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REVIEW

Systematic Review of Functionally Graded Pipelines and Proposal of a New Material Property Variation to Enhance Operational Stability

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ABSTRACT

The global discussion surrounding Functionally Graded Materials (FGMs) highlights their unique and diverse micro-material properties that result from varying two or more materials in a strategic combination profile. These combinations produce distinct physical and chemical characteristics. Changes in these characteristics may occur continuously, referred to as a gradient function, or discontinuously as a stepwise function. The changes can appear within homogeneous or heterogeneous material geometries. The variation in material properties depends on the volume fraction index function. This variation can occur in 1D, 2D, or 3D, either in the thickness or length direction within a material model. The vacuum in the review study on mechanically toughened and thermally resistant Functionally Graded (FG) pipelines prompted the current review study. This study addresses the absence of an appropriate variational function for FG cylindrical pipelines. It proposes a gradation function pattern to improve pipeline structural performance. An appraisal based on relevant FGM literature was conducted to improve the temperature differentials in traditional composite materials and stress-related issues in carbon steel pipelines. The review identifies specific FGM property variations that reduce failures that are possible in conventional materials.

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Reviewed articles and evaluation procedures followed the 2020 PRISMA guidelines. Literature was obtained from Scopus, Connected Papers, and other reputable sources. The study also discusses potential FG pipelines for gas and green energy transportation. The reviewed literature establishes the context for this research and addresses the gap in 3D FG model variation functions involving multiple materials.

Keywords: FGMs; Volume Fraction Index; Pipeline; Homogenous Material; Continuum; Stepwise

1. Introduction

After decades of material instability and integrity challenges in various isotropic metal materials across different engineering applications, the emergence of composite materials continues to evolve. Several engineers and academic researchers have begun working towards resolving such instability and failures in conventional material types with new materials. It is always a fact that the introduction of new materials into engineering construction has improved integrity over the years. However, as the composite materials experience a challenge due to persistent delamination problems at the material interfaces, the birth of Functionally Graded Materials (FMGs) begins a new era in engineering construction. Continuous evolution and refinement of this material have added significant value to our engineering applications across different construction [1–6]. FGM's evolutionary trend resonated with the plant fibres and the human natural bone formation phenomenon [7]. This innovation has become a Standard Operating Procedure (SOP) in engineering practice to strengthen material geometry and enhance operational efficiency. For the energy industry, using new materials such as FGMs in components such as pipelines and flanges is crucial. FGMs enable the reliable and efficient commercial transport of energy over long distances worldwide. Current literature reviews on FGM structures predominantly focus on manufacturing methods and application [3,4,8–15]. Li et al. [4] expanded the review by analysing multiple studies on various FGM combinations and their resulting structural products. Few studies specifically investigate pipeline models and systematically analyse their material variation patterns to improve pipeline strength. Consequently, research addressing FGM pipelines is limited to this end. Hassan et al. [8] reviewed two material combinations and related production methods; however, their analysis does not consider geometric configurations such as pipelines. Fu et al. [16] utilised the Euler-Bernoulli beam formulation to analyse vibrations in a gas-liquid phase of an operationally loaded pipeline. However, Zhou et al. [17] also adopted the Euler-Bernoulli beam theory to study structural defects in a pipeline. A key research gap exists in developing a core grading for pipeline structures using three distinct material properties in FGMs for a defined purpose. Addressing this gap could enhance pipeline operational performance and integrity. This review proposes a focused investigation into this specific area of research.

1.1. Background Structure

In 1972, Shen and Bever [5] found that altering the global material properties of composite materials significantly enhances their capability, leading to broader application possibilities across various engineering sectors. The research presented in Bever and Duwez, and Bohidar et al. [7,18,19] on material variation sheds light on today's FGM formulation through material property gradation patterns in polymeric materials. Furthermore, Kumar et al. [19] re-echoed the research of Bever and Duwez [7] on gradation patterns in polymeric materials which further made Bever and Duwez's 1972 idea more conspicuous. This gradation could have occurred due to changes in the chemical components of the material monomers, the molecular structure of the polymers, and their morphology [4,5]. The long recurrent chain of polymeric material molecules is likely the same as rubber or polyester materials in other composite models. The whole concept of material microstructural sizes, composition, and porosity was to create grading structural patterns for composites and polymeric materials [3,20].

Two years later, after Shen and Bever's study [5] on material gradation and gradient research, an Americantrained Polish chemist, Stephanie Louise Kwolek, tried Kevlar composite material variation in the early 1970s. This discovery resonated with the rationale of much recent research on FGMs [21]. Intensive research and industrial material applicability on engineering infrastructures continued until Koizumi and Niino [22] and Koizumi [23], who reported a severe challenge in the composite material. Before this time, the currently known FGMs were initially known as Poly-Paraphenylene Terephthalamide, named by Stephanie Louise Kwolek while working at DuPont de Nemours Chemical Company. This idea was solely to proffer solutions to the traditional composite materials' delamination problems and poor thermal resistance in engineering applications. The Poly-Paraphenylene Terephthalamide was the K29 version of Kevlar for industrial applications [24]. The variation in material properties was then in a specific Kevlar material (K29) to improve strength. As time progresses, academic literature has revolved around the effect of material stress and thermomechanical loading in numerical analysis [25–29]. The focus was to improve the poor material thermal resistance with the high and advanced variation in FGMs [9,30–34]. As technology advances, material applications for infrastructural construction depend on evolution and development. Material integrity and lifecycle expectation are the engineering factors that measure material capability to reduce failure. Therefore, the emerging FGM is considered under various loading effects during operation for intense computational analysis. Varying the material microstructure in a specific gradient and patterns, for example, across the material thickness, eliminates the well-defined interface seen in ordinary and traditional composite materials.

Several FGM review studies targeted different structural schematics to illustrate grading patterns in the FGM structural formulation and production procedures [3,9,19,32–35]. However, the material property variation is crucial for understanding structural displacements, stresses, and shear deformation under various loading conditions, such as force, strain, temperature, and pressure [36–38]. As illustrated in Medeiros and Ribeiro's [39] study, the gradual change in material properties that occurs along the thickness and length direction demonstrates a stepwise mode variation. In contrast, a non-stepwise structural formulation represents a continuous gradient along the X, Y, or Z directions, with the Z typically referring to the thickness in a three-dimensional (3D) geometry [33,40,41]. Three key properties of FGMs are the composition of material properties, alignment of microstructure, and the gradient of material grain porosity, which support both stepwise and continuous variations [3,42,43]. However, most of the literature assessed has primarily focused on studying material property variation across different dimensions and types of structural elements [43–47]. Remarkably, Singha et al. [48] and other scholars critically focused on element types rather than specific structural geometries to analyse FGM [49–51]. Structural geometries such as offshore energy platforms, energy pipelines, ship hulls, etc. Whether element types or structural geometries, a continuous or stepwise grading pattern is feasible in all directions and dimensions of the model, as numerically investigated in Cho [52]. Additionally, the variation of micro-material properties throughout the thickness of any geometric model addresses the thermomechanical and stress concentration challenges commonly faced by traditional non-FG materials [53]. This innovation in FGM would potentially dominate the metallurgical industry in the coming decades.

1.2. Finite Element Analysis (FEA) of FGMs

The FEA is a certified tool and has been proven worthy by several research publications to analyse FGM structures [54–58]. Existing review studies on FGM structures have demonstrated the efficiency of FEA and shown its capacity for undamaged and damaged FGM structures [59–61]. However, the limitation of studies on the Functionally Graded (FG) pipeline structure regarding natural gas or hydrogen transport is a pressing issue. The study then aimed to propose a structural evaluation of the FG pipelines and flanges to improve understanding of the FGM pipeline research and development on a global scale. In this instance, what is crucial then is the material behaviour and characterisation under various environmental factors. Natural environmental dynamics are, therefore, bound to happen under such harsh conditions that affect marine structures, such as offshore pipelines [46,62].

2. Methodology-Systematic Review Structural Framework

The eligibility criteria used for literature vetting and synthesis action, as recommended by Preferred Reporting Items for Systematic Meta-Analyses (PRISMA) 2020 (see **Supplementary Materials**), are based on the systematic review study title and objective [63]. However, the non-related article titles and keywords originally crossed out were to simplify and narrow down the study objectives, which aimed to address the limited study on FGM pipelines for energy transport. To address this limitation, the review study proposes a unique FGM gradation function for pipeline structures to improve performance in operation. This study documents and prioritises the existing review tools while highlighting the distinctions among the structural FG models discussed in the cited articles. As the FG energy pipeline remains the central focus of this study, other consolidated structural material models are under a general cohesive appraisal. Due to numerous sources of literature database information, it is challenging to use literature sources without following the PRISMA guidelines. From this perspective, the study employs innovative and recommended PRISMA methodology to promote clarity and consistency [63]. The PRISMA guidelines benefit the review study by creating the structural framework and simplifying the study plan. The study framework is organised based on the general Finite Element (FE) geometries and various mathematical model analyses as discussed in the appraised articles. This methodology enhances the practical approach and reduces complexity, allowing for a more straightforward interpretation and application of the study findings.

2.1. Literature Sourcing and Documentation

Application of the PRISMA systematic review style aided in the literature search, record, and evaluation. Scopus, Connected Papers, Google Scholar, Academia.edu, and Search by Literature Citation are used to achieve the studied literature documentation and analysis. The large volume of literature from the databases accessed has undergone effective scrutiny to allow for filtering and comprehensive assessment. Among the databases utilised, Scopus emerged as the most prominent source for the required information to analyse the selected articles. Combining literature data information from different sources has proven to be the most effective approach. The graphical solutions presented in Sections 2.2 and 2.3 provide a clear illustration of the searched and filtered literature. Some of the graphics demonstrate FGM yearly publication trends, subject area percentages, publication channels, and more. The graphical information offers an overview of the FG material's significance. Nonetheless, the Scopus literature database is an arrow source for this study. Meanwhile, other databases are utilised minimally to a lesser extent. However, all the mentioned databases contributed to the systematic review study, as cited and referenced in the bibliography.

The study followed the identification, filtration, integration, and synthesisation process of the auto-generated and selected literature. The approach employed, however, aided in minimising biased views and providing more reliable findings. In addition, the approach brought absoluteness to make informed decisions and draw reasonable conclusions on the subject matter.

2.2. Literature Filtering, Collation, and Synthesisation

The application of Boolean operations effectively illustrates the principle of adding or removing literature searched from the database to refine results. Literature screening was employed to achieve the Boolean operation by removing the duplicates and non-required literature (see **Figure 1**). At the Boolean operation stage of the overall sourced literature, careful inspection of the literature selection aided in streamlining the study objectives. Most FGM articles focused on the fabrication and production process of different structures. A rigorous search process identified the substantial literature database called Scopus. The literature search encompassed various articles on FG structural models, including beams, bars, shell plates, solid blocks, cylindrical disk plates, pipe flanges, pipelines, etc. [46,48,64–70]. A non-structural model study from appraised articles on FGM review, manufacturing, background-based, etc, can be found in the following studies [2,34,71–74]. Notably, the fabrication process of the FGMs had more recorded articles than structural loading analyses over the last three decades. Conversely, the cylindrical FG pipeline, which is the principal focus of this study, has received comparatively less attention in the gathered literature so far. Therefore, the future direction of research, as highlighted in the Recommendation Section of this study, needs prolific research attention, however, for pipelines and their flanges. Pipelines remain the commercial hallmark for large quantities of energy transport across the globe. **Figure 1** shows the total research identification via databases, registers, and other sources, as designated in light blue and green boxes. The light blue boxes indicate the literature flow organogram from Scopus and the Connected Papers database search results. The blue-green gradient box accommodates the total new searches and consolidated report included in the study.

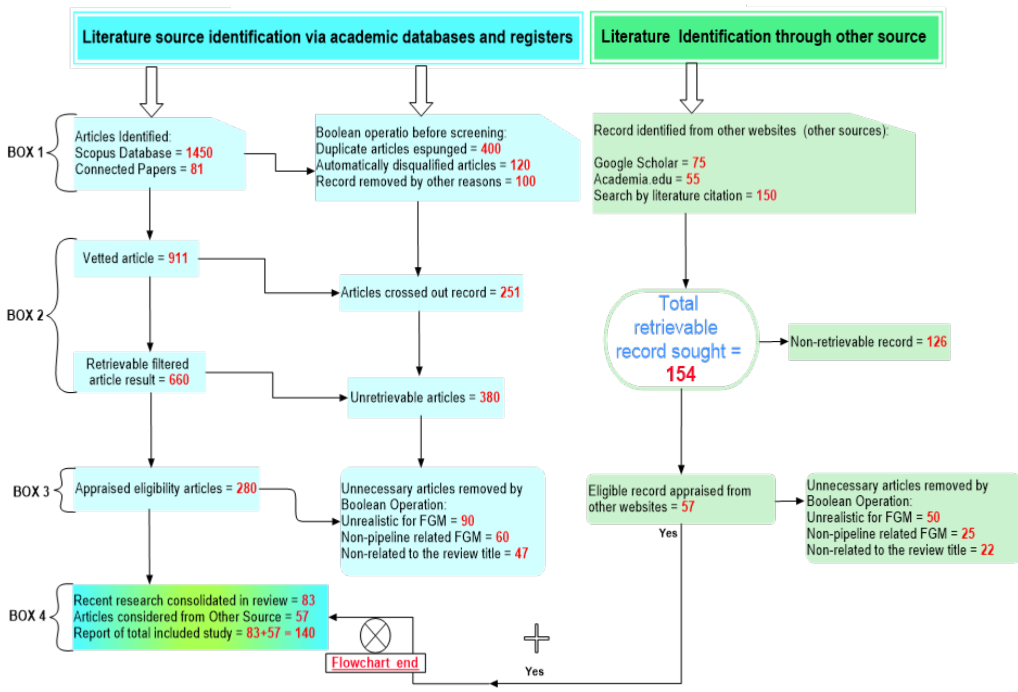

Figure 1. Literature sourcing organogram flows from Scopus and other web sources.

2.3. Literature Organisational System after Mapping

Literature organisation is essential for the study's clarity, coherence, and insightfulness. **Figure 1** presents the PRISMA chronological trajectory, an effective structure that summarises existing research, highlighting connections, research gaps, and emerging trends. Previous studies are grouped thematically by key title, methodologies, and problem domains. This approach establishes a strong link to the current review study, which spans multiple research applications. The logical structure of the literature is schematically illustrated in the chart flow of **Figure 1**. This flow chart guides readers from foundational concepts to detailed sub-titles within the study.

