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Buckling Behaviour of Functionally Graded Plates

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Abstract— **Functionally graded materials (FGMs) have garnered significant attention in structural engineering due to their tailored material properties, offering enhanced mechanical performance compared to conventional homogeneous materials. This study investigates the buckling behaviour of functionally graded plates under various loading conditions and using various deformation theories. The analysis integrates the complexities of material gradation, plate geometry, and boundary conditions to provide a comprehensive understanding of buckling phenomena in FGM plates. Various conditions which include porosity distribution factors are also considered for the analysis. Factors such as material composition, thickness profile, and temperature gradients are considered to elucidate their effects on buckling characteristics. The results contribute to the design optimization and structural integrity assessment of functionally graded plates in engineering applications, offering insights for developing robust and efficient structural systems.**

Keywords—**Functionally Graded Plate, Buckling, Porosity, Shear Deformation theories, Structural integrity.**

INTRODUCTION

Traditionally, structural components have been made from homogeneous materials with uniform properties throughout their volume. However, advancements in material science and engineering have led to the development of functionally graded materials (FGMs), which exhibit spatially varying material properties tailored to specific engineering requirements.

Functionally graded plates (FGPs) represent a subclass of FGM structures that have garnered significant attention due to their potential for optimizing structural performance and efficiency. These plates are characterized by a gradual variation of material properties, typically in one or more directions, across their thickness. This gradient in material properties enables FGPs to exhibit superior mechanical behaviour, such as improved load-bearing capacity, reduced weight, and enhanced resistance to thermal and mechanical stresses, compared to conventional homogeneous plates.

Traditional materials like wood and metal have long been employed extensively in various engineering and industrial industries. Nevertheless, these materials' mechanical characteristics fall short of the unique demands of numerous industries, including nuclear power plants, aircraft, submarine, and defence engineering.[1]

The buckling analysis of functionally graded plates presents a unique set of challenges and opportunities compared to homogeneous plates. Unlike homogeneous plates, where material properties remain constant throughout, the spatial variation in material properties within FGPs necessitates a more sophisticated analytical approach to accurately predict their buckling behaviour. Additionally, factors such as material composition, thickness profile, loading conditions, and boundary constraints significantly influence the buckling characteristics of FGPs, highlighting the complexity of the analysis.

Usually occurring in the structures during the manufacturing process, the porosities can also be purposefully generated to lower the bulk of the structures. Vinh et al.'s [2] finite element model for the mechanical study of FG sandwich plates with various porosity distributions was created using a new hyperbolic shear deformation theory. Vinh et al. (Van Vinh and Huy, 2021) [3] investigated how the porosity and nonlocal parameter variations affected the FG nanoplates' free vibration behaviour.

In recent years, researchers have proposed several analytical and numerical models to investigate the buckling behaviour of functionally graded plates. These models aim to capture the effects of material gradation, geometric nonlinearity, temperature variations, and other influential factors on the buckling characteristics of FGPs. Analytical solutions based on classical plate theory, combined with numerical simulations using finite element analysis, offer valuable insights into the critical buckling modes and load-carrying capacity of FGPs.

The design optimization of functionally graded plates requires a comprehensive understanding of their buckling behaviour under different operating conditions. By integrating advanced analytical and numerical techniques, engineers can identify optimal material compositions, thickness profiles, and geometric configurations to enhance the structural performance and reliability of FGPs.

Furthermore, the development of accurate and efficient computational tools for buckling analysis enables engineers to streamline the design process and mitigate potential failure risks associated with functionally graded plates.

I. CURRENT TRENDS & PERSPECTIVES

Functionally graded plates (FGPs) represent a burgeoning area of research in materials science and structural engineering, with numerous current trends shaping their development and application. One trend involves the exploration and development of advanced manufacturing techniques such as additive manufacturing (AM) processes and deposition techniques, facilitating the fabrication of complex graded structures with precise control over material composition and distribution

Additionally, FGPs are increasingly being explored for multifunctional applications, where they serve multiple purposes simultaneously, thanks to their tailored electrical, thermal, and mechanical properties. Inspired by natural biological systems, researchers are developing FGPs with biomimetic properties, leveraging hierarchical structures and material gradients found in biological tissues for enhanced strength, toughness, and damage tolerance.

