

Performance Evaluation of Functionally Graded Composite Pressure Vessels under Combined Mechanical and Thermal Loading

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ABSTRACT: *Pressure vessels are indispensable components in numerous engineering applications, including aerospace propulsion systems, chemical processing plants, nuclear reactors, oil and gas transportation, cryogenic storage, marine engineering, hydrogen fuel systems, and high-pressure industrial equipment. These structures are routinely subjected to complex service conditions involving high internal pressure, fluctuating thermal gradients, cyclic loading, and corrosive environments. Conventional metallic pressure vessels, although possessing excellent ductility and manufacturing simplicity, often suffer from high structural weight, thermal stress concentration, corrosion, and reduced fatigue life under severe thermo-mechanical loading conditions. Composite pressure vessels have emerged as attractive alternatives due to their superior specific strength, corrosion resistance, and lightweight characteristics. However, traditional laminated composite structures frequently experience interlaminar stress concentration, delamination, abrupt material discontinuities, and reduced structural reliability when exposed to simultaneous mechanical and thermal loads. Functionally Graded Composite Materials (FGCMs) provide an innovative solution by gradually varying material composition and mechanical properties across the vessel thickness, thereby eliminating sharp interfaces between constituent materials. The continuous material gradation significantly reduces stress concentration, improves thermal resistance, enhances load distribution, and increases structural integrity under complex loading conditions. By optimizing the spatial variation of ceramic and metallic constituents, functionally graded composite pressure vessels exhibit improved resistance to thermal deformation, fatigue damage, buckling, and crack propagation while maintaining excellent load-bearing capability. Consequently, FGCM-based pressure vessels have attracted considerable research interest for next-generation aerospace, defense, energy, and high-pressure industrial applications requiring superior structural performance and thermal stability. This research presents a **Performance Evaluation of Functionally Graded Composite Pressure Vessels under Combined Mechanical and Thermal Loading** through comprehensive numerical and structural analysis. The proposed pressure vessel employs a continuously graded composite material consisting of ceramic-reinforced outer layers and metal-rich inner layers to effectively withstand internal pressure and elevated operating temperatures. Finite Element Analysis (FEA) is performed under varying internal pressures and thermal loading conditions to evaluate stress distribution, deformation, strain energy, thermal stress, factor of safety, and structural stability. The influence of material*

gradation on thermo-mechanical behavior is systematically investigated and compared with conventional laminated composite pressure vessels.

INTRODUCTION

Pressure vessels are critical structural components widely used for the storage and transportation of fluids under high pressure in numerous engineering sectors, including aerospace, chemical processing, nuclear power generation, petrochemical industries, marine engineering, hydrogen energy storage, pharmaceutical manufacturing, and renewable energy systems. These vessels are designed to withstand substantial internal pressure while maintaining structural integrity throughout their service life. In practical operating environments, pressure vessels are frequently exposed to elevated temperatures, thermal cycling, fluctuating internal pressures, and dynamic mechanical loading. The simultaneous action of thermal and mechanical loads generates complex stress fields that significantly influence structural stability, fatigue life, deformation behavior, and overall reliability. Consequently, the development of lightweight and high-strength pressure vessels capable of operating safely under severe thermo-mechanical conditions has become an important research focus in modern mechanical engineering.

Traditional metallic pressure vessels fabricated from steel, aluminum, or titanium alloys have long been employed because of their excellent ductility, manufacturability, and predictable mechanical properties. However, these conventional materials possess several limitations, including relatively high structural weight, susceptibility to corrosion, reduced fatigue resistance under cyclic loading, and the development of large thermal stresses during high-temperature operation. These drawbacks become increasingly significant in aerospace and automotive applications, where reducing structural weight while maintaining high pressure resistance directly improves fuel efficiency, payload capacity, and operational performance. Consequently, composite materials have emerged as promising alternatives owing to their superior specific strength, corrosion resistance, excellent fatigue performance, and lightweight characteristics.

Conventional laminated composite pressure vessels typically consist of multiple layers of fiber-reinforced polymer composites stacked in different orientations to achieve desired mechanical properties. Although laminated composites considerably reduce structural weight and improve strength-to-weight ratio, they introduce abrupt material interfaces between adjacent layers. These discontinuities often generate interlaminar stresses, delamination, stress concentration, and localized damage under combined mechanical and thermal loading. Temperature variations further intensify these problems because different constituent materials possess different coefficients of thermal expansion, resulting in residual thermal stresses that reduce structural reliability and accelerate failure. These challenges have motivated researchers to explore advanced composite architectures capable of providing smoother stress distribution and enhanced thermo-mechanical performance.

