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RESEARCH ARTICLE

Design and Analysis of Shop-Built Spherical LNG Pressure Vessel Using Autodesk Fusion 360

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Abstract

Pressure vessels are containers specifically designed to hold fluid at high pressure. In this case, the design analysis is concerned with the containment of Liquefied Natural Gas. Due to the sudden rise in demand for liquefied natural gas around the world, there has been an equivalent rise in demand to improve storage of this gas. As a result, Engineers and Scientist design high pressure vessel containers that will hold LNG at high pressure without failure.Shop-built spherical pressure vessels are designed for uniformity in inner shell thickness, unlike the field-fabricated ones. Field fabricated spherical pressure vessels have gained lots of attention by engineers with regard to its design and analysis, but there is a dearth of material on the subject of shop-built LNG spherical pressure vessel design and analysis. This study expands upon the earlier work that employed the FORTRAN-solved numerical analysis-finite element approach. Models of pressure vessels made of A516 Grade 65 steel of inner shell radius of 1m, subjected to different internal pressure were simulated using a finite element software-Autodesk Fusion 360. The shell thicknesses were calculated using a predetermined safety factor, and Autodesk Fusion 360 was utilized to examine the stress distribution in the spherical pressure vessel. Membrane stresses were developed which was viewed in color codes using Von-mises yield stress criteria. The Von-mises stress distribution was compared to the yield strength of the material and the result showed safe value of stress developed. Thus the pressure vessel is adequately able to withstand the specified internal pressures assumed in each case.Analytical methods from the literature were used to validate the results, and no discernible differences were found. This proved that Autodesk Fusion is a good software tool for finite element analysis application.

Keywords: Shop-built, Pressure Vessel, Membrane stress.

1. Introduction

Liquefied natural gas is a composition of methane and other gases used to convert natural gas to liquid form for ease of storage and transportation. LNG takes occupies about 1/600th of the volume of gas at room temperature and atmospheric pressure (Chen et al, 2004). LNG is a colorless, non-corrosive, non-toxic fuel. The demand for LNG has been steadily rising in recent years, and this trend is expected to continue. LNG facilities are being developed all over the world as a result of the increasing demand for this fuel in the energy market, both small and big (Adeyefa et al., 2013).

The combination of higher natural gas prices, rising natural gas demand, and lower liquefied natural gas (LNG) production costs, is setting the stage for increased LNG trade in the years ahead (Adeyefa, 2013). Liquefied Natural Gas (LNG) weighs equivalently only 45% as much as water. Due to this, and its lesser volume capacity, it is most preferred as a result of its benefits in terms of transportation from its natural rich areas to other areas of demand.

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LNG is stored in containments which are specially designed due to its high pressure vessel applications. LNG is kept in double-walled tanks at atmospheric pressure, with insulation placed between the tanks (Khadera, 2009). Special certificates are needed for the hardware (attachments) on these boats, which are developed under strict monitoring.

LNG is stored in specially constructed cryogenic pressure tanks. The purpose of these pressure containers is to store high-pressure gases and liquids. They are specially designed and built storage tanks with two walls. The spherical pressure vessel type is more widely used for storage of gas and liquefied gas than other storage vessel in the oil, gas, chemical and other fields due to its high pressure capability (Moss, 2004).

Many research works on the design of pressure vessels have been carried out. Some of which are reviewed in this section. Finite element analysis is used in the literature on this topic. When applied properly, finite element analysis is a very effective method for pressure vessel analysis. This finding was supported by tests and runs of the models, which showed errors ranging from seven to almost zero percent and could be completed in a reasonable amount of time.

Even with such outcomes, though, the operator still has to understand how to read the data as well as how to do the finite element analysis. To ensure that the answers are somewhat correct, data must be checked using manual computations. One must comprehend what the finite element model is representing and how closely it resembles the real topic in cases when the findings are dubious, such as in the final contact element model (Heckman et al., 1998). Pressure vessel analysis has been in the area of membrane stresses, pressure and thermal stresses.

The Von-mises stress and displacement in the Liquefied petroleum gas (LPG) pressure tank under different pressure distribution and ambient condition using the finite element method is observed that as temperature increases, the pressure of LPG increases (Ugochukwu et al., 2018). Due to the cryogenic temperature of the product, further investigation was done on how to reduce thickness by improving and analyzing materials for pressure vessel shell (Lu and Hui, 2015). In order to create containers with thinner shells, he studied the mechanical behavior of cryogenic stretched austenitic stainless steel. The maximum loads that might be applied to the spherical storage tank over its design life must be taken into consideration by design engineers when they conduct their modeling and design work (Adeyefa and Oluwole, 2011). Hence, optimum spherical wall thickness with respect of minimal mass and stress equivalent is determined for huge pressure vessel design using the principle of optimization over intercepted zones of mass and stress (Kozak and Sertic, 2006).

