# Burst Stress Analysis of Large Green Hydrogen Offshore Pipeline Under Combined Loads

By

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Dissertation submitted in partial fulfilment of the requirements for the Bachelor of

the requirements for the

Bachelor of Engineering (Hons)

(Civil Engineering)

SEPTEMBER 2022

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# CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Civil Engineering Programme
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BACHELOR OF ENGINEERING (Hons)
(CIVIL)

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# CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and the original work contained herein have not been undertaken or done by unspecified source or persons

(MOHAMMAD SHAZRIEL HAKIMI BIN MOHD IMRAN)

# ABSTRACT

In achieving zero carbon economy by 2050, all the countries around the world have put their efforts and a lot of initiative has been taken in reducing carbon emission. In Malaysia for example, the oil and gas industry such PETRONAS try to avoid from releasing any carbon by-product waste into the air. Carbon and methane are the major components of greenhouse gases that highly contribute in global warming. This kind of problem makes the idea of replacing natural gas with environmentally friendly chemical such as hydrogen arise. But replacing natural gas with hydrogen will require an extensive distribution line such as pipeline for transportation and transmission. The problem of having hydrogen pipeline is that hydrogen is always linked with embrittlement. This embrittlement will reduce the ductility of the pipeline, especially steel pipeline which then will increase the risk of bursting failure. Thus, this parametric study will investigate on how different wall thickness, diameter, and material strength will affect the burst pressure of the pipeline by taking embrittlement effect into account. This study found that as the diameter increase, the burst stress at which will cause the pipeline failure will decrease while as the thickness increase, the burst stress also was increased. The difference of burst stress when those parameters were changed are significant which indicate how critical those parameters are. As for the material strength, stronger material resulted in higher burst stress capacity but the difference of the burst stress magnitude between all materials strength was not too significant. In preserving the validity of the research, analytical equation such as DNV equation, Faupel Burst Pressure equation, and Barlow's equation were adopted and from all the three equations, DNV gave the most acceptable percentage error which was within 10%.

# ACKNOWLEDGEMENT

First and foremost, I would like to express my highest gratitude and my utmost appreciation towards my supervisor, Dr. Ahmad Mahamad Al-Yacouby. Despite his busy schedule, he never miss his duty in guiding me throughout my project execution as he always available whenever I have problems with my projects. Without his knowledge, advice and motivations, I would not have been able to complete my final year projects. Not to forget Dr. Zahiraniza binti Zakaria who also contributed in helping to understand my project even better.

Secondly, I would like to thank and express my greatest respect to both of my parents for their continuous support and encouragement, both mentally and emotionally. Without them, I would never be going to get through this project, which is one of the most important projects during throughout my studies in university years.

Last but not least, my deepest appreciation to all my friends and acquaintances who have been there through thin and thin, who always have my back whenever I need them, who always helped me with my report writing techniques. Without them, it is going to be hard to get through this hectic two semesters.

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# CHAPTER 1

# INTRODUCTION

Field & Derwent (2021) discussed about the idea of using Hydrogen in replacing natural gas in future low-carbon or zero-carbon energy economy due to the concern over climate change that has become more dangerous and also due to the interest that developed in limiting greenhouse gas emission. Other than carbon dioxide emissions, burning natural gas will also emits methane, a powerful greenhouse gas, that leaks into the atmosphere usually in large quantities. Greenhouse gases are known by its ability to cause climate change by trapping heat. In addition to that, natural gas combustion also produces carbon monoxide, nitrogen oxides, and also sulphur dioxide. Exposure to sulphur dioxide can cause changes in airway physiology, including increased airway resistance, while exposure in both acute and chronic to carbon monoxide is linked to an increased risk of adverse cardiopulmonary events, including death. Greenhouse gases also can create an extreme weather, disrupt food supply, and increase wildfires. To overcome this sickening greenhouse gases, there are certain countries were set to reduce greenhouse emission in maintaining the global temperature rise after pre-industrial times below 2 degree Celsius in Paris Agreement (2015).

This is the point where hydrogen is involved as the topic of discussion. Hydrogen fuel could be a replacement of oil fuel or natural gases in every vehicle, ships, energy storage, and power stations. The hydrogen energy system are classified into three types which are brown, blue, and green. A brown hydrogen system obtains hydrogen from fossil fuels like coal. Blue hydrogen is produced by using high temperature steam (700°C-1000°C) to extract hydrogen from a methane source. Green hydrogen is created through electrolysis, which uses renewable energy sources such as solar. However, the blue hydrogen produces carbon dioxide $CO_2$ as the by product which is less desirable for the environment. Nonetheless, all the three types of hydrogen fuel system required some storage facilities in order to manage fluctuation in consumer demand. Just as how oil and gas are managed, hydrogen must be easily accessed while at the same time, remain in a secured storage.

As natural gas can be transported using pipelines, hydrogen also can be transported through the same means. According to Hydrogen and Fuel Cell Technologies Office, until today, there are approximately about 1600 miles of hydrogen pipelines available and currently operating in United States that are located where large hydrogen users such as petroleum refineries and chemical plants, are congested like the Gulf Coast region. Gaseous hydrogen transportation through existing pipelines is a low-cost option for delivering large amounts of hydrogen. The high upfront capital costs of new pipeline construction are a significant impediment to expanding hydrogen pipeline delivery infrastructure. Today's research focuses on overcoming technical concerns related to pipeline transmission, such as embrittlement of the steel and weld used for pipeline construction by hydrogen and controlling hydrogen permeation and leaks through the pipeline's wall. This study now has opened a door to the investigation of burst stress analysis of offshore hydrogen pipeline that is now has become part of the concern in having hydrogen pipelines as a large scale industry replacing natural gas.

