International Journal of Scientific Research and Management (IJSRM)
||Volume||12||Issue||09||Pages||1452-1459||2024||
Website: https://ijsrm.net ISSN (e): 2321-3418
DOI: 10.18535/ijsrm/v12i09.ec05

Finite Element Analysis of the Pressure Vessels with Various Materials and Thicknesses

Mehmet Ali Acar[1], Can Gönenli*, Mustafa Berkant Selek[2]

[1]Ege University, Graduate School of Natural and Applied Sciences, Izmir, Turkey
[*]Ege University, Ege Vocational School, Mechanical and Metal Technologies, Izmir, Turkey
[2]Ege University, Ege Vocational School, Electronics and Automation, Izmir,

Abstract:
Pressure vessels are widely used in many areas. Ensuring the safe operation of pressure vessels is particularly important, especially in residential and industrial applications. Errors made during the use of pressure vessels or mistakes during manufacturing and design can lead to significant accidents, resulting in loss of life and property. With the increase in industrialization and energy production, significant advancements have been made in the field of pressure vessels. These vessels are used in various applications, such as heat exchangers in domestic heating systems, and in industrial facilities for the production of steam, superheated oil, and hot water needed for production and separation processes. The advancement of technology and the updating of design and computer aided design programs enable more accurate results in new design and analysis, allowing to produce more reliable and safer materials. To minimize occupational accidents, necessary precautions must be taken in advance. The development of pressure vessels in terms of occupational safety has been ongoing from past to present and is being further enhanced through ongoing studies. In our study, pressure and stress analysis were conducted using the finite element method on ANSYS. Mechanical analyses were repeated for three different thicknesses and three different material types. The purpose of the mechanical analysis was to examine the effect of the thicknesses and different material types on pressure vessels in terms of stress, deformation, and strain.

Keywords: Pressure Vessel, Mechanical Strength, Computer Aided Analysis, Stress

1. Introduction

Pressure vessels are a type of engineering structure widely used in various areas such as heat exchangers, industrial facilities, superheated oil, and hot water required for production and separation [1]. Due to the risk factors and safety instructions, these vessels continue to be a subject of numerous studies in the literature [2]. Key aspects, such as material selection and structural integrity, are thoroughly evaluated before production using various finite element analysis programs [3]. The initial research on cylindrical pressure vessels was based on the analytical use of the Kabuki equations [4]. In subsequent years, the development of analytical methods enabled the solution of complex pressure vessel problems [5]. During the late 1960s, the focus on nuclear fusion research increased, leading to more studies on pressure vessels in nuclear facilities and the adoption of analysis-based pressure vessel design practices [6]. Due to discontinuities and changes in the wall thickness of pressure vessels, which cause stress concentrations, studies have been expanded to include vessel damage analysis. The literature includes numerous studies on the finite element analysis of pressure vessel damage [7]. Pressure vessels are typically used when there is a need to store liquids at high pressures and temperatures. They are commonly employed in the chemical industry, refineries, nuclear power plants, and the petroleum refining industry. When designing pressure vessels, it is crucial to thoroughly analyze the specific application area to prevent potential issues that could arise from exposure to high internal pressures or temperatures. Errors in design or flawed analyses conducted before the design phase can lead to various hazards, occupational accidents, and consequently, loss of life or injuries. To prevent such occupational accidents, it is necessary to adhere to various internationally recognized standards [8, 9].

In the manufacturing of pressure vessels, steel and steel derivatives are commonly used, with carbon steel being preferred due to its strength and component properties. In addition to carbon steel, non-ferrous materials such as Nickel, Aluminum, or Austenitic and Ferritic steel materials are used to meet specific demands related to the vessel's usage. Due to the high risk of corrosion and erosion in pressure vessels, it is important to prevent the strength values of carbon steel from being exceeded. This can be achieved by coating the vessel with metallic or non-metallic materials. Furthermore, pressure vessels can be made from alloy steels that offer high resistance to high pressure and high temperature conditions. The properties of the chosen materials—such as tensile strength, operating temperature, fracture analysis, safety factor, yield strength, wear factor, and resistance to hydrogen embrittlement—must be well understood. When selecting appropriate materials, factors like the operating period of the pressure vessel and material criteria should also be considered. Additionally, the choice of materials should consider factors such as cost, availability of raw materials, machinability, and weld ability during production to ensure proper assembly of the materials.

