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Design Optimization of Pressure Vessels Using FEA and Computational Techniques: A Review

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ABSTRACT

Pressure vessels are essential engineering components used for storing and transporting fluids under high pressure and temperature conditions. Their safe design is crucial because failure may cause severe economic, environmental, and human losses. This study focuses on the design optimization of pressure vessels using Finite Element Analysis and computational optimization techniques. FEA helps identify stress distribution, deformation, and critical failure zones, while optimization methods improve material efficiency, reduce weight, and enhance structural performance. The study emphasizes the importance of integrating simulation, material behavior, and optimization algorithms to develop safe, cost-effective, and high-performance pressure vessel systems.

Keywords: *Pressure Vessel, Finite Element Analysis, Design Optimization, Structural Performance.*

I. INTRODUCTION

Pressure vessels are critical engineering components extensively used across industrial sectors such as oil and gas, petrochemical processing, power generation, aerospace, and mechanical systems for the safe storage and transport of fluids under high pressure and temperature conditions. The structural integrity of these vessels is of paramount importance because failure can result in catastrophic consequences, including loss of life, environmental hazards, and significant economic damage. Traditionally, pressure vessel design has been governed by established codes and standards such as the ASME Boiler and Pressure Vessel Code (BPVC), which provide conservative guidelines to ensure safety under operational loading conditions. However, these conventional design methodologies often rely heavily on empirical formulations and safety factors, which may lead to overdesigned structures with excessive material usage and increased cost (Zhou et al., 2021). In modern engineering practice, there is a growing need to optimize pressure vessel designs not only for safety but also for weight reduction, cost efficiency, and enhanced performance. This has led to increasing integration of advanced numerical methods such as Finite Element Analysis (FEA) and computational optimization techniques in structural design processes. As highlighted by Mali et al. (2017), pressure vessels operate under complex stress states influenced by internal pressure, thermal loads, corrosion, and cyclic fatigue, making accurate analysis essential for reliable performance prediction. Consequently, the evolution of pressure vessel design has shifted from purely analytical approaches to integrated computational frameworks that combine simulation, data-driven modeling, and optimization algorithms to achieve superior structural efficiency.

In recent years, Finite Element Analysis (FEA) has emerged as a fundamental tool for evaluating stress distribution, deformation behavior, and failure mechanisms in pressure vessels under various loading conditions. FEA enables engineers to model complex geometries and material behaviors with high accuracy, allowing for detailed assessment of critical stress regions and potential failure points. Solangi et al. (2024) demonstrated that FEA-based structural evaluation of pressure vessels provides precise insights into stress concentration zones and deformation patterns, particularly in aerospace applications where lightweight materials such as aluminum alloys are commonly used. Similarly, Hazizi and Ghaleeh (2023) applied FEA using ANSYS and Autodesk Inventor to analyze vertical pressure vessels, identifying critical stress regions such as manways and shell junctions. These studies confirm that numerical simulation plays a vital role in validating design safety and compliance with international standards such as ASME Section VIII. However, while FEA enhances analytical accuracy, it alone does not guarantee optimal design solutions. To address this limitation, researchers have increasingly integrated FEA with optimization techniques such as Response Surface Methodology (RSM), Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and machine learning-based predictive models. Liu et al. (2026) proposed a hierarchical optimization framework combining FEA, RSM, and PSO for composite pressure vessel liner design, demonstrating that surrogate modeling significantly reduces computational cost while maintaining optimization accuracy. Similarly, Shaik et al. (2025) integrated FEA with machine learning models such as XGBoost to predict burst pressure with improved reliability compared to traditional analytical methods. These advancements indicate a paradigm shift toward hybrid computational frameworks where simulation and optimization work synergistically to enhance design efficiency, reduce material usage, and improve structural performance.