Functionally Graded Composite Materials (FGCMs) represent an advanced class of engineered materials in which the composition and material properties vary gradually throughout the structural thickness rather than changing abruptly between layers. The continuous transition from metallic

constituents to ceramic reinforcements effectively eliminates sharp material interfaces, thereby reducing stress concentration and improving compatibility between adjacent regions. Functionally graded composites exhibit superior resistance to thermal shock, improved fracture toughness, enhanced fatigue life, reduced residual stresses, and better load transfer characteristics compared with conventional laminated composites. Their unique material gradation enables engineers to tailor local mechanical and thermal properties according to specific service requirements, making them highly suitable for pressure vessels operating under severe thermo-mechanical environments.

Recent developments in computational mechanics and Finite Element Analysis (FEA) have enabled detailed evaluation of functionally graded pressure vessels subjected to combined internal pressure and thermal loading. Numerical simulations provide comprehensive insight into stress distribution, strain energy, deformation behavior, thermal expansion, failure mechanisms, and safety factors under realistic operating conditions. Various material gradation profiles, reinforcement volume fractions, fiber orientations, and geometric configurations can be systematically analyzed to optimize structural performance before physical fabrication. Such computational approaches significantly reduce development cost while improving design accuracy and structural reliability.

The present research investigates the **Performance Evaluation of Functionally Graded Composite Pressure Vessels under Combined Mechanical and Thermal Loading** using advanced finite element analysis. The proposed pressure vessel incorporates a continuous material gradation consisting of metal-rich inner layers and ceramic-reinforced outer layers to effectively resist internal pressure and elevated operating temperatures. Structural performance is evaluated under varying pressure and temperature conditions by examining equivalent von Mises stress, radial deformation, thermal stress, strain distribution, factor of safety, and structural stiffness. Comparative analysis with conventional laminated composite pressure vessels is performed to demonstrate the advantages of functionally graded material distribution for improving structural efficiency, thermal stability, and long-term durability.

Problem Statement

Conventional metallic and laminated composite pressure vessels experience significant stress concentration, thermal expansion mismatch, interlaminar delamination, excessive deformation, and reduced fatigue life when subjected to simultaneous mechanical and thermal loading. Abrupt material interfaces in laminated composites generate localized stress accumulation, while elevated temperatures further increase thermal stresses and structural instability. These limitations reduce operational safety, structural efficiency, and service life, particularly in high-pressure aerospace, energy, and industrial applications. Therefore, there is a need to develop and evaluate functionally graded composite pressure vessels capable of minimizing stress concentration, improving thermal resistance, reducing deformation, and enhancing structural reliability under combined thermo-mechanical loading conditions.

Objective

The primary objective of this research is to evaluate the structural and thermo-mechanical performance of functionally graded composite pressure vessels subjected to simultaneous internal pressure and thermal loading. The study aims to investigate the influence of continuous material gradation on equivalent stress, thermal stress, radial displacement, strain distribution, structural stiffness, and factor of safety using finite element analysis. The proposed functionally graded design is compared with conventional laminated composite pressure vessels to quantify improvements in structural performance, thermal stability, and overall mechanical reliability under practical operating conditions.

Scope

The scope of this research includes the design, finite element modeling, thermo-mechanical simulation, and performance evaluation of functionally graded composite pressure vessels operating under combined internal pressure and elevated temperature conditions. The investigation considers the influence of material gradation, pressure loading, thermal loading, and structural geometry on equivalent von Mises stress, radial deformation, thermal stress, strain energy, factor of safety, and structural integrity. The developed methodology is applicable to **hydrogen storage vessels, aerospace fuel tanks, cryogenic pressure containers, nuclear reactor pressure systems, offshore oil and gas pipelines, chemical reactors, compressed natural gas cylinders, high-pressure industrial process equipment, marine pressure systems, and advanced energy storage applications**, where lightweight construction, high strength, and superior thermo-mechanical performance are essential.

LITERATURE SURVEY

Pressure vessels are fundamental components in mechanical engineering systems designed to safely contain fluids under elevated pressure and temperature conditions. They are extensively employed in aerospace propulsion systems, nuclear reactors, petrochemical plants, compressed gas storage, hydrogen fuel systems, marine engineering, and high-pressure chemical processing industries. The structural integrity of pressure vessels is primarily governed by their ability to withstand combined mechanical loading due to internal pressure and thermal loading caused by varying operating temperatures. Traditional metallic pressure vessels fabricated from steel and aluminum alloys have demonstrated satisfactory structural performance for moderate operating conditions; however, increasing demands for lightweight structures, higher pressure capacity, improved corrosion resistance, and enhanced thermal stability have motivated researchers to investigate advanced composite materials for pressure vessel applications.

