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Investigation of Fracture Mechanism and Mechanical Properties for Functionally Graded Porous Materials: A Review

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ABSTRACT

This review presents a comprehensive study of recent advances in the fracture behavior of functionally graded porous materials (FGPMs), with a specific focus on application, fracture mechanism, and mechanical characteristics. The mechanism of mechanical fracture involves two stages: the first is the formation of a crack or defect in the material, and the second is the growth of the crack under loads until the material separates and total failure occurs. The most important characteristic of functionally graded porous materials is their very good strength-to-weight ratio; they also possess sound and thermal insulation and impact absorption. The study is based exclusively on data gleaned from published literature, database resources, and previous research reports. The components of functionally graded materials (FGMs), from production techniques to stress analysis and their performance, have already been the subject of a sizable body of work because they have huge potential to be useful in a wide variety of important structural applications, especially when thermo-mechanical loading is applied. The current study concentrates on developments in structural composites derived from FGMs, particularly crack formation and fracture behavior. The review showed that finite element analysis (FEA) is used to simulate the mechanical behavior of functionally graded porous materials (FGPMs), enabling accurate prediction of crack growth, the effect of porosity ratio, and improved structural design to resist crack growth under external loads. Such a review provides useful information on the main issues that have been faced previously and lays the groundwork for future solutions to evaluate the structural integrity of this type of material when cracks are present

1. Introduction

T The 1970s provided the basic foundations for the use of functionally graded materials (FGMs) including composites and polymeric materials intended to replicate the structure and behaviour of such natural materials as bamboo, bones and teeth [1]. The first reported practical applications of FGMs were in Japan for a rocket engine where the problem was to develop a material that could endure extremely high temperature gradients [2].

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The development of functionally graded structures is generally considered amongst the most advanced topics in materials engineering. Here, gradual changes in composition and/or microstructure are proposed to provide superior mechanical performance. FGMs and functionally graded porous materials (FGPMs) represent a new generation of engineered solids that combine desirable characteristics such as an increase in stiffness-to-weight ratio, enhanced toughness, and high energy absorption. These materials were originally inspired by biological tissues—such as bone, dentin, and wood—where natural gradients with their porosity, stiffness, and density provide exceptional resistance to mechanical failure. Over the past decades, FGMs and FGPMs have gained significant attention due to their ability to withstand complex loading conditions. Mechanical properties of FGMs, amongst the most important of which are the coefficient of thermal expansion, Poisson's ratio and Young's modulus, can be varied with location within the body of the material enabling control over, for example, the spatial distribution of internal stress. The analysis and measurement of the effects of internal stress on mechanical strength, fracture mechanics, fracture strength and crack growth of spatially changing elastic materials under different loadings is of considerable importance [1]. Other properties of great current interest, particularly for unmanned aerial vehicles are increasing the mechanical strength of lightweight materials that have good thermal stability and tolerance of high temperatures [1]. The great interest in FMGs has meant many different types being developed. The proposed application will, of course, determine the desired properties of the FGM.

Consider porosity-graded FGM: the distribution and size of the pores are designed to absorb the shock of an impact on one face and limit its transmission to the opposite face. The pores can also provide good thermal insulation which could aid catalytic efficiency and relax both electrical and thermal stresses. Of course, the benefits of the presence of pores have to be balanced against effects on Young's modulus and tensile strength of the material [3].

Another of the numerous challenges that FMG structures encounter is fracture behavior which is a crucial factor governing safety, durability, and reliability. Under different loading scenarios—such as tensile, compressive, and bending forces—cracks can be generated and spread in complex ways precisely because of the spatial variation in material properties and porosity. Unlike homogeneous materials, where crack paths are often predictable, FGMs and FGPMs exhibit intricate crack propagation mechanisms influenced by gradients in the Young's modulus, density, pore volume, and microstructural architecture. This makes understanding fracture behavior an essential prerequisite for the effective design of advanced graded materials [2].

Recent studies have emphasized that FGMs can exhibit improved resistance to crack initiation and slower crack growth rates compared to conventional materials, due to the continuous variation of stiffness and toughness across the structure. FGPMs can offer additional energy dissipation through controlled porosity gradients, by redirecting crack paths, delaying failure, and avoiding stress concentrations. However, these advantages make predicting fractures in graded and porous graded solids highly challenging. The predictions of the simultaneous influences and interactions of material gradation, pore topology, multiaxial stress fields, and nonlinear deformation mechanisms require advanced fracture modeling based on comprehensive experimental testing [3].

A large body of research has investigated the fracture behavior of FGMs and FGPMs under different loading modes. Tensile tests have been widely used to examine crack initiation thresholds and to study how stiffness gradients affect crack branching and propagation. Compression tests, on the other hand, reveal the role of porosity in governing localized crushing, micro buckling, and failure under high stress. Bending tests provide valuable insights into tensile–compressive coupling, where cracks typically originate in the tension zone and follow paths strongly influenced by gradation patterns and pore distribution. Many fundamental questions remain regarding the interaction between graded material architecture and fracture mechanics, especially under mixed-mode and dynamic loading conditions. This review provides a comprehensive examination of the fracture behavior of FGMs and FGPMs under tension, compression, and bending loading scenarios. It highlights the governing mechanical mechanisms, recent advances in experimental and numerical fracture characterization, and the challenges associated with modeling crack initiation and propagation in graded solids.

Furthermore, the study outlines future research directions aimed at enhancing the fracture resistance and structural reliability of FGMs and FGPMs in advanced engineering applications [3].

Extensive research has been conducted on the fracture mechanics of FGMs and FGPMs under various loading scenarios, including tension, compression, and bending. Previous review studies have primarily focused on either (i) homogeneous FGMs without explicit consideration of porosity effects, (ii) isolated aspects of fracture behavior such as crack growth or stress intensity factors, or (iii) specific modeling or experimental techniques. However, a systematic synthesis that simultaneously integrates fracture mechanisms, mechanical property evolution, and the role of graded porosity across multiple loading modes remains limited.

This review addresses this gap by providing a unified and critical analysis of fracture mechanisms and mechanical behavior in FGPMs, with three key novel contributions:

(i) an integrated perspective on the coupling between material gradation and pore architecture in governing crack initiation and propagation,

(ii) a comparative assessment of fracture behavior under tensile, compressive, and bending loading conditions within a single framework, and

(iii) a synthesis of recent advances in experimental characterization and numerical modeling, highlighting their limitations and identifying unresolved challenges.

In addition, this review emphasizes the interaction between multiscale porosity, nonlinear deformation mechanisms, and mixed-mode fracture behavior, which are often treated separately in the existing literature. By consolidating these aspects, the study aims to provide deeper insight into the design principles required to enhance fracture resistance and structural reliability in next-generation graded porous materials.

This review is structured as: Section 2 - Applications of FGMs and FGPMs. Section 3 - Fracture mechanisms of FGMs. Section 4 - Mechanical properties of FGPMs.

2. Applications of FGMs and FGPMs

As illustrated in Figures (1-4), the non-homogenous microstructure of functionally graded materials (FGMs) causes a continual fluctuation in material characteristics. FGMs have garnered significant interest in recent years from researchers in a variety of domains, including engineering, biomaterials, and aerospace, because to their distinctive graded material characteristics [4]. There are structures that contain a double grid of high- strength composite metal bars [5]. In many structure's elements there are porosity in this element plays an important role in influencing the structural properties and how the structure behaves under surrounding conditions [6-7].

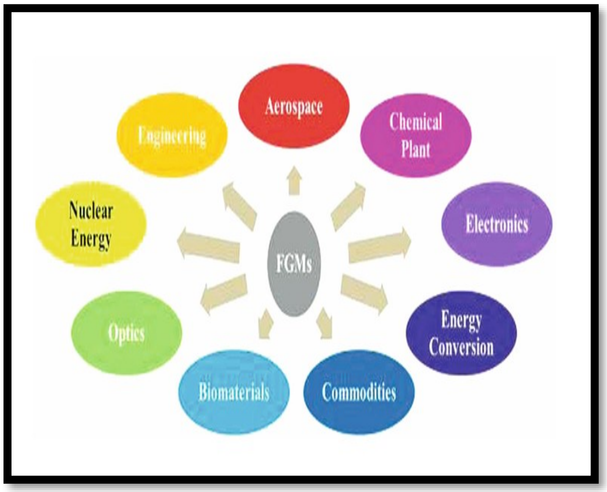


Figure 1. Field application of FGM [4]

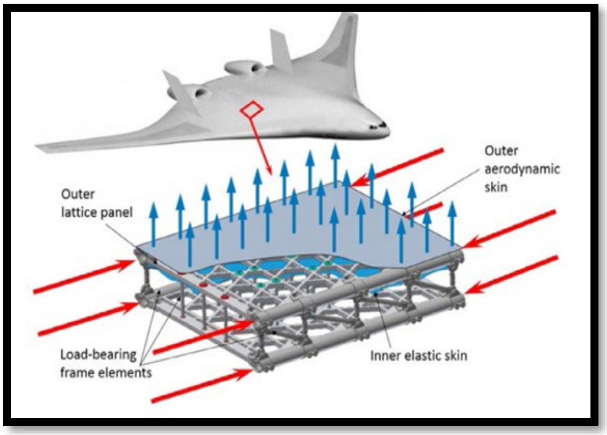


Figure 2. Application of pressurized flat double panel lattice in blended wing body aircraft [5]

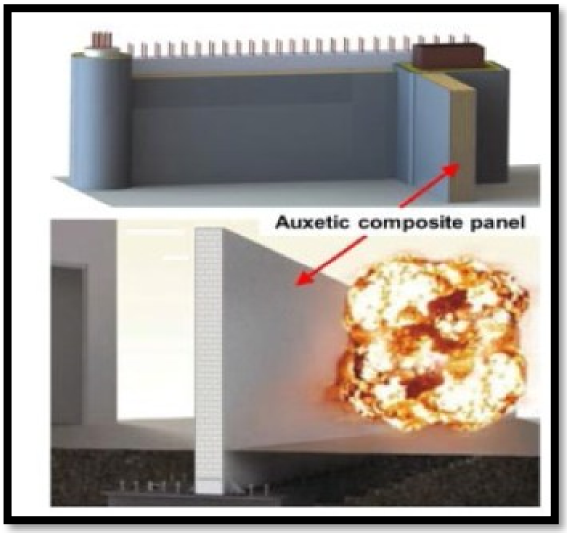


Figure 3. Application of blast resistant porous auxetic panels to protect critical infrastructure[6]

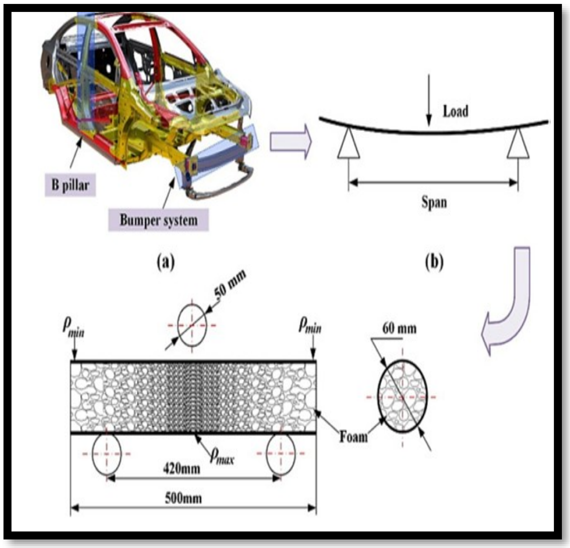


Figure 4. Gradient porous structures in car body panels to enhance crash protection [7]

3. fracture mechanisms of FGM

To provide a clearer synthesis of the literature, this section classifies prior studies based on the fracture modeling framework and methodology employed, including linear elastic fracture mechanics (LEFM), elastic–plastic fracture, cohesive zone models (CZM), extended finite element methods (XFEM), phase-field approaches, peridynamics, and fatigue/dynamic fracture. This structured approach enables a comparative understanding of modeling capabilities, assumptions, and limitations.