Another trend focuses on tailoring material compositions and microstructures to achieve specific performance objectives by optimizing constituent materials, including ceramics, metals, polymers, and composites. Computational modelling and simulation play a crucial role in predicting the mechanical behaviour, thermal response, and buckling characteristics of FGPs under different loading conditions, aiding in design optimization and reducing the need for expensive experimental testing. Moreover, there's a growing emphasis on sustainability and environmental considerations, with researchers exploring eco-friendly materials and conducting life cycle assessment (LCA) studies to evaluate environmental impacts.

Lastly, integration with emerging technologies such as smart materials, nanotechnology, and metamaterials enhances FGPs' performance and functionality, offering capabilities like self-sensing, self-healing, and improved mechanical properties. Together, these trends reflect a concerted effort to advance FGPs through interdisciplinary collaboration, technological innovation, and sustainable design principles, paving the way for their widespread adoption in diverse industrial applications.

II. BUCKLING BEHAVIOUR OF FUNCTIONALLY GRADED PLATES.

a) Analysis of Bi-directional FGM using First order deformation theory

The buckling behaviours of bi-directional functionally graded (BFG) plates with porosity were studied by Pham Van Vinh et al. [4]. Displacement, strain, and strain fields of the plates are described by an improved first-order shear deformation under shear theory that assumes parabolic distribution shear stresses.

To the best of the authors' knowledge, no finite element analysis has been used to examine the bending and buckling behaviors of bi-directional FG porosity plates. Therefore, this study's main goal is to create a novel method for analyzing the static bending and buckling properties of functionally graded porous plates by combining augmented first-order shear deformation theory with mixed finite element modeling. Refinement of longitudinal shear stresses to satisfy upper and lower surface free-conditions is the main contribution of this work. This improvement makes it possible for the suggested mixed finite element model to converge quickly, doing away with the need for reduced integration methods.

For buckling analysis, the bidirectional plates that are taken into account in bending analysis are taken into consideration once more. As illustrated in Fig. 2, the plate is exposed and subjected to biaxial compressive forces and various boundary conditions. The ideal load's critical buckling loads are greater than the porous plates'. When comparing BFG porous plates with type U porosity to those with type E porosity, the critical buckling stresses of the former are greater. The CCCC plates have the largest critical buckling loads, whilst the SFSF plates have the lowest.

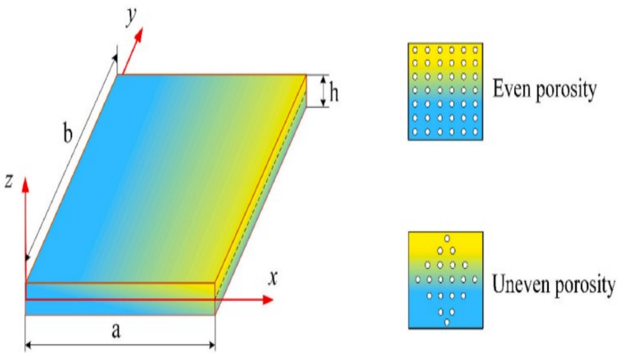


Fig.1 Functionally graded plates with different porosity conditions

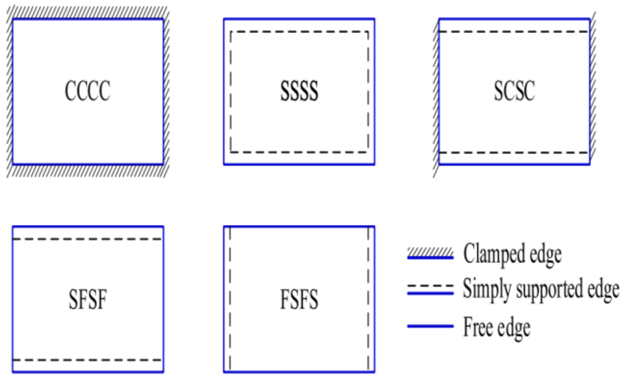


Fig.3 Boundary conditions considered for analysing the plates

The variations in the critical buckling loads of BFG (Bi-directional Functionally Graded) porous plates with respect to the porosity coefficient, represented by ξ, are shown in Figure 4. The graph shows that as the porosity coefficient (ξ) increases, the critical buckling loads of BFG porous plates decrease significantly. It is important to notice that there is a rough association between the varied values of the material gradient coefficients (α and β) and the rates of fall in critical buckling loads. Additionally, BFG porous plates with type E porosity have a significantly stronger effect on the critical buckling stresses due to the porosity coefficient ξ than do porous plates with type U porosity. This observation implies that depending on the particular kind of porosity structure, there may be different sensitivity to changes in porosity.

