Design, Modeling, and Fatigue Life Analysis of a 450 Kg LPG Cylinder

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Abstract

Liquefied Petroleum Gas (LPG) cylinders play a critical role in industrial energy storage, with increasing demand for large-capacity units such as 450 kg cylinders in commercial applications. However, their structural integrity and fatigue performance under cyclic loading conditions remain less explored. This study aims to design, model, and evaluate the fatigue life of a 450 kg LPG cylinder using a combination of analytical methods and finite element analysis (FEA), in accordance with EN 13445 and ASME standards. The research methodology integrates thin-walled pressure vessel theory for preliminary design with three-dimensional modeling and numerical simulation to assess stress distribution, deformation, and fatigue behavior. Results indicate that while the general cylindrical shell experiences uniform stress within allowable limits, localized stress concentrations occur at nozzle connections, support structures, and welded regions, with a maximum equivalent stress of 573.07 MPa and deformation of approximately 3 mm. Fatigue analysis using the S–N approach and Miner's rule indicates that the cylinder can safely withstand the expected service cycles, with a damage factor less than unity and a minimum fatigue life of approximately 57,515 cycles. The study concludes that although the overall design is structurally adequate, fatigue performance is governed by stress-concentration zones, necessitating geometric optimization. The findings have practical implications for improving the safety, reliability, and standardization of large-capacity LPG storage systems in industrial applications. This work contributes to the limited research on large LPG cylinders by providing a combined analytical and numerical framework for design validation and fatigue assessment.

Keywords: *ASME code, EN 13445, fatigue life, finite element analysis, LPG cylinder, pressure vessel design, and stress concentration*

1. Introduction

Liquefied Petroleum Gas (LPG) is widely used as a clean and efficient energy source across residential, commercial, and industrial sectors. In Nepal, it has become one of the primary fuels for cooking and energy use, particularly in urban areas where alternatives remain limited. Over the years, its consumption has steadily increased due to population growth, urbanization, and changing energy demands (International Energy Agency [IEA], 2023). Nepal relies heavily on imports to meet this demand, with petroleum products, including LPG, primarily supplied from neighboring countries. According to the Department of Customs, Nepal (2023), a substantial volume of LPG is imported annually, reflecting the country's growing dependence on this fuel. This reliance makes the safety and reliability of storage and distribution systems critically important, as any failure could pose serious safety risks and disrupt supply. Traditionally, LPG distribution in Nepal has been based on small-capacity cylinders, such as the 14.2 kg units commonly used in households. These cylinders are well-regulated and extensively studied. However, increasing demand from commercial users, including hotels, restaurants, and small industries, has led to a gradual shift toward larger-capacity cylinders, particularly 450 kg units used for bulk storage. While these larger cylinders improve operational efficiency by reducing the need for frequent replacement, they also introduce greater risks due to higher internal pressure and increased stored energy. As pressure vessels, LPG cylinders are designed to withstand significant internal pressure and varying operating conditions. During service, they are subjected to repeated loading cycles associated with filling, transportation, and discharge. Over time, these cyclic loads can lead to fatigue, a primary failure mechanism in such systems (Stephens et al., 2001). International standards such as EN 13445-3 (CEN, 2014) and the ASME Boiler and Pressure Vessel Code (ASME, 2021) provide established guidelines for design and fatigue assessment. However, their application to large-capacity LPG cylinders, particularly under local operating conditions, requires careful evaluation. In recent years, analytical tools such as finite element analysis (FEA) have become essential for understanding stress distribution and identifying critical regions prone to failure. These methods are especially effective in analyzing areas such as supports, nozzles, and welded joints, where stress concentrations are typically high. In parallel, non-destructive testing (NDT) techniques enable inspection and condition assessment without damaging the structure, supporting safer operation and maintenance practices (Hellier, 2013). Despite these advancements, most existing research and design practices focus primarily on smaller LPG cylinders. There is limited work on the structural behavior and fatigue performance of large-capacity cylinders, such as the 450 kg type, particularly in Nepal, where their adoption is still emerging. At the same time, practical challenges persist in commercial applications. Smaller cylinders require frequent replacement, which is inefficient, while alternatives such as LPG banks are sometimes implemented without consistent safety guidelines. This highlights the need for a more reliable and standardized approach to large-scale LPG storage. In this context, a detailed understanding of the structural response and fatigue behavior of large LPG cylinders is essential for ensuring safe and reliable operation. This study focuses on the design, modeling, and fatigue life assessment of a 450 kg LPG cylinder using both analytical methods and finite element analysis in accordance with relevant international standards. The work aims to evaluate stress distribution and deformation characteristics, identify critical regions of stress concentration, and assess fatigue life under cyclic loading conditions. The analytical results are further compared with finite element simulations to validate the modeling approach and provide a more comprehensive understanding of the structural performance of large-capacity LPG cylinders in industrial applications.

