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A Review of Finite Element Methods in Pressure Vessel and Piping Stress Analysis

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***Abstract*—The building blocks of the industrial process systems are pressure vessels and piping networks, in which a leak or a loss of integrity may have disastrous safety, environmental, and economic impacts. With the ever-growing operating pressures, temperatures and the complexity of the systems, stable stress analysis has emerged as one of the major requirements in system design and evaluation. The present paper is a review of traditional and new methods of stress analysis of pressure vessels and piping with emphasis on the Finite Element Method (FEM). The restrictions of traditional analytical and code-based methods of managing complex geometries, combinations of loads, and local stress impacts are addressed. Special focus is laid on the behavior of stress in pipelines, study of nozzle in pressure vessels, classification of stresses and failure mode. Recent research advancements, such as advanced numerical modeling, coupled thermal structural analysis, experimental stress monitoring, and data-based prediction methods, are also surveyed in the paper. This review offers a clear vision of the emerging role of FEM and related methods in the design of safe, efficient, and reliable pressure vessel and piping systems by bringing together the existing methodologies and identifying the available research gaps.**

Keywords—Pressure vessels, Piping systems, Stress analysis, Finite Element Method (FEM), Nozzle stress, Pipeline integrity, ASME codes.

I. Introduction

Over 98% of subterranean oil and gas transmission pipelines are affected, despite their design, construction, and protective measures. These pipelines remain vulnerable to environmental assaults, external impacts, coating deterioration, inherent material flaws, ground movement and instability, as well as damage caused by third parties during field operation. The pipe system is an integral part of the process in the industry for transferring fluids, and it is exceptionally well-designed to safeguard the whole facility. This guarantees the proper and efficient transmission of fluids [1]. A pressure vessel is a confined space that can be subjected to pressure from both inside and outside. Used most frequently as reactors, storage tanks, and heat exchangers in industrial settings. The foundation of pipe design is stress analysis, which addresses whether routing, hangers, nozzle loads, and supports are suitable for withstanding different stresses while staying within allowed bounds. Process and power pipe systems: stress analysis assesses how piping behaves mechanically under normal loads, including internal pressure and temperature stress, as well as pressures brought on by wind, water hammer, earthquakes, and unique vibrations. A crucial aspect of designing pressure vessels is analysing the stress on welded nozzles [2]. The primary issues brought on by stress buildup, material interactions, and external pressures have led to the development of several strategies meant to address these issues. Numerous cylindrical shell nozzles and loading scenarios have benefited from the knowledge provided by these techniques, which have seen extensive use in nozzle stress analysis [3][4]. Nevertheless, these methods do not provide perfect stress concentration monitoring at the nozzle-cylinder interface, especially when dealing with complex mechanical and thermal pressures.

Finite Element Analysis (FEA) has replaced the traditional approach as the gold standard for analysing nozzle stresses, allowing us to overcome these obstacles. Previous papers have extensively compared WRC techniques and FEA, noting their strengths and drawbacks and underlining how both approaches are complementary and should therefore be used in combination to get highly accurate stress analysis [5]. The concept behind developing better stress analysis technology to prevent middle-of-life failures and boost safety is predicated on the continuous inspection and maintenance of the various in-service pressure vessel nozzles [6].

A. *Structure of paper*

This paper is structured as follows: Section II describes the overview of FEA. Sections III and IV discuss pipeline stress analysis and pressure vessel nozzle stress analysis, respectively. Section V presents a review of related literature and identifies research gaps, and Section VI concludes the paper with future directions.

II. Finite Element Analysis

FEA (Solid works) uses the displacement formulation of the finite element method to calculate component displacements, strains, and stresses under internal and external loads. Solid works is mostly engaged in the assumption of triangular (2D) simplification for plant stress. FEA utilising Solid works simulation, which is integrated with Solid works 3D CAD, is aware of the precise geometry throughout the meshing process. Solid works computes the stresses and displacements using the FEA approach [7]. The complex load-deformation relationship of non-metallic components necessitates the use of nonlinear stress analysis methods (for more information, see the SOLIDWORKS Nonlinear Stress Analysis capabilities page).

FEA is a computationally clever method for predicting how an engineering product or component will react to various physical stresses, including vibration, heat, fluid movement, and more [8]. FEA predicts whether a product will work as expected, break, wear out, or collapse. It is used to determine practical stresses for externally loaded nozzles. It resolves software bugs and security issues. It is used to manage intricate geometry [9]. FEM is quite flexible, allowing you to do various things for each element according to your requirements. Problems with built-in variation principles are another drawback. FEMs continue to advance. It is the manner in which a computational mesh depicts damage. The time required to generate a computational mesh from a CAD file is substantial. There can be no simplification without accurately stating the pressures on complicated structures by analytical approaches.