Additionally, it is observed that the critical buckling stresses of the BFG porous plates diminish as the coefficients α and β escalate. This decrease in critical buckling stresses is attributed to the increase in the volume percentage of metal and the decrease in the volume fraction of ceramic with the growth of coefficients α and β. These findings underscore the significant influence of porosity coefficient and material gradient coefficients on the buckling behavior of BFG porous plates.

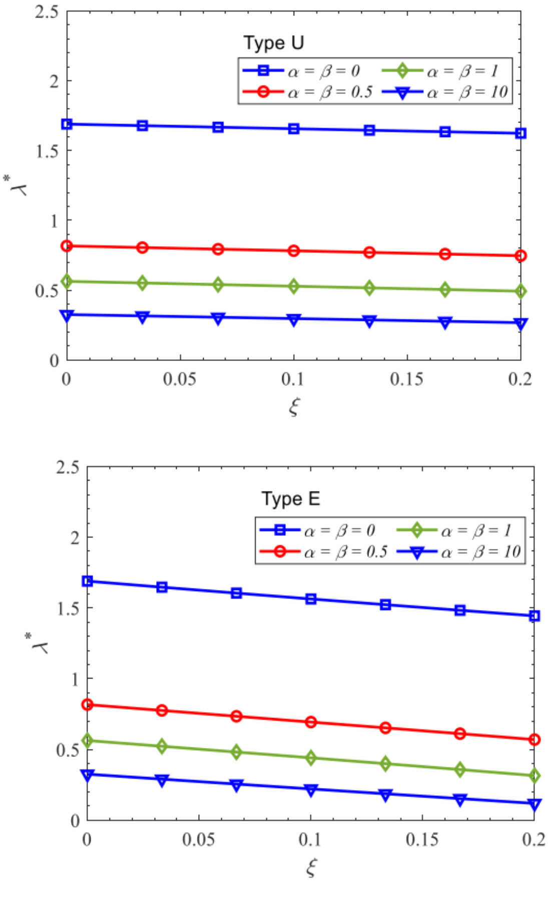


Fig.4. The relationship between the porosity coefficient and the critical buckling stresses of the SSSS BFG plates (a/h = 10).

Figure 5 displays the first 9 buckling modes on the SSSS BFG porosity plates with α = 2, β = 2, and ξ = 0.2. It is evident that the mode shapes exhibit symmetry when viewed in relation to the x-axis, but asymmetry when viewed in relation to the y-axis. As α and β grow, so do the BFG porous plates' deflections. The BFG porous plates' deflections increase as a result of the porosity's reduction in plate stiffness. As α and β increase, the critical buckling loads drop as well.

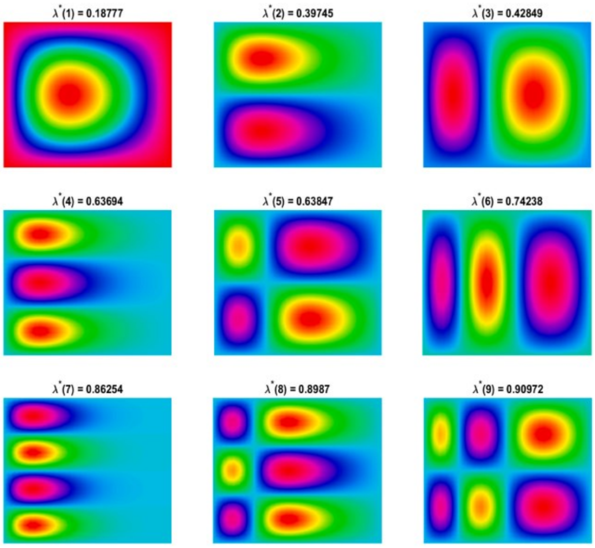


Fig.5 Mode shapes

b) Analysis of Multi-directional FG Sandwich plates

Multi-directional porous FGM sandwich plates were subjected to buckling investigations by Supen Kumar Sah et al. [5]. In both the longitudinal and transverse directions, it is assumed that the material properties of FGM sandwich plates are continuously changing. Using an arbitrary power index and the power law distribution approach, Voigt's micro-mechanical model is used to analyse the material attributes. A multidirectional sandwich plate made of functionally graded material (FGM) with dimensions along the x, y, and z axes that include length (a), width (b), and thickness (h) is shown in Figure 6. The FGM sandwich plate is made up of three different layers: the upper and bottom FGM face sheets are layered on top of a ceramic core. The reference plane that contains the x, y, and z axes, with the z axis running perpendicular to them, is known as the midplane. The FGM sandwich plate's bottom, core, and top layers are defined by vertical coordinates designated as z1, z2, z3, and z4, respectively. Variations in mechanical properties are carefully taken into consideration in the context of a multidirectional FGM sandwich plate in both the longitudinal (x-axis) and transverse (z-axis) directions..