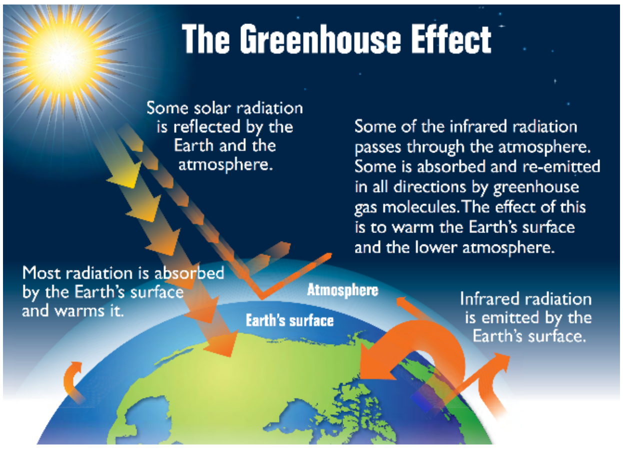


FIGURE 1.1 Greenhouse effect

## 1.1 Background of Study

Burst Stress Analysis of Large Green Hydrogen Offshore Pipeline Under Combined Loads discuss about approach, simulation, and verification using finite element analysis, numerical method, and existing experimental works done by previous researchers in estimating the burst pressure of a pipeline. Compressed hydrogen is used as the fluid inside the pipe due to the idea of replacing it with natural gas which is a limited resources and plays a big role in polluting the environment. Due to the fact that even a hydrogen pipeline has a risk of bursting, an in depth study on the burst strength of the pipeline is required.

Burst stress is a stress at which the vessel will burst or explode due to the internal pressure inside the vessels exceeding the yield strength of the material. This internal pressure exerted in the pipe will induce a circumferential stress in the pipe wall, which also known as Hoop stress that acts perpendicularly to the axial direction throughout the vessel. Usually, Hoop stresses are tensile and generated to resist the bursting effect that caused by the application of pressure. When the pressure is gradually increased to a point that the internal pressure will be sufficient enough to give a stress exceeding the ultimate strength of the vessels or steel pipeline which will be a driving factor to the rupture of the vessel's wall which then will initiate the burst.

For this research, the pipeline will be designed to be under combined loadings such as longitudinal stress and bending moment. The point of introducing these combined loading is to give the idea that most of the time, offshore pipelines will be experiencing these kinds of loadings when sitting on the seabed. This study will be conducted using numerical method which is finite element analysis using ANSYS software to plot the desired pipeline and to analyse the pressure at which the pipeline will burst. From here, the parameters of the pipeline will be manipulated to observe on how it will affect the burst stress of hydrogen pipeline. Since experimental test is not involved due to some limitation such as the cost, time limitation, and the difficulty level of the study, the result from the finite element analysis will be validated using analytical equation as well as findings from previous research experiment on the similar topic to assure the reliability of the study conducted.

## 1.2 Problem Statement

Replacing natural gas with hydrogen has its drawbacks, beginning with how it will affect pipelines and appliances. According to a 2013 study from the US Energy Department's National Renewable Energy Laboratory, "hydrogen embrittlement" can weaken metal or polyethylene pipes and increase leakage risks, particularly in high-pressure pipes (NREL). This embrittlement will significantly affect the burst stress or burst pressure of the pipeline. Changing different parameters such as strength of the pipe, diameter, span length, internal pressure, thickness, and boundary condition of the pipeline might give different outcomes in the burst stress of hydrogen pipeline.

FIGURE 1.2 Pipeline Cracking Due to Embrittlement

## 1.3 Objectives

1. To conduct a parametric study by predicting the burst pressure of hydrogen pipeline when the parameters such as strength of the pipe, diameter, span length, internal pressure, thickness, and boundary condition are changed under combined loadings using Finite Element Analysis
2. To validate FEA result with two method which are the analytical equation that describe the burst stress of the fluid and using the results from published literature on the similar topic.

## 1.4 Scope of Work

1. To model a pipeline geometry in ANSYS Workbench.
2. To run a test for different parameters of the pipeline such as the diameter (D), wall thickness (t) , and material strength (fy).
3. To Analyze and validate the FEA with analytical equation.

## 1.5 Significance of Study

The findings of this study can be referred as an additional information on how the burst strength of brittle pipeline due to hydrogen diffusion can be affected when different parameters are changed throughout the study. Up until today, there is not so many parametric studies that investigate the same parameters used in this research especially for hydrogen pipeline. Outcomes of this study will be discussed further with published literature so that the validity of the research is sustainable.

According to Dwivedi & Kumar (2012), burst strength prediction is very important in designing pressure vessels. Current studies have been only focusing primarily on different types of factors that can significantly affect the burst strength of the pressure vessels . Thus, this study is significant since the objective of this research also to investigate effects of the parameters to the burst strength of pipeline by considering the embrittlement effect.

## 1.6 Chapter Summary

This chapter discussed mainly on the overview of the project which also introduced the primary idea of replacing natural gas with hydrogen and the reason why this idea emerged. On top of that, this chapter also discussed the study that was conducted including, the problem of the having hydrogen in pipeline instead of natural gas, objectives of study, type of works that have been covered, and why this study is important. From here, the literature review has been conducted to justify the study and this topic is discussed further in Chapter 2.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Natural Gas Overview

According to U.S Energy Information Administration, natural gas is a type of fossil energy source that formed beneath earth's surface layer which contains various compounds especially methane. For several years, methane contribution in the climate change discussion has been overlook even though the global warming emissions from natural gas combustion can be said not as significant as coal or oil even though they are considered as fossil fuels. There is around 50 to 60 percent less carbon dioxide emission if natural gas is combusted in a new and efficient power plant compared to emission when it is combusted from a typical coal plant and emits 15 to 20 percent less heat-trapping gases compared to gasoline combustion in vehicles. However, these statistic numbers based on vehicle consumption and power plant are not enough to describe the natural gas as a whole. In industry, works such as drilling, extraction, and transportation of natural gases results in methane leakage that is 34 times stronger than carbon dioxide when it comes to heat trapping in 100 year period and 84 times stronger over 20 years.