3.1 Linear Elastic Fracture Mechanics (LEFM) Approaches

Jin and Batra [8] calculated how well a plate of functionally graded material (FGM) of aluminum oxide-nickel (Al_2O_3–Ni) composite with an edge crack subject to a pure bending moment resisted crack propagation and failure under applied stress to obtain the crack growth resistance curve (the R-curve - fracture toughness). The work was theoretical using numerical analysis, with alternative approaches one based on crack-bridging and the other on the rule of mixtures. It was shown that crack-bridging gave more realistic results than the rule of mixtures. It was also shown that the FGM led to slower crack growth and greater fracture toughness at high Young's modulus.

Grujicic and Zhao [9] analyzed damage to a functionally graded five layered disk from pure 316 stainless steel to pure aluminum oxide (Al_2O_3). The work was a theoretical analysis of thermal stress damage using the finite element model obtained by ABAQUS software . With a concentration profile of the materials based on a power law, it was shown minimum damage and residual stresses were obtained for nonlinear material concentration with concentration index equal 4.

Pitakthapanaphong and Busso [10] studied the mechanical behavior of three layers of thermo-elastic-plastic (metal–FGM–ceramic) under thermal loading. Analytical solutions were obtained based on a self-consistent model for FGM for distributions of complex stress generated by thermal transients, and the results compared with finite element analyses. It was shown that stresses within the given system could be minimised by selection of suitable compositional gradients of the FGM.

Rousseau and Tippur [11] examined fracture behavior of an isotropic and nonhomogeneous FGM (glass-filled epoxy) in the form of a beam under pure bending moment. The beam had an initial edge crack introduced in a direction parallel to the elastic gradient. The analysis process was performed using finite element method (FEM) with the profile grading of the material estimated using the Mori-Tanaka model for a two-phase mixture. Experimental results were obtained using coherent gradient sensing (CGS) interferometry. It was shown that graded property elasticity could reduce the stress intensity factors at the crack edge and, thereby, improve crack growth resistance.

LEFM-based studies consistently show that material gradation reduces stress concentration and enhances fracture resistance. However, these approaches are limited to linear elastic assumptions and cannot capture plasticity, damage evolution, or complex crack initiation phenomena in FGMs, particularly in porous or high-temperature environments.

Jin et al. [12] investigated facture behavior for elastic-plastic FGM of titanium monoboride-titanium (TiB/Ti) composite in the form of a beam with single edge crack and a cohesive zone surface under bending loading. The investigation was a numerical analysis using WARP3D software. The behavior of the elastoplastic FGM was based on the Tamura–Tomota–Ozawa (TTO) model. It was shown that the required load for crack growth in FGM was less than for pure metal with less resistance to crack growth, but crack tunneling was found to be important only with metal-rich specimens.

Wang and Nakamura [13] analyzed fracture behavior for elastic–plastic FGM in the form of a double cantilever beam with crack, subject to a high velocity impact. The analysis of the behaviour of the profile graded material was undertaken using a (FEM) based on a developed power law relation between surface separation energy and peak separation stress. This new model was shown to enhance analysis of the fracture resistance in FGM.

Kim and Paulino [14] analyzed crack propagation in a homogeneous FGM composed of polymethyl methacrylate material (PMMA) in the form of a beam subject to both symmetric and asymmetric loading. This numerical analysis used FEM run in programming language (FORTRAN) with a remeshing algorithm. The results were validated by experiment. The model was shown to predict crack paths with asymmetric loading led to a decrease in fracture resistance and a change in the shape of the load–displacement curve compared to symmetric loading. This was explained as due to the generation of additional shear stresses and deviation of the crack path as shown in Figure 2 and Figure 3.

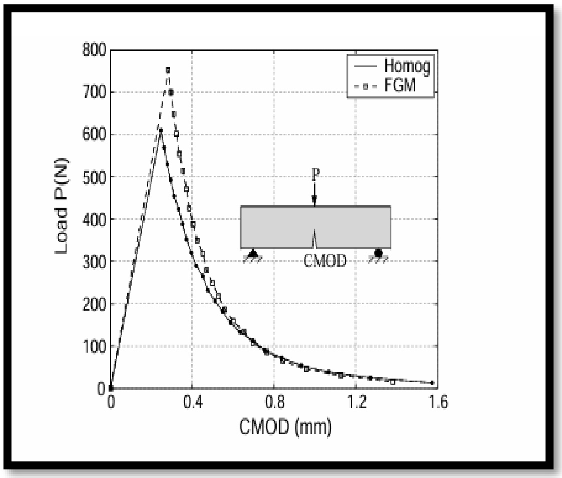


Figure 2. Comparison of FGM and homogeneous material in beam form under symmetric loading [14]

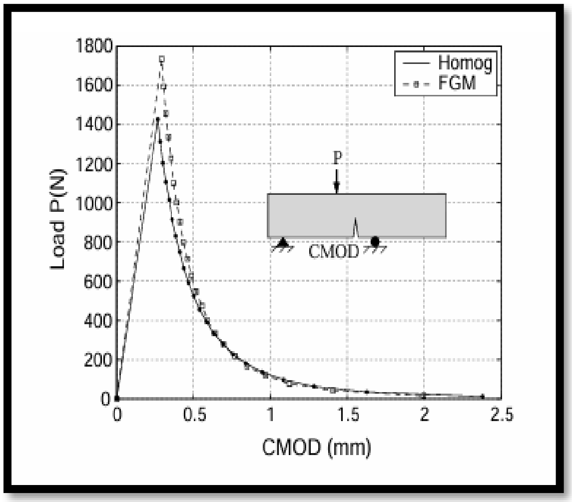


Figure 3. Comparison of FGM and homogeneous material in beam form under symmetric loading [14]

Tham et al. [15] carried out a theoretical study of damage to laminated composite shells of elasto-plastic functionally graded materials (FGMs) undergoing large deflections. The work was carried out using numerical analysis having derived a model of the damage to the elasto-plastic surface based on irreversible thermodynamic processes and a so-called internal damage variable. Numerical simulations presented show the accuracy, stability and range of application of the developed model.

Zhang and Paulino [16] used numerical analysis in terms of (FEM) to investigate dynamic failure of isotopic and homogeneous FMGs. The failure studied was crack growth in beam specimen using a novel cohesive zone model which included the effects of impact loading, and mixed-mode cracking. The authors claim to have shown, by incorporating a cohesive zone model, that the effect of material gradation on dynamic fracture in homogeneous FGM, especially in cases non predefined crack paths and mixed mode that fractures could be accurately modelled.

Kandula et al. [17] studied dynamic failure of FGMs numerically using finite element analysis with an explicit cohesive model. With FGMs comprised of ceramic and metals the model demonstrated increase in crack activity with rate of change of the cohesive failure parameters.

Shim et al. [18] described fracture behavior for elastic-plastic FGMs under tensile and bending loading. The work was a numerical analysis of crack behaviour using FEM, with a cohesive zone model with modified boundary layer. The model contained a crack edge at Mode1. The model claimed to produce a more accurate representation of fracture behavior, crack growth resistance in FGMs, and calculated J-integral of fracture.

Chi and Chung [19,20] studied the mechanical behavior of FGMs in the form of simply supported rectangular plates subjected to a transverse load. The profile of the Young's modulus of the graded material was modelled in three ways: a power-law, and sigmoid, and exponential functions. The work was a numerical analysis using FEM (MARC based on Fourier series expansion). It was shown that the sigmoid distribution was most useful for aerospace applications because of the smooth material gradation with fewer stress concentrations. Interestingly this model predicts the behavior of homogenous and graded materials to be similar except for the bending stiffness, which for FGM plates became extremely complicated.

Kubair and Lakshmana [21] analyzed impact damage to a short beam consisting of a three layer sandwich with two face layers containing an inhomogeneous FGM layer as shown in Figure 4. The meaning α angle was variable distribution material of core.

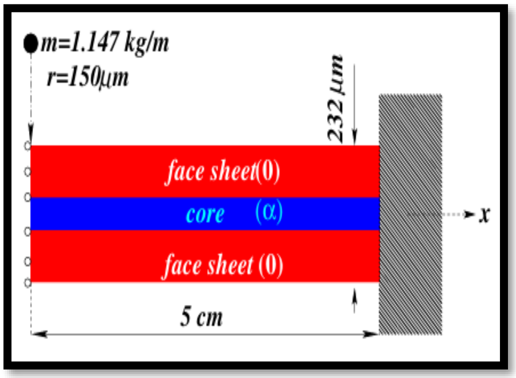


Figure 4. Model geometry [21]

A mixed-mode finite element intrinsic cohesive zone model was used to simulate damage initiation and growth crack mass = 1.147 kg/m . Compared to a cross-ply (90°) core layer the effect of adding an FGM core layer was to advance fracture initiation. However, the effects of adding the FGM core layer were much the same as a core ply with a 45° orientation.

Gao et al. [22] analyzed fracture behavior of non-homogeneous, isotropic and linear elastic FGM in the form of a rectangular plate with an edge crack under tensile stress. The direction of the FGM both parallel and perpendicular of crack edge as shown in Figure 5 were considered. The investigation was to determine the stress intensity factor (SIF) by numerical analysis using a boundary element method. Figure 6 and Figure 7 show effect of SIF under Modes 1 and 2 respectively showing direction of crack propagation on the graded material.