Furthermore, composite materials and advanced structural configurations have significantly transformed pressure vessel design methodologies, particularly in aerospace and high-performance engineering applications. Composite Overwrapped Pressure Vessels (COPVs) have gained prominence due to their high strength-to-weight ratio, corrosion resistance, and ability to withstand extreme internal pressures. Regassa, Gari, and Lemu (2022) investigated COPV configurations using finite element modeling and observed that fiber orientation and ply stacking sequence critically influence burst pressure capacity and stress distribution. Their findings demonstrated that optimized composite layups can significantly enhance structural performance compared to conventional metallic vessels. Similarly, Oliveira et al. (2018) employed derivative-based optimization techniques combined with FEA and Tsai–Wu failure criteria to optimize composite pressure vessel thickness and orientation, ensuring compliance with ASME safety requirements. Abdelsalam (2019) further expanded on this concept by optimizing shrink-fitted multi-layer pressure vessels using Response Surface Methodology and Multi-Objective Genetic Algorithms, achieving improved residual stress distribution and enhanced fatigue life. These studies collectively highlight the importance of integrating material science, computational mechanics, and optimization theory in modern pressure vessel design. Despite these advancements, challenges remain in achieving a balance between computational efficiency, structural safety, and manufacturability. Conventional design approaches often fail to capture multi-variable interactions and nonlinear material behavior, leading to suboptimal solutions. Therefore, there is a strong research motivation to develop integrated design optimization frameworks that combine Finite Element Analysis with advanced optimization techniques to achieve lightweight, cost-effective, and structurally robust pressure vessel systems. The present study is aligned with this objective, focusing on the design optimization of pressure vessels using finite element and computational optimization techniques to enhance structural efficiency while ensuring compliance with engineering safety standards.

II. RESEARCH BACKGROUND

Liu et al. (2026) had reviewed that the weight and functional performance of composite pressure vessels were significantly influenced by liner construction, which had traditionally been determined through theoretical formulations and engineering experience, often resulting in structural failure or excessive weight. The study had proposed a hierarchical optimization technique for improving liner design. In the initial stage, the dome shape had been optimized using the maximum form factor, and comparisons among commonly used dome shape factors had been conducted. In the subsequent stage, an integrated approach combining Finite Element Analysis (FEA), Response Surface Methodology (RSM), and Particle Swarm Optimization (PSO) had been employed to optimize the spout and barrel structures of the liner in accordance with DOT-CFFC standards. It had been observed that the response surface model reduced computational effort by avoiding repeated finite element simulations, while PSO facilitated optimal parameter selection. The study had concluded that the proposed method provided a valuable reference for designing complex liner structures with multiple variables.

Shaik et al. (2025) had examined the critical role of pressure vessels in industrial applications, particularly in the oil and gas sector, where they were subjected to extreme operating conditions. It had been reported that under high pressurization, these vessels accumulated strain energy, which could lead to material degradation and eventual failure, especially in ductile materials. The study had emphasized that accurate estimation of burst pressure was essential for ensuring structural safety and integrity. The authors had proposed a machine learning-based approach utilizing existing literature data, where key parameters such as yield strength, ultimate strength, inner diameter, material type, and thickness had been considered as input variables. It had been observed that the integration of Finite Element Analysis (FEA) with advanced algorithms like XGBoost significantly enhanced prediction accuracy and reliability. The findings had indicated that the XGBoost model outperformed conventional mathematical methods due to its ability to capture complex relationships among variables. Furthermore, it had been concluded that the proposed approach reduced computational effort while maintaining high precision, thereby offering a practical and efficient framework for burst pressure prediction in various engineering applications.

Solangi et al. (2024) had presented a comprehensive analysis of external pressure vessels, emphasizing their performance under extreme operating conditions. It had been highlighted that appropriate selection of material, geometric configuration, and detailed stress analysis were essential for achieving optimal efficiency. The study had aimed to provide a case-based evaluation of material selection, structural design, and stress development to ensure suitability for thermal and load-bearing aerospace applications. An aluminum alloy had been selected due to its favorable properties, such as low density and high strength. The geometry had been developed in accordance with ASME Section VIII Division I standards, and Finite Element Analysis (FEA) had been conducted using ANSYS Design Modeler to assess stress concentration and failure behavior. The findings had demonstrated structural response under applied loads and identified critical weak zones. It had been reported that maximum and minimum stresses were 0.763 MPa and 0.00803 MPa, respectively, while peak strain and deformation occurred at the center. The results had shown close agreement with analytical values, indicating the reliability of the proposed approach for structural integrity assessment.