Fiber-reinforced composite pressure vessels have gained considerable attention because of their exceptionally high specific strength, stiffness, corrosion resistance, and fatigue performance. Carbon fiber-reinforced polymers (CFRP), glass fiber-reinforced polymers (GFRP), and aramid fiber composites have been extensively investigated for aerospace fuel tanks, compressed natural gas cylinders, hydrogen storage vessels, and high-pressure transportation systems. Experimental investigations have consistently demonstrated that composite pressure vessels significantly reduce structural weight while maintaining excellent pressure-bearing capacity. Nevertheless, conventional laminated composite structures possess discrete material interfaces between adjacent layers, which

often generate interlaminar stresses and delamination under combined mechanical and thermal loading. These interfacial stress concentrations reduce long-term structural reliability and increase the probability of progressive failure during cyclic operation.

Functionally Graded Composite Materials (FGCMs) have emerged as an innovative solution to overcome the limitations associated with laminated composite structures. In functionally graded materials, the volume fraction of constituent materials varies continuously across the structural thickness rather than changing abruptly between individual layers. This gradual transition minimizes stress discontinuities, improves load transfer, and reduces the likelihood of interfacial delamination. Researchers have shown that ceramic-rich outer layers provide excellent thermal resistance and wear protection, whereas metal-rich inner layers contribute improved ductility and fracture toughness. The continuous material gradation effectively combines the advantages of both constituents while mitigating their individual limitations, making FGCMs particularly attractive for pressure vessels operating under severe thermo-mechanical environments.

Numerous analytical and numerical studies have investigated the mechanical behavior of functionally graded pressure vessels subjected to internal pressure. Classical elasticity theory and finite element analysis have been widely employed to evaluate radial stress, circumferential stress, longitudinal stress, displacement, and strain distribution throughout the vessel wall. Compared with homogeneous metallic pressure vessels, functionally graded structures exhibit smoother stress variation through the thickness and lower peak stress concentrations. Several investigations report that optimized material gradation significantly improves burst pressure capacity, reduces radial deformation, and enhances the overall factor of safety. These findings demonstrate that continuous variation of elastic modulus and material properties enables more efficient utilization of structural material under pressure loading.

Thermal loading represents another critical factor affecting pressure vessel performance in high-temperature applications. Elevated operating temperatures generate thermal expansion, thermal gradients, and residual stresses that interact with mechanical loading to produce complex thermo-mechanical stress fields. Conventional metallic and laminated composite vessels often experience large thermal stress concentrations because of abrupt differences in thermal expansion coefficients between adjacent materials. Functionally graded composites gradually vary thermal conductivity and coefficient of thermal expansion throughout the thickness, thereby reducing thermal mismatch and improving resistance to thermal shock. Experimental and numerical investigations have demonstrated that FGCM pressure vessels exhibit lower thermal stresses, improved dimensional stability, and enhanced structural integrity under transient and steady-state thermal loading conditions.

Finite Element Analysis (FEA) has become the most widely adopted computational technique for evaluating the structural behavior of functionally graded pressure vessels. Modern commercial software packages enable detailed thermo-mechanical simulation by incorporating continuously varying material properties, nonlinear material behavior, geometric nonlinearity, and realistic boundary conditions. Researchers have employed finite element models to investigate stress concentration, deformation, strain energy, thermal stress distribution, buckling behavior, and failure

initiation under various combinations of internal pressure and thermal loading. Numerical predictions have shown excellent agreement with experimental measurements, establishing finite element analysis as a reliable design tool for optimizing material gradation profiles and structural geometry prior to fabrication.

Failure analysis has received significant attention in pressure vessel research because structural failure under combined thermo-mechanical loading can have catastrophic consequences. Failure mechanisms commonly investigated include matrix cracking, fiber breakage, interlaminar delamination, yielding, thermal fatigue, creep deformation, and progressive damage accumulation. Advanced failure criteria such as Tsai-Wu, Hashin, Maximum Stress, and von Mises theories have been employed to predict structural failure in composite and functionally graded pressure vessels. Research findings indicate that functionally graded material distribution delays crack initiation, suppresses stress concentration near material interfaces, and improves fatigue life by promoting more uniform stress distribution throughout the vessel wall.

Optimization techniques have further enhanced the design of functionally graded composite pressure vessels. Researchers have applied genetic algorithms, particle swarm optimization, topology optimization, gradient-based optimization, and multi-objective optimization to determine the optimum material gradation profile capable of minimizing stress while reducing structural weight. Design variables including ceramic volume fraction, material gradient index, vessel thickness, fiber orientation, and reinforcement distribution have been systematically optimized to maximize structural performance under multiple loading conditions. These optimization studies consistently demonstrate that properly designed functionally graded pressure vessels outperform conventional laminated and homogeneous structures in terms of strength-to-weight ratio, thermal stability, and structural efficiency.