III. Stress Analysis of the Pipelines

The stress study of the pipelines involves specific difficulties, such as unique pipeline characteristics, coding requirements, and methods. The components of the study are soil friction, lateral soil force, pipe movement, anchoring force, and soil-pipe contact. A pipeline's distinctive qualities include:

1) *High Allowable Stress*

A pipeline has a rather straightforward form. It is round and frequently stretches for many km before turning. Therefore, all predicted stresses are derived from simple, very reliable static equilibrium calculations. Because stressors are predictable, the permissible stress is often high.

2) *High Yield Strength Pipe*

Although there may be no problems with the pipeline's structural integrity, excessive deformation and strain follow-up are possible outcomes of operating exceeding its yield strength. As a result, pipelines often use high-test line pipe, which has a very high ratio of yield to ultimate strengths. The yield strength of some pipes may reach 80% of their maximum strength [10]. The yield strength is the only criterion for permissible stresses.

3) *High-Pressure Elongation*

The typical reason for pipeline movement is the growth of a lengthy line at a small temperature difference. The study must take pressure elongation into account since it adds significantly to the overall movement.

4) *Soil-Pipe Interaction*

A pipeline's main section is buried under the surface. Soil force, which may be described as the combined effects of pushing pressure and sliding friction, must be overcome by any pipe movement. Examining the relationship between soil and pipes is the main goal of pipeline analysis.

B. *FEM Applications in Pressure Vessel Nozzle Stress Analysis*

The stress in nozzles of pressure vessels may be studied using the FEM in a variety of designs and under different situations. 2D FEM models work well for symmetrical nozzles with simple loading, while 3D models are essential for capture complex stress distributions in complex geometries and multi-nozzle systems [11]. Various configurations, including radial, tangential, and inclined nozzles, may be properly modelled using FEM in terms of stress concentrations, flexibility, and interactions.

The many types of applications are discussed below:

- Stress and flexibility studies in pressure vessels with various nozzle configurations are often performed using the Finite Element Method (FEM).
- It's capable of building precise models of radial, tangential, and inclined nozzles, as well as their orientations relative to cylinder shells and vessel heads.
- FEM may also take into account the impact of vital components that are geometrically or materially nonlinear under complicated load situations, such as internal pressure, thermal expansion, and external forces caused by interconnected pipe networks.
- FEM can effectively modify meshes in the crucial area surrounding nozzle junctions using sophisticated meshing techniques, allowing for accurate stress distribution determination.
- The FEM is also used for obtaining bending stresses, evaluating the flexibility of nozzle-to-shell connections, estimating strength, and studying crack propagation.
- Nozzle-FEM and NozzlePRO software assess nozzle safety and performance in sectors such as oil and gas, petrochemicals, and power generation.
- These tools are great for improving nozzle designs, making pressure vessels tougher in demanding operating circumstances, and increasing safety.

IV. Stress Analysis of Pressure Vessel Nozzle

Several loads put different amounts of stress on the various parts of the pressure vessels. The form of the vessel, the design of its components, and the sort of load all influence the kinds and amounts of stress [12]. The following factors can cause loads on pressure vessels: internal and external pressures, equipment weight, static reactions, welded components (such as nozzles, pipes, isolations, and internal supports), temperature variations, wind loads, seismic forces, fluid impact reactions, and temperature gradients (as stated in ASME VIII division 1 paragraph UG-22).

A. *Stress Categories*

Stress may be divided into three categories: main, secondary, and peak. The major stresses may be broadly classified into two groups: bending and membrane load. The secondary stresses are membrane and bending stresses.

- **Primary stress:** The primary cause of stress can be shear stress, which is generated by either normal stress or loading. These stresses remain constant regardless of how much the structure bends. There are primarily three forms of primary stress: principal bending stress (Pb), primary local membrane (PL), and primary general membrane (Pm).
- **Secondary stress:** Two types of secondary stress that experience deformation and diminish in value are normal and shear stress.
- **Peak stress:** The peak stress, represented by the letter F, is a cumulative stress. The primary and secondary stresses combine to form peak stresses where the stress is concentrated. Peak stresses are only important in brittle materials or fatigue scenarios. A fatigue crack could form as a result of a peak stress, which can be membrane, bending, or shear stress. The

potential for stress to accumulate in some areas is shown by discontinuity corners.

