Experimental and Finite Element Analysis of Liquefied Petroleum Gas Cylinder

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Abstract

LPG cylinders are a type of pressure vessel that requires extreme care to store pressurized gas. This study addresses the determination and prediction of burst pressure (BP) and burst failure location in liquefied petroleum gas (LPG) fuel tanks using both experimental and finite element analysis (FEA) approaches. Experimental burst test studies were conducted hydrostatically and water was applied to the interior of the

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cylinder. A detailed finite element analysis of LPG cylinders is performed with the ABAQUS software and these analyses help to predict the burst pressure of the LPG cylinder when an internal load acts on it. Therefore, the burst pressure results were predicted and compared to experimental ones.

***Keywords**: Burst Pressures (BP) and failure locations, toroidal shells, LPG Cylinder fuel tank, nonlinear failure analysis, nonuniform FEA model*

1. Introduction

Energy holds a vital importance in our lives. Thus, the ever reduce energy resources must be conserved in order to ensure the sustainable development. One of these forms of energy is employed in cooking (Liquefied petroleum gas LPG). The fuel of LPG finds very wide application in a large variety of domestic, industrial, commercial and leisure uses. In addition to his household uses. Liquefied petroleum gas (LPG) is commonly used as an alternative fuel for internal combustions engines of vehicles in Europe. Liquefied Petroleum Gas (LPG) is a colourless liquid which readily evaporates into a gas. It has no smell, although it will normally have an odour added to help detect leaks. When mixed with air, the gas can burn or explode when it meets a source of ignition. It is heavier than air, so it tends to sink towards the ground [1]. LPG is composed predominantly a mixture of hydrocarbons such as propane, propylene, butane or butylene. The gas can be liquefied at moderate pressure, and can be stored in cylinders as a liquid under pressure and is drawn out and used as gas. This means that it can be transported and stored as liquid and burnt as gas. The expansion ratio of gas liquid is 270:1 at atmospheric pressure [1]. The expansion factor makes LP-gas more economical to transport and stored with large quantities of gaseous fuel in a small container. Containers are normally filled 80-85% liquid, leaving 15-20%vapour space for expansion due to temperature increase. Nowadays, composite materials have been used widely which are proved to be more effective. These composite materials are wound over metal liner thus acting as over wrapped composite pressure vessel. LPG cylinder is one kind of pressure vessel that stores pressurized gases. LPG cylinder material should have high tensile and compressive strength for withstanding the high pressure of the gases [2-4]. The Cylinders play a crucial role in containing and transporting hazardous LPG from filling plant to end consumer [5]. LPG cylinders are to be

manufactured from definitely prescribed raw material to ensure safety of cylinders through material quality specifications [6]. Although there are clear standards and statutory norms for design, manufacturing and usage of cylinders, there are certain gaps in these standards in terms of ensuring material safety compliance. LPG cylinder production is composed of several sheet metal forming, surface treatment and testing processes. The process starts with blanking, deep drawing and piercing, trimming and joggling. Next are the welding operations for valve boss, valve guard ring, foot ring and the two halves. The finished cylinder is then heat treated, tested, shot blasted, painted and then the valve is attached and tested finally [7]. Two cylinders from each manufactured lot are subjected to destructive test for verification of cylinder material properties, as a part of certification process. For every manufactured lot of 203 and below one cylinder is tested for acceptance test [8]. Parent metal physical properties like yield strength, tensile strength, percentage elongation of parent metal, weld tensile strength, weld joint strength etc.

are revealed in acceptance test [9]. Similarly, for every manufactured lot of 403 cylinders and below one cylinder is subjected to various hydro-tests. The hydro-test on cylinder reveals cylinder water capacity, leaks, volumetric expansion, burst pressure and nominal hoop stress at which a cylinder bursts [8]. Requirements of various hydro-tests for LPG cylinders are mentioned in ISO 4706. There, are few factors that can influence these results during manufacturing process and are cylinder raw material selection, cylinder manufacturing process, heat treatment process parameters [10-12]. The burst pressures BP is the maximum pressure cylinders can withstand without bursting. With a note that, the (BP) and burst failure locations of liquefied petroleum gas (LPG) cylinders can be determined also by using finite element analysis (FEA approaches) as mentioned by Kisioglu et al. [13,14]. The Design of Vertical Pressure Vessel using finite element analysis is performed using ANSYS software by applying boundary and loading conditions on the pressure vessel. The total deformation and von-mises stress values are observed to determine the burst pressure of the vertical pressure vessel [15].