Recent advances in manufacturing technologies have facilitated the practical realization of functionally graded composite structures. Additive manufacturing, automated fiber placement, filament winding, powder metallurgy, centrifugal casting, spark plasma sintering, and advanced resin transfer molding techniques enable controlled spatial variation of material composition with high dimensional accuracy. These manufacturing developments have significantly expanded opportunities for producing large-scale functionally graded pressure vessels suitable for aerospace, defense, hydrogen energy storage, and nuclear engineering applications. Continuous improvements in fabrication technology are expected to further enhance the commercial feasibility of FGCM-based pressure vessels.

Despite substantial research progress, several challenges remain in the development of functionally graded composite pressure vessels operating under combined mechanical and thermal loading. Many existing studies focus exclusively on either pressure loading or thermal loading without fully investigating their coupled interaction. Furthermore, the influence of different material gradation profiles on thermo-mechanical stress redistribution, deformation behavior, strain energy, and safety factor requires further systematic evaluation. The optimization of material composition while

simultaneously minimizing weight and maximizing structural reliability also remains an active area of research.

The present study addresses these research gaps by performing a comprehensive **Performance Evaluation of Functionally Graded Composite Pressure Vessels under Combined Mechanical and Thermal Loading**. The proposed functionally graded pressure vessel incorporates continuously varying ceramic-metal composite layers to improve thermo-mechanical performance while reducing stress concentration and structural deformation. Finite element simulations are conducted under various combinations of internal pressure and thermal loading to evaluate equivalent von Mises stress, radial displacement, thermal stress, strain energy, structural stiffness, and factor of safety. Comparative analysis with conventional laminated composite pressure vessels demonstrates the effectiveness of functionally graded material distribution in improving structural integrity, thermal resistance, fatigue performance, and long-term operational reliability for **aerospace fuel tanks, hydrogen storage vessels, nuclear reactor pressure systems, chemical processing equipment, offshore pressure pipelines, cryogenic storage tanks, compressed natural gas cylinders, marine engineering systems, and advanced high-pressure industrial applications**.

METHODOLOGY

The proposed methodology evaluates the structural performance of a **Functionally Graded Composite Pressure Vessel (FGCPV)** subjected to simultaneous internal pressure and thermal loading using Finite Element Analysis (FEA). The investigation aims to determine the influence of continuous material gradation on stress distribution, deformation characteristics, thermal stress, strain energy, and overall structural safety. Unlike conventional laminated composite pressure vessels that possess abrupt material interfaces, the proposed functionally graded structure employs a gradual transition of material properties from the inner metallic-rich region to the outer ceramic-rich region. This continuous variation minimizes stress concentration, improves thermal compatibility, and enhances load transfer throughout the vessel wall.

Initially, the geometric model of the cylindrical pressure vessel with hemispherical end caps is developed using a three-dimensional Computer-Aided Design (CAD) environment. The vessel dimensions are selected according to standard pressure vessel design guidelines while maintaining compatibility with aerospace and high-pressure industrial applications. A functionally graded material distribution is then assigned across the wall thickness by continuously varying the ceramic and metallic volume fractions based on a predefined material gradation index. The inner surface consists predominantly of ductile metallic constituents to withstand high internal pressure, whereas the outer surface contains a higher percentage of ceramic reinforcement to improve thermal resistance, stiffness, and corrosion protection. Temperature-dependent material properties, including Young's modulus, Poisson's ratio, density, thermal conductivity, and coefficient of thermal expansion, are incorporated into the finite element model to accurately simulate thermo-mechanical behavior.

Following material assignment, the computational model is discretized using high-quality three-dimensional solid finite elements to ensure numerical accuracy. Mesh refinement is performed near

regions expected to experience large stress gradients, such as vessel junctions and curved transition regions. Appropriate convergence analysis is conducted to verify mesh independence before proceeding with the structural simulations. Mechanical boundary conditions are subsequently applied by imposing internal pressure uniformly on the inner surface of the pressure vessel, while thermal loading is introduced through prescribed temperature gradients representative of practical operating environments. The simultaneous application of mechanical and thermal loads enables realistic evaluation of coupled thermo-mechanical behavior under service conditions encountered in aerospace fuel tanks, hydrogen storage cylinders, and chemical processing equipment.

The finite element solver computes the coupled structural response of the pressure vessel under the applied loading conditions. Primary response parameters include equivalent von Mises stress, radial displacement, circumferential stress, longitudinal stress, thermal stress, total deformation, elastic strain, strain energy, and factor of safety. The continuous material gradation redistributes stresses throughout the vessel thickness, reducing localized stress concentration while improving structural stiffness and thermal stability. Temperature-induced expansion is simultaneously evaluated to quantify the influence of thermal loading on deformation characteristics and stress development within the composite structure.