During the service life of pressure vessels, material thickness may reduce due to various factors such as wear, erosion, and corrosion. Therefore, the selected material should be thicker than the minimum required thickness. The service life of pressure vessels is economically significant, and the choice of materials used in their production has a long-term impact. In this study, a pressure vessel designed in SolidWorks was analyzed with ANSYS to examine the effects of three different thicknesses and three different material properties on the mechanical characteristics. The effects of each material on stress, deformation, and strain for each thickness were analyzed and discussed.

2. Materials and Methods

2.1 Classification of pressure vessels and testing techniques

Test pressure is applied by the manufacturer to all vessels and assembled components during production or assembly stage [10, 11, 12]. Pressure vessels are generally classified based on their functions, geometries, constructions, modes of operation, and the types of materials used in their production. Specifically, they can be categorized into five classifications:

- Function-Based Classification
  This refers to the specific purpose or application of the pressure vessel, such as storage, heat exchange, or chemical reactions.
- Geometry-Based Classification
  This involves the shape and physical dimensions of the vessel, such as cylindrical, spherical, or conical designs.
- Construction-Based Classification
  This concerns the structural design and fabrication methods, including welded, bolted, or riveted constructions.
- Operation-Based Classification
  This classification relates to the operational conditions under which the vessel is used, such as pressure levels, temperature ranges, and the presence of corrosive or hazardous substances.
- Material-Based Classification
  This focuses on the materials used in the construction of the vessel, including carbon steel, stainless steel, aluminum, or specialized alloys, which are selected based on the vessel's intended use and environmental conditions.

In addition to these classifications, various testing techniques are employed to ensure the safety and integrity of pressure vessels. These may include pressure tests, non-destructive testing (NDT) methods such as ultrasonic testing, radiographic testing, and dye penetrant testing, as well as material tests to assess properties like tensile strength, hardness, and corrosion resistance [13].

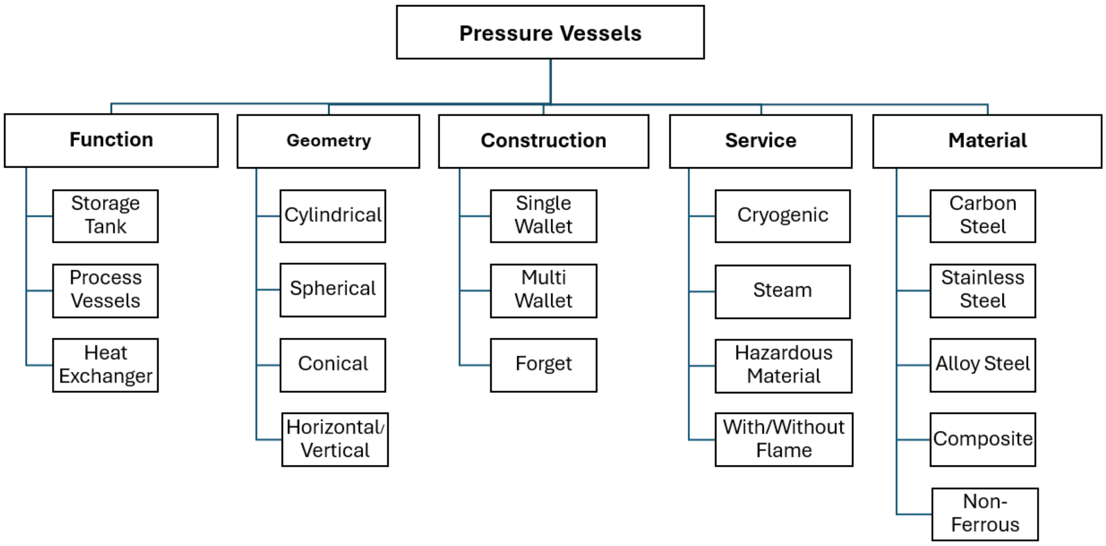

Figure 1: General classification of pressure vessels [14]