The purpose of this study is to investigate the BP and its failure location of the vehicle toroidal oval cross-section LPG fuel tanks using both experimental burst tests and computerized numerical analysis. The experimental burst tests were studied using the research and development laboratory facilities of the manufacturer. The actual shell and weld zone material properties (MPs) including thickness variations of the tanks were investigated to predict the BP and failure location using numerical approach. These properties were used nonlinearly in the numerical modeling process to approximate the BP values obtained by the experimental tests. Besides, these tanks were subjected to incremental internal uniform pressure depending on loading time. Therefore, two different types of 2D nonlinear computerized finite element models, plane and shell, were developed under axisymmetric boundary and nonlinear material conditions.

2. Materials and Design of LPG Cylinders

The household petroleum gas steel cylinders are manufactured either in two pieces or three pieces construction. In this study two household petroleum gas cylinders (C1 & C2) fabricated by welding of two domed ends directly together. The domed ends can be tori-Spherical, Semi ellipsoidal or Hemi-spherical in shap. The tested cylinders have been taken randomly from two different places in the Libyan market for the purpose to reveal burst pressure (BP), and failure locations. Moreover, to be sure this household gas cylinders fits the ISO 4706 requirements in the field of this study. The chemical analysis (Table 1) reveals both cylinders being studied are made of low alloy carbon steel. The low alloy carbon steel, because of low content of carbon (0.0937, 0.0963) it is expected to be has low yielding strength, which makes it suitable for industries that require high formability and weldability similar to gas cylinders industries. While by increasing amount of carbon as in medium carbon steel which exhibits the yield strength in the range of 700- 1000 MPa [16-22] as result the difficulty of welding and shaping processes. Details of specifications of this gas cylinders are given in table 2.

Table 1: Chemical Composition of LPG Cylinders

Gas Cylinder Number	Chemical Composition by W.t %				
	C	Mn	Si	S	P
C_1	0.0937	0.4694	0.0122	0.0074	0.0122
C_2	0.0963	0.4260	0.0215	0.0038	0.0101
ISO 4706 requirements	0.250 Max.	1.60 Max.	0.450 Max.	0.040 Max.	0.040 Max.

Table 2. Specifications of the gas cylinders being studied

Empty Weight by Kg	Overall Height by mm	Inner Diameter by mm
18.5	675	318
Min. Wall Thickness by mm	Test Pressure by bar	Water Capacity by liter
≥ 3.00	30	36

With regards to the guidelines and the design of these cylinders can be found in many international codes such as BS-5500 (British Standard) and the ASME codes (Section VIII, Division 1) [11]. These rules are restricted mostly to the load carrying capacity under internal pressure. However, these LPG cylinders are designed and manufactured according to the restrictions of the refillable welded steel gas cylinders ISO/DIN 4706.2 codes, considering the SP and TP of the LPG cylinders. The pressure specifications of the most commonly manufactured cylinders of 318mm inner diameter used in industrial applications are given as an example in table 2. These cylinders are equipped with a valve system and a label welded to the shell body, as shown in Fig. 1.

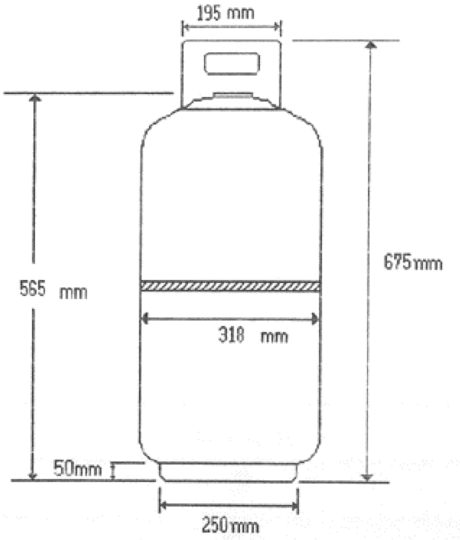

Fig.1 The LPG gas cylinder and its design parameters.

