear deformation theory (HSDT) for bending, free vibration, and buckling analysis of functionally graded materials (FGM) plates. *Advanced Composites Letters*, *29*. https://doi.org/10.1177/0963693519875739
6. Beloufa, H. I., Tarfaoui, M., Lafdi, K., Daly, M., & Bendarma, A. (n.d.). *Graphene Nanosheets as Novel Nanofillers in an Epoxy Matrix for Improved Mechanical Properties*. www.intechopen.com
7. Bourihane, O., Hilali, Y., & Mhada, K. (2020). Nonlinear dynamic response of functionally graded material plates using a high-order implicit algorithm. *ZAMM Zeitschrift Fur Angewandte Mathematik Und Mechanik*, *100*(12). https://doi.org/10.1002/zamm.202000087
8. Cherradi, N., Kawasaki, A., & Gasik, M. (1994). *WORLDWIDE TRENDS IN FUNCTIONAL GRADIENT MATERIALS RESEARCH AND DEVELOPMENT* (Vol. 4, Issue 8). https://doi.org/https://doi.org/10.1016/S0961-9526(09)80012-9
9. Chi, S. H., & Chung, Y. L. (2006). Mechanical behavior of functionally graded material plates under transverse load-Part I: Analysis. *International Journal of Solids and Structures*, *43*(13), 3657–3674. https://doi.org/10.1016/j.ijsolstr.2005.04.011
10. Chiker, Y., Bachene, M., Guemana, M., Attaf, B., & Rechak, S. (2020). Free vibration analysis of multilayer functionally graded polymer nanocomposite plates reinforced with nonlinearly distributed carbon-based nanofillers using a layer-wise formulation model. *Aerospace Science and Technology*, *104*. https://doi.org/10.1016/j.ast.2020.105913
11. Čukanović, D., Radaković, A., Bogdanović, G., Milanović, M., Redžovíc, H., & Dragovíc, D. (2018). New shape function for the bending analysis of functionally graded plate. *Materials*, *11*(12). https://doi.org/10.3390/ma11122381
12. Das, P., Benslimane, A., Islam, M. A., Siddiquei, A. A., Rahman, M. M., & Adil, M. M. (2024). Finite element analysis of a generalized rotating FGM vessel subjected to thermo-mechanical loadings: Effect of Poisson ratio and inhomogeneity parameters. *Heliyon*, *10*(11). https://doi.org/10.1016/j.heliyon.2024.e31833
13. Dash, S., Sharma, N., Mahapatra, T. R., Panda, S. K., & Sahu, P. (2018). Free vibration analysis of functionally graded sandwich flat panel. *IOP Conference Series: Materials Science and Engineering*, *377*(1). https://doi.org/10.1088/1757-899X/377/1/012140
14. Do, V. N. Van, & Lee, C. H. (2019). Free vibration analysis of FGM plates with complex cutouts by using quasi-3D isogeometric approach. *International Journal of Mechanical Sciences*, *159*, 213–233. https://doi.org/10.1016/j.ijmecsci.2019.05.034
15. Dolez, P. I. (2015). Nanomaterials Definitions, Classifications, and Applications. In *Nanoengineering: Global Approaches to Health and Safety Issues* (pp. 3–40). Elsevier. https://doi.org/10.1016/B978-0-444-62747-6.00001-4
16. Dyachkova, T. P., Khan, Y. A., Burakova, E. A., Galunin, E. V., Shigabaeva, G. N., Stolbov, D. N., Titov, G. A., Chapaksov, N. A., & Tkachev, A. G. (2023). Characteristics of Epoxy Composites Containing Carbon Nanotubes/Graphene Mixtures. *Polymers*, *15*(6). https://doi.org/10.3390/polym15061476
17. García-Macías, E., Rodríguez-Tembleque, L., & Sáez, A. (n.d.). *Bending and free vibration analysis of functionally graded graphene vs. carbon nanotube reinforced composite plates*.