Figure 1 would typically illustrate the various categories and subcategories used to classify pressure vessels based on different criteria such as function, geometry, construction, operation, and material. It provides a visual representation of how pressure vessels are systematically organized according to these different characteristics. The history of boilers, which played a central role in the Industrial Revolution, dates back to the 18th century. Boilers are heat sources that introduced steam power to humanity through the work of James Watt and brought more comfortable climate conditions to our living spaces. With the emergence of housing and collective accommodations, the need for heating and comfort increased, leading to the development of technical tools and systems to address this issue. As population growth increased the demand for space, the concept of transporting heat from a central source via water (heating systems) to different locations rather than providing it from a separate source became widely implemented in various environments. Periodic testing usually involves filling the vessel completely with cold water, sealing all inlets and outlets, and pressurizing the vessel with water to the test pressure level. Another method involves pressurizing the vessel with gas, sealing all inlets and outlets, and then examining the vessel after releasing the gas. This technique is known as a pneumatic test and is one of the more rigorous testing methods. Table I shows the periodic control criterias and periods.

Table 1: Check and periodic control criterias [15]

Equipment name	Check Period	Equipment name
Steam Boilers	1 year if the period is not specified in the standards	It is done in accordance with the criteria specified in TS 2025 and TS EN 13445-5 standards
Heating Boilers	1 year if the period is not specified in the standards	It is done in accordance with the criteria specified in TS EN 12952-6 standards
Tanks and Warehouses containing hazardous liquids	10 Years	It is done in accordance with the criteria specified in API 620, API 650, API 653, API 2610 standards

2.2 Design parameters of pressure vessels and loads affecting the vessels

The use of pressure vessels is inherently dangerous and has led to numerous accidents resulting in significant loss of life and property. Several risk factors must be considered to minimize these risks and ensure that pressure vessels can safely operate under these conditions. It is crucial for human safety that all forces acting on the vessel are identified, and their impact calculated during the design phase. After manufacturing, all safety inspections must be conducted in accordance with relevant standards. The primary forces affecting pressure vessels are internal and external pressure. Other loads include temperature, wind, weight, vibrations, static loading, and dynamic loading. Finite element analysis (FEA) is a numerical method used to solve complex engineering problems, providing results for stress, heat transfer, fluid flow, and other issues [16, 17].

In Figure 2, a cylindrical pressure vessel design is depicted, supported by two base-mounted legs. The design specifies a material thickness of 6, 8, and 10 mm, with the front and rear ends featuring an elliptical cap design. An opening is provided on the front cap for the installation of a burner.

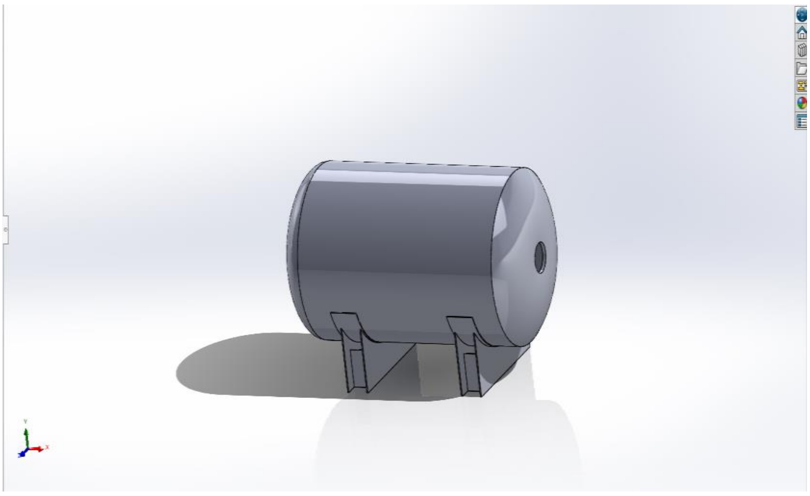

Figure 2: Solid view of a cylindrical pressure vessel

2.3 Finite element analysis of a pressurized boiler

The model is assembled using a meshing package for advanced finite element analysis, a process referred to as "meshing." Meshing is crucial as it defines the component's supported structure and plays a significant role in the finite element analysis (FEA). This step forms the foundation for analyzing the model, ensuring accurate simulation of stresses, deformations, and other physical phenomena under various conditions. Figure 3 shows the mesh view of the pressure vessel.