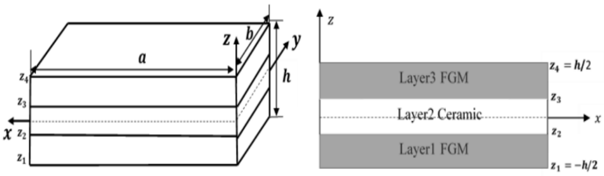


Fig.6 Multidirectional FG Sandwich plate

By leveraging Voigt's model and integrating the power law, this research investigates the effective material characteristics, including Young's modulus and material density, of a multi-directional FGM (Functionally Graded Material) sandwich plate. The study delves into five distinct porosity models, encompassing both uniform and non-uniform distributions, to integrate porosity into the FGM face layers of the sandwich plate.

Furthermore, this section presents analytical solutions elucidating the buckling behavior of porous multi-directional FGM sandwich plates across various porosity distributions. Specifically, under bi-axial compressive loading conditions, the buckling analysis of porous directional FGM sandwich plates is meticulously conducted. Through the utilization of the cyclic shear deformation theory, the equilibrium governing equation (SSDT) is formulated, laying the groundwork for evaluating the non-dimensional critical buckling load (Ncr) by solving this equation. This comprehensive approach sheds light on the intricate interplay between material properties, porosity distributions, and structural behavior within multi-directional FGM sandwich plates, offering valuable insights for advanced engineering applications.

The volume percentage gradation of metal (Al) and ceramic (Al2O3) in the longitudinal and transverse directions is accounted for using the power law to simulate the multi-directional FGM plate. Various porosity models, including even, uneven, logarithmic uneven, cubic uneven, and sinusoidal uneven distributions, are examined to assess the impact of porosity distribution on buckling analysis. Currently, there is no available data for comparison regarding the critical buckling load of porous multi-directional FGM sandwich plates.

Table 7 shows how the non-dimensional critical buckling load (Ncr) of a simply anchored multi-directional FGM sandwich plate changes with nx and nz under biaxial compressive pressure. It is found that as the volume fraction index rises in both the longitudinal and transverse directions (nx and nz), as well as the a/h ratio, the nondimensional critical buckling load increases.

Table 7
Variation of N_{cr} with n_x and n_z multi-directional FGM sandwich plate under biaxial compressive load.

a/h	n_x	n_z	multi-directional FGM models 1-1-1	 1-2-1	 1-1-2	 2-1-2	 2-2-1
5	0	0.5	1.8663	2.2538	1.7693	1.6588	2.0319
		1	2.3557	2.7275	2.2415	2.1307	2.5156
		5	3.6680	3.8791	3.5797	3.5136	3.7567
	0.5	0.5	2.2649	2.5963	2.1959	2.0861	2.4198
		1	2.6826	3.0005	2.5944	2.4896	2.8272
		5	3.8055	3.9867	3.7314	3.6731	3.8828
	2	0.5	3.0534	3.2752	3.0200	2.9313	3.1710
		1	3.3314	3.5436	3.2825	3.2017	3.4370
		5	4.0810	4.2026	4.0335	3.9923	4.1344
10	0	0.5	1.9414	2.3547	1.8417	1.7245	2.1174
		1	2.4667	2.8693	2.3458	2.2267	2.6392
		5	3.9095	4.1464	3.8104	3.7371	4.0085
	0.5	0.5	2.3703	2.7259	2.3021	2.1833	2.5371
		1	2.8220	3.1682	2.7296	2.6154	2.9797
		5	4.0633	4.2672	3.9800	3.9148	4.1498
	2	0.5	3.2314	3.4713	3.2034	3.1046	3.3611
		1	3.5357	3.7692	3.4867	3.3962	3.6532
		5	4.3729	4.5106	4.3193	4.2727	4.4331

In Figure 8, the graph displays the change in non-dimensional critical buckling load under biaxial compressive loading for the multi-directional FGM sandwich model 1-1-1 concerning nx and nz. The non-dimensional critical buckling stress increases in both the longitudinal (nx) and transverse (nz) directions as the volume fraction index rises. As nx and nz increase, the volume fraction of ceramic material (Al2O3) in the FGM plate rises, while the volume fraction of metal (Al) decreases. With the increase in nx and nz, the stiffness of the FGM plate also increases due to the higher Young's modulus of Al2O3 compared to that of Al. Consequently, as nx and nz increase, the non-dimensional critical buckling strain of the FGM sandwich plate also increases.