2. Review of Literature

Liquefied Petroleum Gas (LPG) is widely recognized as a reliable and efficient energy source for domestic, commercial, and industrial applications due to its high calorific value, clean combustion, and ease of storage in pressurized form. It is primarily composed of propane (C_3H_8) and butane (C_4H_{10}), with minor quantities of other hydrocarbons depending on processing conditions. The proportions of these components vary with climate and supply practices: propane is preferred in colder environments for its superior vaporization characteristics. At the same time, butane is more suitable for warmer regions due to its higher energy density (World LPG Association, 2022).In Nepal, LPG composition typically consists of a propane–butane mixture that varies seasonally with supply sources and climatic conditions (Nepal Oil Corporation, 2021). These variations directly influence vapor pressure inside storage cylinders, making thermophysical properties a key consideration in pressure vessel design.

Table 1: *Physical Properties of Propane and Butane*

Property	**Propane**	**Butane**
Chemical Formula		
Boiling Point	-42 °C	−0.5 °C
Density (Liquid)	493 Kg/ m^3	584 Kg/ m^3
Heating Value	46.4 MJ/Kg	45.7 MJ/kg

LPG is stored and transported in cylinders of varying capacities depending on usage. Domestic applications generally rely on small cylinders ranging from 5 kg to 14.2 kg, while the commercial and industrial sectors increasingly depend on larger units, including cylinders ranging from 50 kg to 450 kg (Kumar et al., 2016). The adoption of large-capacity cylinders has grown steadily in sectors such as hospitality, manufacturing, and centralized heating systems due to improved efficiency and reduced handling frequency. These cylinders are essentially pressure vessels designed to safely contain LPG at pressures that may exceed 10–15 bar under operating conditions. Depending on installation requirements, they are typically configured in vertical or horizontal orientations, with horizontal cylinders often preferred for bulk storage due to improved stability and ease of transport. The structural integrity of an LPG cylinder depends on its primary components, including the cylindrical shell, heads, base support, and welded joints. Each component plays a specific role in maintaining pressure containment and structural stability.

Table 2 *: Major Structural Components and Functions*

Components	**Function**
Cylinder Shell	Main pressure-containing body
Dome/Head	Distributes internal pressure uniformly
Valve	Controls LPG flow in and out of the cylinder
Stand/Base Ring	Supports the cylinder during storage
Protective Cap	Protects the valve from mechanical damage
Weld Joint	Connects the shell and head sections
Lifting Lugs	Used for safe handling and transportation