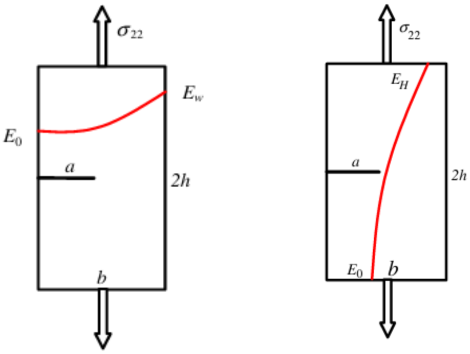


Figure 5. Edge crack: (a) parallel FGM, (b) perpendicular FGM[22]

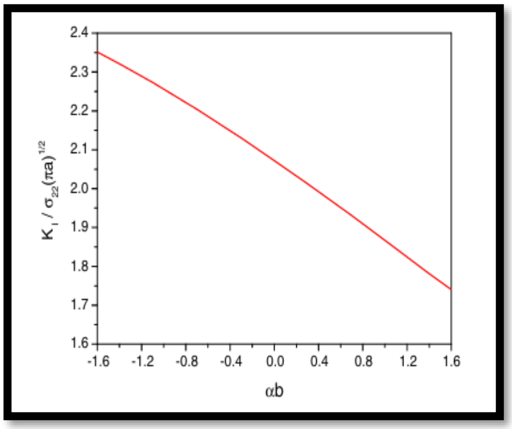


Figure 6. Stress intensify factor under Mode1 [22]

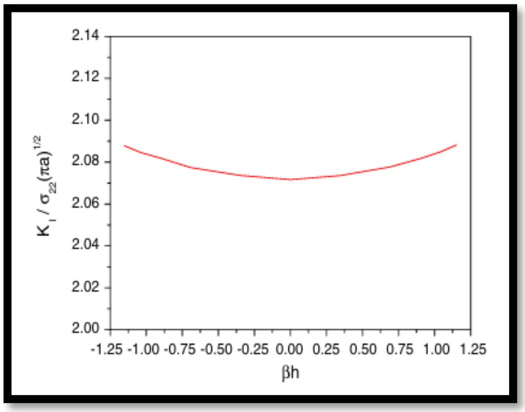


Figure 7. Stress intensify factor under Mode2[22]

Lee et al. [23] carried out a numerical investigation, using FEM, to minimise the number of interlayers of FGM for effectively joining silicon nitride (Si3N4) to aluminum oxide (Al2O3). Damage incurred was due to thermal residual stress and this was determined using maximum values of principal and tensile stress as calculated using thermal residual stresses. As a result of the analysis the number of interlayers could be decreased from 20 to 15, meaning easier fabrication and lower cost with reduced stiffness and predicted crack-free joint.

3.2 Elastic–Plastic Fracture and Damage Models

Miehe et al. [24] studied fracture mechanism in solid material, using numerically analysis based on a phase field model. A robust algorithm was developed for modeling crack propagation based on a history of the field demonstrated a high efficiency in accurately and stably tracking fracture evolution. The authors claim the model was fully validated.

Shanmugavel et al. [25] reviewed fracture behavior for elastic-plastic FGMs. The work concentrated on numerical analysis of crack behaviour under thermo-mechanical loading. It was shown the fracture analysis of FGMs still required extensive research, particularly in the areas of elastic–plastic crack growth. The study highlighted that the gradation of material properties significantly influences the SIFs, fracture toughness and energy release rates. In addition, the need for further experimental validation and advanced FEM to achieve a more comprehensive understanding of the fracture behavior of FGMs was emphasized. However, unlike Shanmugavel et al. [25], which is largely confined to elastic–plastic FGMs and conventional numerical approaches, the present review extends the discussion to functionally graded *porous* materials, incorporating recent advances in multi-scale modeling, porosity-dependent fracture mechanisms, and coupled thermo-mechanical effects. Furthermore, this review integrates both numerical and emerging experimental studies, providing a more holistic perspective on fracture mechanisms. It also synthesizes recent developments in advanced computational techniques (e.g., phase-field methods and extended FEM) and highlights their role in capturing complex crack initiation and propagation in porous FGMs. Therefore, this review advances beyond prior work by offering a broader, updated, and more integrated framework for understanding fracture behavior in next-generation functionally graded porous materials.

Mao et al. [26] studied the mechanical properties of elastic-plastic FGMs in the form of a micro beam under static and dynamic load. The work was a numerical analysis using ABAQUS software with user material (UMAT) subroutine based on strain gradient plasticity. It was shown graded strain plasticity can lead to increasing yield stress and stronger mechanical properties meaning a possible decrease in thickness and improved accuracy in predicted elastic–plastic strain.

Zhang et al. [27] studied buckling behavior of cylindrical shells of elastoplastic FGMs subject to a combination of external pressure and axial compression. This theoretical study used classical shell theory with the Galerkin method and numerical analysis. The predicted behavior of elastoplastic FGMs was based on the TTO model. This paper confirmed some well-known characteristics such as the dimensions of a cylinder of FGM greatly affect its buckling behavior by, for example decreasing the radius-to-thickness ratio. However, using J2 deformation constitutive theory it was also shown how the plastic flow zone of the FGM could be enlarged during buckling by increasing the ceramic volume fraction.

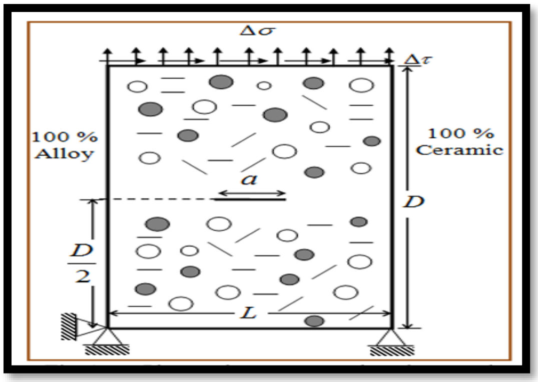


Figure 8 . Geometry of FGM in plate with centre crack under cyclic loading [28]

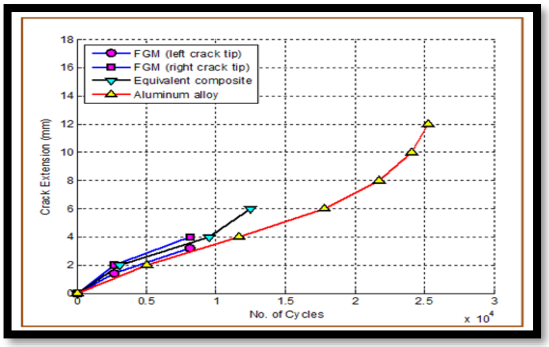


Figure 9. Crack growth and number of cycle[28]

Sharma et al. [28] studied fatigue crack growth in FGM with a hole, and edge and center cracks as shown in Figure 8. The FGM was subject to cyclic loading. The analysis was a numerical simulation using extended finite element method (XFEM) with subroutine of ABAQUS. It was confirmed that when cracks and holes occur in the presence of other discontinuities there is a greater reduction of fatigue life than for either alone. The greatest reduction in fatigue life of the FGM under mixed mode loading was again as would be expected when all types of discontinuities were present as shown in Figure 9.

Bhattacharya et al. [29] used XFEM to numerically analyze fatigue, crack growth and elasto-plastic behavior of an FGM plate with center and edge cracks, and a hole. The FGM was assumed to be a Ramberg-Osgood material, and the SIF was calculated using the interaction integral approach. It was found, as would be expected, that the critical crack length for the FGM in the plate increased with increase in the number of hard inclusions within the plate.

Amirpour et al. [30] studied damage to elasto-plastic FGM in the form of plates with smooth changes in material properties under varying loads. The investigation was a numerical analysis using FEM (ABAQUS with UMAT) with the profile of the FGM varied according to a power law. Treating each spacial operator separately, the authors developed a three-step algorithm comprising an elastic predictor, a plastic corrector, and a damage corrector. The predicted results described damage to the FGM under variable loading, see Figure 10 and showed good agreement with experimental data reported in the literature.

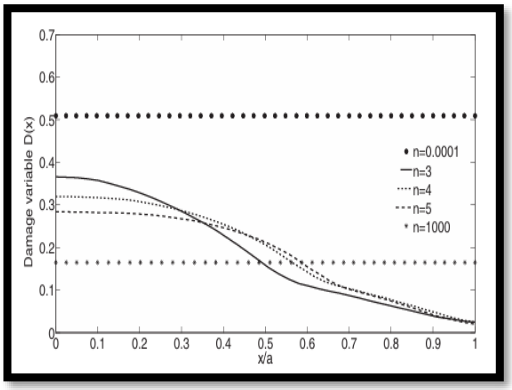


Figure 10. Damage variable for the FG plate with different indices (n)[30]

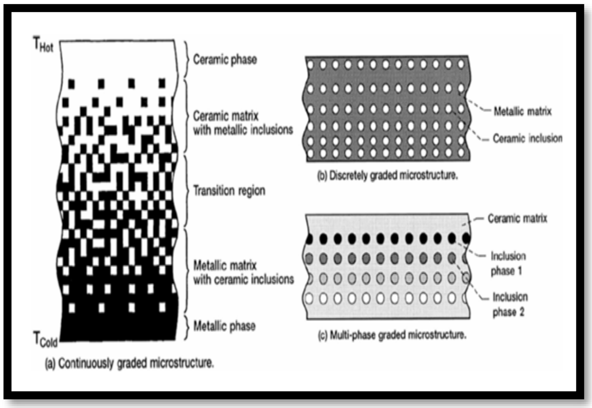
Peyman et al. [31] studied dynamic fracture of FGMs with computation of dynamic SIFs for 3D bodies with cracks. These researchers used the Interaction Integral Method with a new definition of actual and auxiliary fields, independent of material property derivatives. Analysis was performed using FEM and ABAQUS with UMAT subroutine to model continuous material property variations, with temperature included to account for density changes. The study showed how material property gradients affect the dynamic SIFs of FGM bodies with elliptical cracks, revealing different fracture behaviors depending on the material property profile such as a sigmoidal distribution.

Singh et al. [32] analyzed the fracture behavior of FGM in the form of plates with cracks, The properties of the material varied exponentially across the plate thickness. This was a numerical analysis, using FEM based on the generalized higher-order shear deformation theory (GHSDT) to compute the SIF at any location across the plate. The effects of loading, crack length and location, plate thickness and boundary conditions were investigated using the extended iso-geometric analysis (XIGA). It was shown that the GHSDT-XIGA method produced more accurate results than the simpler first-order shear deformation theory with XIGA without a shear correction factor.

Zhu and Cai [33] studied mechanical behavior for elastic-plastic FGMs in plate form subject to impact load. This was a numerical study using FEM. The behavior of the elastic-plastic graded material was based on the TTO model with strain rate and dislocations determined by a combination of the Johnson–Cook and Taylor dislocation models. It was shown, and validated by experiment, that the continuum model and calculated strain rate accurately predicted the stiffness and energy absorption graded composite plates under impact loading.