Nath (2011) used both Lame's theory and the finite element approach to analyze the stress of a thick-walled pressure vessel that was subjected to fluctuating internal pressure. The radius and form of the vessel in question determine the normal stresses brought on by internal pressure (Vyas and Solanki, 2010). As the pressure tank's wall thickness grows, so does the burst pressure. Therefore, indicating the strength of the pressure vessel (Jagali, Kiragat, Arun, and Mahendramani, 2017). Bhargarvi et al. (2016) estimated the radial and circumferential stresses in spherical pressure vessel under pressure and thermal loading. To determine the stress distribution under the combined influence of temperature and pressure loadings, an ABAQUS finite element model was used. The found that the stress distribution results obtained theoretically was in good agreement with Finite Element analysis software tool, ABAQUS.

Thakkar and Thakkar (2012) performed an analysis on pressure vessel using ASME codes and standard to legalize the design and reiterated that design of components using PVElite Software reduces time. Vikram et al. (2012) also presented a work on the stress distribution of ellipsoidal head pressure vessel using FEA and experimentally validating the result obtained by ANSYS. Design analysis of pressure vessel subjected to internal and external pressure governed by ASME pressure vessel code was done by Nishant et al. (2013).

Binesh et al. (2013) concluded that design of pressure vessel by using PVElite gives accurate result. Further work on optimized nozzle location for minimization of stress due to stress discontinuity at junction area using PVElite was performed by Gupta and Desai (2014). Hyder and Asif (2008) presented a work using ANSYS to determine optimize location and size of opening in cylindrical pressure vessel. ANSYS was also used by Chang et al. (2007) in the stress analysis and optimization of thin walled pressure vessel.

1.1 Classifications of Pressure Vessels

I. According to its wall thickness, pressure vessels can be grouped into two namely.

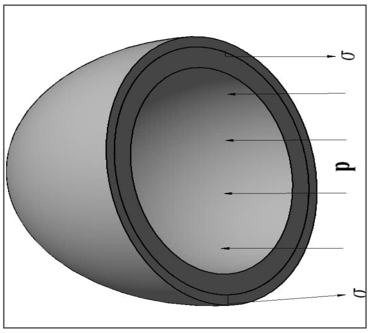
- Thin-walled Pressure vessel: This is a pressure vessel in which the skin of the vessel possesses thickness that is smaller than the entire size of pressure vessel. if the ratio between the mean radius of the vessel and the thickness of the wall is greater than 10.
- Here, $\frac{D}{t} < 10$ means thin-walled pressure vessel.
- Thick walled pressure vessel: here, the ratio between the mean radius of the pressure vessel and the shell thickness of the pressure vessel is less than 10.
- Here, $\frac{D}{t} < 10$ means thick-walled pressure vessel.

II. According to Fabrication, pressure vessel can be grouped into two namely

- Shop-built pressure vessel: this is a type of pressure vessel often manufactured at the workshop or a site which is transportable from a location to another. This type of pressure vessel is designed for uniform shell thickness unlike the field fabricated type. Due to these reasons, they are manufactured for in smaller sizes as compared to field fabricated pressure vessel.
- Field-Fabricated pressure vessel: this type of vessel is as the name implies, field-fabricated. The location of manufacture of these type of vessels are on site, where are needed. They often designed with varying shell thickness due to their size.

The design and analysis of a shop-built pressure vessel are the focus of this study. A shop-built pressure vessel with a spherical shell shape is examined in this study.A spherical pressure vessel has the benefit of homogeneous stress distribution across its walls and is twice as strong as a cylindrical pressure vessel with the same wall thickness.Compared to other vessel shapes, a spherical storage tank has a reduced surface area per unit volume (Ibrahim et al., 2015).