The LPG gas cylinders are usually manufactured within different groups, which are classified by their water capacities (2,5,18 and 35 l). Each group of cylinders has a different wall thickness ranging from 2 to 3 mm. In the present study, the BP and failure locations of the most commonly used group (35 l) of LPG having 3mm wall thickness are investigated. These, cylinders consist of three main parts: one cylindrical shell and two tori spherical end closures. The, cylindrical shell is folded up and welded horizontally at the middle. Some design parameters are also shown in Fig. 1. such as inner diameter (ID), minimum wall thickness (t) and length of the cylindrical shell (L). As represented in table 1, LPG cylinders are constructed from low alloy carbon steel using the welding process for the cylindrical body, which manufactured by deep drawing process. The low alloy carbon steel is a hot rolled steel with 0.094% carbon content and is a ductile material suitable for the cold forming process used to construct the LPG gas cylinders. The deep drawing process changes the material properties (MPs) and thickness variations. After completing all manufacturing and welding processes, these cylinders have been subjected to a heat treatment process before service.

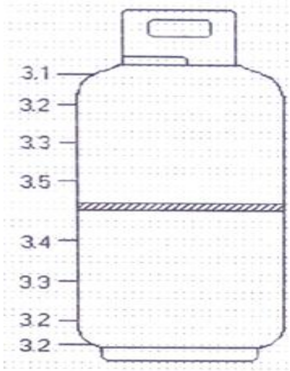

Fig. 2. Results Homogeneity Thickness of the cylinders by mm.

3. The Experimental Burst Tests

The experimental burst investigations of the LPG cylinders were carried out at the research and development laboratory. In order to burst these tanks, two domestic LPG cylinders of 35liter capacity are selected for this study. These cylinders are most common type of cylinders used in Libya houses. The burst test was carried out at room temperature under hydraulic pressure test machine. The pressure to be increased gradually until the cylinder bursts. The specifications of the gas cylinders being studied are shown in Table 2. On the other hand, the requirements according to ISO 4706 of hydro-test of these cylinders are precent in the Table 3. The experimental setup is start by filling the gas cylinders completely by water and the pressure was controlled by means of a single-acting hydraulic pump. The LPG gas cylinder were placed vertically during the experiments and air was vented during filling as seen in Fig. 2 and the burst cylinders is shown in Fig. 3. The wall thickness was variable due to the thickness tolerances for the blank sheet as can be seen from the figure 2. The BP results obtained ranged from a minimum of 10.2 MPa to a maximum of 10.4 MPa. The mean BP values obtained are about 10.3 MPa. Moreover, the burst location of the LPG cylinders is well known from the experimental burst tests (see Fig. 3). The failure initiate in middle area at the top of horizon welding regions (Initiate out of a welding region), cylinder specimens fractured in such a way that the burst crack continues longitudinally) as illustrated as shown in Fig.3. This point defined as the burst failure location of the LPG gas cylinders.

Table.3 Household gas cylinders test results and requirements.

Type of Test	Requirements as per ISO 4706
Burst Pressure (BP)	Min. 5.0 MPa
Failure Locations	Not initiate in a welding region
Household Gas Cylinders Test Results	
Burst Pressure (BP)	10.4 and 10.2 MPa
Failure Locations	Initiate out of a welding region

Fig.3. Failure Locations of the cylinders.

4. Modelling And Finite Element Analysis

A. LPG Cylinder Model

Considering the IS 3196 LPG Cylinder, all the different parts of the LPG Cylinder are modeled in the ABAQUS software by using different commands, and all the individual parts of the LPG Cylinder are assembled as shown in Fig.4

Figure 4. Assembled model of the LPG cylinder

B. Meshing

After assigning the element type to the LPG cylinder, the meshing is an important process of an analysis and should be performed on the LPG cylinder model. Meshing is the process of dividing the created model into a number of subdivisions or elements made up of nodes. An automated mesh generation is shown in Fig. 5.

Figure 5. Meshing of LPG cylinder

Meshing is applied using automatic meshes. Under the mesh size, the mesh size has been adjusted to fine mesh to achieve accurate and precise results. Instead of using a fine mesh for all components, a coarse mesh was used on a larger area and a fine mesh on the stress concentration area.