Jrad et al. [34] investigated the mechanical behavior and temperature distributions in elasto-plastic FGM in shell form with an axial load across its thickness. This numerical analysis used FEM and ABAQUS with UMAT subroutine based on the Mori–Tanaka model and certain formulae derived by Suquet. Comparison of predicted and experimental results for the effects of distribution of constituents and power index on the deflection the shell showed "very good agreement".

Kanu et al. [35] reviewed fracture behavior of FGMs with composite materials , this study illustrated that the fail often occurs when subject to complex loads due to delamination between layers. The authors point out this is most common at high temperatures. However, the mechanical and thermal properties of traditional materials can be improved by specific additions as shown in Figure 11 resulting in greater fracture toughness and reduced SIFs, see Figure 12, and even enhanced thermal properties. The numerical analysis used FEM with XFEM, IGA and XIGA. The study included fracture behavior under thermo-mechanical loading. It was shown that an improved fabrication method would include powder metallurgy which was found to alter the microstructure and enhance the mechanical properties of the manufactured FGMs. The authors claimed FEM methods with XFEM and XIGA allowed accurate simulation of crack and fracture propagation in FGMs without the need to modify the mesh, while enabling the integration of graded material properties to predict mechanical and thermal behavior with high accuracy. However, the present review extends beyond Kanu et al. [35] in several important aspects. First, while their work primarily focuses on layered composite FGMs, this review specifically addresses *functionally graded porous materials (FGPMs)*, where porosity distribution introduces additional complexity in fracture mechanisms and mechanical response. Second, this study provides a more comprehensive synthesis of recent advances by integrating fracture behavior with the influence of porosity gradients, microstructural heterogeneity, and multi-physics interactions. Third, unlike previous reviews that mainly emphasize numerical techniques, the present work critically compares both numerical and emerging experimental approaches, offering a broader perspective on validation and practical applicability. Finally, this review identifies current research gaps—particularly in multi-scale modeling, reliability assessment, and advanced manufacturing strategies for porous FGMs—thereby providing clearer directions for future investigations.



(a) Continuously graded microstructure.

(b) Discretely graded microstructure.

(c) Multi-phase graded microstructure.

Figure 11. Distribution of FGM: (a) continuous, (b) and (c) stepped wise graded structures [35]

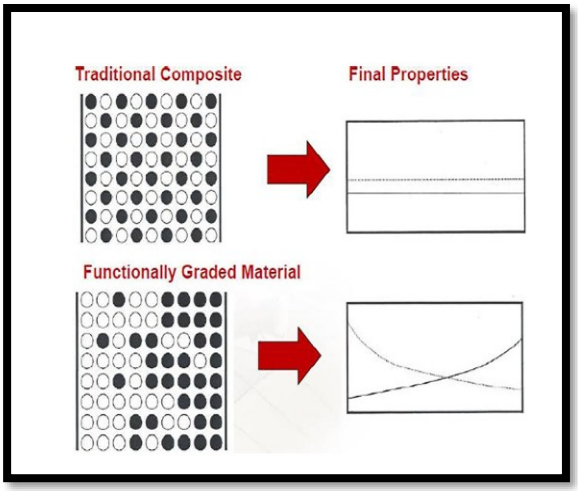


Figure 12. Comparison of compression properties of FGM and traditional composite[35]

However, the present review advances beyond Gayen et al. [36] by specifically focusing on functionally graded ***porous*** materials (FGPMs), where porosity distribution introduces additional complexity in crack initiation and propagation mechanisms. Unlike prior reviews that largely consider fully dense FGMs, this work systematically synthesizes recent developments on the combined effects of material gradation and porosity on mechanical performance and fracture behavior. Furthermore, this review integrates insights from both numerical and emerging experimental studies, highlights multi-scale and porosity-dependent fracture mechanisms, and critically discusses recent modeling approaches addressing coupled thermo-mechanical and porosity effects. In doing so, it provides a more comprehensive and updated perspective, particularly on challenges related to realistic material design, nonlinear behavior, and advanced simulation techniques that were not fully addressed in earlier reviews.

Kumar et al. [37] investigated growth of fatigue cracks in FGMs/plastically graded materials under cyclic loading. With such composites there is no material interface which greatly improves structural integrity and lowers the possibility of failure. In Figure 13, the crack is under Mode I and mixed mode loading. This was a numerical analysis using XFEM with J-Integral to calculate the SIF using a decomposition approach based on Paris law. The direction and behavior of crack growth was predicted for the difficult application an aero-engine turbine disc, see Figure 14.

3.3 Cohesive Zone Models (CZM)

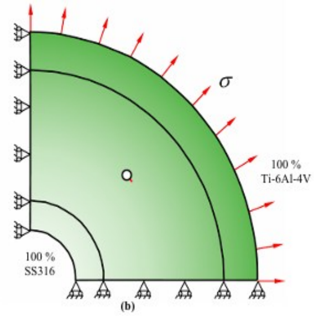


Figure 13. Geometry of aero-engine turbine disc[37]

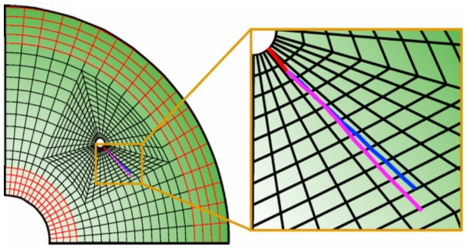


Figure 14. Predicted crack path for Plastically Graded Material[37]

Pañeda [38] investigated the mechanical properties of non-homogeneous FGMs under tensile loading, distribution graded material for parallel and perpendicular loadings. This numerical analysis used FEM and ABAQUS with user-defined field (USDFLD) and user-field (UFIELD) subroutines .Comparison showed the Integration Point-Based graded elements gave more accurate predictions than nodal-based gradation for prediction of crack growth and failure in the FGM.

Li et al. [39] studied damage of FGMs under static and dynamic loading. The model produced addressed complex 3-D transverse cracks with delamination as shown in Figure 15. The numerical analysis used the extended layer wise method (XLWM), with crack analysis based on finite element methods (XFEM). It was shown that XLWM could accurately predict the behavior of FGM under dynamic and static loads.

Madan and Bhowmick [41] reviewed fabrication methods of FMGs with particular reference to powder metallurgy and spark plasma sintering. The authors claimed to have shown that these two techniques are “perfect” methods for fabricating

FGMs. The powder metallurgy method could improve the precision of the gradation of the material, for example linear, exponential or hyperbolic. See Figure 19.

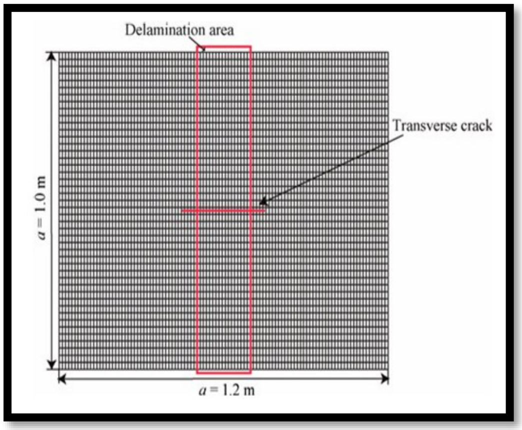


Figure 15 . FGM plate showing transverse crack[40]

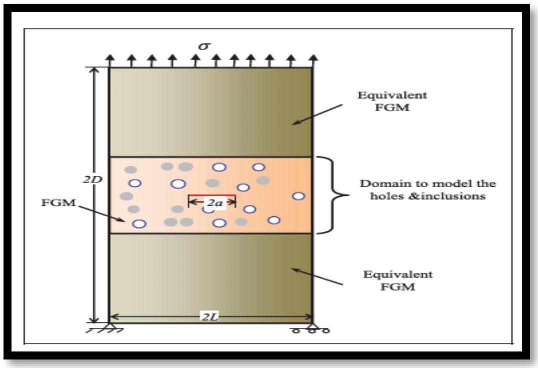


Figure 16. Distribution of FGM[40]

spark plasma sintering increased processing time leading to an increase in density, and improved mechanical properties but at a higher cost. It was noted that increasing the number of layers could improve the bonds of FGM, with less residual stress and fewer stress discontinuities.

Eltaher et al. [42] carried out a numerical analysis using FEM and ANSYS software with the power law function in the TTO model and Coulomb's law of friction for the mechanical response of an elastoplastic FGM in the form of a plate subject to a rigid spherical indenter as shown in Figure 17. This paper further confirmed that the material's gradient index could be used to effectively control the frictional contact response and normalized residual indentation depth.

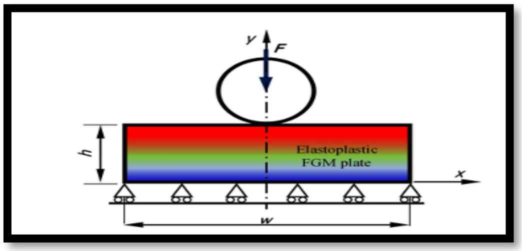


Figure 17. FGM in plate form under rigid spherical indenter[42]

Shahzamanian et al. [43] investigated the fracture behavior of elastic–plastic FGMs in the direction of the tensile test. The numerical analysis used FEM (ABAQUS) and the Gurson–Tvergaard–Needleman (GTN) model of dependent strain in void growth, with the material's profile based on a power law. It was confirmed from the fracture behavior of elastic–plastic FGMs that the profile grading has a noticeable effect on necking and fracture.

Hirshikesh et al. [44] introduced a new numerical model, which claimed to minimize computer time, for fracture in orthotropic FGMs under mixed mode loading. This model takes into account the locational variation of the fracture and its elastic characteristics. It was shown that the profile of the material gradient could increase fracture growth resistance and inhibit the behavior of an unstable fracture, see Figure 18 for comparison of numerical and experimental results.

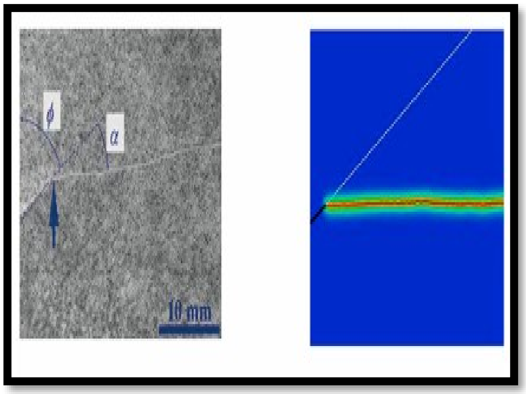


Figure 18. Predicted and measured crack path in FGM under mixed loading conditions[44]

Ammendolea et al. [45] carried out a numerical study of the onset and propagation of cracks in isotropic FGM in the form of beams and plates. The numerical technique used was FEM with adaptive mesh refinement based on the interaction integral method which maintained a necessary mesh density at the crack tip. It was claimed that this model was able to accurately simulate the propagation mechanisms in heterogeneous FGMs to predict complex crack paths as shown in Figure 19.