The simplified PRISMA flowchart for the systematic review study aimed primarily to appraise and analyse the selected literature. The attached word 'box' to each horizontal row in **Figure 1** represents the entire cells in that row based on the 4-step PRISMA analysis. The rationale is to clearly detail the literature selection process and, ideally, to reduce bias in the procedure. Accordingly, literature identified via the 'other source' column was incorporated in this study to maintain balance. Automated methods were systematically used within databases to retrieve relevant and high-quality papers for the review.

4-Step Based Analysis of PRISMA Literature Sourcing Strategy:

- Literature identification**-** Box 1: The literature identification section is a core objective of the review study (see **Figure 1**). It systematically draws on relevant searches using predefined databases and search strategies. The electronic databases probing, such as Scopus, Connected Papers, Google Scholar, and Academia.edu, employed keyword terms, study titles, abstracts, and a free-text approach to match the PRISMA systematic review requirements.

- Literature Screening- Box 2: Both automated and manual literature generation processes were filtered based on titles, abstracts, keywords, publication channels, and language. However, the recorded results from different databases in **Figure 1** possess both recovered and unrecovered literature. In this study, the documentation and application of literature identification and selection of relevant articles are through the PRISMA standard filtration process. The literature titles, abstracts, keywords, and methodologies played a critical role in this evaluation process. All identified and imported literature was managed using Mendeley, the preferred reference management system, and underwent a duplicate removal process before citation.
- Literature Eligibility- Box 3: All searched closely related literature to the study title and abstract were coherently assessed and considered using PRISMA review eligibility criteria. Again, the PRISMA criteria were employed to standardise and benchmark the systematic review study.
- Literature Inclusion- Box 4: This section includes the literature that has been reportedly cited and referenced in this study. Literature inclusion is systematic using automated database criteria, such as the title of the literature, publication year, design objective, and many more. The PRISMA automation method excludes literature that has insufficient data or poor quality to ensure that the analysis portrays the study title.

Literature identification from Other Sources includes Google Scholar and Academia.edu. Note that the reason for including Google Scholar in the second column of **Figure 1** was based on citation search. Manual recovery of literature (ADD or REMOVE) using the Boolean operation method was to complement the Scopus and Connected Papers literature extraction from databases. After careful result filtering and exportation from databases to Mendeley, literature citations are found where they best fit throughout the study. However, in this section, literature from Connected Paper is the only infographic representation from other source databases' documentation.

The connected literature assessed assisted in drawing attention to the lack of review studies in this regard. Additionally, it indicated the slow progression of research on FG structural material for the energy pipelines. However, reviews on FGM production and evaluation since the inception of FGM evolution are geometrically progressing. The appraised connected literature is a buffer to this systematic review study. However, the Connected Papers search is limited to 2021, which is the latest adjustable year from the database. Therefore, from 2022 to 2025, publication information is missing from **Figures 2** and **3** and **Table 1**. The fairly closely related articles on FGM are mostly on pipeline structural analysis. FGMs are narrowly missing in some of the literature titles.

Figure 3 provides a detailed graphical illustration of the synchronised previous studies. The documented studies are related and connected to the FGM structure, as this study appraised past research.

Additionally, other compelling information that supports the connected literature view is presented here through the non-linear and pie chart graphical solutions shown in Section 3.1. The work by Attia et al.[75] serves as a key reference that connects various studies based on their similarities. As portrayed in **Figure 3**, this literature acts as a control centre, fostering synergy and interconnectedness among other study titles with an increased percentage of similarity.

The highest percentile similarity to the study title remains 100 and 16.9, as depicted by Attia et al.[75] and Soliman et al.[76], respectively. The least similar titles to this study range from 9.9% to 5.3%, as shown in **Figure 3** and **Table 1**, indicating a lesser connection to the study. **Table 1** clearly emphasises the research view through previous studies, as documented relative to the percentage similarity value to this study by title and abstract. Scopus Graphical Database validates the Connected Papers analysis with FGM percentage by subject areas, yearly publications trend, and journal title interest (Section 3.4). The **Table 1** reference column is created manually for readers' easy access to the Connected Papers titles. Therefore, the expunction of the automated authors' names and publication years in the Connected Papers analysis agreed with the manually referenced articles in **Table 1**. Among the 41 related publications to this study title is the first literature in **Table 1**, which certifies 100% similarity to this study.

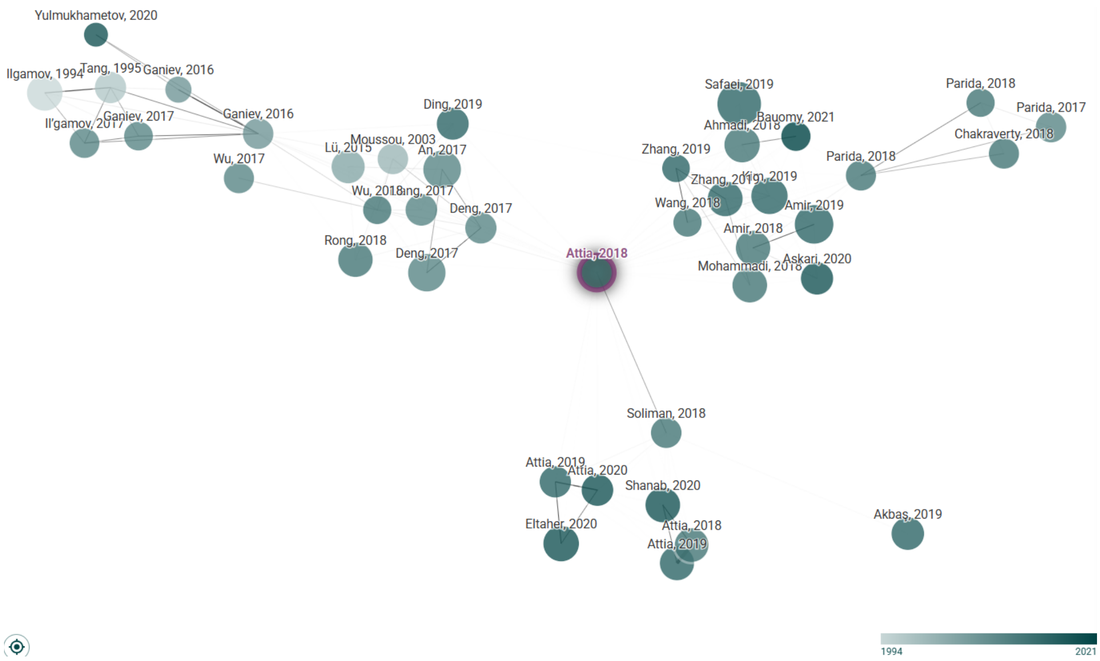

Figure 2. Graphical web view of the Connected Papers to the literature study review.

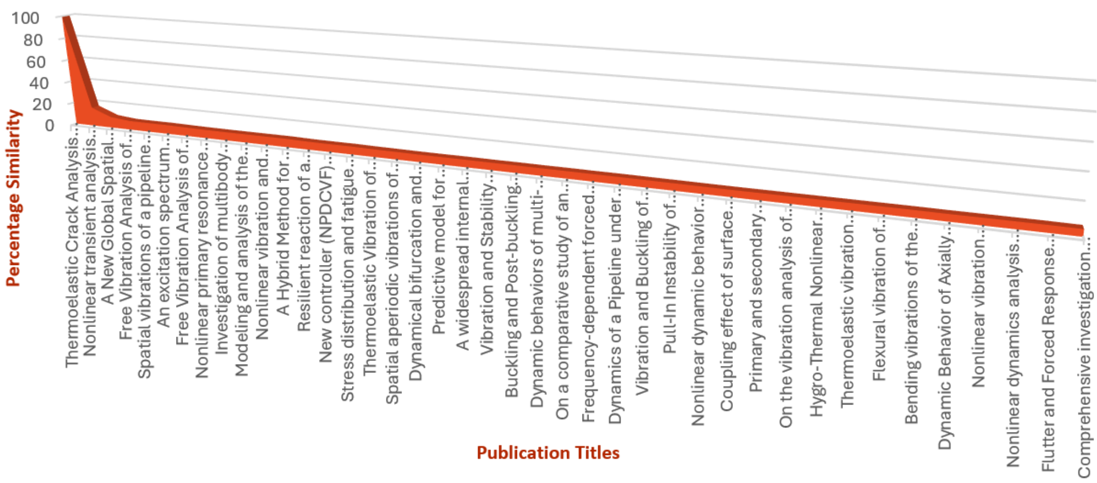

Figure 3. Connected Papers' graphical interpretation of article titles against percentage similarity.

Table 1. A Connected Papers network to the study objectives.

Connected Literature Titles	Cite	Cited Record	Similarity to Review Study
Thermoelastic Crack Analysis in Functionally Graded Pipelines Conveying Natural Gas by an FEM [75]	16	23	100
Nonlinear transient analysis of FG pipe subjected to internal pressure and unsteady temperature in a natural gas facility [76]	11	0	16.9
A New Global Spatial Discretization Method for Calculating Dynamic Responses of Two-Dimensional Continuous Systems with Application to a Rectangular Kirchhoff Plate [77]	6	19	9.9

Table 1. *Cont.*

Connected Literature Titles	Cite	Cited Record	Similarity to Review Study
Free Vibration Analysis of Functionally Graded Skew Plate in Thermal Environment Using Higher Order Theory [78]	9	33	8.1
Spatial vibrations of a pipeline in a continuous medium under the action of variable internal pressure [79]	11	2	8
An excitation spectrum criterion for the vibration-induced fatigue of small-bore pipes [80]	11	7	8
Free Vibration Analysis of Pipes Conveying Fluid Based on Linear and Nonlinear Complex Modes Approach [81]	12	36	7.7
Nonlinear primary resonance of imperfect spiral stiffened functionally graded cylindrical shells surrounded by damping and nonlinear elastic foundation [82]	27	38	7.5
Investigation of multibody receding frictional indentation problems of unbonded elastic functionally graded layers [83]	14	82	7.4
Modeling and analysis of the nonlinear indentation problems of functionally graded elastic layered solids [84]	13	70	7.4
Nonlinear vibration and dynamic buckling of eccentrically oblique stiffened FGM plates resting on elastic foundations in thermal environment [85]	33	38	7.4
A Hybrid Method for Transverse Vibration of Multi-Span Functionally Graded Material Pipes Conveying Fluid with Various Volume Fraction Laws [86]	13	43	7.4
Resilient reaction of a pipeline to an internal impact pressure [87]	3	2	7
New controller (NPDCVF) outcome of FG cylindrical shell structure [88]	8	43	6.9
Stress distribution and fatigue life of nonlinear vibration of an axially moving beam [89]	15	66	6.9
Thermoelastic Vibration of Shear Deformable Functionally Graded Curved Beams with Microstructural Defects [90]	22	66	6.6
Spatial aperiodic vibrations of the pipelines under transient internal pressure [91]	7	1	6.5
Dynamical bifurcation and synchronization of two nonlinearly coupled fluid-conveying pipes [92]	19	44	6.3
Predictive model for indentation of elasto-plastic functionally graded composites [93]	28	70	6.3
A widespread internal resonance phenomenon in functionally graded material plates with longitudinal speed [94]	5	50	6.3
Vibration and Stability Analysis of Functionally Graded Skew Plate Using Higher Order Shear Deformation Theory [95]	6	28	6.2
Buckling and Post-buckling Behavior of a Pipe Subjected to Internal Pressure [96]	13	9	6.2
Dynamic behaviors of multi-span viscoelastic functionally graded material pipe conveying fluid [97]	39	34	6.1
On a comparative study of an accurate spatial discretization method for one-dimensional continuous systems [98]	10	9	6.1
Frequency-dependent forced vibration analysis of nanocomposite sandwich plate under thermo-mechanical loads [99]	85	75	6
Dynamics of a Pipeline under the Action of Internal Shock Pressure [100]	9	7	6
Vibration and Buckling of Shear Deformable Functionally Graded Nanoporous Metal Foam Nanoshells [101]	26	107	5.9
Pull-In Instability of Functionally Graded Cantilever Nanoactuators Incorporating Effects of Microstructure, Surface Energy and Intermolecular Forces [102]	21	99	5.8
Nonlinear dynamic behavior of inhomogeneous functional plates composed of sigmoid graded metal-ceramic materials [103]	5	34	5.7
Coupling effect of surface energy and dispersion forces on nonlinear size-dependent pull-in instability of functionally graded micro-/nanoswitches [104]	22	100	5.6
Primary and secondary resonance analysis of FG/lipid nanoplate with considering porosity distribution based on a nonlinear elastic medium [105]	25	107	5.6
On the vibration analysis of coupled transverse and shear piezoelectric functionally graded porous beams with higher-order theories [106]	16	57	5.6
Hygro-Thermal Nonlinear Analysis of a Functionally Graded Beam [107]	17	45	5.6

Table 1. *Cont.*

Connected Literature Titles	Cite	Cited Record	Similarity to Review Study
Thermoelastic vibration analysis of functionally graded skew plate using nonlinear finite element method [108]	11	24	5.6
Flexural vibration of functionally graded thin skew plates resting on elastic foundations [109]	10	30	5.6
Bending vibrations of the pipeline under the influence of the internal added mass [110]	1	7	5.6
Dynamic Behavior of Axially Functionally Graded Pipes Conveying Fluid [111]	40	44	5.5
Nonlinear vibration characteristics of shear deformable functionally graded curved panels with porosity including temperature effects [112]	43	64	5.5
Nonlinear dynamics analysis of pipe conveying fluid by Riccati absolute nodal coordinate transfer matrix method [113]	23	30	5.5
Flutter and Forced Response of a Cantilevered Pipe: The Influence of Internal Pressure and Nozzle Discharge [114]	29	0	5.5
Comprehensive investigation of vibration of sigmoid and power law FG nanobeams based on surface elasticity and modified couple stress theories [115]	24	81	5.3

Prior Works from Connected Papers

This study prioritises the most cited literature from the automatically generated Connected Papers database. Additionally, prior works are auto-generated too to identify the most relevant publications related to the study title. It is crucial, therefore, to note that Gupta and Talha [116] is a key and pioneering research for the generated literature in **Table 2**. These articles are frequently cited in the same way as in the graph of **Figure 2**, indicating that they are significant research contributions in this field. It would be beneficial for readers, however, to acquaint themselves with these works of literature for a better understanding. According to the Connected Papers guidelines, selecting Prior Work will highlight all papers that referenced the study. Perhaps selecting graph paper will further highlight all prioritised referenced work.

Table 2. Literature Prioritisation and Connection to the Study from Connected Papers.