C. Applying Loads

In the analysis setting, a fixed bearing is assigned to the base ring or foot ring of the LPG cylinder. By assigning the fixed support, the base ring is constrained in all degrees of freedom and would withstand the forces acting on the LPG cylinder. The fluid in the LPG cylinder has a higher internal pressure than the surrounding air. Calculations are made regarding the average internal pressure of the LPG cylinders. The internal pressure of 10MPa is applied to the various internal parts of the LPG cylinder.

5. Results and Discussions

After attaching the base ring and applying the internal pressure of 10 MPa to the LPG cylinder in the ABAQUS software. The following results were observed from finite element analysis.

a. Total Deformation of LPG Cylinder

After performing the finite element analysis on the LPG cylinder model by applying the internal pressure, a maximum total deformation of 1.169 mm is observed in Fig. 8.

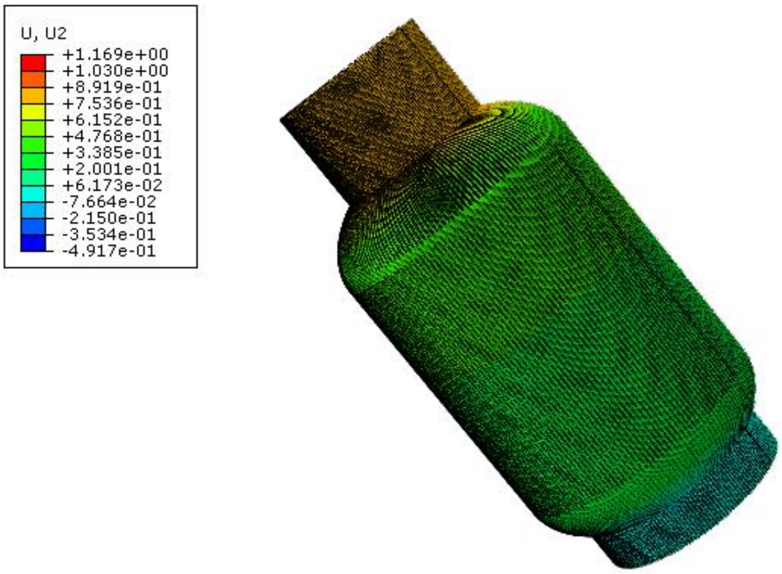

Figure 8. Total deformation of LPG cylinder

b. Von-mises Stress of LPG Cylinder

The LPG cylinder was subjected to finite element analysis after being subjected to internal pressure, and as shown in Fig. 9, the maximum von Mises stress was 497 MPa.

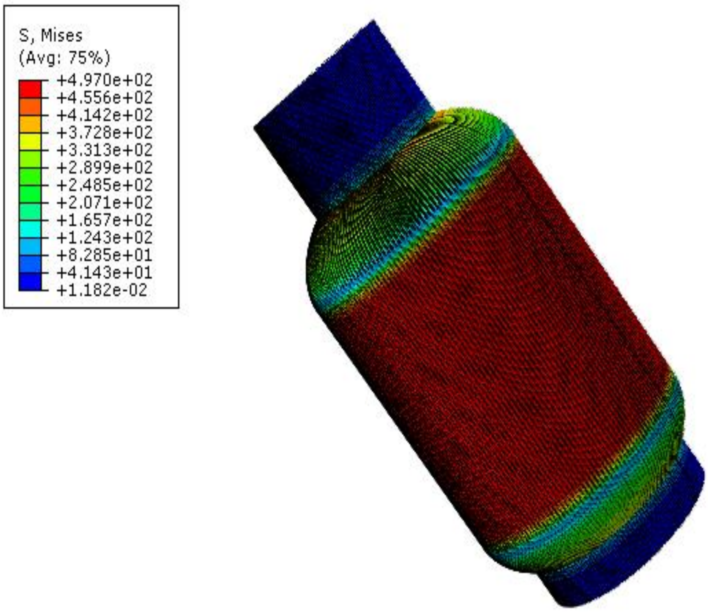

Figure 9. Von-mises stress of LPG cylinder

c. Max-Principal Stress of LPG Cylinder

After performing a finite element analysis on the LPG cylinder and applying an internal pressure, Fig. 10 shows that the LPG cylinder has a maximum principal stress of 561.8 MPa.