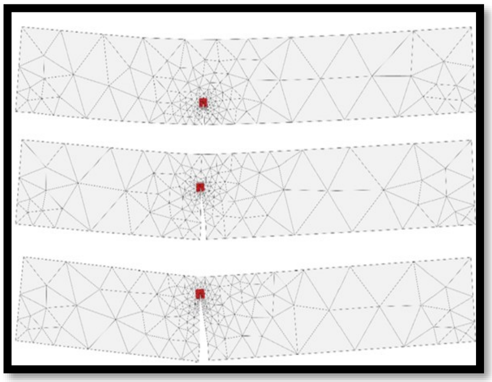


Figure 19. Crack growth in FGM beam[45]

Wang and Zhou [46] proposed a novel method for predicting SIF at the crack tip and for crack propagation in FGMs subject to mixed loading which removed the need for mesh refinement and simplified the forms of the governing equations. The numerical analysis used the field enriched FEM technique which had the same concise form as the governing equations and stiffness matrices. Comparison of predictions with experimental results showed this method could determine the values of the SIFs and simulate crack propagation.

Houari et al. [47] proposed a new FEM technique to study the mechanical behavior and predict damage in three directions (thickness, length and width) to FGMs in the form of a notched quarter plate with center crack under tensile loading. The FEM used ABAQUS with UMAT subroutine, and MATLAB software with user mesh method (UMM). Relative results are as shown in Figure 20. The behavior of elastic-plastic FGMs was based on the rule mixture in the TTO model with relevant parameters taken from previous investigations. The result showed the UMAT subroutine method was more suitable for modeling the elastic–plastic behavior of FGM than UMM. However, when considering behaviour of FGM with increasing layer coverage we see that the load–displacement curves at volume fraction exponent β = 0.5 show only small differences for the two methods, see Figure 21. The path of the crack will depend on the direction of the FGM and the relative values of the volume fractions.

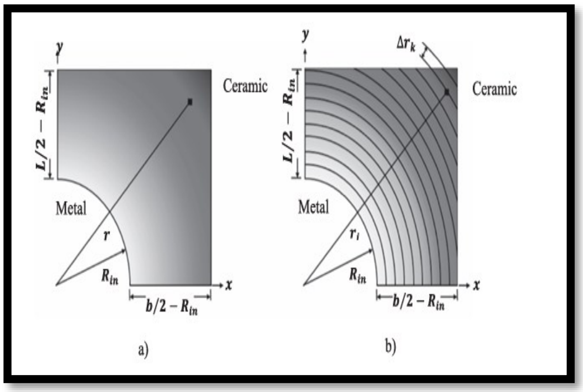


Figure 20. Distribution of FGM: (a)UMAT,(b)UMM[47]

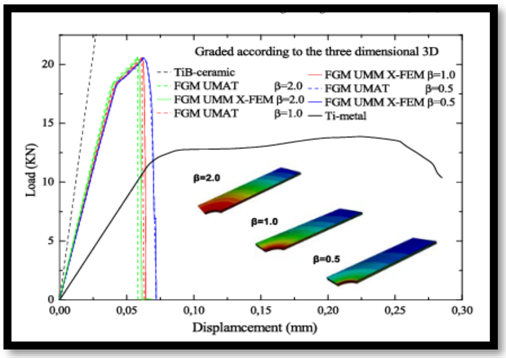


Figure 21. Comparing use of UMAT and UMM with FGM[47]

Bezzie and Woldemichael [48] studied the thermo-mechanical properties in the radial direction for FGM in the form of a cylindrical vessel under thermal and pressure loading. The work was a numerical analysis utilizing Jupyter/Python open-access software, the distribution profile of the material as based on a power law affected the power index of the distribution the volume faction. It was shown that the grading index strongly influences the distribution of the thermo-mechanical properties in a FGM in the radial direction.

Chafia and Boulenouar [49] analyzed the fracture behavior of isotropic FGMs in the form of a beam with a crack under mixed-mode loadings with an initial crack perpendicular to the gradient of the material and then with a crack parallel to the gradient. The study was a numerical analysis using ANSYS Parametric design Language. Crack growth was based on two techniques: displacement extrapolation and maximum circumferential stress. It was shown that gradients of the materials affected both direction and propagation of the crack. The authors reported that their predictions were validated by both experimental results and parallel numerical studies reported in the literature.

3.4 Extended Finite Element Method (XFEM) and Advanced FEM Techniques

Dorduncu et al. [50] investigated the initiation and growth of cracks in of FGM plates under dynamic and quasi-static loading using numerical methods based on the assumption the material was peridynamic. The properties of the graded material were assumed to follow the rule of mixtures. Compositional gradient was confirmed as a major factor in crack growth and trajectories. It was shown that continuous transformation of the properties within the test material could increase strength and fracture toughness, see Figure 22.

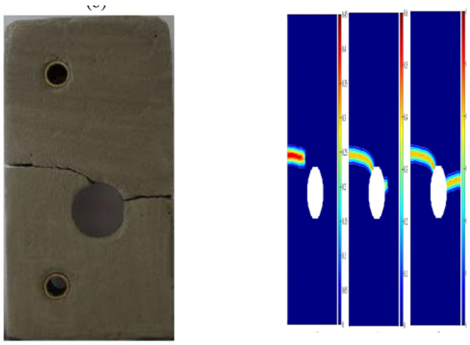


Figure 22. Predictions of damage evolution for pre notched plate with hole[50]

Zemani et al. [51] investigated the mechanical behavior of elastic–plastic homogeneous FGM in the form of plates (body armor) under dynamic load. Here the distribution of the graded material was according to a power law. The experimental work was performed at a high strain rate using a Split Hopkinson Pressure Bar. Numerical analysis used FEM based on the dynamic TTO model and evaluated via a self-consistent method. Strain rate and exponent of the compositional gradient were shown to affect the mechanical behavior of the FGM, including peak stress, overall mechanical response, and less variation of stiffness.

Laaksonen [52] numerically analysed the mechanical properties of FGMs using ABAQUS and ANSYS, comparing gradient stress and deformation performances for FGMs under thermal and mechanical loading. The distribution of graded material was based on a power-law. The results showed both ANSYS and ABAQUS were reliable tools for analyzing the behaviour of FGMs producing highly accurate predictions of their mechanical properties.

Hirshikesh et al. [53] numerically analysed fatigue crack growth in FGMs under cyclic loading in the presence of an edge crack. The numerical analysis used FEM (phase field method with cycle jump and mesh refinement).The distribution of the local properties of the FGM were based on the Mori–Tanaka homogenization scheme. It was again shown that the use of FGM can enhance resistance to fatigue crack growth, see predicted mixed mode crack growth in Figure 23 N meaning number of cycle.

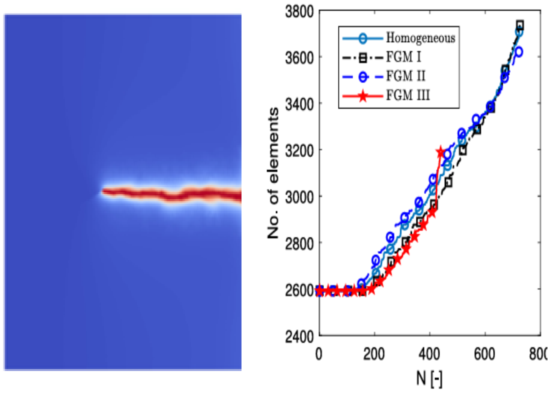


Figure 23. Mix mode crack growth in FGM[53]

Ghanavati et al. [54] produced the layered FGM shown in Figure 24 via additive manufacturing with laser directed energy deposition then analyzed crack formation in the "dog bone" shaped specimen under tensile loading. Distribution of the FGM components and crack initiation were determined using advanced microscopic analysis including a field emission scanning electron microscope. The grading of the material layers was due to differing concentrations of AISI 316L and IN718. It was shown that a perfect varying gradient of 50%, see Figure 25, gives improved mechanical performance with reduction in residual stress concentrations.

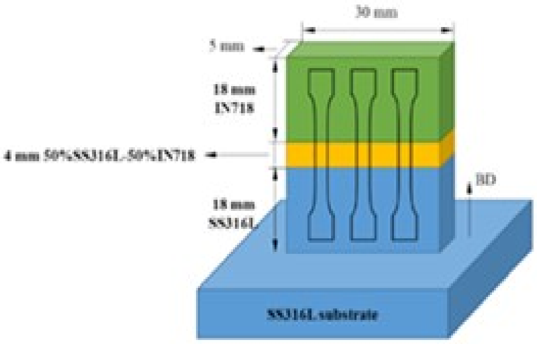


Figure 24. Design of FG-layers[54]

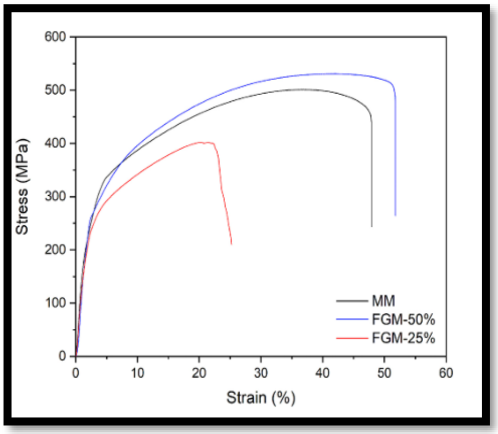


Figure 25. Stress-strain curve of multilayers and FGM[54]

Lammert et al. [55] investigated fracture characteristics and mechanical properties of FGM, including the effects of oxygen diffusing into the crack tip. The FGM was considered as a semi-infinite plane under static load, with three edge cracks of different lengths. In the numerical analysis, the profile of the graded material was Gaussian-like or a polynomial and was bounded to a closed interval and with symmetry based on median adjustment parameter. However, it was found by comparing the FGM with and without oxygen penetration that the elastic modulus increased significantly in the presence of oxygen showing oxygenation can have a substantial effect on critical load. In fact, the presence of oxygen always reduced the critical load. Crack behaviour was analyzed for different crack separations and showed that three cracks close together exhibit greater resistance to failure due to a shielding effect which reduced as the separation of the cracks increased.