Priority Research Title	Last Author	Year	Citations	Graph Citations
Recent development in modelling and analysis of functionally graded materials and structures [116]	M. Talha	2015	419	8
Vibration behaviours of functionally graded rectangular plates with porosities and moving in thermal environment [117]	J. W. Zu	2017	253	13
Electro-mechanical vibration analysis of functionally graded piezoelectric porous plates in the translation state [118]	Y. Wang	2018	207	10
Nonlinear steady-state responses of longitudinally traveling functionally graded material plates in contact with liquid [119]	J. W. Zu	2017	141	10
Vibrations of longitudinally traveling functionally graded material plates with porosities [120]	Y. Zhang	2017	120	9
Large-amplitude vibration of sigmoid functionally graded thin plates with porosities [121]	J. W. Zu	2017	79	9
Nonlinear vibrations of moving functionally graded plates containing porosities and contacting with liquid: internal resonance [122]	Zhengbao Yang	2017	67	8
Nonlinear dynamic thermoelastic response of rectangular FGM plates with longitudinal velocity [123]	J. W. Zu	2017	63	12
Porosity-dependent nonlinear forced vibration analysis of functionally graded piezoelectric smart material plates [124]	J. W. Zu	2017	57	10
Nonlinear Dynamics of a Translational FGM Plate with Strong Mode Interaction [125]	J. W. Zu	2017	48	13

3. Study Findings and Analyses

The findings from existing literature align with the study's main objectives. Data were mainly sourced from Scopus and Connected Papers, then systematically analysed using Excel. The resulting graphics and illustrations offered direct insights and enhanced the review. Supplemental literature searches further reinforced the analysis. These visualizations clarified the study's objectives. Using these tools strengthened the clarity and originality of the study's core concepts. A sub-section of Yao et al.[126] review examined an established FGM additive manufacturing method. The study primarily focused on general FGM structural optimisation in printing procedures. It did not report material property variation patterns relevant to the stability and performance of cylindrical pipelines. In the same vein, recent studies by Pasha and B.m[127], Yadav et al.[128] and Jin et al.[129] also focused on FGM general formulations and fabrications, which do not reflect this study's core objective, which is based on pipeline material structural gradation and index functions. In another study, Cao[130] analyses how buried FGM pipelines respond mechanically to strike-slip fault displacements, using classical beam theory and a first-yielding criterion to estimate yield fault displacement. However, Jing et al.[131] analysed fluid oscillatory motion in aviation fuel engine pipes using Euler-Bernoulli beam theory, identifying axial vibration instability during pulsating fuel flow in jet engines. This method effectively captures the dynamic response of slender pipeline structures under axial excitation and unsteady internal flow. Tuo et al.[132] also used same theory to evaluate pipeline vibration along the thickness direction, confirming its value for assessing deformation in pressurised conduit pipes. The previous works have not only validated the dearth of review studies on pipeline FGM structures but also revealed a lack of research in mechanically toughened and thermally resistant FGM optimisation. In contrast, the FE results in Section 4.3 reveal a distinct radial variation pattern for a static gas pipeline without internal fluid. This comparison underscores the differing vibration characteristics between dynamic systems with internal flow and static, fluid-free conditions. However, this study addresses this research gap by focusing on structural gradation patterns in pipelines and presenting distinct gradation functions as a proposition to enhance pipeline operational stability.

3.1. General View of FGMs Compared to Other Materials

The research study of Zhang et al.[133] investigated the variations of pure aluminium, pure ceramic, and FG aluminium-ceramic materials through a detailed convergence study to uncover thermal distributions across different materials. Remarkably, in the same study by Zhang et al.[133], the higher the mesh size, the higher the temperature across the whole model. However, at about seventy thousand element-meshed sizes and beyond, the temperature variation remained infinitesimally insignificant. Hence, a continuous FG variation pattern is practically possible. Structurally, various studies have conducted one or two experiments, numerically and analytically, by evaluating different carbon steel, composite, and FG material configurations[134–138]. **Table 3** establishes further satisfactory information regarding these three evolutionary material strength parameters. The recent structural review by Ebili et al.[139] comprehensively examined the capabilities and limitations of isotropic carbon steel pipeline materials used for transporting various natural gas products. However, the present study analyses existing articles on FGM structures as it focuses on the FG pipelines. **Table 3** gives a clearer pictorial view for comparing the mechanical strength of carbon steel with that of FGM. Furthermore, on the FGM core value, Sections 3.3 and 4 demonstrate the high strength of material based on the core grading pattern in FGM. Material grading is carried out based on structural application requirements and assigning material properties to achieve core and well graded regions for optimal performance. These analyses show a radial and axial grading functions of an intact pipeline under internal pressure condition. An FG material grading is basically determined by area of application. The schematics in Section 4.1 demonstrate how material variability patterns are addressed during structural project feasibility studies. This connection clarifies how the potential pipeline project feasibility study influences the choice of FGM pipeline gradation. In addition, a numerical investigation of a beam element with material numbers indicates an axial grading and distribution of material properties in FGM (see Section 4.3).

Table 3. Material Strength Along Evolutionary Trend.

Material Evolution → / Material Strength ↓	Isotropic Metal Material Overview					
	Austenitic Stainless Steel	**Ferritic Stainless Steel**	**Martensitic Stainless Steel**	**Duplex Steel**	**Composite Material**	**FG Material**
Corrosion Resistance	L	L/M	M	H	H	H
Temperature Strength	L/M	L/M	H	H	M/H	H/VH
Weldability	H	M	M	M	-	H
Material Toughness	H	L/M	M	H	M/H	H/VH
Deformability	L/M	L/M	L	L	L	L/VL
Ductility Strength	H	M	H/VH	M/H	L/M	H
Tensile Strength	M/H	M	H	H/VH	M/H	H
Elongation	H	L	H	H	L	H
Yield Strength	M	M	H/VH	H	M	H
Price Comparison	M	L	M/H	H	M/H	H/VH

According to **Table 3**, VH, M, and L represent Very High, Medium, and Low, respectively, which indicate the material strength evaluations. The backwards slash (/) signifies 'to' as used in the **Table 3** material overview. The mechanical strength of the FGM meets offshore and onshore environmental standards and requirements for structural applications. Perhaps the information in the table could be utilised as a benchmark tool for a future study. However, this is a general view regarding the under-listed material strength. The area of application determines the structural variation formulation for the FGM, as the material strength section may vary in **Table 3**. FGM is structurally feasible in many engineering and non-engineering applications across many industrial sectors. These sectors include energy pipelines, aerospace, military, and medical, shipping, building and construction, among others, for global technological improvement. Invention of Kevlar as a synthetic fibre is renowned and exceptional in its strength and lightweight (24). This material composition made it highly stronger than austenitic, ferritic, martensitic, and duplex Steel combined. Additionally, the evolution of Kevlar material into FGM could also solve the embrittlement problem in traditional hydrogen pipeline material due to its low temperature −260 °C to −325 °C[140]. Therefore, the information in here is relevant for all engineering and non-engineering construction purposes, depending on the type of structure and application environment.

The material strength characteristics of duplex stainless steel are very high, high, and medium across all parameters, with low deformability quality. Additionally, it is twice the design strength of the ferritic and austenitic combined. However, it is not comparable to FGM material strength and cost. With a suitable temperature for cryogenic environments, FGM can confidently demonstrate exceptional quality in structural operation. **Table 3** presents material progression trends that serve as the foundation for the generational evolutionary pattern shown in **Figure 4**, highlighting how these trends have influenced literature publications over the years. The arrows in **Figure 4** progressively indicate the distribution of the material evolution over the years, which referred to as traditional evolution[74,141]. The FGM in **Table 3** is virtually high to very high material strength across all listed material strength properties, with low deformation under extreme load conditions (90).

3.2. Graphical Illustration and Evaluation of Scopus Database Information

The Scopus database graphical illustrations reveal a satisfactory threshold of how effective systematic review appears under PRISMA innovative guidelines. Previous review literature publications on FGM have demonstrated this quality. The generated FGM publication results of the 2000–2025 yearly survey examined the general publication trend of FGM over the indicated number of years (see **Figure 5**). In 2024, the **Figure 5** graph recorded the highest number of publications with 153, before declining to 41 in 2025, with publications starting in 2000. However, the analysis of non-FGM presence in some of these databases complements the study's aim and objectives. The non-FGM literature, as recorded in this study, is associated with literature related to composite and metal materials that formed the building block of the study.

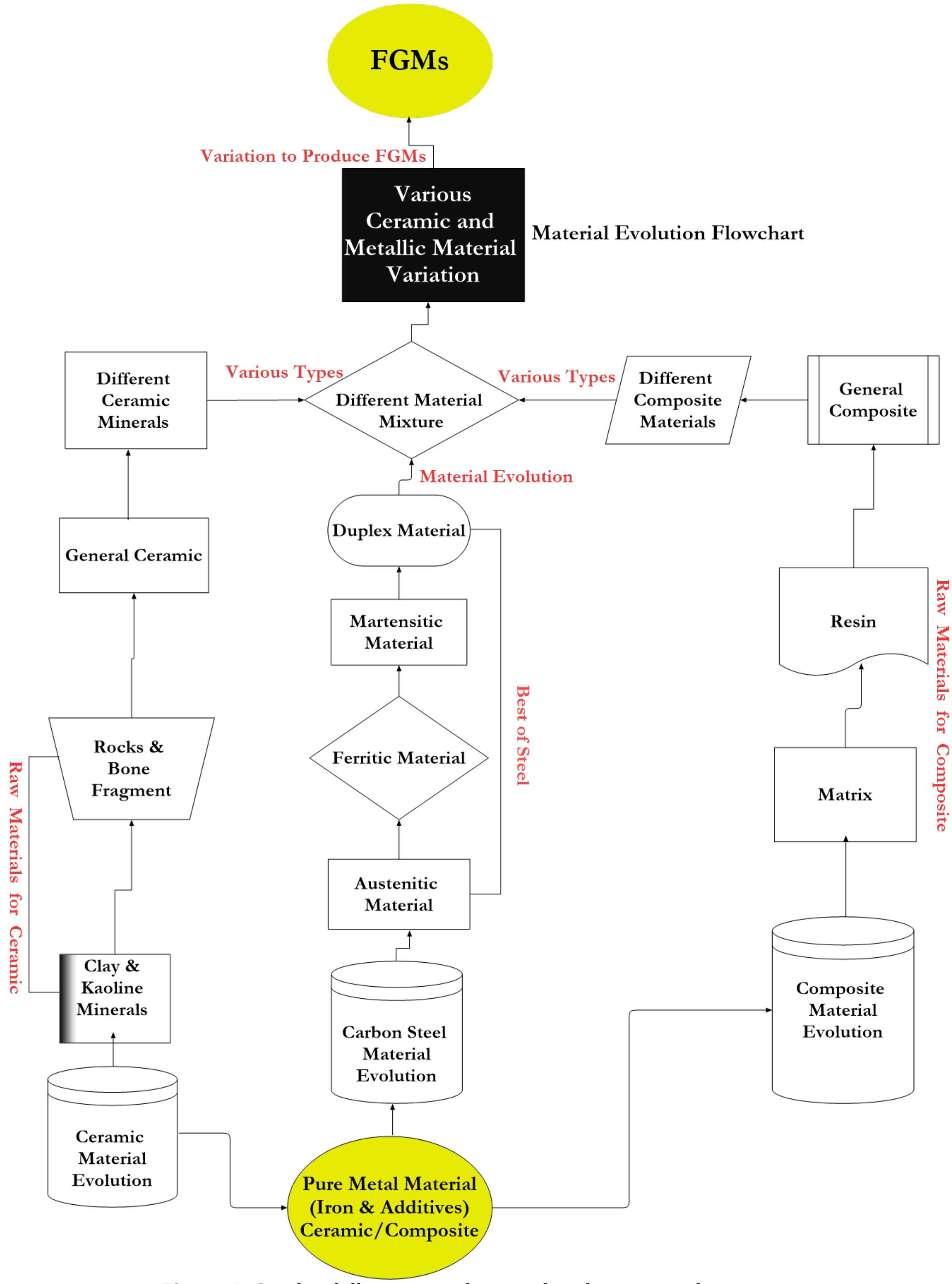

Figure 4. Graphical illustration of material evolution over the years.

The FGM unfiltered data literature survey and analysis in **Figure 5** illustrates FGM's progression by literature publication in general. The sigma phase trend between 2017 and 2024 dropped geometrically in 2025. The graphical analysis is further dependent on current data as 2025 does not have a complete data set to justify the 2025 trend. Hence, the available data predicted an increase between 2016 and 2025. Quantitatively, after further filtering the overall data retrieved by title, abstract, and keywords, the study identified less literature on FGM pipelines than expected. The complete graphical description of the number of publications on FG pipelines is given in **Figure 6**.

The sigma phase view of the graph in **Figure 6** clearly illustrates the rising and falling trend of structural publications related to the FG pipelines. As indicated in **Figure 6**, the literature on the constant phase has shown very little activity concerning FG pipeline research and publication over a span of more than two and a half decades. Interest began to pick up around 2007, reaching a peak by 2024, with about eleven related publications emerging in this field. Despite this notable increase in publications, there is yet no comprehensive review of the literature, ideally focusing on energy pipelines. In light of the observed gap in the literature, the review study created a structural framework and insights to address the identified gap.

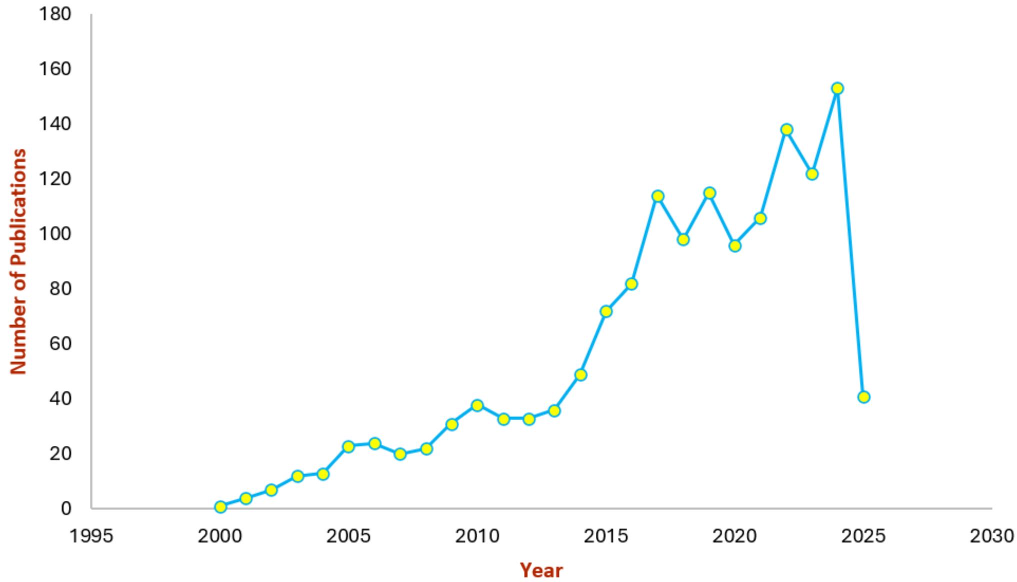

Figure 5. General FGM's Publication Yearly Survey.