## 2.2 Hydrogen as Natural Gas Replacement

The interest of replacing natural gas emerged due to the reason where policy makers started to raise their issue concerning the daily alarming climate changes and also due to their intention to limit the future greenhouse gas emissions (Field & Derwent, 2021). Countries around the world have agreed on pursuing their efforts to limit global warming to well below 2 degrees Celsius, preferably 1.5 degrees Celsius, compared to pre-industrial levels in the Paris agreement. In achieving zero carbon emission by 2050, it requires a new subject to be the main substitute in replacing natural gas.

As per to date, hydrogen is seen as the most suitable replacement for natural gas in the domestic sector towards zero-carbon economy that can also be used even for cooking and heating homes (Field & Derwent , 2021). The reason is that hydrogen can carry energy while giving a minimal environmental impact in reduction of sectors of a future energy system. Besides, hydrogen is a cleaner alternative compared to natural gas, or methane. It can be produced using a variety of resources, including natural gas, nuclear power, biogas, and renewable energy sources such as solar, wind or even electrolysis. "Hydrogen Economy" is the term used by John Bockris, a South African chemistry professor when referring to the use of hydrogen as replacement of fuel. He mentioned that hydrogen can be used in two ways which are firstly, to recreate electricity from fuel cells at efficiencies of 60% and secondly, the hydrogen can be combusted in air without harming the environment to give energy for space heating, and replace natural gas in industry by running aircraft, ships, or trains.

## 2.3 Types of Hydrogen

One of the advantages of using hydrogen is that it does not cause any pollution since its by-product are only heat and water. But the process of producing hydrogen itself does contribute to pollution. By assessing the source of the production, hydrogen are classified into four types which are as shown in the table below :

TABLE 2.1 Types of Hydrogen

| Hydrogen types | Description |
|---|---|
| Grey | Grey hydrogen is a type of hydrogen that extracted from hydrocarbons such as natural gas and fossils fuels. Even though it is common method used for hydrogen production, it also produce carbon dioxide as by-product at the end of the process. |
| Brown/Black | This method is known as the oldest method in hydrogen production which involving coal transformation into gas. The term brown hydrogen and black hydrogen are used interchangeably when either lignite coal that describe its brown colour is used or black bituminous coal is used during the process. The con of using this method is that it produces |

| Hydrogen types | Description |
|---|---|
|  | both carbo dioxide and carbon monoxide as its by-product which are not reusable |
| Blue | In blue hydrogen, emission from hydrogen production process using hydrocarbons will be captured and stored underground using Industrial Carbon Captured and Storage (CSS). Blue hydrogen is considered as a better alternative compared to grey hydrogen where the emissions form its process will be released. However, about 10-20 percent of the carbon dioxide emission is unable to be captured. |
| Green | Different from other types of hydrogen, blue hydrogen is generated by using renewable and clean energy such as solar and wind. Electrolysis where electricity will be used to splits water into oxygen and hydrogen. Due to the by-product of this process is only water and vapour, blue hydrogen is considered as the cleanest form of hydrogen compared to other hydrogen types. |

## 2.4 Burst Stress and the Importance of Study

As hydrogen is apparently seen as the most suitable alternative in replacing natural gas, and its transportation through pipeline is inevitable, the reliability of the pipeline to withstand the stress or pressure exerted by the hydrogen under offshore environment is highly necessary. Since the pressure or stress mentioned is coming from the hydrogen, bursting is the common failure that expected to happen.

According to Puneet & Firoz (2016), burst pressure is the pressure at which vessels will burst or cracking will occur, and internal fluid will start to leak. A lot of industries such as chemical, aviation, and medical industry apply pressure vessels for daily uses, and because of pressure vessels contains a huge amount of energy, bursting will be a catastrophe. Thus, an accurate estimation of bursting pressure become very important.

To date, oil and gas transmission around the world uses pipeline as the main route for transportation and it is considered as the most reliable and the most secure method to transport the product that need to be processed and distribute to the clients. But the concern is to maintain the pipeline integrity in order to make sure that it is safe for operation uses. Corrosion is one of the traits that can affect the pipeline integrity. The effect of corrosion is it can reduce the thickness of the pipeline's wall. This wall thinning will getting severe with time and will crack and leak at peak point. Hence, the study on burst pressure due to corrosion has to be done in order to take an early precaution measure (Saravanan et al., 2012).

Based on Pipeline and Hazardous Materials Safety Administration (PHMSA) database of pipeline failure, in the last six years, there are several significant incidents took place from 2010 to 2015 involving crude oil pipeline failures and 238 natural gas pipeline failure (Dai et al., 2017). According to PHMSA, an incident is considered significant when any of the specifically defined consequences occur such as fatality or injury requiring in-patient hospitalization, $50,000 or more in total costs which is measured in 1984 dollars, 210 gallons or more of highly volatile liquid releases or 2100 gallons or more of other liquid releases, and lastly the liquid releases from the failure resulting in an unintentional fire or explosion. Hence, the study of burst stress of pipeline is very important because of its significant impact on cost, people, and the surrounding environment. By conducting a burst stress analysis, the burst pressure of pipeline can be predicted and in real life situation, a lot of damages can be prevented.

## 2.5 Hydrogen embrittlement in Pipeline

The hydrogen embrittlement is a result of hydrogen diffusion into the material layers when being introduced to metals. From this, metals will start to become more brittle, or less ductile in terms of its physical properties. The severity of the embrittlement is depending on two things which are the amount of hydrogen being absorbed into the material and also the microstructure of the material itself.

Kei et al. (2010) mentioned that hydrogen embrittlement, or also known as unstable ductile fracture, is the major concern in assessing the integrity of hydrogen gas pipeline and it is quite hard to do an experimental study on this topic because hydrogen diffusion into pipeline's wall require certain period of time to happen. Embrittlement become more concerning when its effect can lead to pipeline's cracking especially when a sufficient load is imposed on the objects that are under hydrogen embrittlement influence. Moreover, high-strength steel pipelines have the highest susceptibility to hydrogen embrittlement. The susceptibility of hydrogen embrittlement increase drastically with the steel strength. The hydrogen also can act a grain boundary surfactant which induce the surface microcracks within the steel due to the decrease of energy between the surface grain boundaries (Branko, 2015).