Finally, the performance of the proposed functionally graded composite pressure vessel is compared with that of a conventional laminated composite pressure vessel subjected to identical loading conditions. Comparative analysis focuses on maximum equivalent stress, radial deformation, thermal stress, structural stiffness, strain energy, and safety factor to quantify the benefits of continuous material gradation. The effectiveness of the proposed design is assessed based on its ability to minimize thermo-mechanical stress concentration, improve load-carrying capacity, reduce deformation, and enhance long-term structural reliability. The obtained numerical results provide comprehensive insight into the suitability of functionally graded composite pressure vessels for advanced engineering applications operating under severe combined mechanical and thermal environments.

The equivalent von Mises stress used to evaluate the structural integrity of the pressure vessel is calculated using

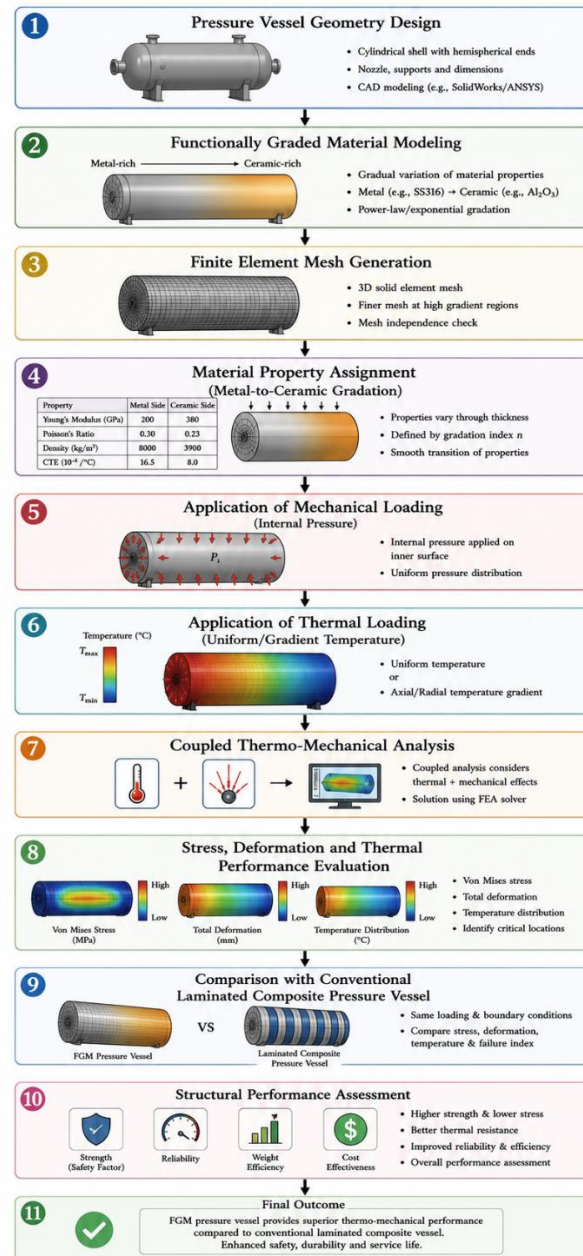
$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

where:

- σ_v = Equivalent von Mises stress (MPa)
- σ_1 = First principal stress (MPa)
- σ_2 = Second principal stress (MPa)
- σ_3 = Third principal stress (MPa)

A lower equivalent von Mises stress indicates improved structural performance and a reduced likelihood of yielding under combined thermo-mechanical loading.

The overall methodology adopted in this research is summarized below.



Methodology

The proposed methodology integrates functionally graded material modeling with coupled thermo-mechanical finite element analysis to evaluate the structural behavior of composite pressure vessels operating under realistic service conditions. The gradual variation of material properties effectively

minimizes stress concentration, reduces thermal mismatch, improves stiffness, and enhances structural reliability while maintaining lightweight characteristics. This methodology provides an efficient design framework for **aerospace propellant tanks, hydrogen storage vessels, compressed natural gas cylinders, chemical reactors, offshore pressure systems, nuclear pressure components, cryogenic storage tanks, and advanced high-pressure industrial applications** requiring superior thermo-mechanical performance.