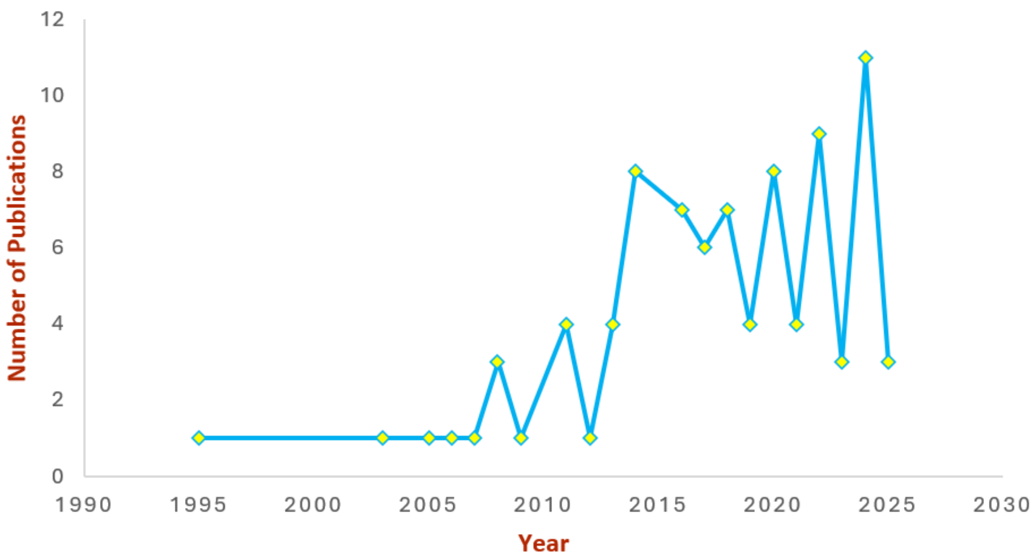

Figure 6. A graphical illustration of the FG pipeline literature trend with no review studies.

In a similar context, the pie chart in **Figure 7** offers a comprehensive analysis that aims to address the distribution of various subject areas of applications for FGMs. The study meticulously adopted a filtration method for the data extracted from Scopus. Notably, the nine distinct subject areas graphically plotted are to pinpoint the most prevalent applications of the FGM technology in general. The engineering sector possesses a higher percentage of FGM applications, with 49%. As depicted in **Figure 7**, the significant adoption and utilisation of FGMs in structures measure their application percentage level in each area. Following closely behind, material science emerges as another critical area of application based on production. This domain plays a crucial role in evaluating the strength and quality of materials before actual application, underlining its importance in ensuring the efficacy and reliability of FGMs.

Furthermore, the pie chart's legend provides a detailed overview of the various subject areas where FGMs are applied, acting as a valuable reference for understanding real-world applications. Notably, environmental science, chemical engineering, and chemistry are capped as the least engaged subject areas in the context of FGM use, each reporting a utilisation rate of less than 1%. This stark contrast emphasises the potential for growth and innovation within these fields concerning the implementation of FGMs.

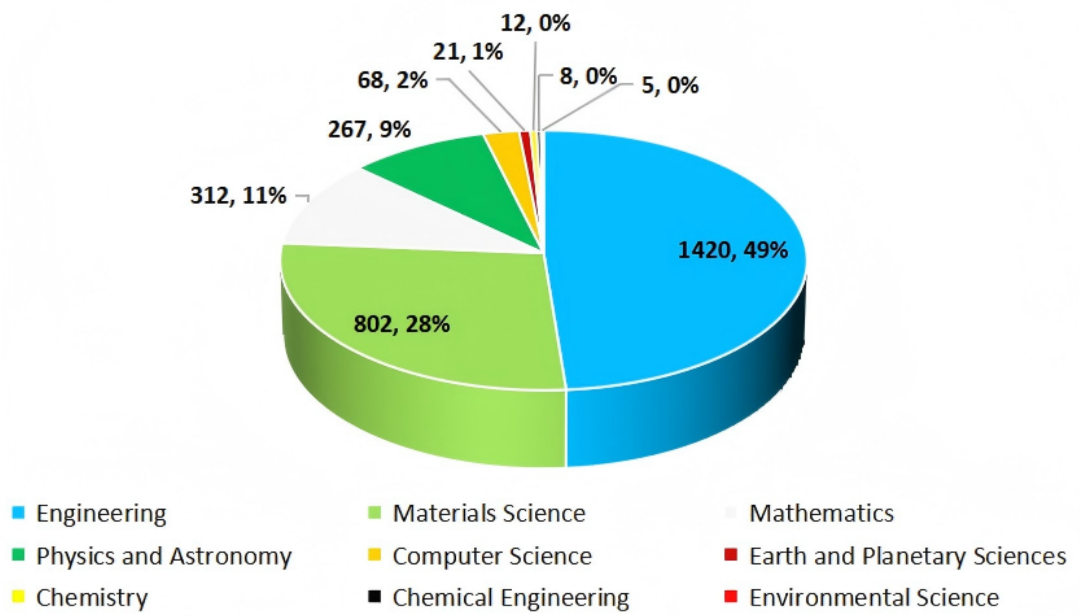

Figure 7. A pie-chart graphical illustration of closely related subject areas to the study.

The pie chart presented in **Figure 8** vividly showcases the varying proportions of different publication types within the fascinating realm of FGM research. This colourful representation reveals a landscape where three primary formats of research literature are employed to gauge the fame and impact of FGMs over recent decades. Notably, the literature review publications depicted in the pie chart barely make a mark in the FGM evolutionary trend, accounting for 1%. While the traditional article-type publication domain made an impressive 96%. Again, a significant gap is observed in this research direction, showing a scarcity of comprehensive reviews in FGM literature. In particular, it is striking that no review studies have addressed the FG pipeline for energy transport, underscoring a potential area for exploration and growth in this dynamic field.

In **Table 4**, the study showcases over 47 esteemed journals from the Scopus database that primarily focus on research related to FGM. **Figure 9** features a visually engaging TreeMap that categorises these potential journals for FGM and its related structural research. The rectangular blocks TreeMap compare citation scores while highlighting the significance of each journal's contributions. Moving towards the right direction across the block, TreeMap, the citation scores gradually decrease, with "Sustainable Materials and Technologies" recording the lowest score at 13.4. In contrast, "Nature Reviews Materials" achieves the highest citation score at an impressive 119.4, underscoring its crucial role in disseminating impactful FGM structural investigations and review literature. Principally, the study suggests Elsevier as the vanguard publisher of FGM articles, as demonstrated in **Table 4**, supported by robust data from the Scopus database. It is, therefore, paramount to note that Elsevier encompasses a broad range of journals, establishing itself as a significant platform in this field. The second most prominent platform for FGM publications is Springer Nature; however, based on the data, Elsevier emerges as the most reliable choice for comprehensive research on FGMs and related studies. Additionally, the affiliation of the Scopus database with Elsevier further reinforces its credibility. The exceptional citation performance highlighted in the Journal Source Comparison for FGM General Review Papers not only reflects the quality of the journals analysed but also serves as a compelling recommendation for researchers seeking authoritative sources in this evolving area of research.

The Scopus citation list column in **Table 4** provides valuable insights into previous literature publications, showcasing key developments in the FGM field. In this study, the structural articles are evaluated based on FGM publications across various journals over the years in an auto-generated timeframe. The SCImago Journal Rank (SJR) indicator serves as an effective tool for rating and positioning the impact of academic articles on society. By utilising these evaluation metrics, the study gained a clearer understanding of an article's quality within the Scopus database. The SJR serves as a benchmark for assessing scholarly journals, considering both the number of citations received and the academic research view from which these citations originate. This standard makes SCImago a recognised and reliable metric for evaluating research in the fields of science and technology. Progressively, the Source Normalised Impact per Paper (SNIP) complements the SJR by measuring citation impact at the article level. Together, these metrics, SJR and SNIP, are crucial for understanding the academic landscape, with SNIP providing insights into publication trends. Notably, the Nature Reviews Materials journal under Springer Nature recorded a high citation score, as reflected in **Table 4**. The highlighted cells in **Table 4** indicate the journals with the highest publication counts and citation percentages, aligning clearly with their respective column headers. The auto-generated **Table 4** for the pipeline FGM literature review is based on citation scores, which further confirm that Nature Reviews Materials is among the leading journals in this field. The highlighted journal literature scores' publishers are indicated in light coloured orange accent 2 type of font. This analysis not only supports ongoing research but also offers a solid foundation for future exploration in FGMs.

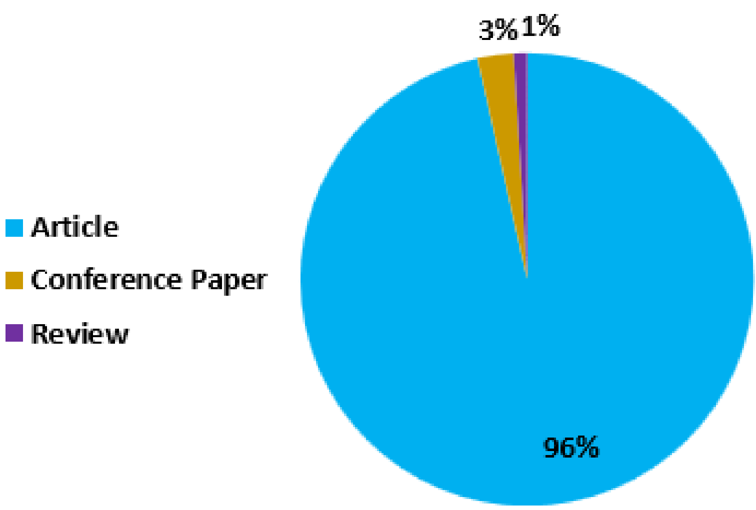

Figure 8. FGM percentage analysis according to the publication channel.

Table 4. Journal Source Comparison of General Review Papers on FGMs.

Journal Source	Cite Score	2020–2023 Citations	2020–2023 Documents	% Cited	SNIP	SJR	Publisher
Nature Reviews Materials	**119.4**	30099	252	79	**12.106**	**21.836**	Springer Nature
Materials Science and Engineering R: Reports	60.5	6111	101	95	6.823	6.822	Elsevier
Nature Nanotechnology	59.7	37891	635	94	6.292	14.577	Springer Nature
Progress in Materials Science	59.6	19738	331	94	8.581	7.796	Elsevier
Progress in Energy and Combustion Science	59.3	7536	127	98	7.566	6.114	Elsevier
Proceedings of the IEEE	46.4	16286	351	93	6.982	6.085	IEEE
Advanced Materials	43	**302064**	7025	93	3.856	9.191	John Wiley & Sons
Advanced Energy Materials	41.9	130903	3126	92	3.289	8.748	John Wiley & Sons
Military Medical Research	38.4	8251	215	90	3.384	2.745	Springer Nature
Materials Today	36.3	23435	645	90	3.257	5.949	Elsevier
Renewable and Sustainable Energy Reviews	31.2	112715	3612	93	3.592	3.596	Elsevier
Advanced Functional Materials	29.5	267474	9056	92	2.516	5.496	John Wiley & Sons
International Materials Reviews	28.5	2680	94	95	5.12	3.233	SAGE
Applied Mechanics Reviews	28.2	1127	40	**100**	5.078	2.908	American Society of Mechanical Engineers
Advanced Industrial and Engineering Polymer Research	26.3	2659	101	93	3.746	2.234	KeAi Communications Co.
Advanced Composites and Hybrid Materials	26	16922	652	85	2.566	3.623	Springer Nature
Polymer Reviews	24.8	2258	91	98	2.861	2.529	Taylor & Francis
Composites Part B: Engineering	24.4	65504	2689	93	2.599	2.802	Elsevier
Critical Reviews in Solid State and Materials Sciences	22.1	1898	86	93	2.863	1.959	Taylor & Francis
Journal of Advanced Research	21.6	13737	635	97	2.258	1.905	Elsevier
Journal of Advanced Ceramics	21	10099	482	87	3.369	3.457	Tsinghua University Press
Progress in Aerospace Sciences	20.2	2625	130	92	5.505	2.57	Elsevier
Journal of Magnesium and Alloys	20.2	16036	793	91	2.972	2.93	KeAi Communications Co.
Journal of Materials Science and Technology	20	62611	3125	96	2.168	2.309	Chinese Society of Metals
Additive Manufacturing	19.8	50844	2574	90	2.399	2.837	Elsevier
Materials Horizons	18.9	24615	1301	79	1.854	3.376	Royal Society of Chemistry
Advanced Fiber Materials	18.7	5354	286	92	2.23	3.398	Springer Nature
Nano Materials Science	17.8	2374	133	98	1.779	1.721	KeAi Communications Co.
Accounts of Materials Research	17.7	5384	304	88	1.914	4.403	American Chemical Society
Energy and Environmental Materials	17.6	7921	449	96	1.67	3.493	John Wiley & Sons
Composites Science and Technology	16.2	30743	1900	90	1.699	1.8	Elsevier
NPJ Computational Materials	15.3	13198	863	88	2.017	2.447	Springer Nature
Applied Materials Today	14.9	21796	1465	88	1.249	1.623	Elsevier
NPJ 2D Materials and Applications	14.5	4314	297	87	2.077	2.46	Springer Nature
ES Materials and Manufacturing	14.4	2178	151	80	0.914	0.583	Engineered Science Publisher
Materials and Design	14.3	59186	4127	87	1.918	1.684	Elsevier
Journal of Materiomics	14.3	6770	474	89	1.498	1.654	Chinese Ceramic Society
Materials Today Advances	14.3	5337	373	83	1.58	1.826	Elsevier
Sustainable Structures	14.2	454	32	84	5.115	1.93	Sustainable Development Press Limited

Table 4. *Cont.*

Journal Source	Cite Score	2020–2023 Citations	2020–2023 Documents	% Cited	SNIP	SJR	Publisher
Materials Today Physics	14	13345	953	84	1.633	2.304	Elsevier
Energy Material Advances	13.8	1395	101	83	1.69	3.563	American Association for the Advancement of Science
Construction and Building Materials	13.8	211152	**15336**	87	2.11	1.999	Elsevier
Corrosion Science	13.6	39078	2868	89	2.054	1.897	Elsevier
IEEE Open Journal of Industry Applications	13.5	1401	104	78	2.604	2.805	IEEE
International Journal of Hydrogen Energy	13.5	163206	12093	91	1.38	1.513	Elsevier
Journal of Computational and Cognitive Engineering	13.5	890	66	89	N/A	N/A	Bon View Publishing Pte Ltd.
Sustainable Materials and Technologies	13.4	8464	632	80	1.693	1.681	Elsevier

Note: the table provides a review of FGM journal papers, documenting each cited paper alongside its corresponding journal. Highlighted cells and distinct journal font styles facilitate the identification of journals with a higher number of cited articles. This visual representation serves as a criterion for ranking journal sources. The meaning of the cells highlighted and font colours is explained in detail below **Figure 9**.