Hazizi and Ghaleeh (2023) had examined the hazards associated with the design and manufacturing of pressure vessels used for storing dangerous liquids, particularly in response to the rising global demand for liquefied petroleum gas (LPG). The study had aimed to design a vertical pressure vessel in accordance with ASME standards for safely storing 10 m³ of pressurised LPG. The researchers had utilized Autodesk Inventor Professional 2023 for geometric modelling and Inventor Nastran for finite element analysis to evaluate displacements, deflections, and von Mises stresses. It had been reported that the cylindrical vessel, equipped with elliptical heads, nozzles, a manway, and leg supports, required certain structural modifications to reduce stress concentrations. The findings had indicated an inverse relationship between displacement and shell thickness, while the factor of safety had increased linearly with thickness. The manway had experienced the highest stress, whereas other components had shown comparatively lower stress levels. The results had been validated through theoretical calculations, confirming that the design remained within safe limits.

Regassa, Gari, and Lemu (2022) had examined the application of Composite Overwrapped Pressure Vessels (COPVs), which had been widely utilized in aeronautical fields and by organizations such as SpaceX for storing high-pressure fluids. It had been reported that these vessels were preferred over conventional metal counterparts due to their significantly lower weight, although they required specialized design, manufacturing, and testing procedures. The study had employed finite element modeling to perform stress and damage assessments on a COPV with a 4 mm thick aluminum core cylinder. It had been observed that parameters such as lamina sequence, thickness, and fiber winding angle were systematically varied to determine an optimal design configuration. Using ABAQUS composite modeler, 14 models had been developed with carbon fiber/epoxy plies of uniform thickness but different fiber orientations. The findings had indicated that the [55°, −55°] ply stacking sequence provided the best performance, achieving a maximum burst pressure capacity of 24 MPa. Furthermore, the stress–strain distribution had been found to be generally uniform, with peak stresses concentrated near the polar boss region and sharp gradients occurring at geometric transitions due to overlapping fiber orientations.

Zhou et al. (2021) had examined the design and verification of pressure vessels under the guidelines of the ASME Boiler and Pressure Vessel Code (BPVC). It had been observed that conventional design approaches, while complying with BPVC requirements, often resulted in overly conservative structures. The study had suggested that such limitations could be addressed through the application of modern structural optimization techniques. The authors had discussed size optimization of pressure vessels in accordance with the design-by-analysis provisions outlined in ASME Section VIII Division 2. An integrated methodology had been adopted, wherein stress analysis had been performed using ANSYS, and the obtained results had been utilized within a MATLAB-based optimization framework. This automated approach had been applied to the optimal design of an actual pressure vessel. The findings had indicated that material usage could be effectively minimized while still adhering to the maximum stress constraints specified by the BPVC.

Arunkumar, Moorthy, and Karthik (2020) had reported that the design of horizontal pressure vessels subjected to internal pressure, particularly those with dished heads, was generally guided by established codes and standards, which also facilitated the determination of safe dimensional parameters. However, it had been observed that critical design aspects such as the selection of head type, as well as the positioning of nozzles and supports, were largely dependent on the designer’s discretion. The study had emphasized that during the selection of fundamental vessel components, it was essential to ensure that the structure could withstand applied loads while maintaining safe and reliable operation. Furthermore, it had been highlighted that identifying an optimal combination of vessel components, along with appropriate nozzle and support placement, was necessary. The researchers had designed and optimized a horizontal pressure vessel using analysis software, and based on the obtained results, suitable head configurations and optimal locations for inlet and outlet nozzles and supports had been recommended.

Abdelsalam (2019) had investigated the optimization design of a three-layer shrink-fitted cylinder composed of different materials subjected to extremely high internal pressure. The study had aimed to enhance beneficial compressive residual stresses to improve the load-carrying capacity and fatigue life of the cylinder. A finite element model had been developed to evaluate residual hoop stress, equivalent von Mises stress, and equivalent plastic strain. The design variables had included layer thicknesses and diametral interference, while constraints had ensured that von Mises stress in each layer remained below the respective material yield strength under both shrink-fitting conditions and an internal pressure of 750 MPa. Design of Experiments (DOE) and Response Surface Methodology (RSM) had been integrated to formulate an effective objective function. Multi-Objective Genetic Algorithm (MOGA) and Lagrange

Multiplier methods had been applied sequentially to determine optimal parameters. The results had shown a 31% increase in residual hoop stress near the bore and an improvement of fatigue life by 10,900 cycles after optimization.