From an engineering perspective, LPG cylinders fall under the broader category of pressure vessels, which are designed to store fluids at pressures significantly different from ambient conditions. The design of such vessels must account for internal pressure, temperature variations, and mechanical loads during service. As highlighted by Megyesy (2008), cylindrical shells combined with ellipsoidal or hemispherical heads are commonly adopted because they provide a more uniform stress distribution compared to flat geometries. To ensure safe operation, pressure vessel design is governed by established international standards, particularly the ASME Boiler and Pressure Vessel Code and EN 13445. These standards define requirements for material selection, allowable stresses, fabrication methods, inspection procedures, and fatigue assessment. 13445, specifically developed for unfired pressure vessels, provides two primary design approaches: Design by Formula (DBF) and Design by Analysis (DBA) (CEN, 2021). DBF relies on simplified analytical equations derived from classical mechanics, whereas DBA enables more detailed evaluation using numerical methods such as finite element analysis. The standard also defines allowable stress limits based on material strength properties to ensure adequate safety margins. Stress analysis forms the foundation of pressure vessel design. Under internal pressure, cylindrical vessels experience two principal stresses: hoop (circumferential) and longitudinal (axial). For thin-walled cylinders, hoop stress is typically the governing parameter, being approximately twice the longitudinal stress. While analytical expressions provide a useful starting point, real structures often exhibit stress concentrations at discontinuities such as nozzles, supports, and weld joints. These localized effects are critical in fatigue assessment, as they often become initiation points for crack formation. Material selection plays a central role in determining the structural performance and durability of LPG cylinders. Pressure vessel standards recommend materials that provide adequate strength, ductility, and resistance to cyclic loading.

Steels such as P355GH are widely used due to their favorable mechanical properties and weldability (CEN, 2021). In some applications, higher-strength materials such as E450BR are adopted to improve load-bearing capacity and structural efficiency.

Table 3: *Chemical Composition of E450BR*

Grade	%C	%Mn	%S	%P	%Si	CE, max	Mode of Deoxidation
E 450 BR	0.22 max	1.65 max	0.045 max	0.045 max	0.45 max	0.52	Semi-killed/Killed

Table 4: *Mechanical Properties of E450BR*

Grade	UTS MPa min	YS, MPa min	%EL min
E450BR	588	519	38

In addition to the main shell material, components such as nozzles and couplings are often manufactured from low-temperature steels, such as SA-350 LF2, which retain toughness at sub-zero temperatures (ASME, 2021). The use of elliptical heads further enhances structural performance by reducing stress concentration at critical junctions. Manufacturing processes, including plate rolling, welding, heat treatment, and hydrostatic testing, significantly influence cylinder reliability. Among these, welding is particularly critical, as weld regions are more susceptible to defects and fatigue damage (Patil & Yadav, 2019). Beyond material and geometry considerations, pressure vessel failure is often influenced by geometric imperfections and structural discontinuities. EN 13445 identifies issues such as peaking and angular distortion at weld seams, which introduce additional bending stresses not captured by simple analytical models (CEN, 2021). These imperfections can significantly accelerate fatigue crack initiation, especially in large-capacity vessels. Similarly, structural attachments such as supports and lifting lugs introduce localized stress concentrations. These discontinuities can result in secondary stresses that exceed nominal design values, increasing the risk of cyclic plastic deformation and long-term damage. Fatigue behavior is a critical concern in LPG cylinders due to repeated filling and discharge cycles. Even when operating stresses remain below yield strength, cyclic loading can initiate and propagate cracks over time (Stephens et al., 2001). Fatigue life is commonly evaluated using S–N curves, which relate stress amplitude to the number of cycles to failure.