This implies that a spherically shaped tank will transfer less heat to the liquid from warmer surroundings than a cylindrical storage vessel. Despite its distinct advantage, its design complexity limits its maximization to its usefulness. Also, its cost of fabrication is high compared to cylindrical shelled type. Pressure vessel materials, such as mild steel and stainless steel of the austenite type, are often ductile. When pressure vessel are subjected to internal and (or) external pressure, it undergoes deformation and hence, stress in all direction. Tensile forces within the container walls hold pressure vessels together against gas pressure. The vessel's wall's tensile stress is inversely related to its thickness and proportionate to its pressure and radius. As a result, the thickness of pressure vessels is inversely proportional to the maximum normal stress of the vessel material and proportionate to the tank's radius and pressure.



The free-body diagram above gives the equilibrium condition.

$$\sigma 2\pi r t = p\pi r^2$$

Hence

$$\sigma = \sigma_h = \sigma_a = \frac{Pr}{2t}$$

Where

P = Internal Pressure

r = Radius of sphere

t = spherical shell thickness

σ_h = hoop stress

σ_a = Axial stress

π = 3.142

Using the von-mises stress yield criteria,

$\sigma_1 = \frac{Pr}{2t} \quad \sigma_2 = \frac{Pr}{2t}$ ……………………………….. (i)

Since the stress developed are the same on any point on the spherical pressure vessel

Thus,

Von-Mises stress σ' = $\sqrt{\sigma_1{}^2 - \sigma_1\sigma_2 + \sigma_2{}^2}$……….(ii)

Substituting (i) into (ii) we get

Von-Mises stress σ' = $\sigma_1 = \sigma_2$

2. Design Methodolody

Considerable attention has been given by researchers and engineers in the analysis of pressure vessel using finite element method. This project will specifically employ finite element analysis based software, Autodesk Fusion 360, in the design and analysis of a spherical pressure vessel. The finite element analysis has proven to be very reliable due to its advantage over other methods. Some of its advantages include; comprehensive result set, safe simulation of potentially dangerous, destructive or impractical load conditions and failure modes, optimal use of model etc. Thus, the main tools used during the course of the project are a computer and the computer software, Autodesk Fusion 360.

This project involves two major aspects which include.

- 3D Modeling of pressure vessel
- Simulation (Analysis) of pressure vessel under different boundary conditions

Here, the models of spherical pressure vessel are analyzed under different internal pressure with its corresponding shell thickness derived from eqn. (i). four different points representing different elements are investigated and the Von-Mises stress is noted.

2.1 Governing Equations

2.1.1 Plane Elasticity Problem

$$\frac{\partial \sigma_x}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + f_x = \rho \frac{\partial^2 u}{\partial t^2}$$

$$\frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial y} + f_y = \rho \frac{\partial^2 v}{\partial t^2}$$

f_x and f_y denotes the body Forces per unit Volume along x and y direction respectively.

σ_x is the normal stress in the x direction and σ_y is the normal stress in the y direction.

U and V are displacement in x and y directions respectively

ρ = density of material

σ_{xy} = shear stress on the xz and yz planes

2.1.2 Strain-Displacement Relations

$$\varepsilon_x = \frac{\partial u}{\partial x}, \qquad \varepsilon_y = \frac{\partial v}{\partial y}, \quad 2\varepsilon_{xy} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}$$

For the pressure vessel application, stress and strain are related by the constitutive matrix D, as expressed below:

$$\{\sigma_x \sigma_y\ \sigma_z\} = [d_{11} d_{12} 0 d_{21} d_{22} 000 d_{33}]\{\varepsilon_x \varepsilon_y 2\varepsilon_x\}$$

Assuming isotropic material, in plane stress d_{ij} is given by

$$d_{11} = d_{22} = \frac{E}{1-v^2}, \ d_{12} = d_{21} = \frac{Ev}{1-v^2}, \ d_{33} = \frac{E}{2(1+v)}$$

Where E = Young's modulus

v = Poisson's ratio

2.2 Design Parameter of Spherical Pressure Vessel

The following are the design parameters of the pressure vessel

1. Design pressure
2. Internal shell radius of pressure vessel
3. Pressure vessel shell thickness

Assumptions to be employed for design are

- Plane stress condition
- Pressure vessel material is isotropic
- Vessel made of uniform thickness
- Vessel subjected to uniform internal pressure
- The spherical shell is taken as thin shell.

2.3 Mechanical Properties of Astm A516 Grade 65

Material Allowable stress = $128M\frac{N}{m^2}$
Specified minimum yield stress = $240M\frac{N}{m^2}$
Material Minimum Tensile strength = 485MPa
Modulus of elasticity = $200G\frac{N}{m^2}$
Material density = 7850 kg/m^3
Material Factor of Safety = 3.5

3. Static Stress Analysis

Case 1

Internal radius of spherical pressure vessel = 1.0

Thickness of shell = 0.039m

Internal pressure = 10MPa

The above parameters were used in the static stress analysis of a spherical pressure vessel with an internal pressure of 10MPa exerted by the LNG on the wall of the container.