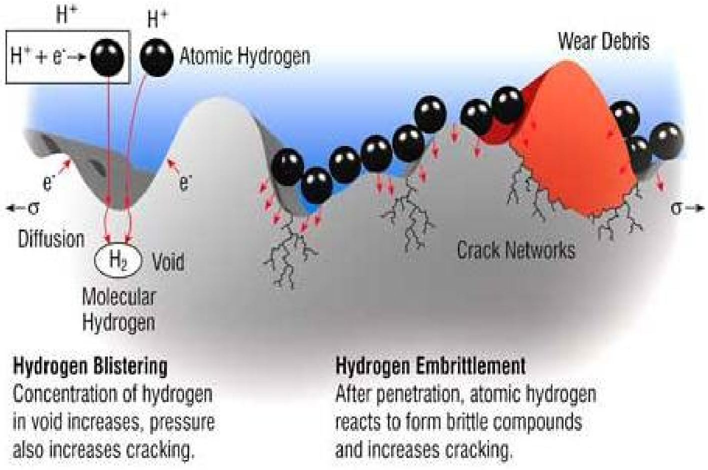


FIGURE 2.1 Hydrogen Embrittlement Process

## 2.6 Calculation of Burst Pressure

Burst stress equation were categorizes into three types of failure criterion which are Tresca Criterion, Von-Mises, and average shear stress criterion by Do-Han Oh (2020). Tresca Criterion is defined as yielding that occurs when the maximum shear stress at any point exceeds the maximum allowable shear stress. For this criterion, yielding take place when the maximum shear stress at any point exceeds the maximum allowable shear stress. DNV (2013) and Barlow OD equations falls under this category, and both of them were used in this analysis as the analytical equation to validate the result obtained from numerical method which in this case, the finite element analysis.

Next, for the Von-Mises criterion, it described as the occurrence of failure when the maximum distortion energy reaches the limit of failure which is equal to the distortion energy required for a material to start yielding. From this group, Faupel (1956) equation, which was said to be the most accurate equation in predicting the burst pressure of a ductile material.

The third category are the equations that apply the average shear stress criterion, which is defined as occurrence of failure when the average shear stress reached the allowable average shear stress. Zhu and Leis (2005,2006,2007,2010,2012) proposed that the allowable average shear stress is calculated by using the average of the maximum shear stress and the Von-Mises equivalent shear stress. There were no equation adopted from this category for the result validation part.

## 2.6 Summary of Literature Review

| No. | Author | Date | Country | Topic | Problem | Method | Research Gap |
|---|---|---|---|---|---|---|---|
| 1 | Puneet Deolia, Firoz A. Shaikh | 2016 | India | Finite Element Analysis to Estimate Burst Pressure of Mild Steel Pressure Vessel Using Ramberg-Osgood Model | Burst pressure estimation is very important and necessary in chemical, medical, and aviation industry. As pressure vessels store large amount of energy, it would be disastrous if it burst. | 1.A Static nonlinear finite element<br>2.Numerical method<br>3.Experimental Analysis using burst stress test | The journal only discussed and study about the internal pressure of the vessels. |
| 2 | Saravanan Karuppanan,Azmi Abdul Wahab, Santosh Patil,Mohamad Armiya Zahari | 2012 | Malaysia | Estimation of Burst Pressure Corroded Pipeline Using Finite Element Analysis (FEA) | Corrosion is one of the major concerns in maintaining the structural integrity of the pipeline. Corrosion will deteriorate the pipes and cause in metal loss, resulting in thinning the pipeline. Given enough time period, the pipe will start to crack and leak which will lead to pipeline bursting | 1.Experimental Analysis using Burst Stress Test<br>2.Finite Element Analysis using ANSYS<br>3.Mathematical Calculation using codes | The finite element method used only consider one thickness only which is 12 mm. |
| 3. | Bipul Chandra Mondal, Ashitosh Sutra Dhar | 2019 | Canada | Burst Pressure of Corroded pipelines considering combined axial forces and bending moments | Most of the Onshore/Offshore pipeline only consider the internal pressure only when. Due to that, strength of corroded pipeline is also generally assessed by only considering the internal pressure such as burst stress. However, in real life application, pipelines | 1.Finite Element Analysis<br>2.Experimental | Limited to the burst pressure assessment of corroded pipelines only. |

| No. | Author | Date | Country | Topic | Problem | Method | Research Gap |
|---|---|---|---|---|---|---|---|
| | | | | | are often exposed to axial forces and bending moments. | | |
| 4. | Thibankumar Arumugam, Muhammad Kasyful Azhim Mohamad Rosli, Saravanan Karuppanan, Mark Ovinis, Michael Lo | 2020 | - | Burst Capacity Analysis of Pipeline with Multiple Longitudinally Aligned Interacting Corrosion Defects Subjected to Internal Pressure e and Axial Compressive Stress | Pipeline's strength is the main concern as it determines its service lifespan. The environment around pipeline can deteriorate its integrity due to exposure to internal pressure and axial compressive stress. With the presence of internal and external corrosion, the strength of the pipeline must be evaluated. | 1.Finite Element Method<br>2.Experimental | This study only consider one thickness which is 12 mm. |
| 5. | Ji-Seok Kim, Myeong-Woo Lee, Yun-Jae Kim, Jin-Weon Kim | 2019 | South Korea | Numerical Validation of Burst Pressure Estimation Equation for Steam Generator Tubes with Multiple Axial Surface Cracks | Up to present, some burst stress data are available only for multiple through wall cracks and part-through surface cracks and still limited considering many cases of multiple cracks. In multiple cracks, the major concern is there is no quantification the interaction effects of multiple adjacent cracks on burst pressure | 1. Finite Element Damage<br>2. Numerical Method | One types of material strength |
| 6. | Zhen-Yu Wang, Yang Zhao, Guo-wei MA, Zhi-guo HE | 2016 | China | A Numerical Study on High-Velocity Impact Behaviour of Pressure Pipes | Pressure pipes are widely used around the globe, but it comes with the risk of explosion due to the pressure inside of the pipe. | 1. Numerical analysis<br>2. Experimental | The paper should consider changing the length of the pipe. |