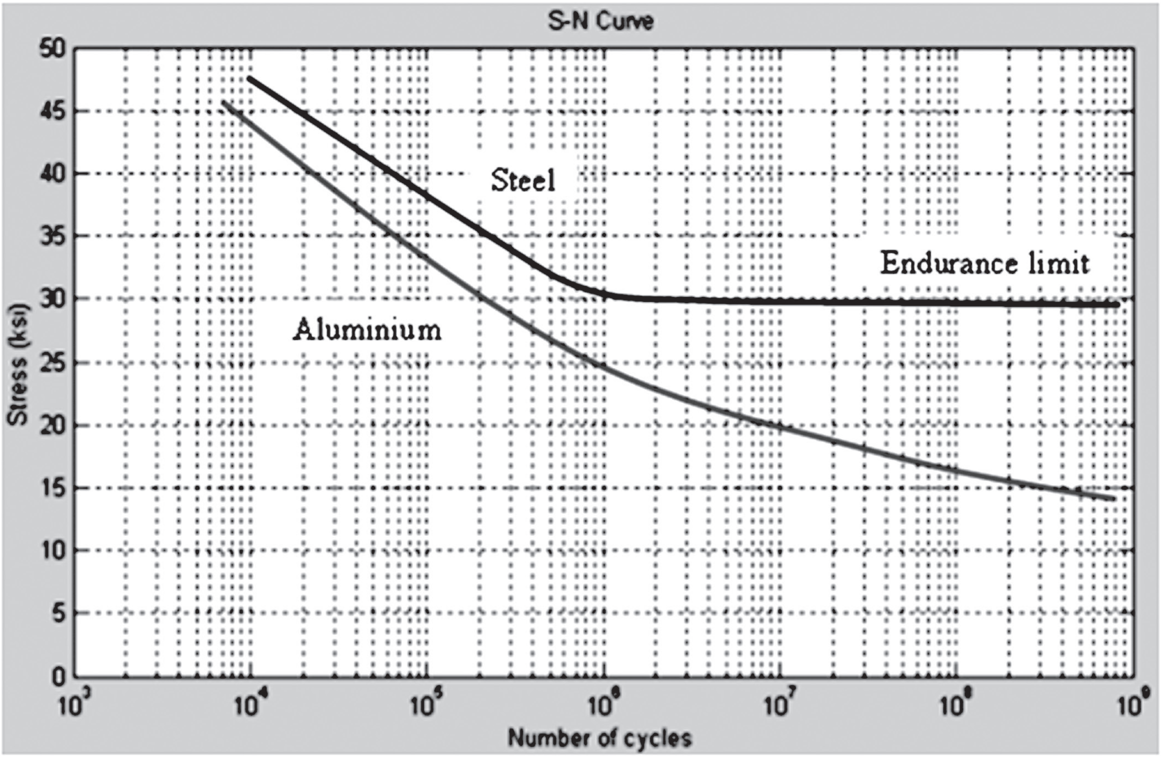


Figure 1: *S–N Curve for Steel & Aluminium*

Standards such as EN 13445 require fatigue analysis when the number of pressure cycles exceeds a defined threshold, typically around 500 full cycles (CEN, 2021). The evaluation involves comparing calculated stress ranges with standardized fatigue design curves. Similarly, ASME Section VIII Division 2 provides a structured approach to fatigue assessment, including stress evaluation, calculation of alternating stress, and cumulative damage analysis using Miner's rule. A design is considered safe when the cumulative damage factor remains below unity (ASME, 2021). As pressure vessel design becomes increasingly complex, numerical methods such as finite element analysis (FEA) have become essential tools. FEA enables detailed evaluation of stress distribution across complex geometries and helps identify critical regions prone to failure. For LPG cylinders, these regions often include weld joints, supports, and nozzle connections. To ensure accuracy, analytical calculations based on classical theory are often used alongside FEA results. This combined approach improves confidence in predictions and helps identify any inconsistencies in modeling assumptions. Despite extensive research on LPG cylinders, most existing studies focus on small and medium-capacity units. There is comparatively limited work addressing large-capacity cylinders, particularly the 450 kg type used in industrial applications. This gap becomes more significant in contexts such as Nepal, where the adoption of such systems is increasing alongside the gradual implementation of international standards like EN 13445. A more detailed understanding of stress distribution, fatigue behavior, and structural reliability in large LPG cylinders is therefore necessary. Addressing this gap through combined analytical and numerical approaches can contribute to safer design practices and more reliable industrial applications.

3. Research Methodology

3.1 Introduction

Liquefied Petroleum Gas (LPG) storage systems require pressure vessels that can safely withstand internal pressure and cyclic loading during service. In practical applications, LPG cylinders undergo repeated pressurization and depressurization during filling, transportation, and discharge. These cyclic effects can lead to fatigue damage, which may compromise structural integrity if not properly addressed during design. This study presents the design, structural evaluation, and fatigue assessment of a 450 kg (≈1 m³) LPG storage cylinder**.** The methodology integrates analytical pressure-vessel design calculations with finite element analysis (FEA) to evaluate stress distributions and fatigue performance. The design approach follows EN 13445-3:2021 and the ASME Boiler and Pressure Vessel Code Section VIII Division 2, which provide standardized procedures for thickness design, stress analysis, and fatigue evaluation (American Society of Mechanical Engineers [ASME], 2021; European Committee for Standardization [CEN], 2021).