Figure 9. FGM percentage analysis according to the publication channel.

Figure 10 is a comparison of 22 academic journal sources, using an Area Graphic *plot* based on FGM publication database levels established through literature sourcing and organisation. Filtration by language, subject area, and publication type was applied to streamline the literature to the language choice and required subject area. The Composite Structures Journal holds the highest number of publications, 247, and the number of publications per journal decreases as it approaches the Structures Journal.

3.3. FGM Forms and Production Processes

The selection of materials and design specifications for commercial energy transport is mandatory for ensuring safe energy transport and achieving net-zero carbon emissions. Combining two or more materials with different properties can enhance this goal by leveraging their high mechanical, physical, and chemical characteristics to reinforce a desired material's structural strength. To gain a better understanding of various parametric studies and analyses from the existing literature, the study utilised a systematic review framework. The auto-retrieved data from journal publications in the Scopus database, as shown in **Figure 1**, compares trends and key issues related to FGMs and other related review papers. The graphical illustration in **Figure 11** depicts the generic production processes of FGMs based on research investigations [34,142,143]. It is noteworthy that the number of FGM literature present in the compared publication journals concerning pipelines is far lower than expected (**Table 1**, **Figure 10**).

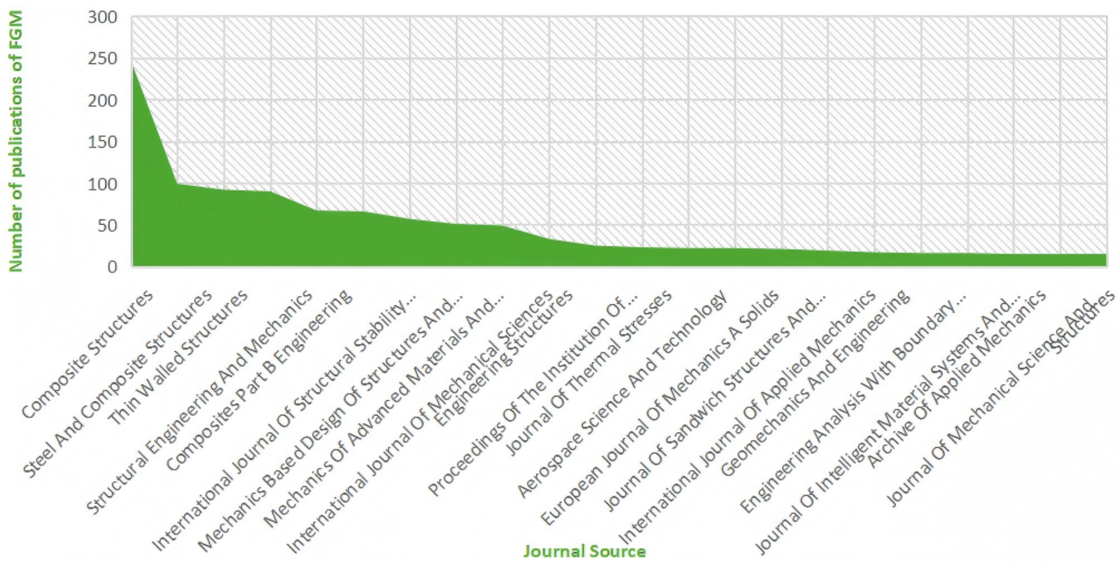

Figure 10. Data area graphical solution for journal publication comparisons on FGMs.

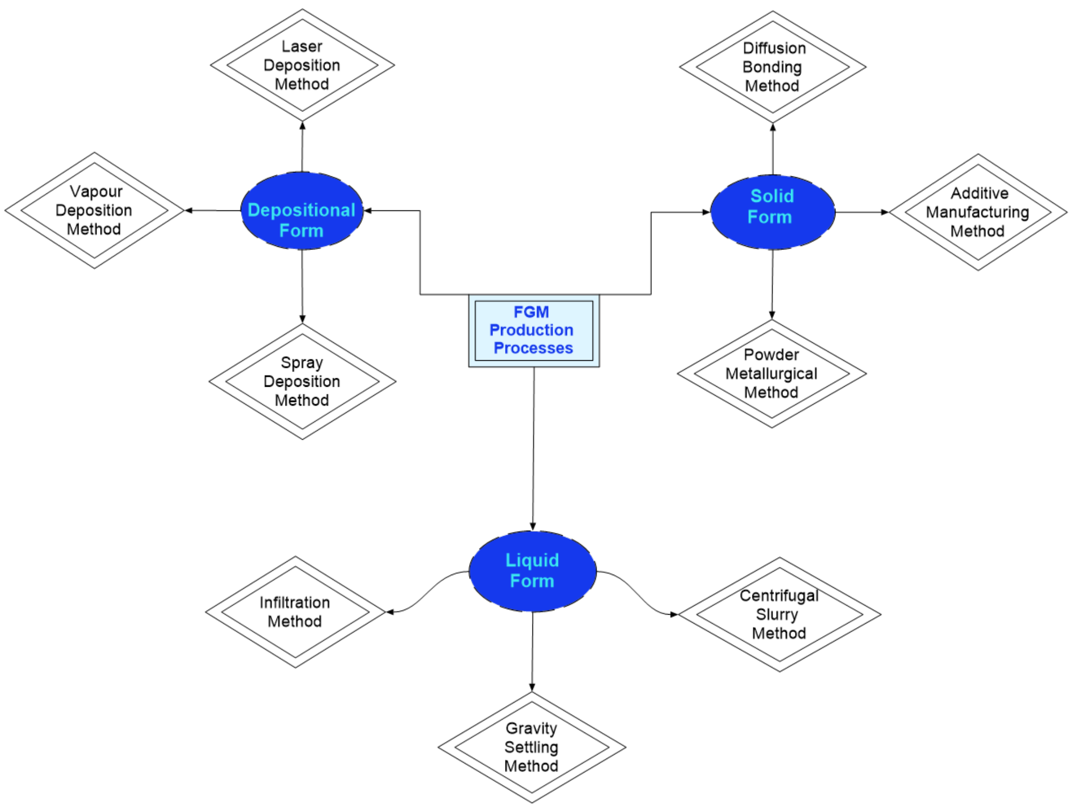

Figure 11. A tree diagram of the FGM production process.

Some parts of the FGM production process, as shown in **Figure 11**, are described in the research on FGM 3D additive printing technologies cited in sources [34,142]. **Figure 12** illustrates possible FG structural geometric models and formulations, while **Figure 11** presents the tree diagram of the available FGM production methods.

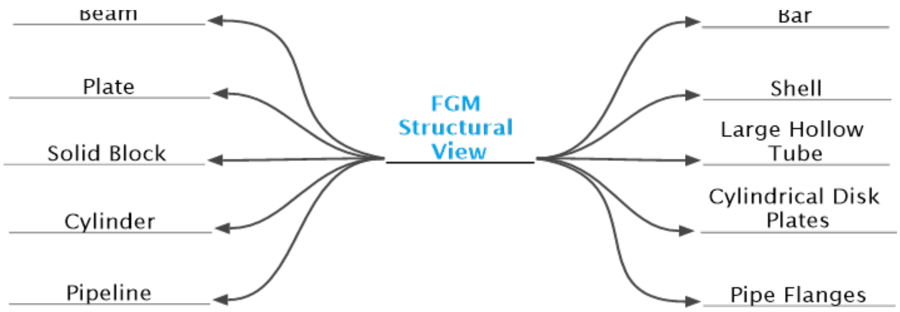

Figure 12. Preview schematic of FG-structures reviewed.

4. FG Structural Material Graphics

The morphology of FGM, however, is a critical aspect of this study. FGM structures are considered for greater understanding and incorporated into this study to provide readers with an FGM structural perspective. They reveal how different models vary through their microstructural properties, thereby enhancing their structural and operational capacity. The study, however, focused on the FG pipeline structure but never neglected other FG structural formulation geometries and variation patterns, as depicted in **Figure 12**.

4.1. Schematic Views of FGM Structural Geometry

The variation involved in FGM through the microstructural property of a material geometry creates the expected strength and reinforcement. That, however, depicts the continuous or discontinuous grading pattern that occurs in material models. Such a variation pattern is known as a gradient (continuous) type of FGM if the material property variation runs smoothly across a model. Conversely, a discontinuous or stepwise type of FGM formulation possesses a conspicuously defined interface. Interestingly, Young's modulus and Poisson's ratio are the material model properties proposed for these variations. However, they often vary to determine the nature and strength of the material. Another significant parameter is the material volume fraction index (n), which is a key parameter that determines the level of variation. Note that in the FGM formulation, different application areas can adapt different gradation patterns. This expression is a recommended practice for structural and material engineers. An overview of the 3D discontinuous (stepwise) beam element and pipelines along the lateral direction and gradient (continuous) along the longitudinal direction is overwhelmingly expressed in Section 4.1. In another vein, two different material gradients can be expressed at the top and bottom of a single model with two different material properties based on gradation. However, the reverse is the case, where the highest point of micro-material distribution of the two-grading material records the highest material property at the midpoint. For example, a 50% centroid mark of two material contributions is often established based on the average material variation point.

Figure 13 shows a simplified schematic variation of Young's modulus-to-thickness ratio with index volume fraction *n,* which justifies the rate of material microstructure distribution. However, most scientific literature publications depict their volume fraction index with the n or N symbol. In this study, *n is* the volume fraction index, which is a material exponent. **Figure 13** is a Power Law expression for material property variation in FGM models. It is the most analysed law among the three FGM-formulated laws to express material property variation for different FGM structures. The other two variations considered in this study are the Exponential and Sigmoid Laws. Similarly, the Vasavi et al. [144] review study analyses FGM laws and critically examines the most widely validated analytical models proposed by previous researchers.

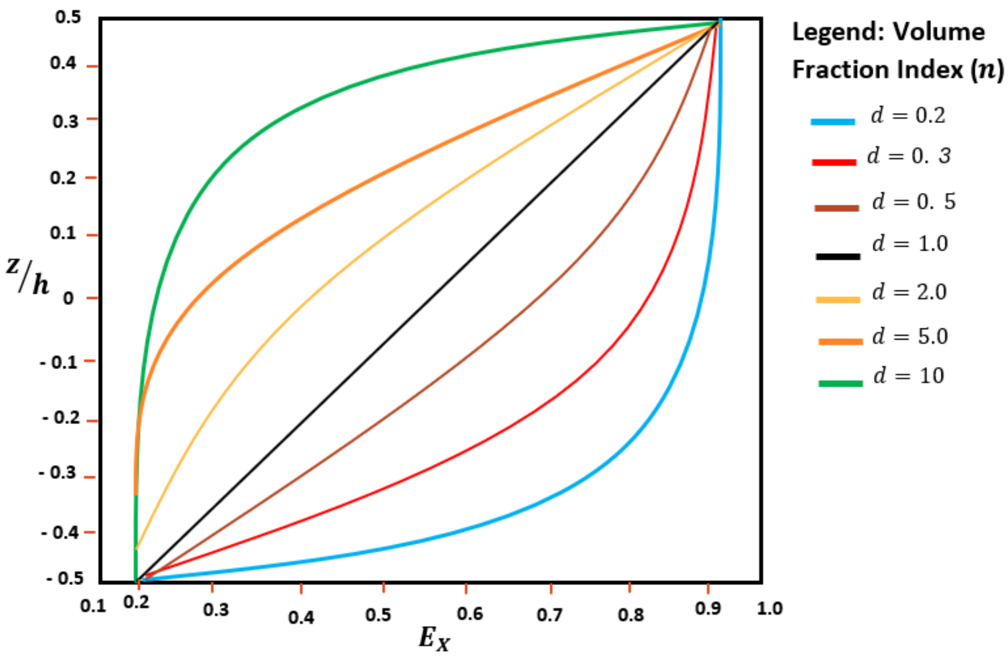

Figure 13. Schematic of the ratio of Young's modulus to material thickness variation.

The Power Law is used to express how Young's modulus varies with material thickness. Analytically, the Power Law calculates the variation of the volume fraction index as it varies with each material property gradation. **Figure 13** demonstrates the Power Law regarding the variation of material volume fraction and can grade in any direction. However, Equation (1) provides a formulation for grading specifically in the z-direction.

$$P(z) = (P_m - P_c)\left(\frac{2z+h}{2\text{h}}\right)^n + P_C \quad (1)$$

By simplification:

$$P(z) = (P_m - P_c)\left(\frac{z}{\text{h}} + \frac{1}{2}\right)^n + P_C \quad (2)$$

Mori-Tanaka used the fraction index to demonstrate the variation of material in the FG model analysis [145], where is the material property grading along the thickness direction, is the material property of metal, is the material property of ceramic, and is the thickness of the material. However, analysis of FG thick-layered materials is more effectively conducted by examining the thickness in both the upper and lower directions of the model.

$$V_1 + V_2 = 1 \quad (3)$$

Be it a continuous or stepwise gradation pattern, the material model's parameter *n* remains the active determinant factor that controls the micromaterial property variation to achieve the engineering choice of design purposes. Such material property variation progressively and collectively adds up, as expressed in Equation (3), to achieve a gradient pattern.

Therefore,

$$V_2 = 1 - V_1 \quad (4)$$

If

$$\&V_c = V_2 \quad (5)$$

where is the volume of material number 1, while is the volume of material number 2.

Therefore, two different materials are involved in this formulation.