| No. | Author | Date | Country | Topic | Problem | Method | Research Gap |
|---|---|---|---|---|---|---|---|
| | | | | | Thus, a numerical study must be conducted to investigate the dynamic behaviour of pressure pipe subjected to high velocity impact. | | |
| 7. | Hareram Lohar, Susenjit Sarkar, Samar Chandra Mondal | - | India | Stress Analysis and Burst Pressure Determination of Two Layer Compound Pressure Vessel | Multilayer pipe/vessels are design to work under high pressure. Under cooling condition, the outer cylinder will shrink and give compression to the inner cylinder. Thus, a study is required to enhance the strength the pressure capacity/lifetime of the compound cylinder. | 1. Analytical method<br>2. Finite Element Analysis | There is no experimental analysis was conducted during the study. |
| 8. | Kei Misawa, Shuji Aihara, Erling Ostby, Yasuhito Imai, Hans I. Lange,Yu Sedei,Christian Thaulow | 2010 | Canada | Full Scale Burst Test of Hydrogen Gas X65 Pipeline | Although hydrogen gas pipelines already exist in the world for industrial use and standard for hydrogen gas pipelines has been published [4], extensive studies should be conducted for realizing mass transportation of hydrogen gas pipelines for the future hydrogen economy. | 1. Experimental test<br>2. Numerical Analysis | Only consider one strength, one diameter, and one thickness |
| 9. | Zhanfeng Chen,Yipeng Chen, Wen Wang, Keqing Lu, He Yang, Weiping Zhu | 2020 | China | Failure pressure analysis of hydrogen storage pipeline under | Most burst stress study are conducted at room temperature. No study for burst stress of pipeline under low temperature. | 1. Finite Element Analysis | Formula produced only for extremely low temperature WITH corrosion defects only.<br>No study on the embrittlement. |

| No. | Author | Date | Country | Topic | Problem | Method | Research Gap |
|---|---|---|---|---|---|---|---|
| | | | | low temperature and high pressure | | | |
| 10. | L. Xue, G. E. O. Widera, Z. Sang | 2010 | - | Parametric FEA Study of Burst Pressure of Cylindrical Shell Intersections | Agreement between numerical and experimental study done previously on the burst pressure has sparked the interest of conducting a parametric study to see the correlation between the burst strength and the parameters. | 1. Finite Element Analysis | The length, diameter, and thickness of the two nozzle pipe are used in ratio to one another |
| 11. | J. Koto, Abdul Khair. J, Ali Selamat | 2015 | Malaysia | Ultra-Deep Water Subsea Pipeline Design and Assessment | Ultra-deep water is a severe condition that leads to a challenge to the subsea pipeline during installation and operation. Since the pipeline is exposed to both internal and external pressure, the knowledge on pressure difference in the ultra-deep sea will influence the pipeline wall thickness selection | 1. Simulation | The paper does not mention the type of fluid used inside the pipe |

## 2.7 Critical Literature Review

Puneet and Firoz (2016) performed finite element analysis on the burst stress estimation of mild steel pressure vessels using Ramberg-Osgood model . But in the research, the researchers only consider the internal pressure of the vessels. Environment condition such as temperature and external pressure might also can affect the burst stress of the vessels.

In addition, Saravanan, Wahab, Ssantosh, & Zahari (2019) studied on the burst pressure due to corrosion defects using finite element analysis, mathematical calculation, and burst stress experiment. In the study, a constant wall thickness is used throughout the investigation. Thicker wall might give a different value and different interpretation on the burst stress studied which means that wall thickness is significant to the study.

Moreover, Hareram, Susenjit, & Samar performed an investigation on Stress Analysis and Burst Pressure Determination of Two Layer Compound Pressure Vessel. From this research the authors managed to validate the analytical results with FEM calculations. But the authors only validate the analytical method with FEM. The authors did not perform any experimental works for further validation of the result obtained.

Also, Kei et al. (2010) conducted a full scale burst test of hydrogen pipeline. In this experiment, there are three things that are not changing throughout the test which are the outer diameter which is only 559mm was used, the 13.5mm thickness, and the pipe strength which is X65 pipeline.

Plus, in 2020, Zhanfeng et al. analysed the hydrogen storage pipeline failure under low temperature and high pressure. The authors successfully developed and proposed a numerical equations of the line pipe. But the numerical equation proposed is only can be used if the pipeline is under a very low temperature with corrosion defects only. This equation will be not applicable for other type of pipeline without those condition. Plus, in this study, no hydrogen embrittlement is considered as one of the traits that can affect the pipeline integrity.

Based on the critical literature review conducted, the research gap identified are as follows :

1. Authors used a constant diameter was used throughout the study
2. Authors used the same strength of pipeline throughout the investigation
3. A numerical equation is only applicable for low temperature pipeline with corrosion defects.
4. There is no diameter and thickness variation from the study.
5. Only internal pressure is considered during the tests
6. No experimental validation for the result obtained.
7. No hydrogen embrittlement is considered.
8. Some parametric study does not include the effect of length on the bursting pressure.
9. No defined end supports or boundary conditions of the pipelines

From the above research gaps, the objective of this study will cover more on :

1. Wall thickness
2. Pipeline diameter
3. Material Strength
4. Embrittlement

## 2.8 Chapter Summary

This chapter discussed all relevant and related works that has been conducted throughout the study through various published literatures. Moreover, in this chapter the studies and research that have been carried out by previous authors such as their method of works and the results they produced also were discussed and the gap of studies were identified. From the gap of studies, certain parameters were chosen to become the variables for this project.

# CHAPTER 3

# METHODOLOGY

## 3.1 Planning of The Study

In ensuring the success and smoothness of the study, an early plan has been made earlier in the semester. This study will be carried out in the duration of two semesters. In the first semester, all the planning, research, proposal, gap study, literature review, and topic discussion took place. For the second semester, simulation using Finite Element Analysis using ANSYS Workbench Software will be used, while analytical equation method and comparing findings from previous research will be conducted as the validation of the results.