3.2 Determination of Cylinder Capacity and Geometry

The design process begins by determining the required internal volume based on the LPG storage capacity. The filling ratio method is used to relate the mass of LPG to the water capacity of the cylinder:

$$F = \frac{\text{Mass of LPG}}{\text{Water Capacity}}$$

Using a typical filling ratio of 0.425 kg/L, the required water capacity for storing 450 kg of LPG is approximately 1.06 m³**.** This ensures sufficient vapor space for the liquid's thermal expansion. The LPG cylinder is modeled as a vertical cylindrical vessel with 2:1 ellipsoidal heads, which provide efficient stress distribution and are commonly used in industrial applications (Moss & Basic, 2013).

The total internal volume is expressed as:

$$V = V_{\text{shell}} + 2V_{\text{head}}$$

where the cylindrical shell volume and ellipsoidal head volume are given by:

$$V_{\mathrm{shell}} = \frac{\pi D_i^2}{4} L \mathrm{and} V_{\mathrm{head}} = \frac{\pi}{24} D_i^3$$

Based on these relations, the shell length is determined to satisfy the required total volume.

3.3 Design Parameters and Material Selection

The design parameters are selected based on operating conditions and code requirements. The cylinder is designed for an internal pressure of 1.76 MPa and a design temperature of 65°C. A joint efficiency of 0.85 and a corrosion allowance of 0.5 mm are considered. The selected material is E450BR structural steel (IS, 2062), which offers high yield strength, good weldability, and adequate toughness. The allowable stress used in the design is 245 MPa, consistent with code-based limits for pressure vessel materials (CEN, 2021).

3.4 Analytical Pressure Vessel Design

The analytical design is carried out using thin-walled pressure vessel theory, which is valid since the thickness-to-diameter ratio is significantly less than 0.1 (Budynas & Nisbett, 2020).

3.4.1 Cylindrical Shell Thickness

he hoop stress in a thin cylindrical pressure vessel is expressed as:

$$\sigma_h = \frac{PD}{2t}$$

The required shell thickness is calculated using EN 13445-3:

$$t = \frac{PD}{2f\eta - P}$$

Based on the design parameters, the minimum required shell thickness is 4.2 mm. A higher thickness is selected to account for corrosion allowance and manufacturing considerations.

3.4.2 Ellipsoidal Head Thickness

The thickness of the 2:1 ellipsoidal head is determined according to EN 13445-3 by considering three criteria: membrane stress, knuckle yielding, and buckling resistance. The governing thickness is selected as the maximum value obtained from these criteria, including corrosion allowance. Based on this approach, the required head thickness is approximately 5.3 mm**,** and a standard thickness of 5.5 mm is adopted.

3.5 Stress Verification

The stresses developed in the cylindrical shell are evaluated to ensure they remain within allowable limits. The hoop and longitudinal stresses are calculated using thin cylinder theory, and the equivalent stress is determined using the von Mises criterion:

$$\sigma_v = \sqrt{\sigma_h^2 + \sigma_l^2 - \sigma_h \sigma_l}$$

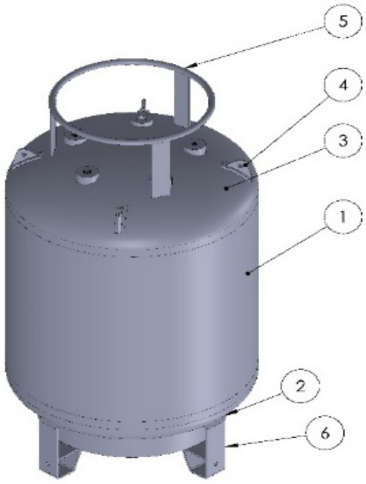
The calculated equivalent stress is found to be lower than the material's allowable stress, confirming the safety of the design.