Hence,

$$V_1 = \left(\frac{z}{\text{h}} + \frac{1}{2}\right)^n \quad (6)$$

Substituting Equation (6) into (4)

$$V_2 = 1 - \left(\frac{z}{\text{h}} + \frac{1}{2}\right)^n \quad (7)$$

However, the FG material variation of a thick plate geometry can be illustrated based on the thickness direction as follows:

$$V_m \text{ or } V_c = \left(\frac{2z+h}{2h}\right)^n \text{ w.r.t} - \frac{h}{2} \le z \le \frac{h}{2} \quad (8)$$

Several pieces of literature have shown that FGMs are practically designed by varying two or more materials with completely different material properties through mathematical variation functions [45,88,97,146–148]. Following the above principle of FGM formulation, the material volume fraction index remains within the range of (**Figure 13**). Note that if the volume fraction is grading along the thickness direction, for example, a 3D thick plate analysis, the mathematical formulation can be expressed with Equation (8) that further elaborates the plate thickness variation which is equal to $\frac{h}{2}$ and for the top-down FGM geometry cases, respectively. Thus, thickness represents the resolution of the height in positive and negative values reflecting the material geometry in the 3D formulation. However, the symbol V_m denote the volume fraction index function of metal, while the is the volume fraction index function of ceramic.

Exponential Law: The FGM law expressed here is an exponential increase function of Young's modulus, shown by the **Figures 14** and **15** schematics. In this instance, the reverse is the case for the Power Law. The material property gradient calibration is along the material thickness (height or vertical) direction of the model.

$$E(x) = E_0 e^{\beta x} \tag{9}$$

Figure 14 schematically presents the distribution of material property (Young's modulus) formulation along the longitudinal direction for any model in question. Equation (8) confirms the variation along the x-direction.

$$E(z) = E_0 e^{\beta z} \tag{10}$$

The exponential function in **Figure 15** illustrates the variation of material properties along the thickness direction.

Sigmoidal Law expression of FGM: This FGM formulation function conveys succinct details of the Power Law volume fractions combination. According to Ji et al.[74], Walters et al.[149], and Cho et al.[150], the FGM product of the two symmetric layers of the Power Law variation function combination can withstand high stresses and combat material temperature differentiation.

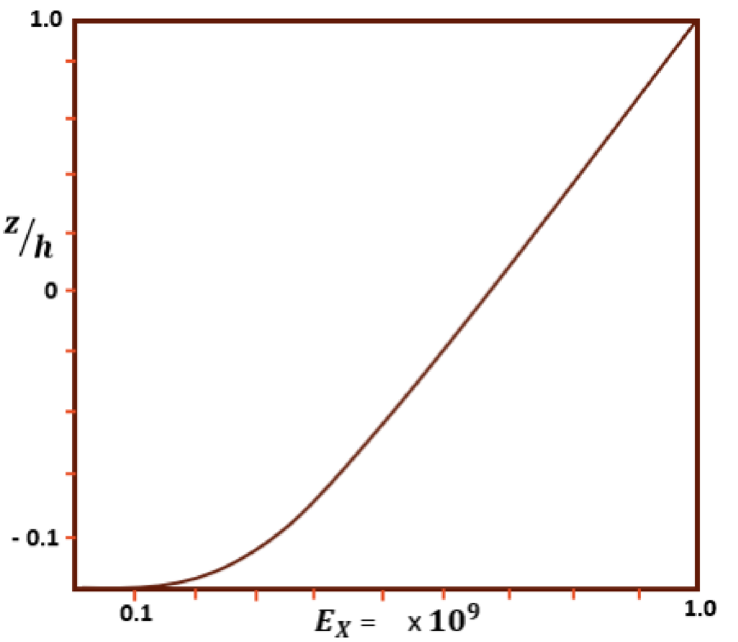

Figure 14. Exponential Law of FGM formulation varying in the x-direction.

Figure 16 presents a schematic representation of a Sigmoidal Law, where E_x, denotes the horizontal axis (longitudinal) direction and $\frac{z}{h}$ indicates the vertical axis (material thickness). The gradation of Young's modulus across the material thickness is characterized by the volume fraction index (d), as illustrated in **Figure 16.** Equation (1) represents a valid gradation of material properties in the thickness direction w.r.t the height of the material model. The thickness in both the negative and positive averages of the model height shown in **Figure 17** indicates the bottom-up gradation value, respectively. This expression clearly shows coarse materials dominating the bottom part and finer materials at the top surface. The material's volume fraction index determines the variation in material properties, while denotes the volume fraction of the material model type, as formulated in Equations (6) and (7). This variation can occur in one or multiple directions across 1D, 2D, or 3D geometries.

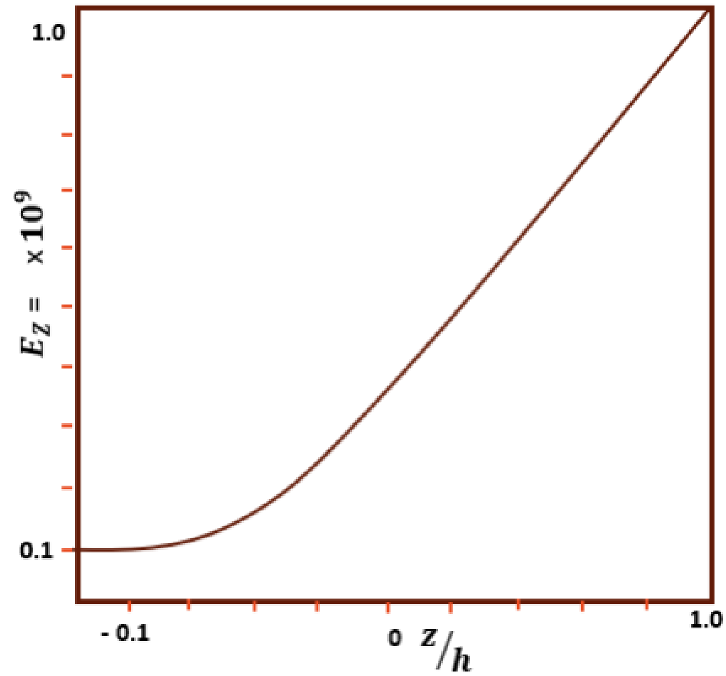

Figure 15. Exponential Law of FGM formulation varying in the z-direction.

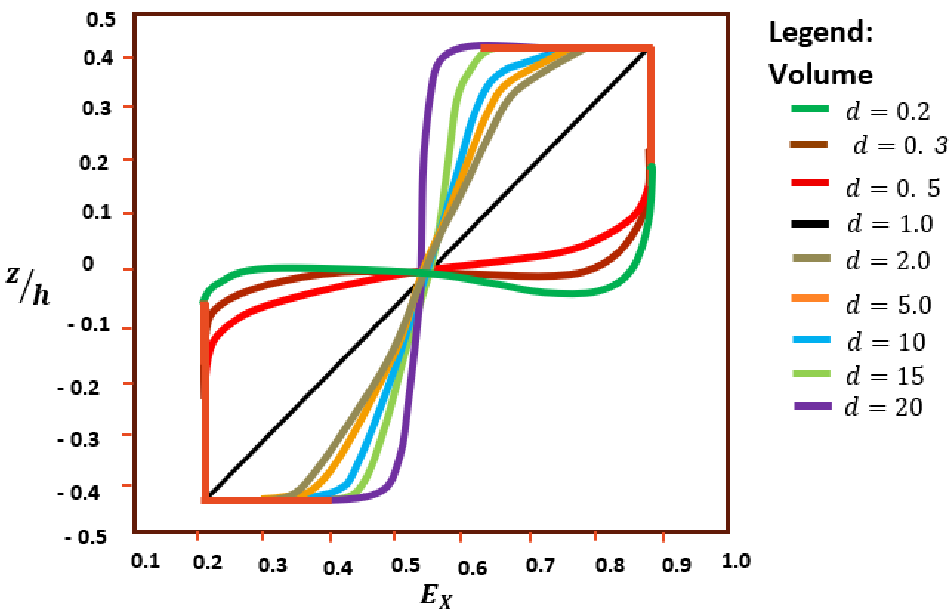

Figure 16. Schematic expression of the Sigmoidal Law of FGM with 2D variations.

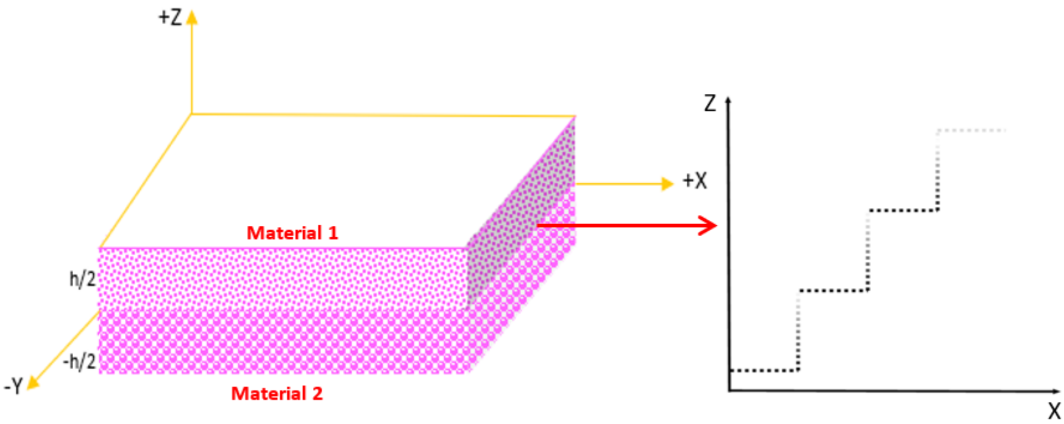

Figure 17. Schematic showing stepwise bi-material Power Law gradation function.

$$V_{1(z)} = 1 - (0.5)\left(\frac{\frac{h}{2} - z}{\frac{h}{2}}\right)^n \; 0 \leq z \leq \frac{h}{2} \quad (11)$$

$$V_{2(z)} = 1 - (0.5)\left(\frac{\frac{h}{2} - z}{\frac{h}{2}}\right)^n \; -\frac{h}{2} \leq z \leq 0 \quad (12)$$

$$P_{(z)} = P_m V_1(z) + P_m\left[1 - V_{(1)}(z)\right] \;\; 0 \leq z \leq \frac{h}{2} \quad (13)$$

Equations (11) and (12) analytically present the volume fraction formulation from the Power Law volume fraction combination. Chi and Chung[151] combined two material model layers involved in the Power Law material property distribution to achieve the Sigmoid Law. The and describe the top-down variation function in FGM.

The variation pattern presented in **Figure 17** is a practical expression of Power Law implemented equations. From Equation (5), the effective volume fraction in **Figure 17** possesses different materials at the top and bottom of the model. These materials represent material phases 1 and 2. Therefore, the equation for material variation is expressed as follows:

$$E_{eff} = E_t * V_{m(1)} + E_b * V_{m(2)} \quad (14)$$

where is the effective material property of materials 1 and 2 combinations, and E_t, remains the material property (Young's modulus) of the top and bottom material. While and represent the volume fraction of material 1 and 2, respectively.

The stepwise or discontinuous distribution of material properties in **Figure 18** supports the analysis in **Figure 17** which is a thick plate model. The gradient starts a few increments from the origin and moves vertically along the thickness direction. This pattern shows the same averaging edge nodal load pattern in FEA. Such a distribution can be represented numerically during FGM simulation in FEA.

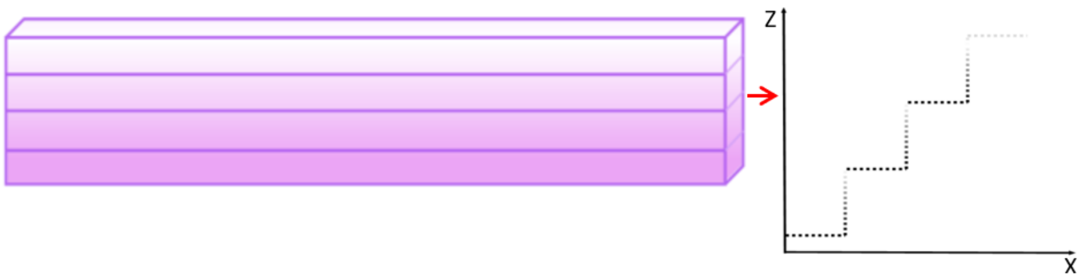

Figure 18. Stepwise gradation in the thickness (transverse) direction.

Figure 18 is also governed by Equation (8), which applies to the **Figure 17** schematic of stepwise operation. **Figures 18** and **19** clearly depict structural models to validate the first paragraph of Section 4.1, as the material properties vary across the lateral and axial directions. Another version of the material property variation using volume fraction index is the continuous pattern of material distribution across the selected model direction, see **Figure 19**.

Figure 19 illustrates the composition of material microstructure and porosity behaviour under a continuum variation. The uniformly and continuously material property gradation along the axial direction in the 3D beam element geometry is an example of a volume fraction index function. The primary objective of FGM models in this study is to provide a geometric demonstration of potential functions and mathematical formulations previously discussed in the referenced literature. Additionally, this study introduces innovative functions, such as **Figures 20** and **21** to describe the innovative functions FGM and further develop the new modelling framework. **Figures 20** and **21** illustrate the primary innovation of this study by presenting highly reinforced FGM functions controlled by the volume fraction index (n).

Figure 19. Continuous gradation of material property across the longitudinal direction.

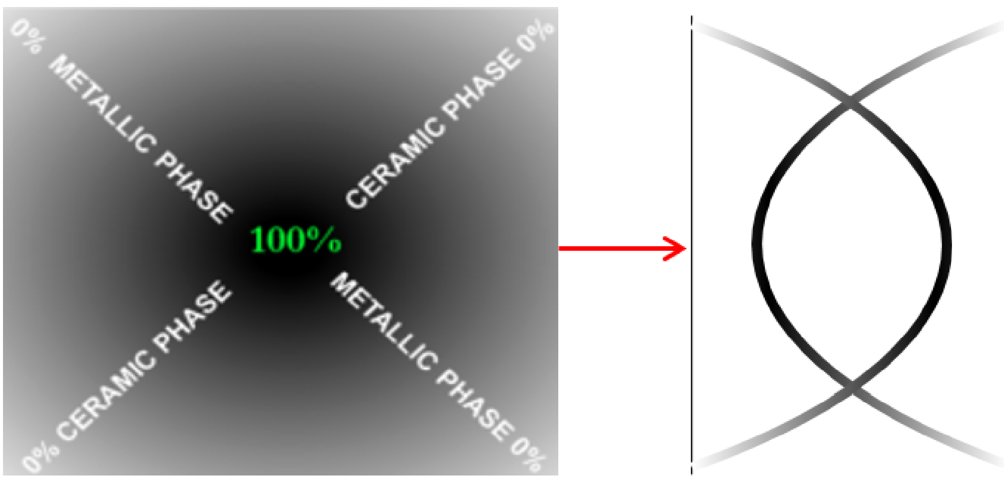

Figure 20. 2D schematic of continuous variation with two materials converging at the centre.