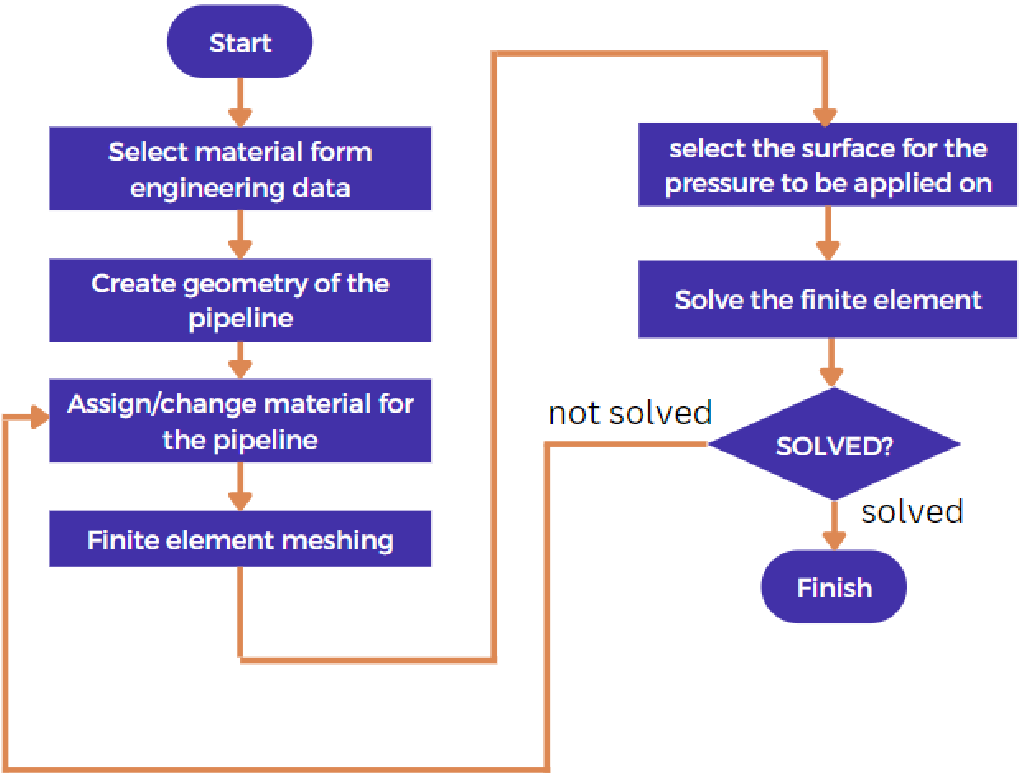


FIGURE 3.1 ANSYS Workbench Methodology

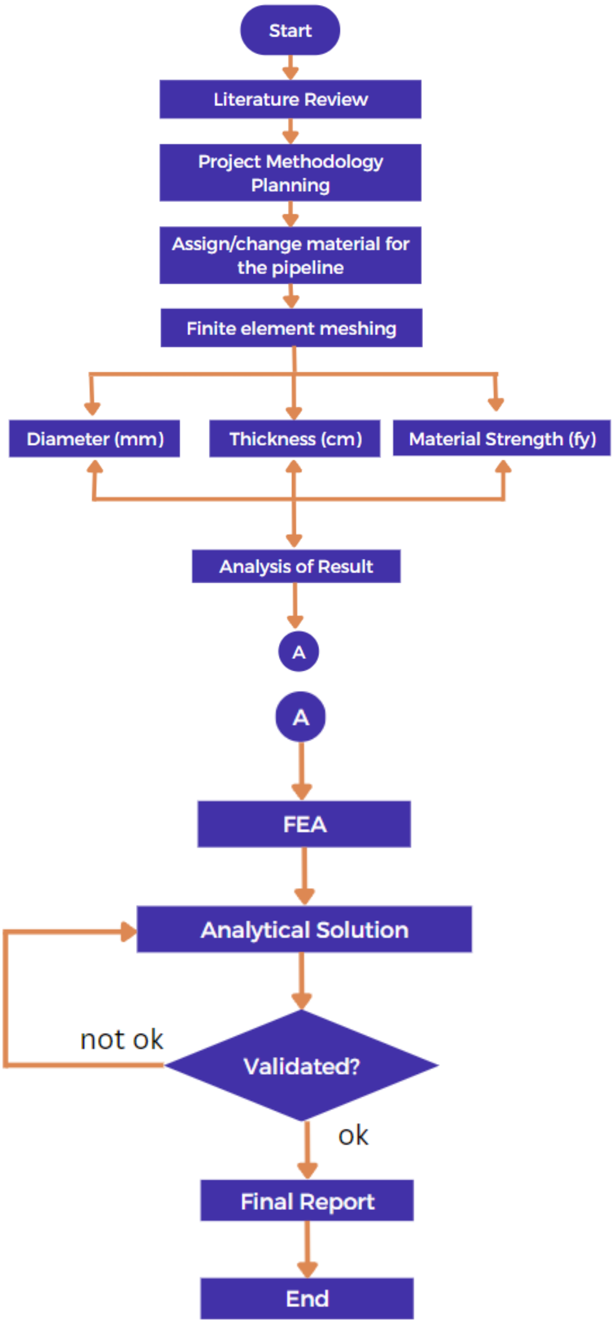


FIGURE 3.2 Overall FYP Flowchart

### 3.2 Data Collection

Since this is a parametric study, the data is basically the parameters that are going to be used for the analysis. These parameters are obtained from the literature review conducted and the choices of some of these parameters are based on previous parametric study. The value that will be used are based on the Petronas Technical Standard (PTS). The parameters are as follows:

TABLE 3.1 List of Parameters

| Parameters | | | | | |
|---|---|---|---|---|---|
| Thickness (mm) | 10 | Material Strength (MPa) | 289 (X42) | Diameter (cm) | 40 |
| | 12.5 | | 317(X46) | | |
| | 15 | | 358(X52) | | 80 |
| | 17.5 | | 386(X56) | | 120 |

### 3.3 Finite Element Analysis

By using ANSYS Workbench the pipeline geometry will be designed first. During the early of FEA, the length of the pipeline will be constant first which is 6 m. Before creating the pipeline, the types of material desired will be chosen first. In this study, stainless steel will be selected as the material. Since hydrogen embrittlement is considered in this study, a brittle material might be used for the pipeline to observe its effect when pressure is applied on.