Oliveira et al. (2018) had presented a study focused on the design optimization of a thin-walled elliptical-headed pressure vessel with a 2:1 axis ratio. The objective had been to optimize the thickness of fiber-reinforced composite layers composed of carbon fiber and epoxy resin using a derivative-based optimization approach. The layup orientations had been treated as key design variables. It had been reported that the Tsai–Wu failure criterion was adopted as a constraint, which had been evaluated through stress analysis based on classical laminate theory and membrane forces derived from finite element analysis (FEA). To reduce computational cost, the optimization process had initially avoided direct interaction with FEA, instead assuming constant membrane forces while updating stiffness. Subsequently, membrane forces had been recalculated using FEA based on the updated structural rigidity. This iterative procedure had continued until the stress values satisfied the defined convergence criteria. Finally, the safety factor, as prescribed by ASME standards for a specific class of pressure vessel, had been verified.

Mali et al. (2017) had reviewed that pressure vessels were specialized containers designed to store and handle fluids that were often toxic, compressible, and operated under high pressure conditions. The authors had highlighted that these vessels had been widely utilized across various industries, including oil and gas, petroleum, chemical processing, power generation, beverages, and food sectors. It had been emphasized that the failure of pressure vessels could lead to severe consequences, such as loss of life, property damage, and environmental hazards. The study had indicated that the design of pressure vessels depended on multiple factors, including operating pressure, temperature, material selection, corrosion resistance, and applied load conditions. Furthermore, the paper had examined parameters responsible for fatigue failure and stress concentration within the vessels. It had also discussed the application of finite element methods and analytical techniques to evaluate failure behavior. Additionally, future advancements in pressure vessel design using modern software tools had been explored.

Elhewy et al. (2016) had examined the conventional ship design process, which had largely depended on statistical data and comparisons with existing vessels rather than analytical and optimization-based approaches. It had been reported that although such practices were commonly preferred by designers to meet owners' requirements, more efficient and cost-effective solutions could exist for both shipbuilders and owners. The study had emphasized the significance of evaluating life cycle cost during the early design stage and had suggested structural optimization as a viable approach to achieve this objective. A detailed structural model of an offshore supply vessel had been developed, and various environmental loads, including still water and wave-induced forces, had been considered. Different loading conditions had been analyzed to identify the most critical scenario affecting the vessel. Furthermore, the concept and characteristics of structural optimization had been outlined, and a blind search optimization technique had been applied, resulting in significant reductions in structural weight and overall cost without compromising structural integrity.

III. KEY FINDINGS FROM STUDY

Author(s) & Year	Objective	Methodology	Key Findings	Research Contribution
Liu et al. (2026)	Optimize composite pressure vessel liner design	FEA, RSM, PSO	Reduced computational cost; improved liner geometry optimization	Developed hierarchical multi-stage optimization framework

Shaik et al. (2025)	Predict burst pressure of pressure vessels	FEA integrated with XGBoost ML model	Higher prediction accuracy than traditional methods	Demonstrated ML-FEA hybrid for structural integrity prediction
Solangi et al. (2024)	Analyze vacuum pressure vessel for aerospace use	FEA using ANSYS	Identified stress zones; max stress 0.763 MPa	Validated ASME-based design using numerical simulation
Hazizi & Ghaleeh (2023)	Design vertical LPG pressure vessel	FEA using Autodesk Inventor & Nastran	Manway showed highest stress; thickness reduced deformation	Improved safe design under ASME standards
Regassa et al. (2022)	Optimize COPV design	FEA (ABAQUS), fiber orientation study	[55°, -55°] layup gave best performance (24 MPa burst)	Showed importance of fiber orientation in composites
Zhou et al. (2021)	Optimize pressure vessel design under ASME BPVC	ANSYS + MATLAB optimization	Reduced material usage while meeting stress limits	Proposed integrated stress-analysis-based optimization
Arunkumar et al. (2020)	Optimize horizontal pressure vessel design	FEA-based design simulation	Head type and nozzle position strongly affect safety	Improved layout optimization of vessel components
Abdelsalam (2019)	Enhance shrink-fitted multi-layer vessel performance	FEA + RSM + MOGA	31% stress increase; improved fatigue life	Optimized residual stress distribution in layers
Oliveira et al. (2018)	Optimize composite pressure vessel design	FEA + derivative-based optimization	Satisfies Tsai–Wu failure criteria	Reduced computational cost in composite design
Mali et al. (2017)	Review pressure vessel design & failure	Literature review	Identified key failure factors (stress, fatigue)	Provided broad overview of vessel design issues
Elhewy et al. (2016)	Reduce weight of offshore vessel	FEA + structural optimization	Significant weight and cost reduction achieved	Demonstrated effectiveness of optimization in ship structures