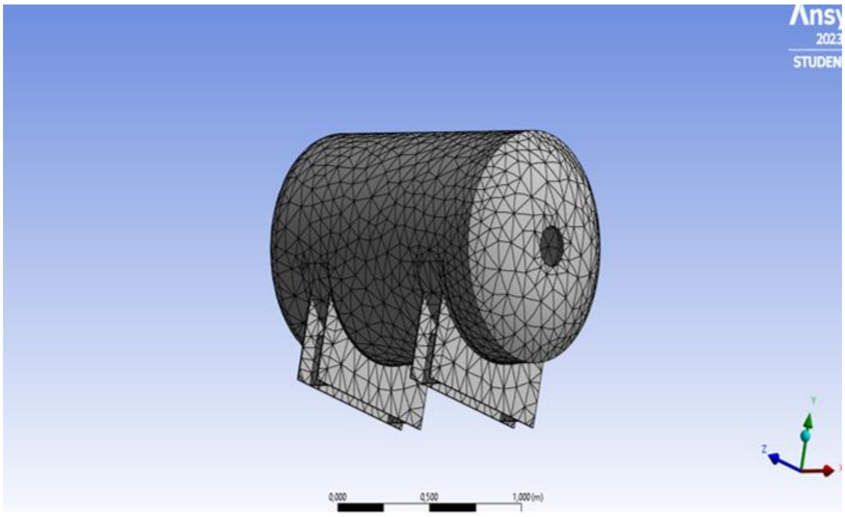

Figure 3: Mesh view of pressure vessel

3. Results

After applying the mesh to the model using the ANSYS software, a "Fix Support" operation was performed, and material assignment was carried out. In this study, Aluminum Alloy, Stainless-Steel, and Copper materials were selected. Table II shows the material properties of the selected materials.

Table 2: Material properties

Material	Young's Modulus	Density	Poisson's

	(GPa)	(kg/m^3)	Ratio
Stainless Steel	193	7750	0.31
Aluminium Alloy	71	2770	0.33
Copper	110	8300	0.34

According to the TS 2025 [10], before the boiler is operated or after undergoing extensive repairs, a hydrostatic test must be conducted at 1.5 times the operating pressure to verify the vessel's integrity. For the boiler analyzed in this study, with an operating pressure of 6 bar, the maximum test pressure applied was 9 bar, equivalent to 900,000 Pascals. The test pressure value varies for each boiler and is specified on the boiler's information label after production. The finite element analysis indicated that, the maximum stress occurred at the model's lid sections for the stainless steel pressure vessel with 6 mm thickness, as illustrated in the Figure 4.