B. working of pressure vessel

Canister and missile components are pressure qualified using the current pressure vessel to determine whether or not the component can resist the imposed pressure. The cylindrical canister, which is a crucial component of the underwater missile launch mechanism, has a top dome [13][14]. This canister prevents the missile from coming into contact with water during launch and permits its movement after ignition. Figure 1 depicts the operation of a pressure vessel.

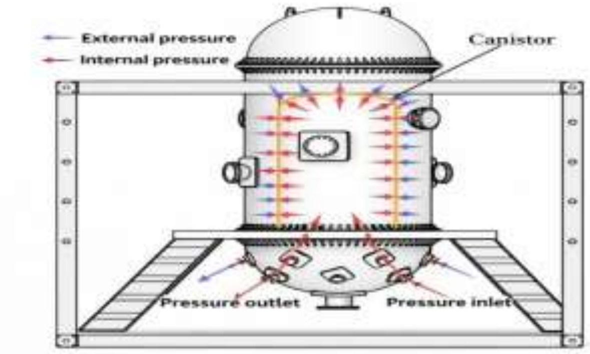

Fig. 1. Working of pressure vessel[15]

There are twelve auxiliary communication chambers in the bottom dome of the pressure vessel, six of which are in lower PCD and the other six in higher PCD. The canister is pressurised internally by inserting pressure into a few lower PCD chambers; the remaining chambers of the same PCD are used for depressurisation, in order to establish the desired pressure [16]. Some of the higher PCD communication chambers allow for the external pressurisation of canister pressure. Cylinders of nitrogen are integrated for the necessary pressurisation [17]. The canister is fastened to the base plate using bolted joints.

C. Classification of the pressure vessel

The design characteristics of pressure vessels usually differ. The industry offers a wide variety of designs, but they always fall into one of these two categories. Vessels with a solid wall and multi-layered vessels [18]. Additionally, pressure vessels may be further classified according to factors including materials, orientation, pressure-bearing conditions, manufacturing processes, technical advancements, and mode of use[14].

- **Solid Wall Vessel:** The diameter-to-wall-thickness ratio characterises a solid-wall vessel, also referred to as a monobloc pressure vessel, which is defined as a closed-end, cylindrical cylinder with sealed ends. A thick-walled or thin-walled cylinder can be identified from the vessel exterior by utilising this ratio as a reference standard[18].
- **Multi-layered Vessel:** It is possible to construct a simple multilayer vessel by compressing two or more layers into a central tube of different diameters made of homogenous and isotropic materials [19]. The right multilayering procedures and volume requirements must be understood in order to use this multilayer vessel design efficiently; otherwise, it would be a complete waste of investment and materials.

Figure 2 shows two kinds of pressure vessels: those with a solid wall and those with several layers. The thickness of the shell or the internal fluid pressure dictates the thickness of the solid wall vessel's shell.

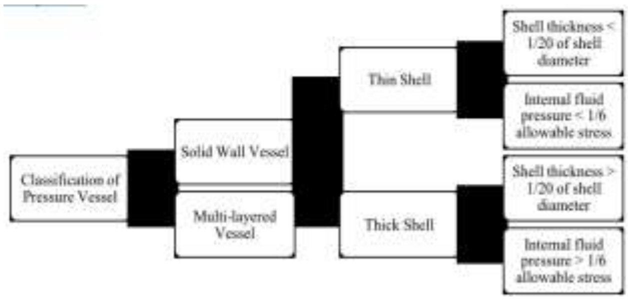

Fig. 2. Classification of pressure vessel [20]

D. Applications of the pressure vessel

Figure 3 below illustrates a few examples of pressure vessel uses in the commercial and industrial sectors. There are too many uses for pressure vessels to list them all here.

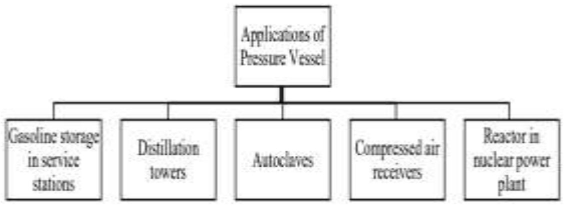

Fig. 3. Application of pressure vessel [21]

An essential piece of pressurised equipment, the pressure vessel serves numerous industries, especially those involving storage. There has been a meteoric rise in their global use as production technology has advanced. Future advancements in the material will allow for an ever-expanding range of vessel applications.

E. Failures in the pressure vessel

A larger vessel indicates a greater potential for harm or hazard due to the fact that its energy storage capacity grows in direct proportion to its size. It is important to recognise the many kinds of vascular failure in order to avoid a rupture [22]. This section presents instances of vessel failures from the viewpoints of materials, design, fabrication, and service.