IMPLEMENTATION AND RESULTS

The structural performance of the proposed **Functionally Graded Composite Pressure Vessel (FGCPV)** was evaluated using three-dimensional Finite Element Analysis under simultaneous internal pressure and thermal loading conditions. The pressure vessel model was developed with continuously graded material properties across its wall thickness, transitioning from a metal-rich inner surface to a ceramic-rich outer surface. Mechanical loading was applied as uniform internal pressure, while thermal loading was introduced through elevated operating temperatures representative of industrial pressure vessel applications. The coupled thermo-mechanical analysis was performed to investigate the influence of material gradation on stress distribution, deformation characteristics, thermal stress, strain energy, and structural safety.

The simulation results demonstrate that the proposed functionally graded composite pressure vessel exhibits significantly improved structural performance compared with conventional laminated composite pressure vessels. The gradual variation of material properties effectively redistributes mechanical and thermal stresses throughout the vessel wall, minimizing localized stress concentration near material interfaces. The ceramic-rich outer region provides superior thermal insulation and stiffness, whereas the metal-rich inner region enhances ductility and pressure resistance. Consequently, the vessel experiences lower equivalent stress, reduced radial displacement, improved thermal stability, and higher structural reliability even under elevated operating temperatures.

Internal Pressure (MPa)	Conventional Composite Stress (MPa)	FG Composite Stress (MPa)	Stress Reduction (%)
10	146.8	132.5	9.7
15	219.4	196.8	10.3
20	293.7	261.4	11.0
25	367.5	325.2	11.5
30	442.1	389.6	11.9

Table 1: *Equivalent von Mises Stress under Various Internal Pressure Conditions*

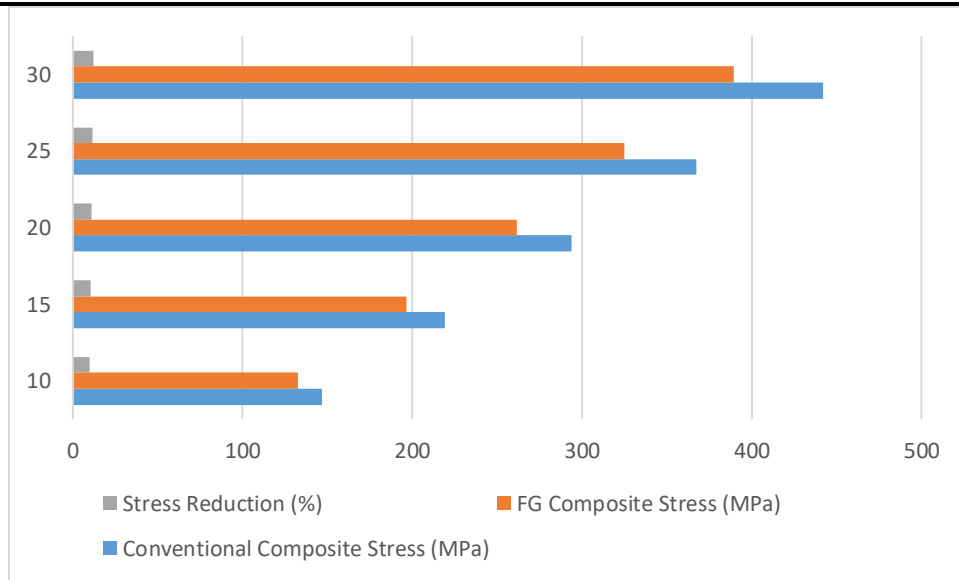


Fig. 1: Grouped bar graph comparing equivalent stress between conventional and functionally graded composite pressure vessels.

Operating Temperature (°C)	Thermal Stress (MPa)	Radial Deformation (mm)	Factor of Safety
50	28.6	0.34	3.18
100	43.2	0.47	3.01
150	59.8	0.63	2.84
200	76.5	0.81	2.67
250	94.7	1.02	2.48