Case 2

Internal radius of spherical pressure vessel = 1.0m

Thickness of shell = 0.079m

Internal pressure = 20MPa

The above parameters were used in the static stress analysis of a spherical pressure vessel with an internal pressure of 20MPa exerted by the LNG on the wall of the container.

Case 3

Internal radius of spherical pressure vessel = 0.5m

Thickness of shell = 0.059m

Internal pressure = 30MPa

The above parameters were used in the static stress analysis of a spherical pressure vessel with an internal pressure of 30MPa exerted by the LNG on the wall of the container.

4. Results and Discussions

Von-mises stress distribution obtained from the simulation using Autodesk Fusion 360 is compared with using ASME result and result obtained from literature.

Case 1. *Internal pressure of 10MPa, Element shell thickness of 0.039*

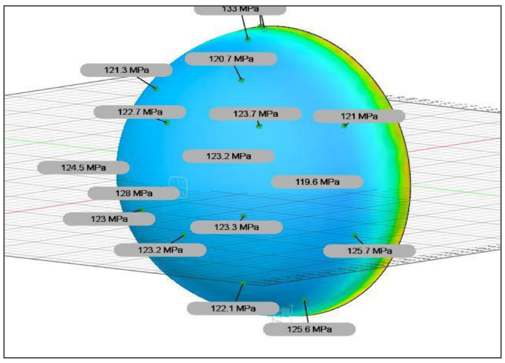
Element	Thickness(m)	Von- Mises Stress Obtained using Fusion 360(MPa)	Von-Mises Stress using ASME CODE (MPa)	Von –Mises Stress obtained by Adeyefa and Oluwole (2013) MPa	Factor of Safety using Autodesk Fusion 360
Element 1	0.039	120.7	129.2	128.6	1.99
Element 2	0.039	123.2	129.2	127.4	1.95
Element 3	0.039	123.3	129.2	123.5	1.97
Element 4	0.039	125.6	129.2	127.8	1.91

Case 2. *Internal pressure of 20MPa, Element shell thickness of 0.079m*

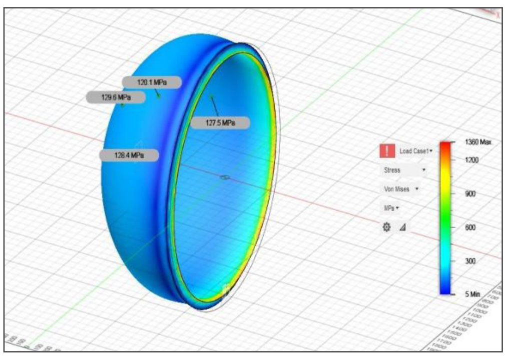
Element	Thickness(m)	Von- Mises Stress Obtained using Fusion 360(MPa)	Von-Mises Stress using ASME CODE (MPa)	Von –Mises Stress obtained by Adeyefa and Oluwole (2013) MPa	Factor of Safety using Autodesk Fusion 360
Element 1	0.079	120.1	128.6	123.9	1.99
Element 2	0.079	129.6	128.6	131.6	1.85
Element 3	0.079	128.4	128.6	124.6	1.87
Element 4	0.079	127.5	128.6	127.8	1.88

Case 3. *Internal pressure of 30MPa, Element shell thickness of 0.059m*

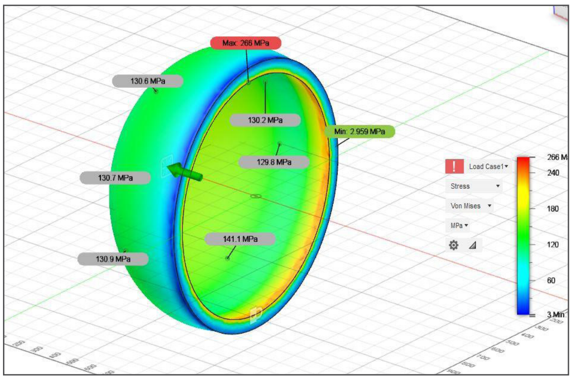
Element	Thickness(m)	Von- Mises Stress Obtained using Fusion 360(MPa)	Von-Mises Stress using ASME CODE (MPa)	Von –Mises Stress obtained by Adeyefa and Oluwole (2013) MPa	Factor of Safety using Autodesk Fusion 360
Element 1	0.059	130.6	129.2	128.1	1.84
Element 2	0.059	130.7	129.2	131.7	1.84
Element 3	0.059	130.9	129.2	130.4	1.83
Element 4	0.059	141.1	129.2	127.7	1.70