After the 2 m geometry of the pipe is created, it will be mesh for finite element solution. Meshing is done by turning irregular shapes into more recognizable volumes known as elements. Mesh is created to split the domain into discrete number of elements that makes the solution can be calculated.

After done with meshing, the important part where the parameters that were decided to be manipulated throughout the study is implemented. For example, the thickness of the pipeline will be put as 10 mm first to observe on how the burst stress will be. Then, it is very important to make sure that the load is applied on the pipeline's wall to allow the failure or crack happens on the wall only. After that, the finite element analysis will be solved. When the desired result is obtained, the analysis will be repeated using different parameters until all the required parameters are studied.

### 3.4 Results Validation

After the results from the simulation using ANSYS Workbench are obtained, it requires certain method to justify or validate the work that have been done. The validation part is divided into two method which are analytical analysis and by comparing result with previous findings on similar project background. Analytical analysis will involve the equation that is suitable in describing the burst pressure of hydrogen pipeline.

*A) Analytical Analysis*

For analytical analysis, Barlow's Equation will be used. This equation relates the internal pressure that a pipe can withstand based on the dimensions and its strength. The internal pressure from the formula will indicate the burst pressure of the hydrogen content inside the fluid. As shown below, this formula only relate with the material strength, diameter, and thickness and nowhere it describes the relation between the length of the pipeline and burst pressure.

$$\mathrm{P} = \frac{2\sigma \mathrm{t}}{\mathrm{D}} \tag{1}$$

Where

P : Internal pressure

σ : Allowable stress of material

t : Wall thickness

D : Outer diameter

This formula is often used in the pipeline industries around the world in determining whether the pipeline can safely withstand the operating pressure that will be used for gathering, distribution lines, and transmission. For this, United States has classified the location of the application into 4 locations.

TABLE 3.2 Design Factor for Barlow's Equation Based on Location from Wikipedia

| Class | Definition | Design factor |
|---|---|---|
| 1 | An offshore area or any class location unit that has 10 or fewer buildings intended for human occupancy | 0.72 |
| 2 | Any class location that has more than 10 but fewer than 46 buildings intended for human occupancy | 0.60 |
| 3 | Any location that has 46 or more buildings intended for human occupancy or any area where the pipeline lies within 100 yards (91 meters) of a building or a small, well-defined outdoor area (such as a playground, recreation area, outdoor theatre, or place of public assembly) that is occupied by 20 or more persons at least five days a week for 10 weeks in any 12-month period—weeks need not be consecutive | 0.50 |
| 4 | Any class location unit where buildings with four or more stories above the ground are prevalent | 0.40 |

Since the pipeline that will be design is located at offshore and under combined loadings, the most suitable design factor, according to DOT Part 192, is 0.72.

On the previous study of Stress Analysis and Burst Pressure Determination of Two Layer Compound Pressure Vessel , Hareram et al. referred to Faupel in describing the burst pressure of a hollow mono-block vessels. The equation is given as follows :

$$p = \frac{2f_{y.p.}}{\sqrt{3}}\left[\ln\frac{r_o}{r_i}\right]\left[2-\frac{f_{y.p.}}{f_{t.s.}}\right] \quad (2)$$

Where

$f_{y.p}$ = yield point of the material

$f_{t.s}$ = ultimate tensile strength

$r_o$ = Outer radius of vessels

$r_i$ = Inner radius of vessels

The third formula that was also being considered in this study was DNV formula. This formula was used due to non-acceptable range of the two previous equation that did not falls under 10% of percentage error. DNV (2013) is given by :

$$Pmax = \frac{2t}{D-t} fcb \frac{2}{\sqrt{3}} \tag{3}$$

Where

f.c.b = Min [$\sigma$y ; $\sigma$UTS]

### 3.5 Mesh Sensitivity Analysis

Meshing is one of the important aspects in acquiring an accurate result from using finite element model. Usually, the result will be better as the size of element is smaller. The problem of having a smaller size of element is that it will require more time to obtain the solution since the total number of elements will be larger. This is the only trade-off in having a more accurate result in the analysis. The idea of mesh sensitivity analysis to get the most optimum meshing size that saves time while giving a sufficient result that is desired. This analysis is important in determining the best meshing size to be used in the analysis.

K. Ji-Seok et. al (2019) maintained the total number of elements in finite element meshes ranged from 13008 to 77190 elements. This number of elements was adopted as the baseline for finite element meshing in this project. Thus, the number of required elements in this analysis was at least 13000 elements. For this analysis, the mesh sensitivity analysis was conducted, and the meshing size was started with 0.03 m. From this mesh size, the total number of elements was assessed, which resulted in 6700 total number of elements. Since the number of elements was still below the desired number, the size was then decreases to 0.02 m which resulted in 13266 elements. Even though the total number of elements already reached the desired value, the mesh sensitivity analysis was continued until a consistent value of maximum equivalent stress obtained. Then, the mesh size was reduced to 0.019 m, 0.018 m, and 0.017 m. From here, it was observed that the maximum equivalent stress obtained for 0.02 m mesh size and 0.017 m had no difference which both sizes produced 241 Mpa. Due to consistent value has already obtained, mesh sensitivity analysis was stopped.

For different diameter and thickness combination, the mesh size was different from each other. It is because larger size of model produced higher number of total elements. For those cases, same analysis was conducted. The only problem was this study was limited to certain number of total elements only. Because of that, the mesh size was chosen to be as smallest as possible that it would not exceed the limit number of total elements.