Note that, n quantifies the distribution of material properties during grading, facilitating the formation of a well-blended model when combining different materials. A 100% gradation of material properties at the middle indicates complete internal reinforcement of the constituent materials in the FGM formulation process, as shown in **Figure 20**. This FGM function is designed to be unique and to provide enhanced toughness for applications involving significant thermal gradients, such as hot gas pipeline transport. In contrast, **Figure 21** depicts external and mechanical reinforcement through the grading of material properties between two or more parent materials. In this case, the variation pattern preserves the parent materials at the model's edges, with little or no evidence of material mixing. This is represented as 0% contribution from each material at the edges, maintaining 100% of the parent material in the volume fraction index function, as shown in **Figure 21**. However, **Figure 20** schematic gives a contrary expression to **Figure 21**, as the gradient is 100% of the two materials at the centre and varies less towards the corners. The two materials have a 0% gradient at the edges. Although **Figures 20** and **21** present 2D models, this function can also be applied in one-dimensional (1D) and 3D models.

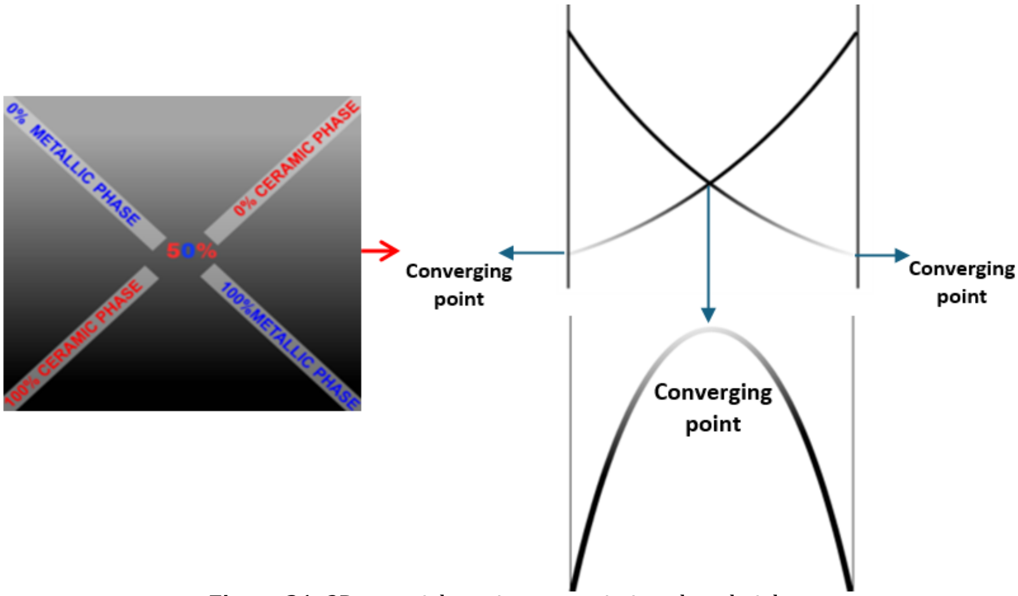

Figure 21. 2D material continuous variation along height.

4.2. Schematic Examples of FG Patterns in Pipeline

Numerous researchers have investigated either intact or damaged pipeline geometries to assess the performance capabilities of FGMs under varying loading conditions. Included but not limited to harsh environmental conditions, internal pressure, stress, thermal and free-loading BCs. Focusing on this exploration is the strategic integration of both continuous and discontinuous material variations. This process has solidified an FGM's research base for a variety of experimental, analytical, numerical, and mathematical formulations that enable the adjustment of material properties throughout a pipeline geometry. These variations are typically visible in three primary directions: axial, radial, and circumferential. Each direction allows customised modifications to enhance specific performance criteria that reinforce the model. However, its performance also encourages high mechanical strength to mitigate complex loading conditions encountered in real-life applications. To illustrate this concept, **Figure 22** depicts a detailed transition in the radial direction grading of the pipeline model. It highlights the variations in material composition and microstructural distribution with transition from the inner surface to the outer surface of the pipe wall. This gradation is essential for optimising the durability and functionality of the pipeline under operational stresses. For each pipeline geometry featured in this section, variations often involve two materials with different compositions and characteristics, except for **Figure 22**, with a single material grading pattern. This single grading, however, is tagged as uniformly a mono-grading phase of a solo material.

Despite the significance of this research area, there is still a dearth of publications that have not effectively reviewed FGM pipelines for energy transport. Furthermore, computational methods in the pipeline context underscore a gap in the current understanding and potential for future exploration in this domain.

Akshaya et al.[152] confirmed in their review study that FGM followed a progression trajectory for its evolutionary trend from conventional material. **Figure 22** is however regarded as a mono FGM which portrays an advanced composite material.

The quarter symmetry section in **Figure 23** shows the continuous variation of the pipeline model's material property in the radial direction. **Figure 24** illustrates a contrasting gradation pattern, characterized by continuous variation in the pipeline thickness axis, which represents material property changes along the longitudinal section of the pipeline (axial gradation). The schematic illustrates a pipeline section with a radially grading pattern outward to withstand internal pressure from gas energy or other green liquid or gas energy during transport operations (**Figure 23**). In this context, R denotes the inside and outside radii combined, which together define the total thickness of the pipe, while z represents the total length of the pipeline section. This in a way gives an interpretation of porosity, grain size distribution, and interaction within the pipeline structural model.

Mathematically,

$$R = r_i + r_o \tag{15}$$

where is the inside radius, is the outside radius, and is the two radii combined.

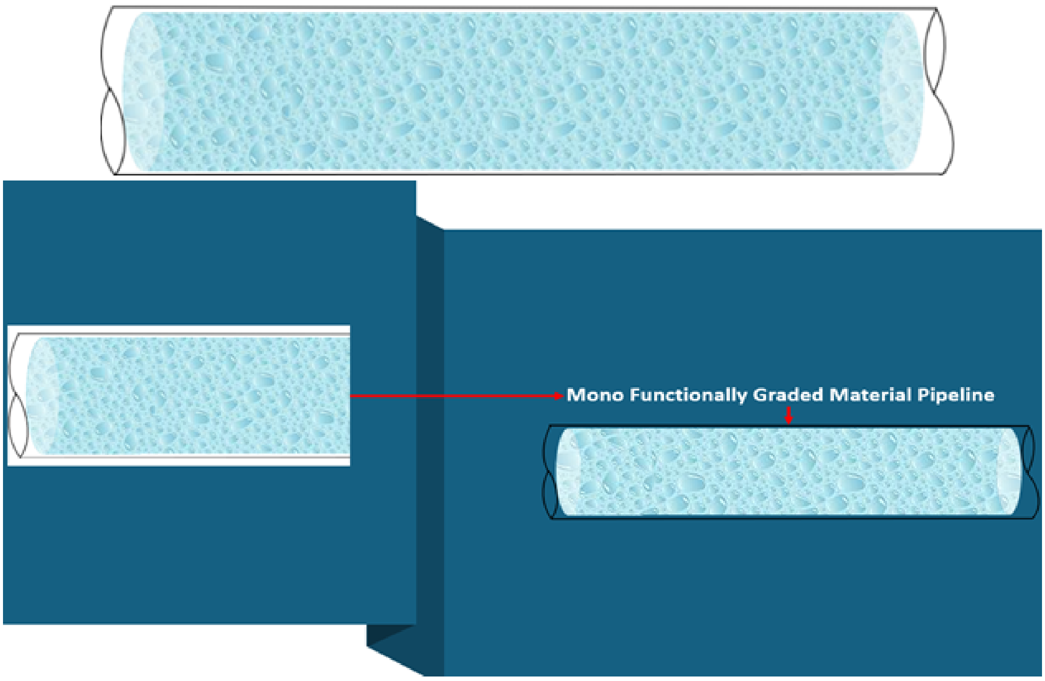

Figure 22. A mono-graded offshore pipeline (single material phase).

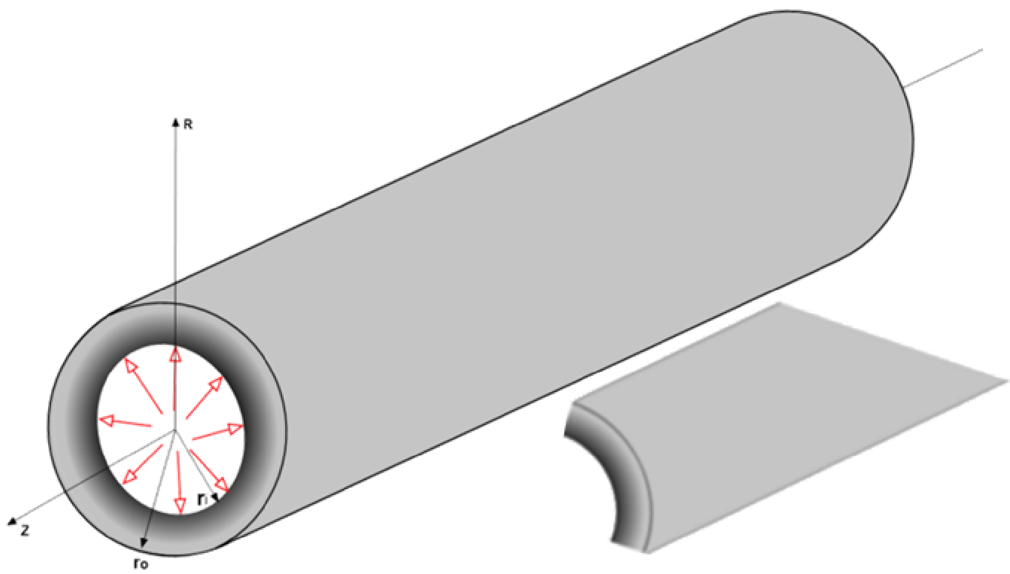

Figure 23. Radial grading pattern in an intact pipeline.

Asymmetry operation is a fundamental standard in industrial pipeline operations. This SOP is maintained to adhere to industry-established standards, such as those from the American Society of Mechanical Engineers (ASME) and the American Petroleum Institute (API). It provides detailed requirements and authoritative guidance for most industrial pipeline operations. This guided SOP is influenced by four main parameters: internal pressure, radial angle function, material thickness of the pipeline, and axial behaviour of the pipeline. The ASME and API are globally accepted standards; however, other countries' standards, such as British Standard 1710 (BS), Canadian Standards Association (CSA), Det Norske Veritas (DNV), and others. Notably, countries respect each other's standardisation guidelines to protect and prevent pipeline operation legacy.

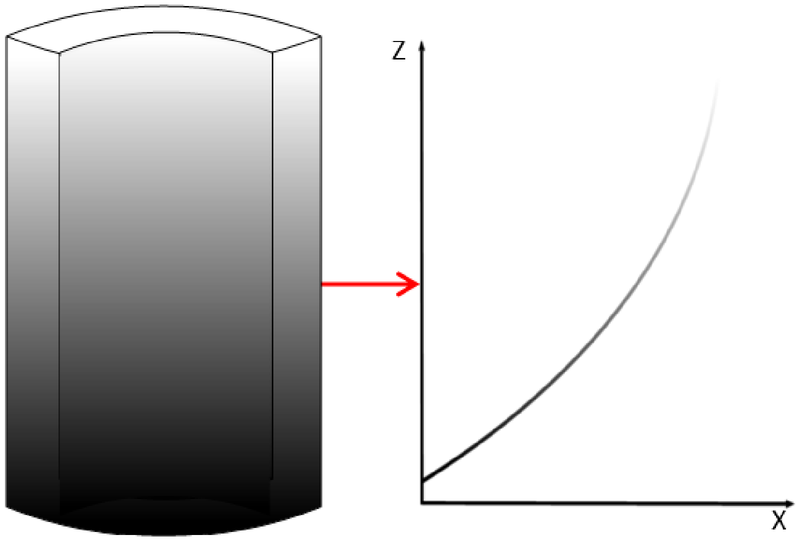

Figure 24. Schematic of a quarter symmetry section of an intact pipeline grading in the axial direction.

Figure 25 provides a detailed representation of how material properties vary along the axial direction of the pipeline. This variation displays a smooth continuous grading pattern that characterises the FGM type used in the construction of the pipe. The graphical depiction clearly illustrates how different regions of this model exhibit distinct material characteristics. The shown gradient colour fades down the pipe and depicts different material properties (**Figure 25**). Furthermore, the axial direction of the pipe corresponds directly with its longitudinal direction, restating the significance of understanding the material distribution and its implications for the overall operation of the pipeline.

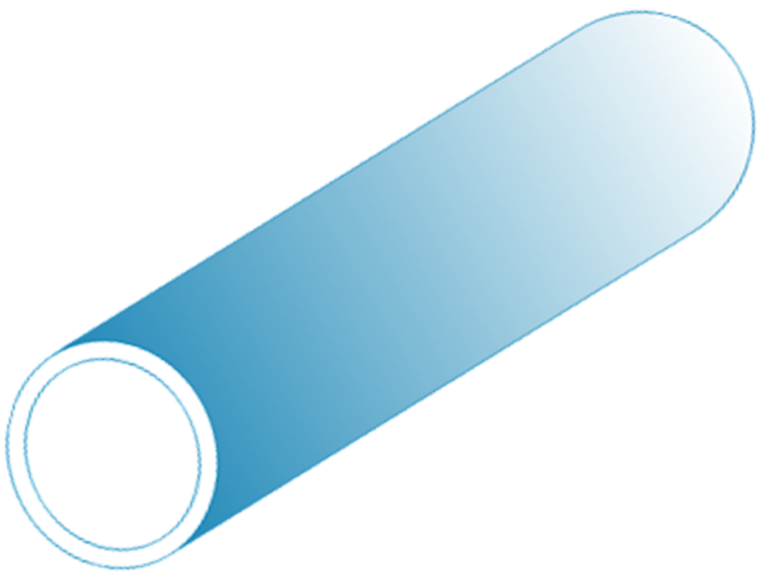

Figure 25. A whole section of cylindrical pipe continuously graded in the axial direction.

A transition zone in the grading formulation of FG pipeline material or other structures indicates non-uniformity of material property variation across geometry. **Figure 26** clearly illustrates this concept with two materials, Material A and Material B, separated by a mid-point transition zone. This formation is known as a circumferential or radial grading in a pipeline. The grading is non-uniform, resulting in a discontinuity in the material properties with an infinitesimal interface. Such a grading allows the material to withstand high circumferential (hoop) stresses. However, the introduction of FGM is to address the sharp interface challenge in composite materials design, whether the grading is continuous or discontinuous.