Das et al. [56] studied the thermo-mechanical response of FGMs in the form of simply supported multi-layered plates under thermal and mechanical loading. This numerical analysis was based on zigzag theory with the profile of the grade material based on a power law. The results obtained showed the FGM plate presented different behavior at different loadings, load distributions, and layer thicknesses. However, it was shown that for certain combinations, such as zirconium dioxide (ZrO_2)/ steel use stainless (SUS304) at a transition temperature (1180 K°),deformation and stress became independent of the power law index, layer thickness and relative thickness of the material layers distribution.

Bagheri and Yazdi [57] carried out an experimental and analytical study to improve the mechanical properties and failure mode of single-lap joints of overlapping strips where the adhesive was an FGM of polylactic acid (PLA) with added amounts of acrylonitrile butadiene styrene (ABS) under tensile loading. The strips were fabricated using a 3D printer via fused deposition modeling, and the numerical analysis used FEM and ANSYS with contact cohesive zone model for continuum damage mechanics . Figure 26 shows enhanced adhesion, ductility and joint strength when ABS was added to the (PA-based adhesive) . In particular, the pattern of adhesive failure differs in pure materials compared to graded materials.An FGM (ABS-PLA) adhesive improved mechanical properties, strength and ductility, and controlled stress concentrations to enhance joint durability.

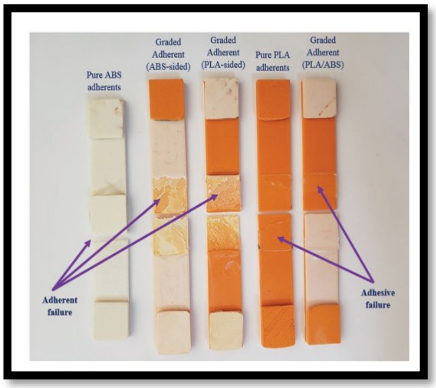


Figure 26 . Failure mode after tensile test loading [57]

Nguyen and Huang [58] studied crack propagation in FGMs in the form of a plate with central crack. The numerical analysis used FEM and ANSYS to predict the direction of the crack growth by considering the maxima of the tangential normal stress and energy release, and the minimum strain energy density. The numerical analysis was accompanied by an experimental program. It was shown that the difference between FEM predictions and experimental measurement was less than 2% for the SIFs and 0.15% for the crack propagation angle.

Shamim [59] improved the energy absorption performance of columns of FGM foam subject to dynamic crushing. This numerical analysis used FEM and ABAQUS to investigate the change in column mechanical property with the gradient of a foam density. It was claimed that energy absorption efficiency was increased by nearly 18%, with corresponding improvement in structural stability demonstrating the possible benefits of FGM foams.

Thirugnanasamabandam et al. [60] studied the mechanical properties of FGMs containing wood flour intended for structural use under tensile, compression and three point bending tests. Numerical analysis used FEM and ABAQUS . The test pieces were fabricated using material extrusion via a 3D printer. FGMS was composed of layers of polylactic acid reinforced with wood flour and parallel layers of ceramic-reinforced polylactic acid. This combination of layers substantially improved compressive and tensile strengths compared to the use of wood flour alone without detracting from the properties of the ceramic. The fracture shown in Figure 27 is brittle, caused by voids between layers and weak bonding.

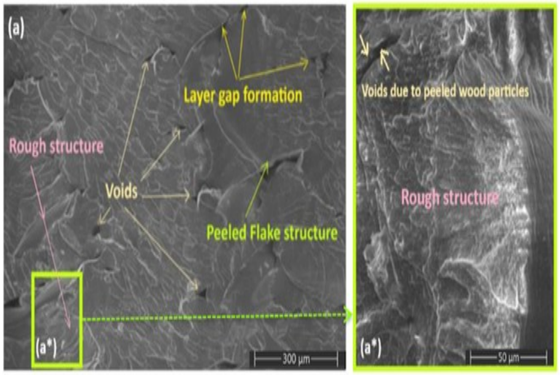


Figure 27. Fracture surface of FGSM[60]

Hamza et al. [61] predicted fatigue behavior under cyclic loading of functionally local graded isotropic material in three dimensions around a notch and a crack. This was a numerical analysis using ABAQUS with XFEM and subroutine USDFLD in Fortran. The fatigue behavior was modelled based on combined kinematic and isotropic hardening. It was confirmed that the volume fraction index had a significant effect on the damage to functionally graded material under cycle loading and could lead to lower damage and crack growth.

3.5 Experimental Studies on Fracture Behavior of FGMs

Compared to numerical investigations, experimental studies on fracture behavior in FGMs remain limited but provide critical validation insights. Available experimental works can be categorized based on specimen type, loading conditions, and observed crack behavior.

(i) Beam and Plate Specimens under Bending and Tensile Loading

Rousseau and Tippur [11] conducted one of the notable experimental studies using glass-filled epoxy FGMs in beam form with an edge crack under pure bending. Using coherent gradient sensing (CGS) interferometry, they observed that material gradation reduces stress intensity factors and alters crack-tip fields, leading to improved crack growth resistance. Similarly, Kim and Paulino [14] validated numerical predictions using PMMA-based FGMs, showing that crack paths deviate under asymmetric loading due to induced shear stresses.

Nguyen and Huang [58] experimentally examined central crack plates under tensile loading, reporting excellent agreement with FEM predictions (within 2% for SIFs), and confirming that crack propagation direction strongly depends on material gradients.

(ii) Additively Manufactured and Layered FGMs

Recent studies have focused on additive manufacturing techniques to fabricate FGMs for fracture testing. Ghanavati et al. [54] produced multilayer FGMs using directed energy deposition and examined crack initiation in “dog-bone” tensile specimens. Microscopic observations revealed that crack initiation is strongly influenced by compositional gradients and interlayer bonding quality.

Thirugnanasamabandam et al. [60] investigated 3D-printed FGMs reinforced with wood flour, showing brittle fracture behavior dominated by voids and weak interfacial bonding, which are not typically captured in numerical models.

(iii) Dynamic and High-Strain Rate Testing

Zemani et al. [51] used a Split Hopkinson Pressure Bar (SHPB) to study high strain-rate behavior of FGMs. Their results demonstrated that strain rate and gradient index significantly affect peak stress and fracture response, highlighting the importance of rate-dependent effects.

(iv) Adhesive and Joint-Based FGMs

Bagheri and Yazdi [57] experimentally investigated FGM adhesives (PLA–ABS) under tensile loading. They observed improved ductility and controlled crack propagation compared to homogeneous adhesives, with failure modes transitioning from brittle to more distributed damage patterns.

3.6 Comparison between Experimental and Numerical Results

Although several studies report good agreement between numerical and experimental results, notable discrepancies remain:

Crack Path Prediction: Numerical models often assume smooth material gradation, whereas experiments reveal localized heterogeneities, porosity, and defects, leading to deviations in crack trajectories.

Fracture Toughness and SIFs: While studies such as Nguyen and Huang [58] show close agreement, others report differences due to simplified constitutive models and neglect of microstructural effects.

Damage Mechanisms: Experimental observations frequently show void-induced cracking, interfacial debonding, and microcrack coalescence, which are not fully captured in conventional FEM or CZM approaches.

Effect of Manufacturing Defects: Additive manufacturing introduces residual stresses, porosity, and imperfect bonding, significantly influencing fracture behavior but often ignored in simulations.

3.7 Validation Gaps and Research Needs

Despite progress, several key validation gaps remain:

Limited Experimental Data for Porous FGMs (FGPMs): Most experimental studies focus on fully dense FGMs, with very few addressing porous architectures, which are central to this review.

Lack of Standardized Testing Protocols: Variations in specimen geometry, loading conditions, and fabrication methods hinder direct comparison between studies.

Insufficient Multi-Scale Validation: Current models rarely incorporate microstructural features (pores, inclusions, interfaces) observed experimentally.

Dynamic and Fatigue Validation: Experimental data under cyclic and high-rate loading are scarce compared to numerical predictions.

Coupled Multi-Physics Effects: Effects such as thermal gradients, oxidation, and environmental degradation are often modeled but rarely validated experimentally.

4. Elastic modulus-porosity relationships and compression behavior

Kovacik [62,63] studied relationship between shear, Young modulus and porosity in porous materials. The work was theoretical based on percolation theory. It was shown that an increase of porosity decreased both shear and the Young modulus as shown in Equation1:

- The Young's modulus MMM can be expressed as:

$$M = M_0\left(\frac{p_c - p}{p_c}\right)^f \qquad (1), \text{ when } p_c \geq p$$

- where:
- Mo is the Young's modulus of the fully dense (non-porous) material,
- p is the material porosity (volume fraction of voids),

- pc is the critical porosity threshold, above which the material loses percolation connectivity and the modulus drops to zero,
- f is a critical exponent determined by the microstructure and connectivity of the pores.

Assumptions of the Percolation Model:

1. The solid phase forms a continuous network that carries the applied load until porosity reaches pc
2. Pores are randomly distributed and non-interacting, such that long-range percolation theory applies.
3. Elastic behavior is linear up to the critical porosity.

Validity Limits:

- The equation is valid only for p≤pcp. Beyond pc, the solid framework is disconnected, and the modulus approaches zero.
- The model assumes isotropic pore distribution and uniform microstructure; highly anisotropic or engineered pore architectures may deviate significantly.
- f depends on the pore geometry; typical values for random 3D networks range between 1.5 and 3.0, but should be calibrated for specific materials.

This formulation provides a theoretical framework to predict the degradation of elastic properties with porosity and has been widely used in studies of porous ceramics, metals, and functionally graded porous materials. Experimental validation, however, often shows deviations due to pore shape, distribution, and size effects.

Wu et al. [64] reviewed mechanical analyses and properties of functionally graded porous materials (FGPMs) such as foams, particularly those used in structures such as beam, plate, shell, and etc. under different loading conditions. See Figure 28 for types of distribution in FGPMs. It was confirmed that FGPMs can be an ideal material for specific engineering application, providing strong and lightweight structures. Micromechanical models provided useful estimates of their elastic properties, but significant challenges remain: in fabrication of these materials, in accurately analyzing their mechanical behavior especially for asymmetric porosity distributions.