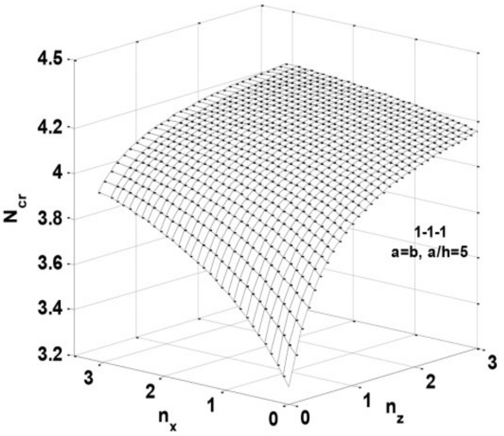


Fig.8 Variation of critical buckling (Non dimensional)

Similar to this, the large volume fraction of metal in the plate causes the effective Young's modulus of the FGM model 2-1-2 to decrease. The plate's stiffness decreases as a result of the higher volume percentage of metal than ceramic in the plate. The FGM model 1-2-1 achieves the largest non-dimensional critical buckling load in contrast to the other FGM models, whereas the FGM model 2-1-2 achieves the lowest.

c) Analysis of Buckling behaviour of FG sandwich plate using hyperbolic shear deformation theory

Le Quang Huy and colleagues [6] focused their research on developing a finite element model based on a creative hyperbolic shear deformation theory. This model was developed to carefully examine the free vibration, buckling, and static bending behaviors displayed by functionally graded sandwich plates that have been given porosity. Their research focuses on analyzing the mechanical details of a novel porous sandwich plate design that consists of two different functionally graded face sheets that are paired with a ceramic core that is uniform in size.

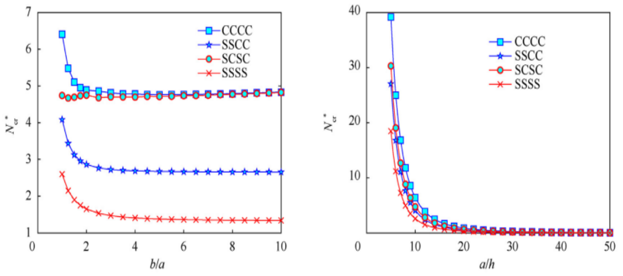
These sandwich plates are shown in Figure 9 with dimensions represented by "a" in the x-direction, "b" in the y-direction, and an overall thickness parameterized by "h." The goal of this extensive analysis was to help the researchers understand the complex structural dynamics andHSDT takes into account the variation in material properties across the thickness of the FGM, allowing for more precise predictions of buckling behavior. This is particularly crucial in FGMs where material properties continuously vary, providing a smooth transition between different constituents.

By incorporating HSDT into buckling analysis, engineers can better understand the influence of material gradation on the buckling resistance of FGM structures. This includes studying the effects of varying volume fractions, material compositions, and loading conditions on buckling modes and critical loads.

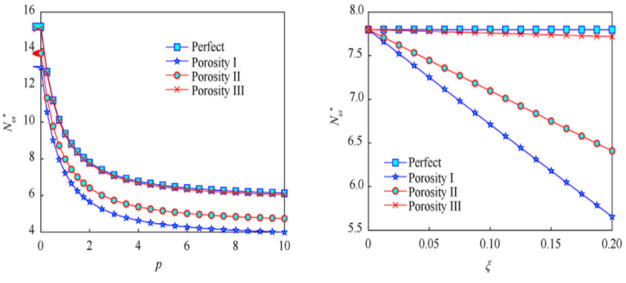
In particular, the study explores how functionally graded sandwich plates (FGSP) with porosity buckle under biaxial compressive pressures. The fully simply supported (SSSS) FGSP with porosity's non-dimensional critical buckling loads are given in Table 16 with the parameters "b=a = 1" and "a=h = 10". It is interesting that these plates' buckling properties are highly influenced by both porosity and the power-law index. Furthermore, Table 17 investigates how various boundary conditions, while preserving uniform geometric and material features, affect the critical buckling stresses of sandwich plates with porosity. The findings show that, in comparison to other configurations, plates with clamped-clamped (CCCC) boundary conditions have larger critical buckling loads, while SSSS plates have the lowest critical buckling loads.