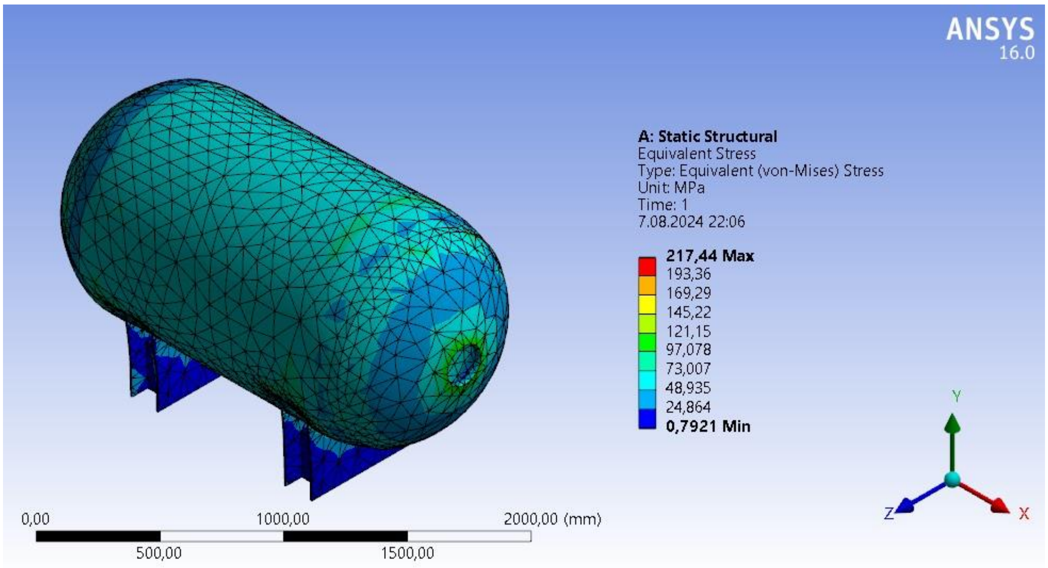

Figure 4: Stress analysis of pressure vessel

The deformation view for stainless steel is given in Figure 5. After the material change, it is observed that stainless steel is more resistant to deformation. The smallest deformation in 6 mm walled vessels was calculated for the stainless steel material type. It was also observed that the maximum deformation value calculated by increasing the wall thickness by 67% depending on the thickness decreased by 14%.

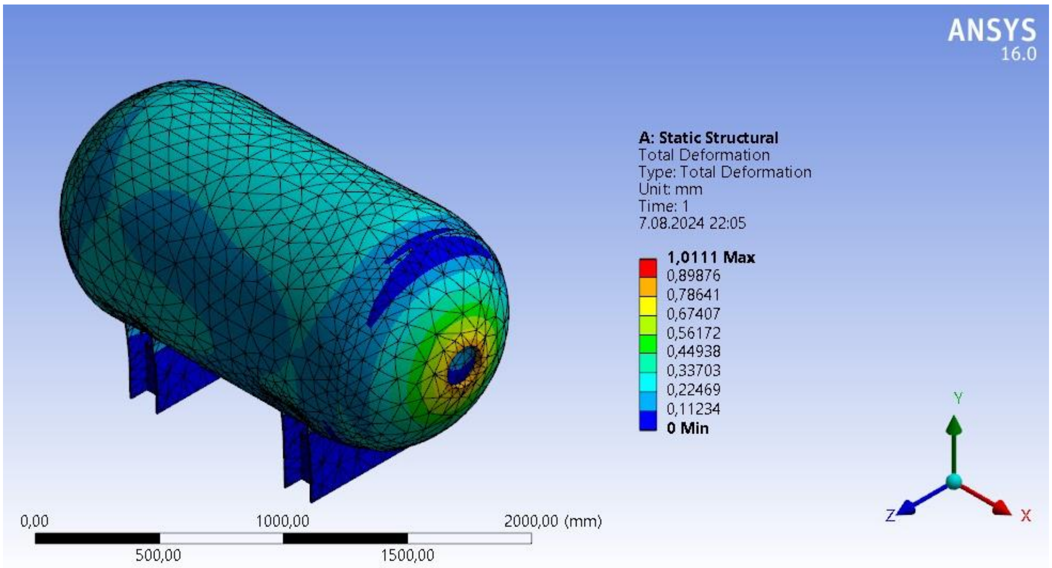

Figure 5: Total deformation view of pressure vessel

When the strain values obtained for 3 different material types and 3 different thicknesses were compared, the strain value was determined at least in the stainless steel vessel with a thickness of 10 mm, while the maximum was determined in the aluminum vessel with a thickness of 6 mm. The maximum principal elastic strain for the stainless steel vessel is given in Figure 6.