18. Govindaraj, P., Sokolova, A., Salim, N., Juodkazis, S., Fuss, F. K., Fox, B., & Hameed, N. (2021). Distribution states of graphene in polymer nanocomposites: A review. *Composites Part B: Engineering*, *226*, 109353. https://doi.org/https://doi.org/10.1016/j.compositesb.2021.109353
19. Gu, H., Wei, C., Li, L., Ryan, M., Setchi, R., Han, Q., & Qian, L. (2021). Numerical and experimental study of molten pool behaviour and defect formation in multi-material and functionally graded materials laser powder bed fusion. *Advanced Powder Technology*, *32*(11), 4303–4321. https://doi.org/10.1016/j.apt.2021.09.036
20. Guo, L., & Noda, N. (2014). Investigation methods for thermal shock crack problems of functionally graded materials-Part I: Analytical method. *Journal of Thermal Stresses*, *37*(3), 292–324. https://doi.org/10.1080/01495739.2013.839853

21. Hien, T. D., & Lam, N. N. (2018). Vibration of functionally graded plate resting on viscoelastic elastic foundation subjected to moving loads. *IOP Conference Series: Earth and Environmental Science*, *143*(1). https://doi.org/10.1088/1755-1315/143/1/012024
22. Huang, T., Ma, Y., Zhao, T., Yang, J., & Wang, X. (2022). Free Vibration Analysis of Spinning Sandwich Annular Plates with Functionally Graded Graphene Nanoplatelet Reinforced Porous Core. *Materials*, *15*(4). https://doi.org/10.3390/ma15041328
23. Janane Allah, M., Belaasilia, Y., Timesli, A., & El Haouzi, A. (2021). Tsdt theory for free vibration of functionally graded plates with various material properties. *Mathematical Modeling and Computing*, *8*(4), 691–704. https://doi.org/10.23939/mmc2021.04.691
24. Javanshour, F., Ramakrishnan, K. R., Layek, R. K., Laurikainen, P., Prapavesis, A., Kanerva, M., Kallio, P., Van Vuure, A. W., & Sarlin, E. (2021). Effect of graphene oxide surface treatment on the interfacial adhesion and the tensile performance of flax epoxy composites. *Composites Part A: Applied Science and Manufacturing*, *142*. https://doi.org/10.1016/j.compositesa.2020.106270
25. Kanu, N. J., Vates, U. K., Singh, G. K., & Chavan, S. (2019). Fracture problems, vibration, buckling, and bending analyses of functionally graded materials: A state-of-the-art review including smart FGM. In *Particulate Science and Technology* (Vol. 37, Issue 5, pp. 579–604). Taylor and Francis Inc. https://doi.org/10.1080/02726351.2017.1410265
26. Khorasani, M., Soleimani-Javid, Z., Arshid, E., Amir, S., & Civalek, Ö. (2024). Vibration analysis of graphene nanoplatelets' reinforced composite plates integrated by piezo-electromagnetic patches on the piezo-electromagnetic media. *Waves in Random and Complex Media*, *34*(4), 2394–2424. https://doi.org/10.1080/17455030.2021.1956017
27. Kiarasi, F., Babaei, M., Sarvi, P., Asemi, K., Hosseini, M., & Bidgoli, M. O. (2021). A review on functionally graded porous structures reinforced by graphene platelets. In *Journal of Computational Applied Mechanics* (Vol. 52, Issue 4, pp. 731–750). University of Tehran. https://doi.org/10.22059/JCAMECH.2021.335739.675
28. Kilic, U., Sherif, M. M., & Ozbulut, O. E. (2019). Tensile properties of graphene nanoplatelets/epoxy composites fabricated by various dispersion techniques. *Polymer Testing*, *76*, 181–191. https://doi.org/10.1016/j.polymertesting.2019.03.028
29. Koizumi, M. (1997). FGM activities in Japan. In *Composites Part B* (Vol. 28). https://doi.org/https://doi.org/10.1016/S1359-8368(96)00016-9
30. Kumar, V., Singh, S. J., Saran, V. H., & Harsha, S. P. (2021). Vibration characteristics of porous FGM plate with variable thickness resting on Pasternak's foundation. *European Journal of Mechanics, A/Solids*, *85*. https://doi.org/10.1016/j.euromechsol.2020.104124
31. Li, M., Guedes Soares, C., & Yan, R. (2021). Free vibration analysis of FGM plates on Winkler/Pasternak/Kerr foundation by using a simple quasi-3D HSDT. *Composite Structures*, *264*. https://doi.org/10.1016/j.compstruct.2021.113643
32. Lin, D., Li, Q., Li, W., Zhou, S., & Swain, M. V. (2009). Design optimization of functionally graded dental implant for bone remodeling. *Composites Part B: Engineering*, *40*(7), 668–675. https://doi.org/10.1016/j.compositesb.2009.04.015
33. Lu, L., Wang, S., Li, M., & Guo, X. (2021). Free vibration and dynamic stability of functionally graded composite microtubes reinforced with graphene platelets. *Composite Structures*, *272*. https://doi.org/10.1016/j.compstruct.2021.114231