3.6 Geometric Modeling of LPG Cylinder

A three-dimensional geometric model of the 450 kg LPG cylinder was developed to represent the actual configuration used in industrial applications. The model consists of a cylindrical shell with two 2:1 ellipsoidal heads, which are commonly used for their improved stress distribution. The complete geometric model is shown in Figure 2.

***Figure 2:** Three-dimensional CAD model of the LPG cylinder*

The internal diameter and shell length were determined from the volume requirement, while the thickness of the shell and heads was obtained from analytical design calculations. Additional features such as nozzles, supports, and end connections were incorporated into the model to capture realistic boundary conditions and stress concentrations. A detailed view of these geometric features is presented in Figure 3.



ITEM NO.	PART NUMBER	QTY.
1	LPG CYLINDER MIDDLE PART	1
2	LPG CYLINDER BOTTOM PART	1
3	LPG CYLINDER TOP PART	1
4	LIFTING HOOK	4
5	VALVE GUARD	1
6	LEG SUPPORT	4

***Figure 3 :** Detailed view of 450 kg LPG cylinder*

The modeling was carried out using SolidWorks. Proper geometric continuity was maintained at the junctions between the cylindrical shell and ellipsoidal heads to avoid artificial stress discontinuities. Special attention was given to critical regions such as the head-to-shell junction, nozzle intersections, and support attachments, as these locations are highly susceptible to stress concentration and play a significant role in fatigue behavior. The final geometry was exported in a standard format (e.g., STEP/IGES) and imported into ANSYS Workbench for further finite element analysis.

3.6 Finite Element Analysis

To capture localized stress concentrations, a three-dimensional finite element model of the LPG cylinder is developed. The model includes the cylindrical shell, ellipsoidal heads, nozzles, and support structures. The mesh is generated using a combination of tetrahedral and hexahedral elements, with refinement applied in critical regions such as nozzle connections and head-to-shell junctions. Appropriate boundary conditions are applied to simulate actual operating conditions, including internal pressure, self-weight, and external loads on nozzles, enabling detailed evaluation of stress distribution and identification of critical regions that may influence fatigue life (Cook et al., 2002).

3.7 Fatigue Assessment

Fatigue behavior is evaluated using both the stress-life (S–N) approach and the ASME fatigue methodology.

The stress amplitude is defined as:

$$S_a = \frac{\Delta S}{2}$$

The S–N relationship is expressed using the Basquin equation:

$$\sigma_a = AN^b$$

In the absence of experimental data, the S–N curve is constructed using empirical relations based on the material's ultimate tensile strength (Budynas & Nisbett, 2020; Dowling, 2013). Additionally, fatigue life is estimated using ASME Section VIII Division 2 procedures. The alternating stress obtained from FEA is used to determine fatigue parameters, and the allowable number of cycles is calculated.

Cumulative fatigue damage is evaluated using Miner's rule:

$$D_f = \frac{n}{N}$$

The calculated damage factor is less than unity, indicating that the cylinder can safely withstand the expected number of service cycles.

3.8 Analytical Validation

To validate the numerical results, analytical calculations of stress and deformation are performed using the thin cylinder theory. The radial deformation is estimated using elasticity relations and compared with FEA predictions. Although slight differences are observed due to localized stress effects and modeling assumptions, the results show reasonable agreement, confirming the reliability of the analysis.

4. Results

4.1 Stress Distribution

The finite element analysis was performed to evaluate the stress distribution in the 450 kg LPG cylinder under combined loading conditions. The stress state was assessed using the von Mises equivalent stress criterion. The stress contour obtained from the simulation is presented in Figure 4. The results show that the maximum equivalent stress is 574.66 MPa, occurring at localized regions such as Nozzle connections, Base support attachments, and welded junctions. In contrast, the majority of the cylindrical shell experiences relatively uniform stress in the range of 127 MPa to 191 MPa.