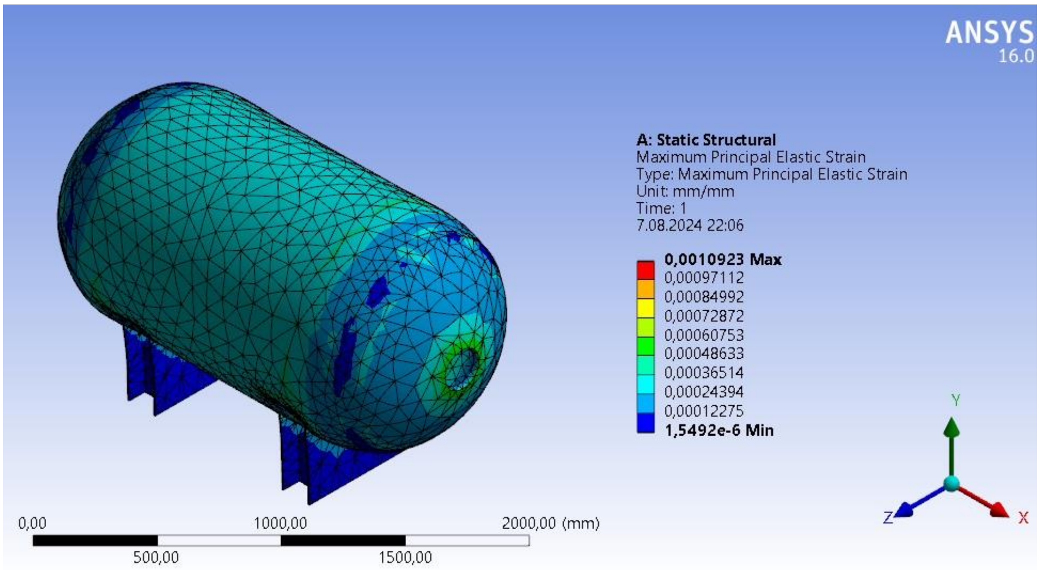

Figure 6: Maximum principal elastic strain for the stainless steel vessel

The stress, deformation and strain results obtained for three different material types for the pressure vessel with 6 mm thickness are given in the Table III.

Table 3: Pressure vessel with 6 mm thickness

Material	Weight (kg)	Von-Mises Stress (MPa)	Max Deformation (mm)	Max Strain ($x10^3$)
Stainless Steel	394.01	217.44	1.0111	1.0923
Aluminium Alloy	139.03	217.13	2.8229	3.1016
Copper	416.59	217.09	1.8160	2.0067

While the resulting stress values show very small differences because they are geometry-based, the weight, deformation and strain values calculated depending on the material type show significant differences. The mechanical properties for the pressure vessel with 8 mm thickness are given in Table IV.

Table 4: Pressure vessel with 8 mm thickness

Material	Weight (kg)	Von-Mises Stress (MPa)	Max Deformation (mm)	Max Strain ($x10^3$)
Stainless Steel	483.03	164.45	0.9252	0.8981
Aluminium Alloy	170.44	161.32	2.5732	2.4979
Copper	510.72	160.37	1.6528	1.6045

Considering the three different types of thicknesses examined, it is seen that the lowest stress calculated in terms of stress values occurs in copper at 6 mm and 8 mm thicknesses and in steel at 10 mm thickness. Table V shows the mechanical properties of the pressure vessel with 10 mm thickness.

Table 5: Pressure vessel with 10 mm thickness

Material	Weight (kg)	Von-Mises Stress (MPa)	Max Deformation (mm)	Max Strain ($x10^3$)
Stainless Steel	571.59	131.80	0.8665	0.6735
Aluminium Alloy	201.69	132.04	2.4096	1.9031
Copper	604.35	132.08	1.5478	1.2269

4. Conclusions

In general, increasing the thickness of a structure tends to improve its mechanical properties, offering enhanced strength and durability. However, this improvement comes with trade-offs, as the structures inevitably become heavier and more expensive to produce. For each type of material analyzed in this study, it was found that a 67% increase in thickness results in a significant 39% reduction in stress values, indicating a more robust structure. Additionally, this increase in thickness leads to a 37% decrease in strain, reflecting the material's reduced tendency to deform under load. Despite these benefits, the reduction in deformation was relatively modest, with only a 14% decrease observed, suggesting that while the material becomes stronger and less prone to strain, it doesn't necessarily become significantly stiffer. Furthermore, these changes in thickness have a notable impact on the overall weight of the structure. Specifically, the structure's weight increases by 45%, highlighting the balance that must be struck between achieving desired mechanical properties and managing the associated costs and practicality of the design.