IV. CONCLUSION

The reviewed literature on the design optimization of pressure vessels using Finite Element Analysis (FEA) and advanced optimization techniques clearly indicates a significant evolution in structural engineering practices from conventional conservative design approaches to modern computationally driven methodologies. Earlier studies primarily relied on empirical equations and code-based design standards such as ASME BPVC, which ensured safety but often resulted in overdesigned structures with unnecessary material usage and increased cost. However, recent research trends have demonstrated that integrating numerical simulation tools like FEA with optimization algorithms and data-driven models provides a more efficient and accurate framework for pressure vessel design. Studies such as Zhou et al. (2021) and Liu et al. (2026) have shown that hybrid optimization techniques combining FEA with methods like Particle Swarm Optimization (PSO), Response Surface Methodology (RSM), and machine learning algorithms significantly enhance design efficiency while reducing computational cost. Similarly, research by Shaik et al. (2025) and Regassa et al. (2022) highlights the growing importance of artificial intelligence and composite material optimization in predicting structural behavior and improving burst pressure performance. Across all reviewed studies, it has been consistently observed that stress concentration, material selection, geometric configuration, and loading conditions are the most critical factors influencing pressure vessel performance and safety. Furthermore, finite element-based analysis has proven to be an essential tool for accurately identifying failure zones and validating analytical models under complex loading conditions. The integration of optimization techniques with FEA has not only improved structural reliability but has also contributed to weight reduction, cost efficiency, and enhanced fatigue life of pressure vessels. Therefore, it can be concluded that modern pressure vessel design is increasingly dependent on computational intelligence and numerical optimization frameworks, which collectively enable engineers to achieve safer, lighter, and more efficient structural systems that comply with international design standards while meeting industrial demands.

V. FUTURE SCOPE

The future scope of research in the design optimization of pressure vessels using Finite Element Analysis (FEA) and advanced optimization techniques is highly promising, as ongoing developments in computational mechanics, artificial intelligence, and material science continue to transform engineering design methodologies. One of the major future directions lies in the integration of multi-physics simulation frameworks that simultaneously consider mechanical, thermal, corrosion, and fatigue effects to provide a more realistic prediction of pressure vessel behavior under actual service conditions. This will significantly improve the reliability of structural assessment beyond conventional single-domain analysis. In addition, the increasing adoption of artificial intelligence and machine learning techniques is expected to revolutionize pressure vessel optimization by enabling data-driven predictive modeling of failure behavior, burst pressure, and fatigue life with minimal reliance on repeated finite element simulations. Hybrid models combining deep learning algorithms with FEA can further enhance accuracy and reduce computational cost, making real-time design optimization feasible in industrial applications. Another important area of future research is the advancement of composite materials, particularly nano-reinforced polymers and hybrid composites, which can offer superior strength-to-weight ratios and improved resistance to extreme pressure environments. Optimization of fiber orientation, stacking sequence, and hybrid layering using evolutionary algorithms and metaheuristic techniques will play a key role in next-generation pressure vessel design. Furthermore, digital twin technology is expected to become a transformative tool in pressure vessel monitoring and lifecycle management by enabling continuous simulation and real-time structural health monitoring using sensor data integration. The incorporation of cloud computing and high-performance computing (HPC) will also allow large-scale optimization problems to be solved more efficiently, supporting complex geometries and multi-variable constraints. Additionally, future research may focus on sustainability-driven optimization approaches aimed at reducing material waste, energy consumption, and environmental impact during manufacturing and operation. Improved compliance-based optimization frameworks aligned with evolving international standards such as ASME BPVC will further ensure safety and performance consistency. Overall, the future of pressure vessel design lies in intelligent, adaptive, and sustainable engineering systems that combine simulation, optimization, and real-time data analytics to achieve highly efficient and reliable structural solutions.

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