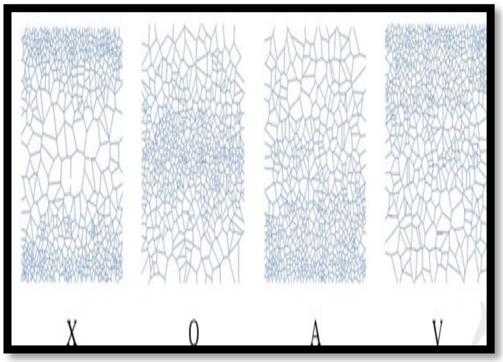
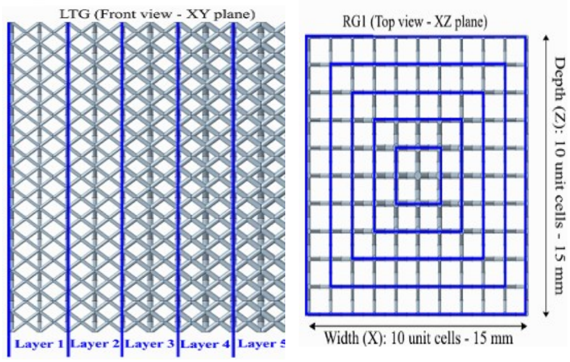


Figure 28. Types of distribution in FGPM [64]

Galarreta et al. [65] performed an analytical and experimental study of the mechanical behavior of FGPMs with different porosity gradients longitudinally, laterally, radially and in combinations, see Figure 29, in beams under quasi static compressional loading. The numerical analysis used finite element analysis (FEA) in MATLAB software and fabrication was by laser powder bed fusion. The distribution of FGP structures was based on a Kelvin-Voight material and the rule of mixtures. The results showed that distributing functionally graded porous (FGP) structures perpendicular to the load provided the highest yield strength and elastic modulus. The correspondence of predicted and measured results was deemed adequate.



(a) (b)

Figure 29 . FGP structure at : (a) Lateral gradient LTG,(b) radial gradient RGI [65]

Kas and Yilmaz [66] studied mechanical behavior and failure of functionally graded porous material (FGPMs) struts under compression loading. The fabrication of the struts was by adaptive manufacturing by laser powder bed fusion and the failure of the specimens investigated using a scanning electron microscope. The results showed FPGM could provide an optimal balance between strut thickness, weight and mechanical strength. Mechanical performance with improved 6% and increased energy absorption and failure mechanisms as shown in Figure 30 and Figure 31.

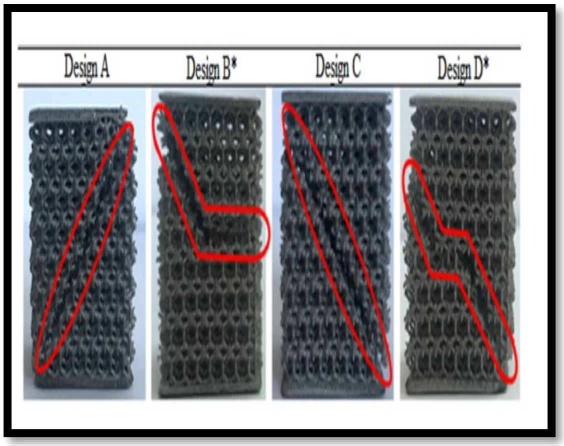


Figure 30. Failure mechanisms in compression test [66]

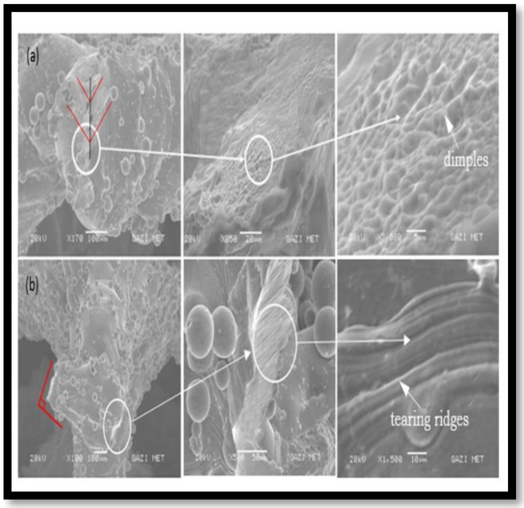


Figure 31. Surface fracture[66]

Barbaros et al. [67] reviewed FGPMs containing nano-composites. It was shown that the methods used for manufacturing functionally graded materials (FGMs) containing polymers depend on the type of polymer, ceramic or other material used. It was also shown that addition of carbon nanotubes and graphene platelets as reinforcement could improve the mechanical properties of FGMs whether porous or not. The geometry of the added nano-composites, such as their shape, size and distribution affected the mechanical performance of the FGPM as did the mechanical properties of the nanomaterial.

Mojahedin [68] analyzed the mechanical behavior of FGPM in beam form subject to thermal and mechanical loading. Using exact solutions and deep energy method with neural networks to enhance computation different beam theories were investigated. It was shown that pore size, distribution, compressibility and whether the pores contained a fluid, all strongly affect beam behavior.

Emir and Bahçe [69] investigated theoretically and experimentally the mechanical characteristics of FGPMs with fixed pore size and used for structures under compressive loading. Here the forms were a primitive and a Gyroid lattice. The numerical analysis used finite element method (FEM), ANSYS software, and triply periodic minimal surfaces (TPMS).The shapes used in the experimental work were produced by fused deposition modelling. The material of the lattices used pore size fixed at values in the range 20% to 40%. This study showed that Gyroid lattice structures had a higher mechanical performance and greater resistance to deformation and energy absorption, which makes them more suitable for applications requiring lightweight and high strength, see Figure 32.

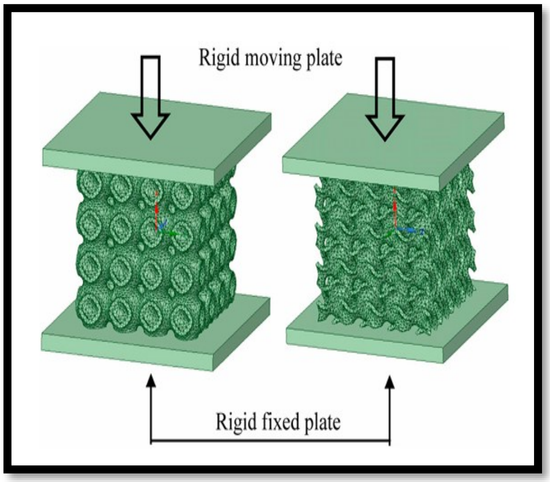


Figure 32 . Compressive test of different FGP structure[69]

Joshi and Kar [70] studied mechanical behavior in (1, 2, and 3) dimensional for elastic–plastic FGMs panels with porosity evenly and unevenly distributed. The numerical analysis used FEM, with the profile graded according to the Tamura–Tomota–Ozawa (TTO) power law. It was shown stiffness increased with increase in distribution direction of FGM, improved performance in other application, 3D FGM distribution resistance effect of porosity. The authors claimed good agreement with available reported results but did not mention whether these were for numerical studies or experiment.

Chen et al. [71] reviewed the analyses of the mechanical performance of functionally graded porous structures (FGPSs) with particular emphasis on the development of strong lightweight structure due to changes in the profile and density of the pores as shown in Figure 33.

This review included appraisal of fabrication techniques such as additive manufacturing and the behavior of the material under more than a single mechanical tests such as buckling, bending, and compressive energy absorption. Figure 34 presents the reported common materials and lattices used in FGPSs. The report states that lightweight FGPMs with graded porosity can increase stiffness and improve mechanical performance in a controlled manner but are difficult to fabricate. It is noted that previous analyses of porous composites to be used for load bearing were investigated with only dry air in the voids. However, unlike Chen et al. [71], the present review extends beyond general mechanical performance by providing a focused and critical synthesis of fracture mechanisms, crack initiation, and propagation behavior in functionally graded porous materials (FGPMs). It integrates recent advances in fracture modeling approaches, including microstructural-based and multi-scale techniques, which were not systematically addressed in prior reviews. Furthermore, this work incorporates the role of pore morphology, size distribution, and environmental interactions (e.g., fluid-filled porosities and thermo-mechanical coupling) on fracture behavior—an aspect only marginally considered in earlier studies. By linking mechanical performance with failure mechanisms, this review offers a more comprehensive framework for understanding the reliability and structural integrity of FGPMs in practical applications.

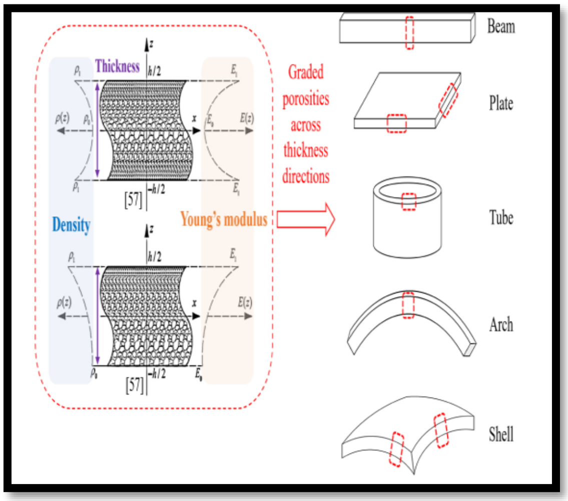


Figure 33. Types of FGPSs[71]

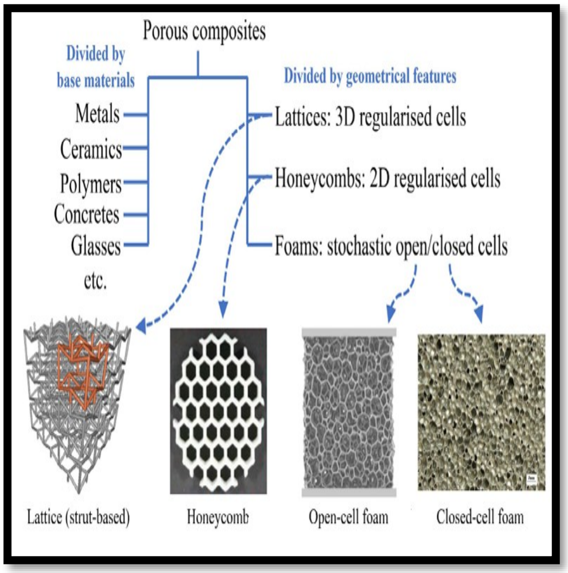


Figure 34. Common materials and latticies used in FGPMs[71]

Mellouli et al. [72] aimed to produce a computer model using ABAQUS with user material UMAT subroutine to numerically investigate the effects of porosity fraction and gradient on the fracture mechanics of bi-directional FGM structures. The Voigt model was used for homogenization. The mechanical properties of bi-directional FGPMs, where porosity is varied in the two main directions, and tri-directional FGPMs affect properties such as density, mechanical strength, and thermal conductivity as shown in Figure 35, Figure **36**, and Figure **37**).

It was reported that in FGPM structures fabricated by sintering, it was possible for micro-voids (small pores) to be introduced during the process and then persist subsequently. Figure 38 shows how bi-directionality in FGPMs can have a significant impact on brittle fracture behavior. The material's fracture resistance can be reduced or improved by controlling the gradient distribution and porosity levels which can lead to crack initiation and propagation. In this way it is possible to either enhance or reduce the material's fracture resistance, providing an effective tool for designing smart materials capable of precisely controlling crack initiation and propagation paths cy meaning power index at y-direction ,py porosity coefficient .