The highest calculated stress value was observed in the 6 mm thick stainless steel material, indicating a significant load-bearing capacity under given conditions. In contrast, the lowest stress value was recorded in the 10 mm thick stainless steel material, demonstrating the substantial impact of increased thickness on reducing stress. The fact that both the highest and lowest stress values were found within the same material type highlights the pronounced effect of thickness variation in stainless steel. This suggests that changes in thickness play a critical role in the mechanical performance of this material. Additionally, the highest deformation value was observed in the 6 mm thick aluminum alloy material, which is known for its lightweight and ductile properties. On the other hand, the 10 mm thick steel exhibited the lowest deformation, underscoring its superior rigidity and resistance to shape change.

When conducting safety tests, especially within the scope of occupational safety, it is essential to perform these tests at 1.5 times the working pressure to ensure the structure's integrity under extreme conditions. During these periodic inspections, it is crucial to consider that the deformations induced by the testing process itself could have negative implications in subsequent evaluations. Over time, these test-induced deformations might accumulate, potentially leading to a gradual weakening of the structure or masking the detection of more critical issues. This underscores the importance of not only monitoring the immediate results of such tests but also understanding their long-term impact on the structural integrity of materials like stainless steel, aluminum alloy, and copper, particularly in scenarios where thickness plays a vital role in performance.

References

1. M. Azeem, et al., "Influence of winding angles on hoop stress in composite pressure vessels: Finite element analysis", Results in Engineering, 23 (2024), 101667.
2. J. Monteiro, S. Y. Nayak, K. A. Mathias, and N. Patil, "Effect of fiber orientation and reinforcements on the performance of composite pressure vessel using finite element analysis, Cogent Engineering, 11(1) (2024).
3. I. Gophane, N. Dharashivkar, P. Mulik, and P. Patil, "Theoretical and finite element analysis of pressure vessel", Indian Journal of Science and Technology, 17(12) (2024), 1148-1158.
4. G. W. Watts, and H. A. Lang, "The stresses in a pressure vessel with hemispherical head", Journal of Fluids Engineering, 75(1) (1953), 83-89.
5. P. P. Radkowski, R. M. Davis, and M. R. Bolduc, "A numerical analysis of the equations of thin shells of revolution", American Rocket Society, 32(1) (1962).

6. M. Kandaz, “Computer aided design and structural analysis of pressure vessels”, M.S., Middle East Technical University, (2006).
7. F. Tinis, and F. Bazman, “Silindirik ince cidarlı basınçlı kolonların artan deprem yüklerine karşı takviyelendirilmesi”, TMMOB Makina Mühendisleri Odası Konya Şubesi III. Makina Tasarımı ve İmalat Teknolojileri Kongresi, (2005).
8. M. F. Opačić, A. Sedmak, G. Bakić, N. Milošević, and N. i Milovanović,, “Risk assessment of pressure vessels by using fracture mechanics and advanced ultrasonic testing”, Tehnički vjesnik, 31(1) (2024), 118-124.
9. J. Jegatheesan, Z. Zakaria, “Stress analysis on pressure vessel”, Environment & Ecosystem Science, 2(2) (2018), 53-57.
10. TS 2025, “General Rules for Operation Inspection and Maintenance of Steam Boilers”, Turkish Standards Institution, 2021.
11. TS 430, “Sectional Cast Iron Boilers”, Turkish Standards Institution, 1984.
12. TS EN 303-1, “Heating Boilers, Turkish Standards Institution, 2017.
13. M. Akpolat, “Türkiye ve Avrupa’da kazanların güvenli çalışma ve periyodik control kriterleri, Ankara, 2014.
14. İ. Sancaklı, “Basınçlı kap konstrüksiyonlarına etki eden parametrelerin incelenmesi ve tasarımı, İstanbul, 2017.
15. BPVC, “Boiler and Pressure Vessel Code”, ASME, 2011.
16. E. Koç, İ. Keleş, and K. Yıldızlı, “İnce cidarlı silindirde gerilme ve şekil değiştirme analizi deneyi”, Ondokuz Mayıs Üniversitesi Makine Mühendisliği Bölümü, 2012.
17. S. Chattopadhyay, “Pressure vessels design and practice”, CRC Press, 2004.