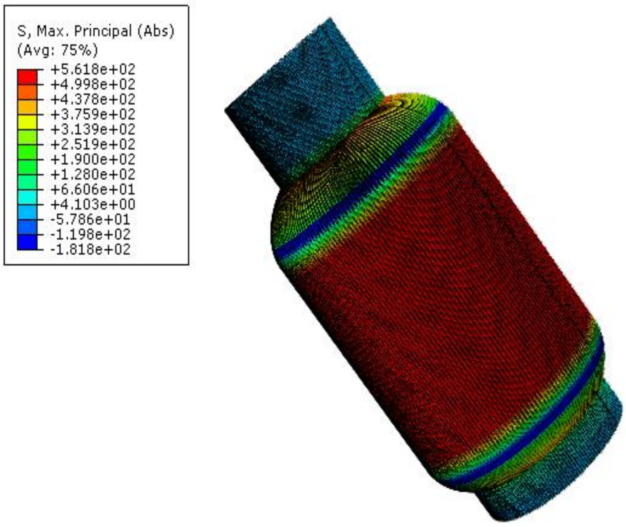

Figure 10. Max. Principal stress of LPG cylinder

d. Longitudinal Stress of LPG Cylinder

By applying internal pressure to the LPG cylinder and performing finite element analysis on it, Fig. 11 shows that the LPG cylinder has a longitudinal stress (S22) of 471.4 MPa.

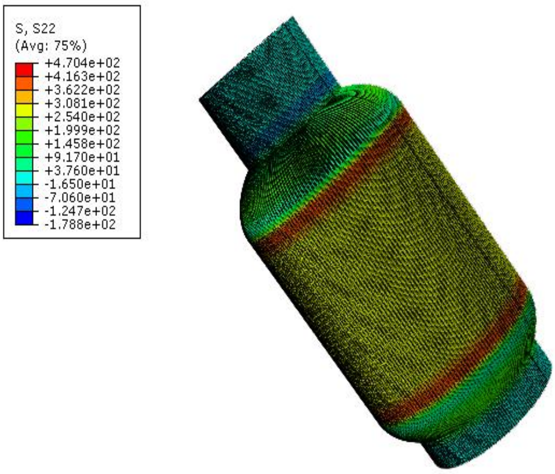

Figure 11. Longitudinal Stress of LPG cylinder

e. Circumferential Stress of LPG Cylinder

After performing a finite element analysis of the LPG cylinder by applying the internal pressure, a hoop stress (S33) of 561.8 MPa is observed in the LPG cylinder of Fig. 12.

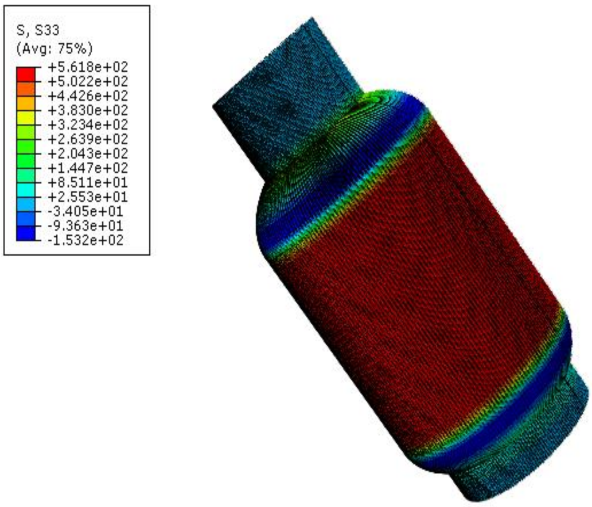

Figure 12. Circumferential Stress of LPG cylinder

6. Conclusions

In order to determine the exact pressure point and burst failure location, the case of a thin-walled LPG fuel tank with increasing internal pressure was investigated using both experimental and computational FEM approaches. In this work, an LPG cylinder used to store the liquids is modeled in ABAQUS software and a finite element analysis of an LPG cylinder with an internal pressure of 10 MPa. The total deformation, von Mies stress, longitudinal stress and hoop stress of the LPG cylinders are studied. Based on the results, it is determined that the maximum deflection and von Mies stress of the LPG cylinder are within the safe ranges. As a result, model LPG cylinders are safe to use and have a long service life as they can withstand the internal pressure of the liquids.

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