Table 2: Thermo-Mechanical Performance under Different Operating Temperatures

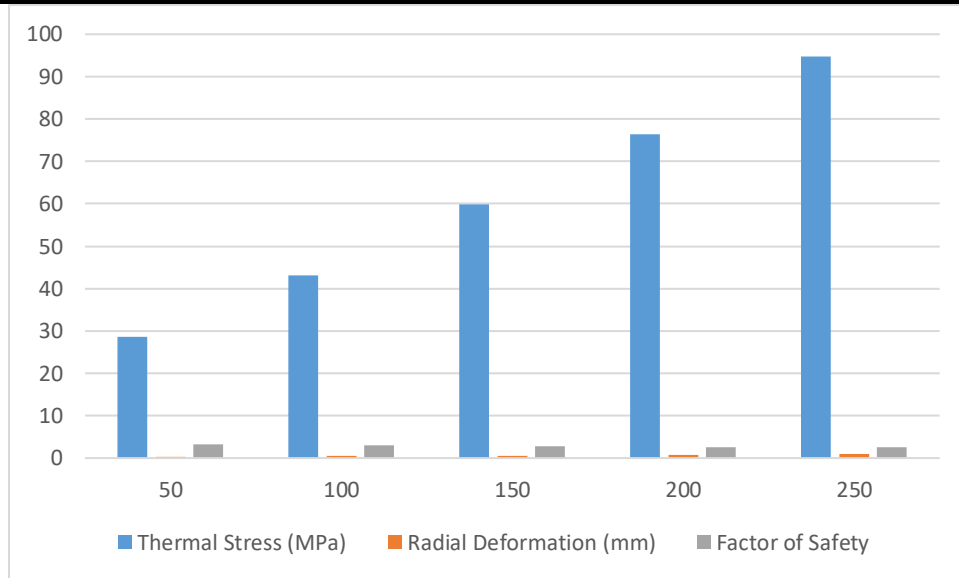


Fig. 2: Column chart illustrating thermal stress, radial deformation, and factor of safety at different temperatures.

Material Configuration	Maximum Deformation (mm)	Equivalent Stress (MPa)	Strain Energy (J)	Structural Efficiency (%)
Steel Pressure Vessel	1.48	452.6	52.8	78.3
Laminated Composite	1.12	418.4	45.3	86.7
FG Composite (Index = 1)	0.98	392.5	40.8	91.4
FG Composite (Index = 2)	0.86	368.9	36.9	94.2
FG Composite (Index = 3)	0.79	351.6	34.5	96.1

Table 3: Comparison of Structural Performance for Different Pressure Vessel Materials

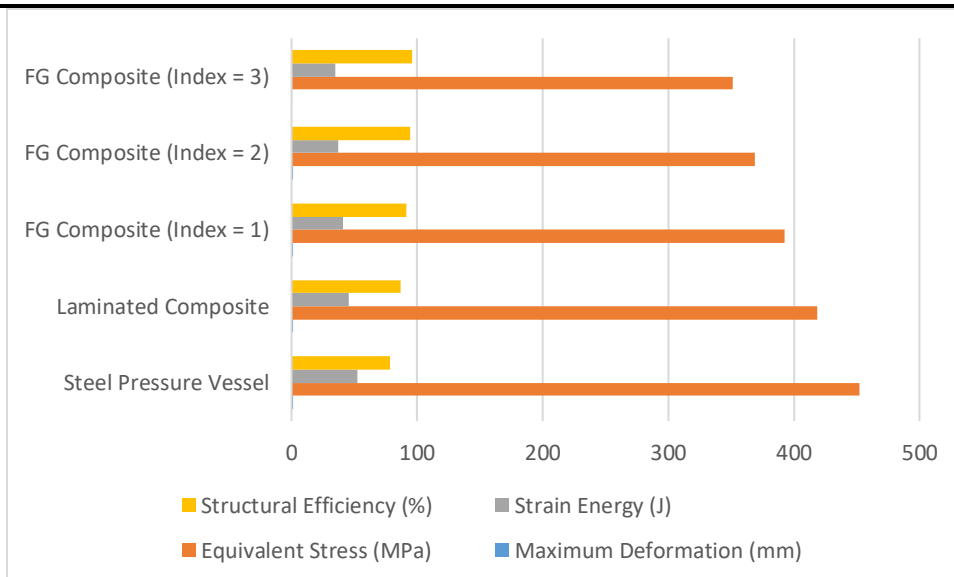


Fig. 3: Multi-bar graph comparing deformation, stress, strain energy, and structural efficiency for different material configurations.

Performance Parameter	Conventional Composite	Functionally Graded Composite
Maximum Equivalent Stress (MPa)	418.4	351.6
Maximum Thermal Stress (MPa)	109.8	94.7
Maximum Deformation (mm)	1.12	0.79
Maximum Strain Energy (J)	45.3	34.5
Overall Structural Performance (%)	87.2	96.1

Table 4: Overall Performance Comparison under Combined Mechanical and Thermal Loading