- Vessel material thinning, erosion, corrosion, and cracking that is hard to detect; inadequate material selection; failure due to creep and fatigue; and material embrittlement due to lower temperatures.
- Poor safety valve implementation, inaccurate design data, inadequate or non-existent testing, failure to identify design flaws early, and inappropriate vessel content composition.
- Inadequate welding, fabrication mistakes, standard requirements violations, erroneous manufacturing procedures, and inappropriate assembly or installation.
- An inexperienced operator, inadequate vessel maintenance, operating at temperatures and pressures higher than permitted, changes in service conditions, dangerous or unauthorised alterations, incorrect leak repair, low water conditions, and high stress conditions.

V. Literature review

This section delves into prior studies that compared various methods of piping stress analysis using various tools, techniques, and best practices.

Yuejun and Feilong (2025) presents a hybrid approach that integrates the semi-analytical finite element (SAFE) method with a modal superposition strategy. A one-dimensional axisymmetric model is constructed using COMSOL, and guided wave modal characteristics are extracted through MATLAB-based post-processing. Radial data are then extended to the circumferential plane using analytical harmonic functions, significantly reducing the mesh density required. Additionally, the method enhances computational efficiency and numerical stability through optimized matrix operations and an improved scattering boundary integration scheme. Numerical results demonstrate that the proposed hybrid method maintains the strengths of the original computational framework while substantially lowering mesh and computational resource requirements, thereby offering an effective tool for the efficient detection and quantitative evaluation of non-axisymmetric defects in pipelines [23].

Weishen *et al.* (2025) mechanical response characteristics under specific working conditions were analyzed by employing Workbench, and the circumferential and axial stress distribution characteristics of the pressure vessel were clarified. Based on the above outcomes, a stress monitoring scheme based on fiber Bragg grating was constructed. The stress values at the corresponding positions were determined through system experiments. By comparing the measured data with the simulation results, the scientificity and feasibility of the stress monitoring method were verified, providing an engineering implementable technical approach for the structural health monitoring of this type of pressure vessel [24].

Chan *et al.* (2024) use of machine learning offers a promising alternative by providing a faster and more efficient approach to predicting stress distribution. This paper shows a prototype focused on the development of a stress distribution surrogate prediction model using an encoder-decoder-based convolutional neural network to analyze the stress distribution of a 3D cylindrical pipe. The related works and methodology are discussed. Then, the results of the study are presented, followed by main conclusions and ideas for future work [25].

Hazizi and Ghaleeh (2023) stressed the importance of designing pressure vessels in compliance with ASME standards in order to ensure safety and prevent hazards associated with erroneous design and manufacture. The combination of InventorNastran and AutodeskInventor Professional was effective for modelling and evaluating the performance of the pressure vessel. The investigation led the scientists to conclude that modifying the structure of the pressure vessel was essential for diminishing stress. Displacement was found to be inversely proportional to tank section shell thickness, whereas safety factor rose linearly with shell thickness. An analysis of the stress distribution revealed that the manway and shell had the greatest stresses, whereas the heads, nozzles, and leg support had the lowest strains. The finite element approach allowed for the required safety-enhancing changes by identifying potential stress spots in the pressure vessel[26].

Thakran (2022) provide an exhaustive synopsis of all the methods, tools, and best practices that have been created for analysing pipe stress. The article makes an effort to establish the key points of stress analysis, including the many forms of stress and the proper standard controls for evaluating them. The CAESAR II and other programs like AutoPIPE and ROHR2 frequently use piping stress analysis to explain the software's capabilities, accuracy of the results, and flaws. A comprehensive literature evaluation reveals information gaps and reiterates the significance of sensitivity analysis, especially when it comes to static and dynamic analysis. The findings should help academics and engineers select suitable methods and instruments for conducting reliable piping stress analyses[14].

Wenhui *et al.* (2022) offers a quantitative foundation for the product's concept, fabrication and manufacturing. Cooling pipes and heat exchangers both make use of heat sinks. The direct coupling analysis approach is used to study thermal structural coupling, which is the connection between an object's structure and heat. The ability to address two physical field problems with a single element type is known as direct coupling. Real coupling and cost savings in issue analysis are possible using heat and structure [27].