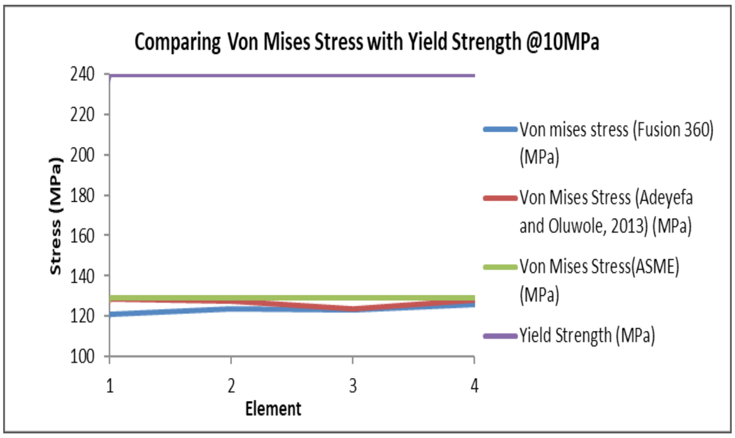
CASE 1

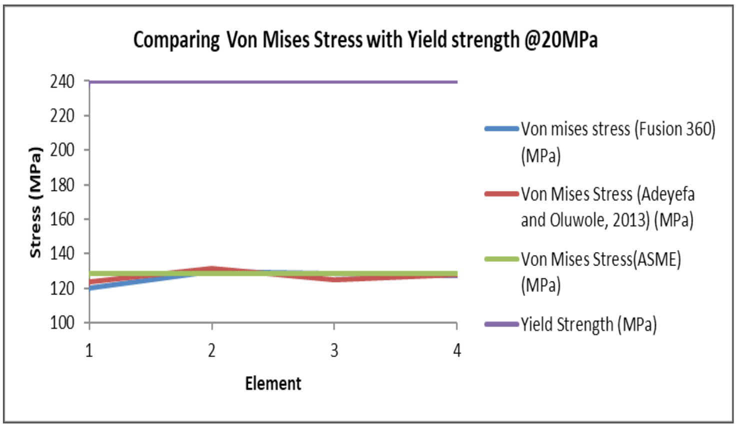


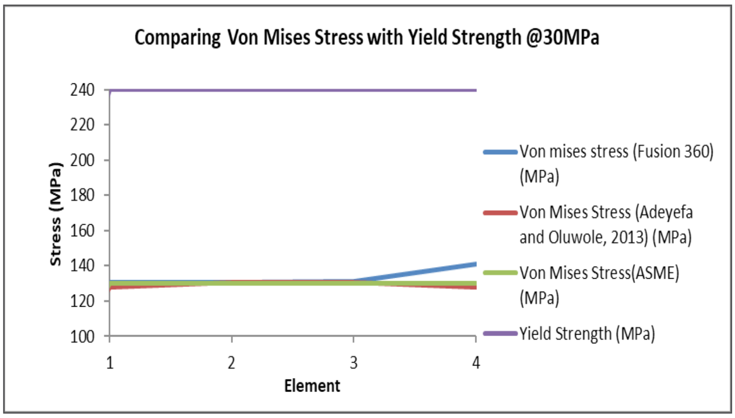
CASE 2



CASE 3







The result of von-mises stress compared to the yield strength for each cases yield a safety factor value of above 1. This shows that for this application using the conventional spherical pressure vessel formulae, the vessel is designed to be safe and can withstand for each analyzed, its corresponding internal pressure. It is noted from the graph that the von-mises stress obtained using Autodesk Fusion 360 is in close correlation with results obtained from ASME and Adeyefa and Oluwole (2013). This proves that Autodesk Fusion is a good software tool that can be employed by designers and Engineers for any finite element application. However, it must be noted that if stress developed in the pressure vessel is lower than the result of stress developed using ASME calculation, the corresponding ASME shell thickness must be used in the design of the spherical pressure vessel. This work does not take into account welded spherical pressure vessel. Thus, further work can be done using this software to determine the stresses developed especially in welded regions of the spherical pressure vessel.

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