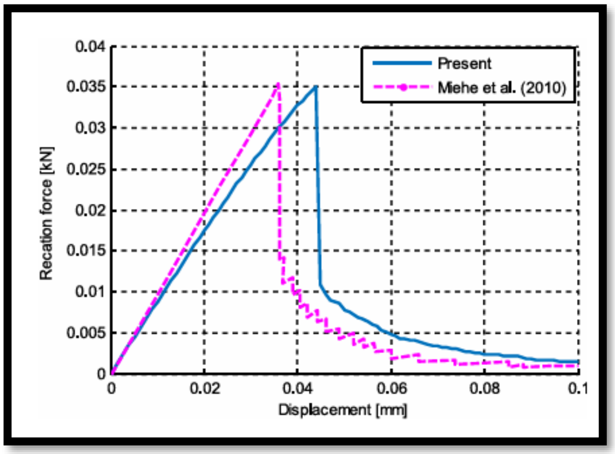


Figure 35. Validation of symmetric notched in beam [72]

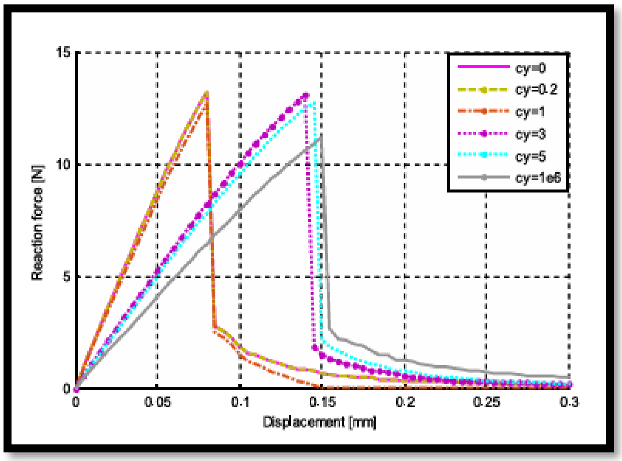


Figure 36 . Force-displacement of y-distribution[72]

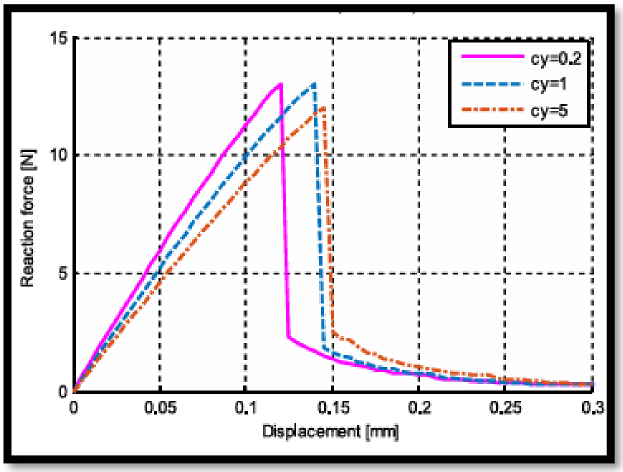


Figure 37. Force-displacement bi-directional distribution [72]

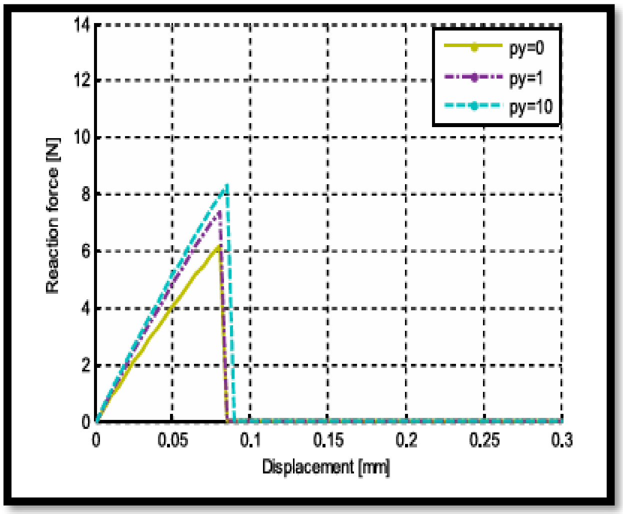


Figure 38. The load–displacement response of bi-linear porosity in the unidirectional y-FGM[72]

Fan et al. [73] sought to improve the mechanical behavior and performance of 3D printed sandwich structures in the form of beams with a graded porous lattice core. The design of the beams was accomplished via numerical analysis. Fabrication of the beams was by a 3D printer where the distribution of a graded porous lattice core was based on a power law. The mechanical properties were determined experimentally by three point tensile and compression tests which showed a lightweight material with high mechanical performance suitable for many applications. The gradient of the core was shown to be able to enhance mechanical behavior, see Figure 39.

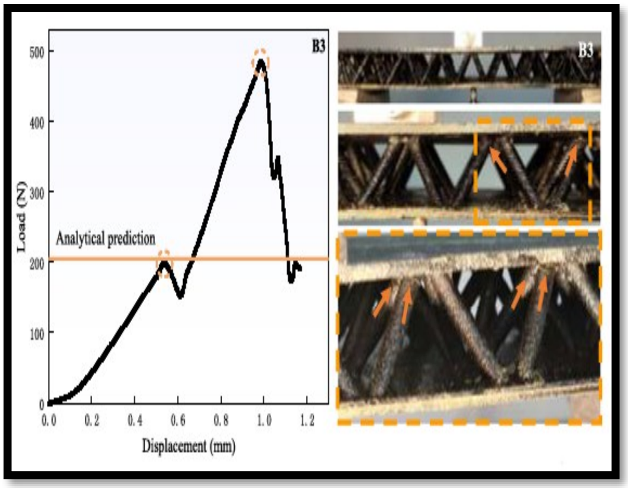


Figure 39 .Curve between load-displacement and failure specimen under three-point bending test[73]

Jabarzadeh et al. [74] enhanced the mechanical properties and performance of a FGPM under tensile and compressive loads. The material of the FGPM was 316L stainless steel with dry air in the pores. The numerical analysis used ABAQUS with UMAT subroutine and the size of the representative volume element determined using scanning electron microscopy. The steel mesh was fabricated using laser power bed diffusion. The difference between the predicted and measured stress–strain curves was found to be less than 1 % at the peak stress point under both tension and compression loads.

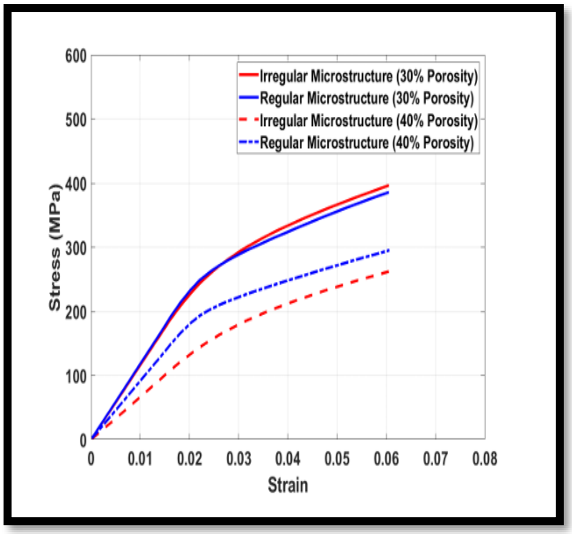


Figure 43. Stress –strain curves[75]

Chakma [75] analyzed mechanical behavior for elastic-plastic with regular and irregular microstructures of graded porosity, both linear and nonlinear. The investigation was a numerical analysis using the microstructure free FEM.

It was confirmed that both regular and irregular distribution of microstructural porosity affected the mechanical properties, see Figure. It appears that regular patterns of the porosity gave a higher stiffness than irregular patterns. The increase of porosity from 30 % to 40 % as shown in Figure 43 had a greater effect with an irregular distribution.

5. Conclusion

functionally graded materials (FGMs) have emerged as a promising paradigm for the design of advanced, flexible structures, primarily due to their superior thermo-mechanical characteristics. This review summarizes recent developments concerning the application and numerical investigation of cracks, crack growth, and fracture mechanisms within such structures.

Many computational methodologies have been adopted in relevant studies, including the MARC technique based on Fourier series expansion, various implementation approaches within the ABAQUS finite element program, and other software such as ANSYS and FORTRAN programming.

It is generally perceived that the resistance of all types of FGMs to crack growth is enhanced as the material gradient resulting in a higher elastic modulus value making them more fracture resistant. The effect of porosity and FGM proportion on mechanical properties and fracture behavior is highly dependent on factors such as pore distribution, gradient profile, loading type, and environmental conditions. In some cases, high porosity or abrupt gradients may exacerbate stress concentrations, leading to reduced fracture resistance.

Unlike previous reviews that treat fracture behavior and porosity effects in isolation, this study provides an integrated synthesis linking material gradation, porosity distribution, and crack propagation mechanisms within a unified framework.

This review further identifies critical gaps in current modeling approaches, particularly the

limited coupling between multi-scale porosity effects and fracture mechanics in numerical simulations.
In addition, a comparative evaluation of widely used computational techniques is presented, highlighting their relative strengths and limitations in predicting fracture responses of functionally graded porous materials.

Based on these insights, the review proposes future research directions focused on the development of more robust multi-physics models and experimental validation strategies to improve predictive accuracy and practical applicability.

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Conflicts of Interest

The authors declare no conflict of interest.

Nomenclature

CMOD Crack mouth opening displacement

σ_22 loading at y-direction in tensile test

E_°,

E_W Young's modulus at the bottom and the top side of the cracked plate.

2h plate length

a Initial crack length

b plate width

kI stress intensity factor mode-I

αb gradient parameter

βh gradient parameter

D Width of plate

L Length of plate

Δσ Cyclic Tensile Stress Range

〚(σ)〛_max-σ_min)

Δτ Cyclic shear Stress Range

〚(τ)〛_max-τ_min)

ρmin,max DENSITY , porosity (min,max)

T_(Hot,Cold) Tempreture

SS 316 Stainless Steel 316

Ti-6Al-4V Titanium-6Aluminum-4Vanadium

h Width of beam

w Length of beam

F Mass loading

α Crack Kinking Angle

φ Initial Crack/Notch Angle

MM Multi material layer

BD Build Direction

Δr_k Δrk=(Rex -Rin)/nk , Rex and Rin respectively represent the external and internal radius, Δrk, and to calculate the latter we divide the value of the radius of the plate (Rex Rin)by the number of rows (nk)

b,L Width and length of plate

X,O,A,V Shape of distribution porosity

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