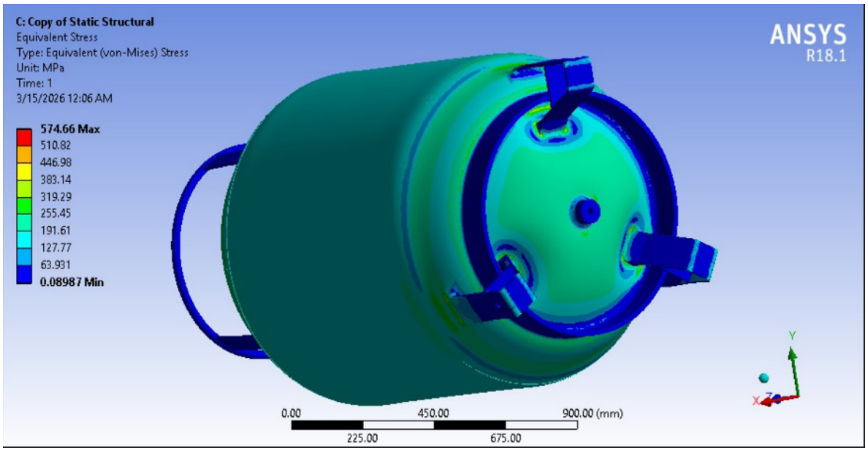


__Figure 4:__ Maximum Equivalent Stress

4.2 Deformation Results

The total deformation of the LPG cylinder under applied loads is shown in Figure 5

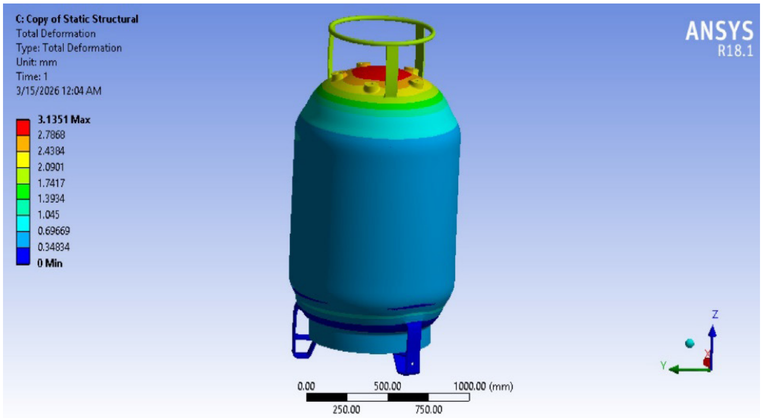


Figure 5: *Total deformation of the LPG cylinder*

The simulation results indicate a maximum deformation of approximately 3 mm. The deformation is primarily concentrated near the support structures and nozzle regions, while the cylindrical body shows relatively uniform displacement.

4.3 Identification of Critical Regions

The finite element results highlight several critical regions of stress concentration. These regions are shown in Figure 6

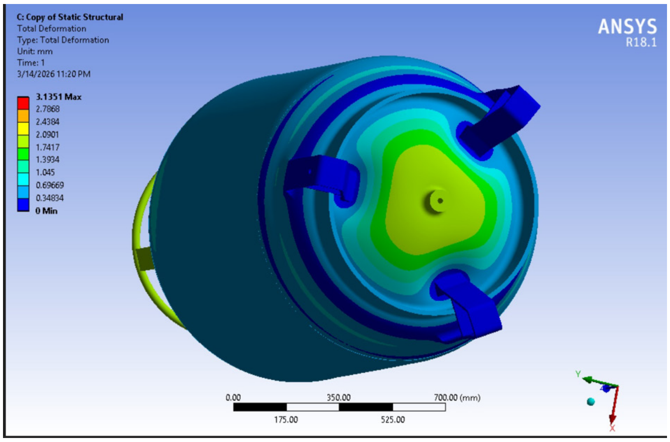


Figure 6: *Stress concentration in critical regions of the LPG cylinder*

4.4 Fatigue Analysis Results (Analytical Method)

The fatigue analysis was carried out in accordance with ASME Section VIII, Division 2 procedures. Based on the stress range obtained from FEA, the effective alternating stress amplitude was calculated as approximately 286 MPa.