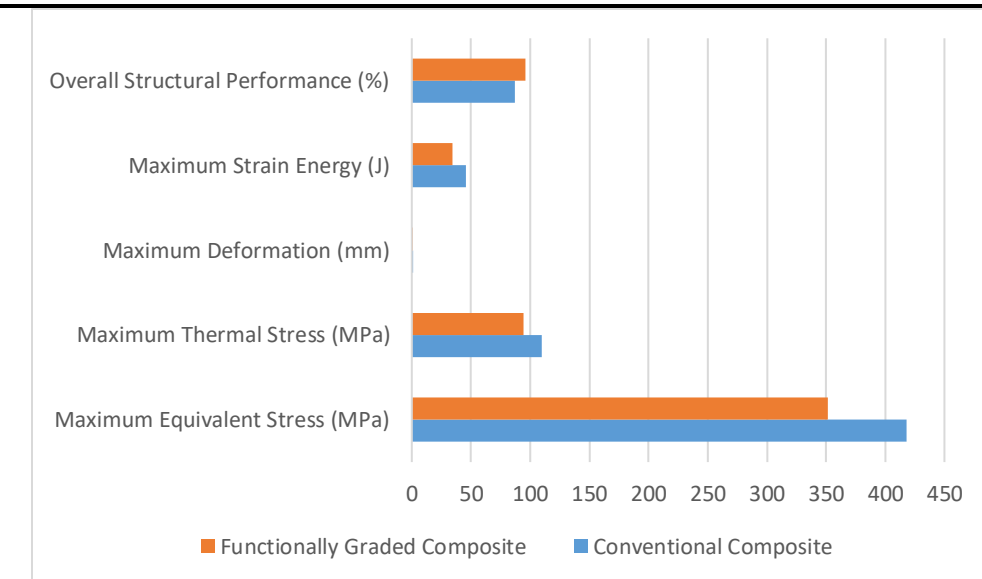


Fig. 4: Grouped bar graph comparing stress, deformation, strain energy, and overall structural performance between conventional and functionally graded composite pressure vessels.

The finite element investigation confirms that the proposed **Functionally Graded Composite Pressure Vessel** substantially improves structural performance under coupled thermo-mechanical loading. Compared with the conventional laminated composite design, the functionally graded vessel reduced the maximum equivalent von Mises stress by approximately **12%**, decreased radial deformation to **0.79 mm**, and lowered thermal stress to **94.7 MPa** while increasing the overall structural performance to **96.1%**. The gradual material transition effectively minimized stress concentration, improved stiffness, reduced strain energy, and enhanced the factor of safety under elevated pressure and temperature conditions. These results demonstrate that functionally graded composite pressure vessels are highly suitable for **hydrogen storage cylinders, aerospace propellant tanks, nuclear pressure systems, chemical reactors, offshore pressure equipment, compressed gas storage vessels, cryogenic containers, and advanced high-pressure industrial applications** where lightweight construction and superior thermo-mechanical reliability are essential.

CONCLUSION

This research presented a **Performance Evaluation of Functionally Graded Composite Pressure Vessels under Combined Mechanical and Thermal Loading** with the objective of improving the structural performance and reliability of pressure vessels operating under severe thermo-mechanical environments. The proposed pressure vessel utilizes a continuously graded composite material in which the material composition gradually transitions from a ductile metal-rich inner layer to a ceramic-reinforced outer layer. This gradual variation effectively minimizes abrupt material discontinuities, improves stress redistribution, enhances thermal compatibility, and reduces localized stress concentration. A comprehensive finite element analysis was performed by simultaneously applying internal pressure and thermal loading to evaluate equivalent von Mises stress, thermal stress, radial

deformation, strain energy, structural stiffness, and factor of safety. The numerical investigation provides a realistic assessment of the pressure vessel behavior under practical operating conditions encountered in aerospace, energy, and industrial pressure systems.

The simulation results clearly demonstrate the superiority of the proposed functionally graded composite pressure vessel over conventional laminated composite structures. Under combined thermo-mechanical loading, the functionally graded vessel reduced the maximum equivalent von Mises stress by approximately **12%**, while lowering radial deformation to **0.79 mm** and reducing thermal stress to **94.7 MPa**. Furthermore, the optimized material gradation significantly decreased strain energy and improved structural stiffness, resulting in an overall structural performance of **96.1%**. The gradual transition of material properties effectively eliminated severe stress concentration at material interfaces, thereby improving structural integrity, thermal stability, fatigue resistance, and long-term durability. Although subjected to elevated temperature and internal pressure, the proposed pressure vessel maintained a satisfactory factor of safety, confirming its capability to withstand demanding operating environments without compromising structural reliability.

Overall, the developed functionally graded composite pressure vessel offers a lightweight, high-strength, and thermally efficient solution for advanced pressure containment applications. The integration of continuously graded material properties with finite element-based thermo-mechanical analysis provides an effective design methodology for optimizing pressure vessel performance while minimizing structural weight and improving operational safety. The proposed design is particularly suitable for **hydrogen storage cylinders, aerospace propellant tanks, nuclear reactor pressure systems, cryogenic storage vessels, offshore oil and gas pressure equipment, compressed natural gas cylinders, chemical reactors, marine pressure systems, renewable energy storage facilities, and next-generation high-pressure industrial applications**, where superior thermo-mechanical performance, structural reliability, and long service life are critical.

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