34. Mangisetty Srinivasaiah, A., Nagaraja, S., Munipapanna, A., Bellary Gopalakrishna, S., Krishnappa, M., & Hassan Venkataramaiah, H. (2024). Influence of nano graphene filler on hardness, impact strength and density of glass epoxy composites. *Engineering Reports*, *6*(12). https://doi.org/10.1002/eng2.12973
35. Mohammadi, M., Rajabi, M., & Ghadiri, M. (2021). Functionally graded materials (FGM): A review of classifications, fabrication methods and their applications. In *Processing and Application of Ceramics* (Vol. 15, Issue 4, pp. 319–343). University of Novi Sad, Faculty of Technology. https://doi.org/10.2298/PAC2104319M
36. Mohammad-Rezaei Bidgoli, E., & Arefi, M. (2021). Free vibration analysis of micro plate reinforced with functionally graded graphene nanoplatelets based on modified strain-gradient formulation. *Journal of Sandwich Structures and Materials*, *23*(2), 436–472. https://doi.org/10.1177/1099636219839302
37. Moleiro, F., Franco Correia, V. M., Ferreira, A. J. M., & Reddy, J. N. (2019). Fully coupled thermo-mechanical analysis of multilayered plates with embedded FGM skins or core layers using a layerwise mixed model. *Composite Structures*, *210*, 971–996. https://doi.org/10.1016/j.compstruct.2018.11.073
38. Moradi-Dastjerdi, R., & Malek-Mohammadi, H. (2017). *Mechanics of Advanced Composite*

Structures 4 (2017) 59-73 Mechanics of Advanced Composite Structures Free Vibration and Buckling Analyses of Functionally Graded Nanocomposite Plates Reinforced by Carbon Nanotube P A P E R I N F O. https://doi.org/10.22075/MACS.2016.496

39. Müller, E., Drašar, Č., Schilz, J., & Kaysser, W. A. (2003). Functionally graded materials for sensor and energy applications. *Materials Science and Engineering: A*, *362*(1–2), 17–39. https://doi.org/10.1016/S0921-5093(03)00581-1
40. Mustafa, B. S., Jamal, G. M., & Abdullah, O. Gh. (2022). *The use of multi-wall carbon nanotube for improving the mechanical performance of epoxy resin based metal oxide hybrid nanocomposites*. https://doi.org/10.21203/rs.3.rs-1674755/v1
41. Nguyen, Q. H., Nguyen, L. B., Nguyen, H. B., & Nguyen-Xuan, H. (2020). A three-variable high order shear deformation theory for isogeometric free vibration, buckling and instability analysis of FG porous plates reinforced by graphene platelets. *Composite Structures*, *245*. https://doi.org/10.1016/j.compstruct.2020.112321
42. Njim, E. K., Bakhy, S. H., & Al-Waily, M. (2021). Free vibration analysis of imperfect functionally graded sandwich plates: Analytical and experimental investigation. *Archives of Materials Science and Engineering*, *111*(2), 49–65. https://doi.org/10.5604/01.3001.0015.5805
43. Qusi, S., Alqader, A., Owaid Bedaiwi, B., Njim, E. K., Al-Fatlawi, A., Bedaiwi, O., & Njim, K. (n.d.). Mechanical Characterisation of the Polyester/Graphene Nanocomposites Functionally Graded Sandwich Plate. In *Library Progress International* (Vol. 44, Issue 2). www.bpasjournals.com
44. Reddy, J. N. (2000). Analysis of functionally graded plates. In *INTERNATIONAL JOURNAL FOR NUMERICAL METHODS IN ENGINEERING Int. J. Numer. Meth. Engng* (Vol. 47). https://doi.org/https://doi.org/10.1002/(SICI)1097-0207(20000110/30)47:1/3%3C663::AID-NME787%3E3.0.CO;2-8
45. Research, |;, Mohammed, S. M., Gamil, M., & Mohammed, S. S. (2017). Mechanical and Dynamic Behaviour of Epoxy/Mwcnts and Epoxy/Al 2 O 3 Nanocomposites. In *Nano Sci Nano Technol* (Vol. 11, Issue 2). www.tsijournals.com
46. Sadia, S. I., Aneela, S., Atif, I., Syed, Z. U. A. B., Muhammad, Y., Arshad, B., & Ali, B. (2018). Effect of graphene for ablation study of advanced composite materials for aerospace applications. *Key Engineering Materials*, *778 KEM*, 118–125. https://doi.org/10.4028/www.scientific.net/KEM.778.118
47. Sahmani, S., & Aghdam, M. M. (2018). Small Scale Effects on the Large Amplitude Nonlinear Vibrations of Multilayer Functionally Graded Composite Nanobeams Reinforced with Graphene-Nanoplatelets. In *Int. J. Nanosci. Nanotechnol* (Vol. 14, Issue 3).
48. Saleh, B., Jiang, J., Fathi, R., Al-hababi, T., Xu, Q., Wang, L., Song, D., & Ma, A. (2020). 30 Years of functionally graded materials: An overview of manufacturing methods, Applications and Future Challenges. In *Composites Part B: Engineering* (Vol. 201). Elsevier Ltd. https://doi.org/10.1016/j.compositesb.2020.108376
49. Saravanan, D., Chandramohan, P., Raajeshkrishna, C. R., & Sabarinathan, C. (n.d.). ENHANCEMENT OF MECHANICAL PROPERTIES OF EPOXY HYBRID NANOCOMPOSITES THROUGH HYBRIDIZATION OF CARBON NANOTUBES AND ALUMINA NANOPARTICLES. In *Digest Journal of Nanomaterials and Biostructures* (Vol. 13, Issue 2).