Salins, Mohan and Stephen (2021) focus on simulating the pressure vessel using the finite element technique with typical dimensions in CREO 6.0 and then analysing it for three different materials and pressure environments. This investigation is looking at the feasibility of using carbon steel, stainless steel, and titanium alloy as building blocks for pressure vessels. The results of the finite element analysis may be shown graphically now. Titanium alloy proved to be quite safe with a factor of 4.10 and capable of withstanding heavy loads. Stainless steel has the weakest structural performance compared to the other steels [28].

TABLE I. Comparative Summary of Piping and Pressure Vessel Stress Analysis Methods, and Tools

Author (Year)	Tools / Techniques	Application Focus	Key Contribution	Limitations
Yuejun & Feilong (2025)	SAFE method, Modal Superposition, COMSOL, MATLAB	Pipeline defect detection	Proposed a hybrid SAFE–modal framework that reduces mesh density and computational cost while accurately identifying non-axisymmetric pipeline defects.	Primarily validated numerically; experimental validation and large-scale industrial applicability were not addressed.
Weishen et al. (2025)	ANSYS Workbench, Fiber Bragg Grating (FBG) sensors	Pressure vessel stress monitoring	Developed and experimentally validated an FBG-based stress monitoring scheme aligned with simulation results for structural health monitoring.	Limited to specific operating conditions and vessel geometry; long-term durability of sensors was not evaluated.
Chan et al. (2024)	Encoder–Decoder CNN, Machine Learning	Stress prediction in 3D cylindrical pipes	Introduced a deep learning surrogate model enabling rapid stress distribution prediction with reduced computational effort.	Model performance depends on training data quality; generalization to complex geometries remains uncertain.

Hazizi & Ghaleeh (2023)	Autodesk Inventor, Inventor Nastran, FEM, ASME codes	Pressure vessel structural design	Demonstrated FEM-based design optimization to reduce stress concentrations and improve safety through shell thickness variation.	Focused on static loading; fatigue, thermal, and dynamic effects were not considered.
Thakran (2022)	CAESAR II, AutoPIPE, ROHR2	Piping stress analysis methodologies	Provided a comprehensive review of piping stress analysis tools, standards, and best practices, emphasizing sensitivity analysis.	Lacks quantitative comparison or experimental validation of reviewed software tools.
Wenhui et al. (2022)	Direct thermal–structural coupling, FEM	Heat exchanger and cooling pipes	Showed effective thermal–structural interaction analysis using direct coupling, improving accuracy and reducing computational cost.	Application scope limited to coupled thermal problems; mechanical-only scenarios were not analyzed.
Salins, Mohan & Stephen (2021)	CREO 6.0, Finite Element Analysis	Pressure vessel material evaluation	Compared materials under varying pressure loads and identified titanium alloy as having the highest factor of safety.	Material behavior under cyclic and thermal loading conditions was not investigated.

Research Gap: Although there have been enormous developments in the piping and pressure vessel stress analysis, as summarized in Table 1, a number of research gaps can still be identified. Majority of the studies in existence are majorly based on numerical simulation or surrogate models, and few experimental validation studies are carried out on them under real operating and service conditions under long-term conditions. Finite element, commercial tools and finite element using methods are common but there is still a lack of comparative benchmarking between various software platforms, loading conditions (static, dynamic, thermal, and coupled), and complex geometries. The machine learning-based stress predicting models demonstrate potential improvements in the cost of computation but the generalizability, interpretability, and adherence to the existing design codes are still poorly studied. Moreover, the behavior of fatigue, transient loading effects, quantification of uncertainty, and sensitivity analysis are usually ignored or handled separately. These gaps point to the necessity of an all-encompassing, tool-agnostic comparative framework that integrates numbers, experimentation, and data-driven methods to attain more credible and code-compliant piping stress analysis.

VI. CONCLUSION AND FUTURE WORK

In the contemporary industrial infrastructure, pressure vessels and piping systems are essential elements, and the safe and reliable functioning under the high pressure, thermal, and environmental loads is especially significant. This review has discussed the basic elements of stress analysis in such systems, including the development of traditional analytical and code-based methods to the development of sophisticated numerical methods. Although the traditional techniques are still handy in initial design and simplified problems, they tend to be insufficient to reflect on complex stress conditions, localized stress concentration and nonlinear forces present in actual operating conditions. FEM has consequently emerged as a powerful and popular technology, which provides high precision in the analysis of any complicated geometry, nozzle-shell contact, soil-pipe behavior, and integrated mechanical and thermal loading as required by the standards, including ASME. The analyzed literature shows that the combination of FEM with experimental verification and new data-intensive approaches contributes greatly to design optimization, failure prevention, and structural safety, which supports the idea that stress analysis with FEM is one of the critical stages in the design and evaluation of pressure vessels and piping systems.

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