Further analysis considers a (1-1-1) FGSP with porosity, investigating the influence of the aspect ratio "b/a" on its critical buckling loads. The findings reveal that an increase in the aspect ratio "b/a" results in decreased critical buckling loads. Additionally, the study explores the effect of the side-to-thickness ratio "a/h" on the critical buckling loads of FGSP with porosity, indicating a significant impact of variations in this ratio on the critical buckling loads of FGSP. These observations highlight the importance of considering a range of geometric and material parameters when predicting the buckling behavior of functionally graded sandwich plates, particularly when incorporating porosity, which significantly affects structural stability and performance.

Moreover, the influence of the power-law index, denoted as "p," on the critical buckling loads of FGSP with porosity is depicted in Figure 9. It is noted that as the value of "p" increases, the critical buckling loads decrease. Interestingly, the rate of decrease is more pronounced when the power-law index transitions from 0 to 2 compared to the increase from 2 to 10. Additionally, the impact of porosity III is relatively minor when contrasted with the effects of porosity I and porosity II. Figure 9 illustrates the dependency of critical buckling loads on variations in the porous coefficient..



(a) Porosity II, a/h=10, p=2, ξ= 0.2 (b) Porosity II, b/a=1, p=2, ξ= 0.2



(c) CCCC, b/a=1, a/h=10, ξ= 0.2 (d) CCCC, b/a=1, a/h=10, p=2

Fig.9 Effect on the center deflection

In general, the critical buckling loads of plates containing porosity are observed to be lower compared to those of perfectly solid plates. Specifically, the critical buckling loads of plates characterized by porosity levels I and II exhibit a rapid decrease with an increase in the porous coefficient, denoted as 'x'. However, for plates featuring porosity III, the reduction in critical buckling loads occurs at a slower rate as the coefficient 'x' increases. This trend underscores the significant influence of the distribution of porosities throughout the thickness of the plates on the buckling behavior of functionally graded sandwich plates (FGSP) with porosity.

Several notable conclusions emerge from this study. Notably, the bending, free vibration, and buckling behaviors of FGSP exhibit distinct differences from conventional FGSP, particularly regarding the stress distribution across the plate thickness. The introduction of porosity leads to increased deflections and critical buckling loads, indicating the pronounced effect of porosity on the structural response of FGSP. However, the alteration in natural frequencies is contingent upon the specific distribution of porosity within the plates. The location and arrangement of porosity significantly influence the behaviour of FGSP. Notably, porosity situated within the face sheets has a substantial impact, while porosity within the core layer has a comparatively minor effect on the mechanical response of FGSP.

III. CONCLUSION

In conclusion, the buckling behaviour of functionally graded plates (FGPs) represents a multifaceted phenomenon influenced by various factors such as material composition, thickness profile, loading conditions, and boundary constraints. Through comprehensive analysis and advanced computational techniques, researchers have gained valuable insights into the critical buckling modes and load-carrying capacity of FGPs. It has been observed that the spatial variation in material properties within FGPs, typically achieved through tailored material compositions and thickness profiles, plays a significant role in determining their buckling characteristics. Additionally, the effects of porosity, boundary conditions, and geometric parameters on the buckling behaviour of FGPs have been thoroughly investigated.

Several notable conclusions emerge from this study:

1. The bending, free vibration, and buckling behaviours of FGSP exhibit notable distinctions from conventional FGSP, particularly in terms of stress distribution across the plate thickness.
2. The introduction of porosity leads to increased deflections and critical buckling loads. However, the alteration in natural frequencies depends on the specific distribution of porosity.
3. The location and arrangement of porosity significantly influence the behaviour of FGSP. Notably, porosity situated within the face sheets has a substantial impact, while porosity within the core layer has a comparatively minor effect on the mechanical response of FGSP.

The study of buckling behaviour in FGPs has revealed several key findings. Firstly, the introduction of material critical buckling loads, with the distribution of porosity throughout the plate thickness influencing its mechanical response.

Overall, the study of buckling behavior in functionally graded plates provides valuable insights for the design optimization and structural integrity assessment of these advanced materials. By understanding the complex interactions between material properties, geometric parameters, and loading conditions, engineers can develop robust and efficient structural systems capable of withstanding various operating conditions. Continued advancements in computational modeling, experimental validation, and manufacturing techniques will further enhance our understanding of buckling behavior in functionally graded plates and drive innovation in structural engineering applications.

IV. ACKNOWLEDGEMENT

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