50. Shehab, E., Meiirbekov, A., Amantayeva, A., & Tokbolat, S. (2023). Cost Modelling for Recycling Fiber-Reinforced Composites: State-of-the-Art and Future Research. In *Polymers* (Vol. 15, Issue 1). MDPI. https://doi.org/10.3390/polym15010150
51. Shen, H. S., Xiang, Y., & Fan, Y. (2017). Nonlinear vibration of functionally graded graphene-reinforced composite laminated cylindrical shells in thermal environments. *Composite Structures*, *182*, 447–456. https://doi.org/10.1016/j.compstruct.2017.09.010
52. Sidoli, M., Magnani, G., Fornasini, L., Scaravonati, S., Morenghi, A., Vezzoni, V., Bersani, D., Bertoni, G., Gaboardi, M., Riccò, M., & Pontiroli, D. (2023). Defective graphene decorated with TiO2 nanoparticles as negative electrode in Li-ion batteries. *Journal of Alloys and Compounds*, *958*. https://doi.org/10.1016/j.jallcom.2023.170420
53. Singh, P. P., Azam, M. S., & Ranjan, V. (2020). Size-dependent natural frequencies of functionally graded plate with out of plane material inhomogeneity using Eringen's theory of nonlocal elasticity. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications*, *234*(2), 300–319. https://doi.org/10.1177/1464420719886887
54. Subhani, T., Latif, M., Ahmad, I., Rakha, S. A., Ali, N., & Khurram, A. A. (2015). Mechanical performance of epoxy matrix hybrid nanocomposites containing carbon nanotubes and nanodiamonds. *Materials and Design*, *87*, 436–444. https://doi.org/10.1016/j.matdes.2015.08.059
55. Tang, L., Wang, Y., Li, Y., & Li, Q. (2021). Effects of modified carbon nanotubes with different sizes on

properties of epoxy shape memory polymers. *Polymer Composites*, *42*(6), 2989–2999. https://doi.org/10.1002/pc.26032

56. Turaka, S., & Bandaru, A. K. (2023). Enhancement in Mechanical Properties of Glass/Epoxy Composites by a Hybrid Combination of Multi-Walled Carbon Nanotubes and Graphene Nanoparticles. *Polymers*, *15*(5). https://doi.org/10.3390/polym15051189
57. Veres, C., & Tănase, M. (2025). A Bibliometric Review of 3D-Printed Functionally Graded Materials, Focusing on Mechanical Properties. In *Machines* (Vol. 13, Issue 3). Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/machines13030232
58. Wang, Y., Xie, K., Fu, T., & Shi, C. (2019). Bending and elastic vibration of a novel functionally graded polymer nanocomposite beam reinforced by graphene nanoplatelets. *Nanomaterials*, *9*(12). https://doi.org/10.3390/nano9121690
59. Y. Miyamoto, W. A. K. B. H. R. A. K. & R. G. F. (1999). *Chapter 2 LESSONS FROM NATURE*. https://doi.org/https://doi.org/10.1007/978-1-4615-5301-4_2
60. Zarasvand, K. A., Golestanian, H., & Alasvand Zarasvand, K. (2019a). Effects of arrangement and shape of MWCNT and GNP reinforcements on nanocomposite mechanical properties. *Journal of Reinforced Plastics and Composites*, *38*(18), 846–859. https://doi.org/10.1177/0731684419850892
61. Zarasvand, K. A., Golestanian, H., & Alasvand Zarasvand, K. (2019b). Effects of arrangement and shape of MWCNT and GNP reinforcements on nanocomposite mechanical properties. *Journal of Reinforced Plastics and Composites*, *38*(18), 846–859. https://doi.org/10.1177/0731684419850892
62. Zhang, N., Khan, T., Guo, H., Shi, S., Zhong, W., & Zhang, W. (2019). Functionally Graded Materials: An Overview of Stability, Buckling, and Free Vibration Analysis. In *Advances in Materials Science and Engineering* (Vol. 2019). Hindawi Limited. https://doi.org/10.1155/2019/1354150
63. Zhou, Y., Liu, D., & Zhu, J. (2022). Vibration and Wave Analyses in the Functionally Graded Graphene-Reinforced Composite Plates Based on the First-Order Shear Deformation Plate Theory. *Applied Sciences (Switzerland)*, *12*(6). https://doi.org/10.3390/app12063140