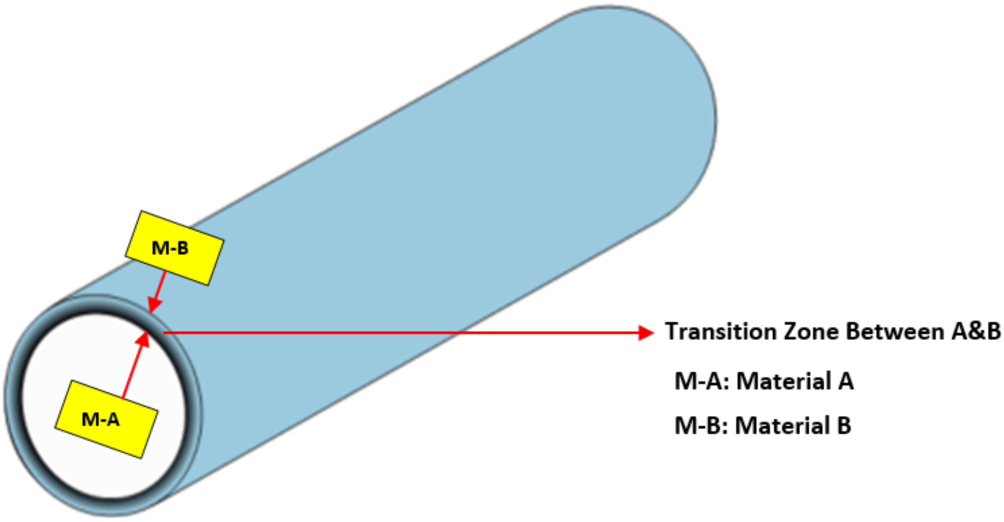

Figure 26. Schematic is an example of stepwise gradation in radial or lateral direction.

4.3. FEA Sample for FGM Structures

This section considered and numerically analysed FG pipeline articles based on their Finite Element Method (FEM) in ABAQUS, ANSYS, and other software domains from Gupta and Talha [116] and Amos [153], Mao et al. [154], and Bhardwaj et al. [155]. **Figures 27** and **28** are pipeline and beam material property variation results from the ANSYS Mechanical APDL domain. The reason is to draw attention based on the FEM computational capability for FGM in ANSYS. In light of the above thought, Abdali and Madeh [156] have maximised Hamilton's principle to analyse a shell plate made of FGM using Sigmoidal and Power Law. Numerous articles have also studied tensile stress, shear force, fracture effect, crack propagation, and fatigue growth of FGM using FEM. Such studies validate the high strength capability of FEM for analysing FG structural materials. Nonetheless, many studies have employed either one or two of the following structural geometries, such as beams, plates, bars, quarter, or full-section pipeline FG elements, to understand their behaviour under immense loading conditions. Structural material variation in pipeline models, however, differs from the other mentioned geometries due to their axisymmetric nature. Studies including Sidhoum et al. [157], Wang and Liu [158], Fan et al. [159], and Akbaş [160] have, however, employed the same Hamilton principle in their study to analyse FG pipelines for vertical vibration evaluation. According to Yulmukhametov et al. [110], Wang and Liu [158], and Li et al. [161], it is crucial, then, to note that transverse vibration in a cylindrical beam is applicable and comparable to results from high-pressure fluid flow in pipelines. A simplified Power Law is used to assess the variation in a material property along the thickness direction of the geometry model. Such research addresses problems related to the transverse vibration of an FGM pipe conveying fluid. Research studies of Pradhan et al. [41] and Chang and Zhou [162] analysed thermal buckling after intense internal structural loading conditions in an FG pipeline. Their study further implements pipeline natural frequency to understand the natural vibration under internal pressure conditions. Another research development by Li et al. [163] used a sandwich plate of FG auxetic material to analyse its vibration and natural frequency.

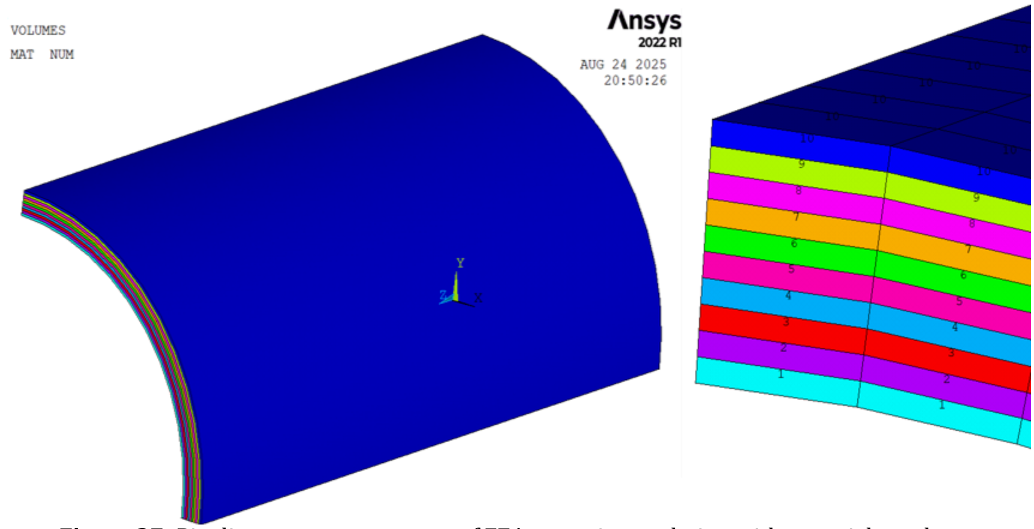

Figure 27. Pipeline quarter-symmetry of FEA, stepwise gradation with material numbers.

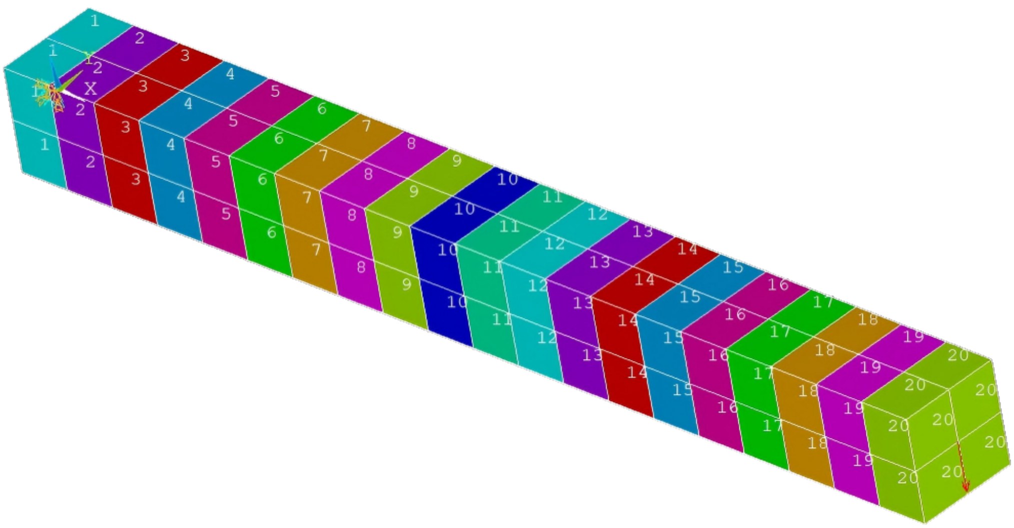

Figure 28. FEM of a simply supported FGM beam under free-end point load.

Quite a few research studies including Xin et al.[145], Shen and Wang[164], Xin et al.[165], Kiani and Eslami[166], and Najibi et al.[167], have confirmed that the Mori-Tanaka principle is quite suitable and productive for micro-material homogenisation during variations in FGM. The investigation by Xin et al.[145] ascertained that the Mori-Tanaka approach may be more efficient than Voigt's method. However, both approaches address the complexity of micro-material volume fraction variations with porosity in the material model. The numerically layered FG cylinder in **Figure 27** portrays the ideal FGM functionality of a long pipeline. The material property is in continuous gradation through the thickness direction in an isometric view. The beam material property variation of **Figure 28** runs through the axial direction of the model. The beam, however, was under a free-end concentrated load, which resulted in slight deflection of the beam.

Figure 27 presents a numerical simulation that characterises the material properties and structural behaviour of an intact pipeline subjected to internal pressure. In comparison, **Figure 28** is designed to evaluate the pipeline's yield stress. The corresponding results are omitted to maintain the review's focus on its primary subject matter. In contrast, the research of Zhang et al.[53] and Foroutan et al.[168] applied radial grading to implement FGM strength in the pipeline model. However, investigation was based on an aircraft engine pipe to simulate the interaction between fluid flow and the pipe structure[168]. The numerical model incorporates a Power Law function to represent the gradation of material properties. Simulation results indicate that material properties vary across the pipe thickness. However, further investigation is required to determine how peak radial and hoop stresses decrease as the gradation index function increases. The gradation index controls the rate of property transition across the thickness, with a higher index indicating a more significant shift toward the stronger material at the outer pipeline wall. These analyses are essential for optimising the design of pressure-resistant pipelines, as they enable engineers to tailor material distributions to specific operational requirements, thereby improving safety and efficiency.

A general and simplified power law mathematical formulation for **Figure 27**.

$$E(z) = +E_1\left(1-\left(\frac{z-a}{b-a}\right)^n\right) \qquad (16)$$

The pipeline is typically modelled as a thick-walled cylinder with inner radius and outer radius and the grading index function applied at $r = a$. However, the material properties, such as elastic modulus and Poisson's ratio vary continuously in the radial direction. The transition in these properties through the pipe wall is characterised by the Power Law, which governs how and change as functions of radius in this FGM nonlinear formulation.

The numerical analysis of **Figure 28** is performed for an FG beam whose material properties vary along its length, as expressed by Equation (17) based on the FGM simple power law.

$$\mathcal{X}\epsilon[O, L] \qquad (17)$$

The symbol denotes the grading direction along the beam FG model, starting at one end of the total model length and ending at the other part of the model (from 0 to 20 mm along the model, as shown in **Figure 28** with colourful material property indication). The gradation pattern shown in **Figure 28** is defined by a continuous function, described by Equation (18) (Power Law function). Notably, expresses the value of $[O, L]$ in the x-direction of the model.

$$E(x) = \ E_0\left[1+\alpha\left(\frac{x}{L}\right)^n\right] \qquad (18)$$

Here, represents the initial elastic modulus, and represents the final elastic modulus of the beam materials 1 and 2 along a specified direction of the beam model (x-direction). Again, the above FEA results suggest an important analysis that should be carried out before pipeline engineering construction for energy transport, either for gas or liquid.

Necessary Presumptions during the Numerical FE Beam and Pipeline Analysis

The pipeline quarter symmetry and beam geometries were numerically analysed based on the following mathematical assumptions:

Beam

- A simply supported cantilever beam was adopted
- In Euler-Bernoulli-beam theory, plane sections remain plane and perpendicular to the axis, with shear deformation damage neglected
- A simply supported boundary condition was applied in the beam analysis
- The beam model is treated as a continuous medium, where material properties are assumed to vary gradually and without discontinuity
- The elastic modulus is assumed to vary continuously along the structural length
- Upon loading conditions, a concentrated load is applied at the free end of the beam
- The Euler-Bernoulli beam theory is a classical first-order shear deformation model assuming plane sections remain planar and perpendicular to the neutral axis
- Material gradation is governed by a predefined continuous power law function, ensuring perfect bonding between infinitesimal layers with varying material compositions
- Unless stated otherwise, deformations are considered small in the beam analysis

Pipeline

- A quarter symmetry geometry was imposed in the pipeline to prevent rigid-body motion
- The pipeline was treated as continuous media, where material properties are assumed to vary gradually and without discontinuity

- The elastic modulus $E(z)$ is assumed to vary smoothly through the pipeline thickness
- Material gradation is governed by a predefined continuous power law function, ensuring perfect bonding between infinitesimal layers with varying material compositions
- Internal pressure load was applied to the inside pipeline surface
- Both linear and nonlinear evaluations are conducted based on the stress–strain relationship from zero up to the yield point. Beyond the yield point until fracture, a nonlinear analysis was performed. However, nonlinear large deformation relations and geometric nonlinearities are possible in the pipeline.

5. Conclusions

This systematic review offers a detailed assessment of FGM structures, with a particular focus on applications in energy pipelines. The review effectively incorporates both previous and current state-of-the-art research on FGM structures. It advances the literature review by critically appraising and synthesising primary research through the application of multiple research review tools. Specifically, databases and software including Scopus, Connected Papers, Google Scholar, NCH Graphics, ANSYS Mechanical APDL, and Excel are systematically employed for literature searches, study selection, schematic visualisation, and FEA. The study's successful outcome confirms that articles from Scopus, Connected Papers, and other sources were quite relevant. The PRISMA 2020 systematic review method was implemented to innovate the review study style, which was very useful for literature search, collection, and collation. The selected literature information was systematically organised to improve clarity and coherence when presenting the findings. **Figure 1** presents a framework that outlines the article selection process and enumerates the number of studies included in the analysis. This approach promotes transparency and enables a comprehensive understanding of the data selection and organisation procedures.

Schematics show different structural designs of FG pipelines to illustrate the reviewed literature and validate the study's objectives. Many reviewed articles on FG structures in additive manufacturing show their mechanical strength and thermal resistance, making them attractive for future use. The FEA results in **Figures 27** and **28** show the high potential of FG pipelines in energy transport. However, to improve reliability studies, it is important to consider both internal and external complex loading conditions during FG pipeline analysis. FGMs are gaining global attention for their impact on material and structural dynamics. Academic research is advancing FGM production and applications, focusing mainly on metal and ceramic materials. The illustrated grading patterns in the study also present FG material laws based on the volume fraction index functions, as cited in the reviewed articles. The study addresses the FG pipeline application and integrity challenges using previous research articles.

Simulations and implementations of energy pipelines using commercial software packages such as ANSYS Mechanical APDL are critical for advancing FG pipeline applications in the liquid or gas energy transport sector. Further investigation is necessary to expand the role of FGM in the energy sector and facilitate broader adoption of the FG pipeline material structure. More review studies on FG pipelines also require more attention to address the current lack of studies in this regard. A systematic review method for the FG pipeline, particularly within the FEM domain, is essential to close this research gap. Furthermore, an improved understanding of material property variations in FGM would enhance the performance and reliability of these pipeline models in demanding energy industrial applications.

Supplementary Materials

The supporting information can be downloaded at https://journals.nasspublishing.com/files/SMS-2726-Supplementary-Materials.zip.

Author Contributions

Conceptualization, F.E., S.O., and E.O.; methodology, F.E., S.O., and E.O.; data curation, F.E., S.O., and E.O.; writing—original draft preparation, F.E., S.O., and E.O.;

writing—review and editing, S.O. and E.O.; supervision, S.O. and E.O. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data will be available upon request.

Conflicts of Interest

All authors disclosed no conflict of interest.

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