The number of cycles to failure was determined as:

$$N = 3.085 \times 10^4 \text{ cycle}$$

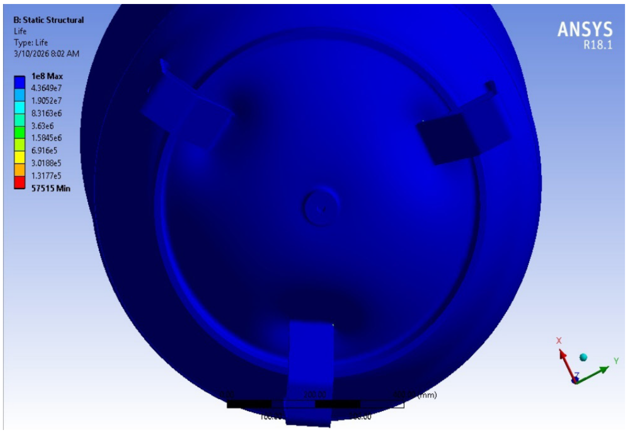
4.5 Fatigue Damage Factor

The fatigue damage factor was evaluated using Miner's rule. For an expected operating life of 12,000 cycles, the damage factor is:

$$D_f = 0.3889$$

Since the value is less than unity, the design satisfies fatigue safety requirements.

4.6 Fatigue Life Results (Numerical Method)



Fatigue life prediction was also performed using ANSYS Workbench. The fatigue life contour is shown in Figure 7.

Figure 7: Fatigue life distribution of the LPG cylinder

The results indicate:

- Minimum fatigue life ≈ 57,515 cycles
- Maximum fatigue life ≈ 1×10^8 cycles

The minimum life occurs near the base support regions, indicating these areas are critical for fatigue performance.

5. Discussion

The results demonstrate that the overall LPG cylinder design is structurally adequate; however, localized stress concentrations significantly influence performance.

Although the cylindrical shell experiences stress within acceptable limits, the maximum stress of 573.07 MPa exceeds the allowable stress, indicating that certain regions are highly stressed. These high stresses are confined to small areas and are primarily caused by geometric discontinuities such as nozzles and support attachments. The deformation obtained from FEA (3 mm) is considerably higher than the analytical prediction (~0.3 mm). This difference arises because analytical methods assume ideal geometry and loading, whereas the numerical model incorporates realistic conditions, including supports, nozzles, and gravity effects.

Fatigue analysis shows that the cylinder can withstand the expected number of cycles, as the calculated damage factor is less than unity. However, fatigue life is governed by stress-concentration regions rather than by the main cylindrical body. The numerical fatigue results further confirm that the support structures are the most critical components, with the lowest fatigue life observed at their inner radius. This indicates that the design is safe under pressure loading but may require improvements to the support geometry. To enhance performance and reliability, the following design improvements are recommended:

- Introduction of fillets at sharp geometric transitions
- Optimization of support structure design
- Reduction of stress concentration at nozzle connections

Overall, the study highlights the importance of combining analytical design with finite element analysis to evaluate the structural and fatigue behavior of LPG cylinders accurately.

6. Conclusion

This study presented the design, structural analysis, and fatigue assessment of a 450 kg LPG storage cylinder using a combination of analytical methods and finite element analysis. The analytical design, based on pressure-vessel theory, provided baseline dimensions and confirmed that the general shell structure meets strength requirements under internal pressure. Finite element analysis enabled detailed evaluation of stress distribution and revealed localized stress concentrations at nozzle connections, support attachments, and geometric discontinuities. While the majority of the cylindrical shell experienced stresses within acceptable limits, peak stresses were observed in critical regions, highlighting the limitations of analytical approaches in capturing localized effects. The fatigue assessment, performed using both analytical procedures and numerical methods, indicates that the cylinder can safely withstand the expected number of operating cycles. The calculated fatigue damage factor remained below unity, confirming the adequacy of the design under cyclic loading conditions. However, fatigue life was found to be governed by stress concentration regions, particularly near support structures.

Overall, the study demonstrates that integrating analytical design with numerical simulation provides a more realistic and reliable evaluation of LPG cylinder performance. The findings also emphasize the importance of addressing geometric discontinuities to improve structural integrity and fatigue life.

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