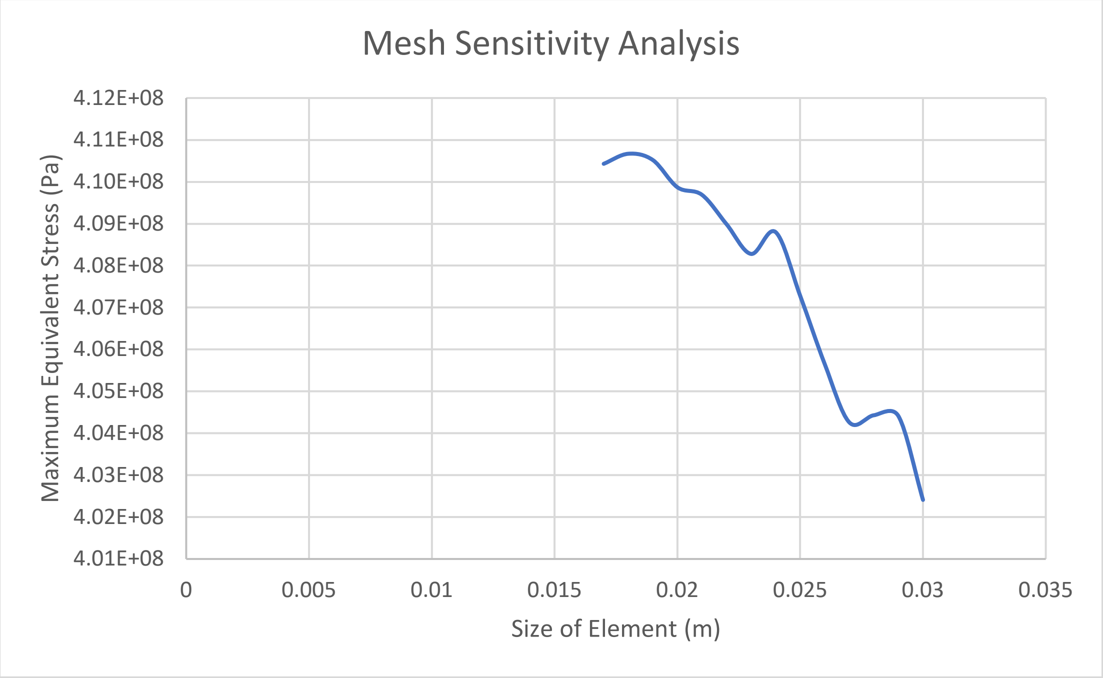


FIGURE 3.3 Mesh Sensitivity Analysis

TABLE 3.3 Mesh Sensitivity Analysis Summary

|  |  | Elements | Size (m) | Maximum Equivalent Stress (Pa) | Deformation (m) |
|---|---|---|---|---|---|
| 1 | Coarse | 6700 | 0.03 | 2.37E+08 | 1.86E-04 |
| 2 | Medium | 6700 | 0.03 | 2.37E+08 | 1.86E-04 |
| 3 | Fine | 6700 | 0.03 | 2.37E+08 | 1.86E-04 |

|  |  | Elements | Size (m) | Maximum Equivalent Stress (Pa) | Deformation (m) |
|---|---|---|---|---|---|
| 1 | Coarse | 13266 | 0.02 | 2.41E+08 | 1.86E-04 |
| 2 | Medium | 13266 | 0.02 | 2.41E+08 | 1.86E-04 |
| 3 | Fine | 13266 | 0.02 | 2.41E+08 | 1.86E-04 |

|  |  | Elements | Size (m) | Maximum Equivalent Stress (Pa) | Deformation (m) |
|---|---|---|---|---|---|
| 1 | Coarse | 17775 | 0.017 | 2.41E+08 | 1.86E-04 |
| 2 | Medium | 17775 | 0.017 | 2.41E+08 | 1.86E-04 |
| 3 | Fine | 17775 | 0.017 | 2.41E+08 | 1.86E-04 |

## 3.7 Embrittlement Effect

As discussed in the literature review, the embrittlement is a serious problem, and it is one of the main points of this study. Embrittlement which causes by the hydrogen liquid, is very tedious and cumbersome to be modelled in this level of study. As embrittlement reduces ductility and lower the load-bearing capacity of ductile material, it also reduces the strength of the material. A failure of the embrittled material can occur below its yield strength and ultimate tensile strength. Thus, for this study, since plotting hydrogen that can induced into the material is beyond the scope and capability, the embrittlement effect was represented by reducing the yield strength and ultimate strength by 0% , 10% and 15%. For further understanding, the embrittlement was represent as shown in the table below which illustrate the reduction in both yield strength and tensile strength.

TABLE 3.4 Embrittlement Representation on Pipeline Strength

| Pipeline Strength (Mpa) | 0% Embrittlement | 10% Embrittlement | 15% Embrittlement |
|---|---|---|---|
| X42 (289 - YS) | 289 | 260.1 | 245.65 |
| X42 (413 - TS) | 413 | 371.7 | 351.05 |
| X46 (317 - YS) | 317 | 285.3 | 269.45 |
| X46 (434 - TS) | 434 | 390.6 | 368.9 |
| X52 (358 - YS) | 358 | 322.2 | 304.3 |
| X52 (455 - TS) | 455 | 409.5 | 386.5 |
| X56 (386 - YS) | 386 | 347.4 | 328.1 |
| X56 (489 - TS) | 489 | 440.1 | 415.65 |

### 3.8 Failure Criterion

Baseline for the failure of the pipeline models was standardize first before proceeding with the analysis in order to obtain a consistent desired result throughout the study. Burst pressure of pipeline correspond to the ultimate strength of the pipeline and thus, the ultimate tensile strength of each pipeline were used as the baseline to determine whether the pipeline has reached the burst limit or not in this assessment.

The determination of the burst pressure assessment commonly executed by comparing the equivalent stress or Von Mises stress. Therefore, in this analysis, the assessment was conducted by the evaluation the maximum equivalent stress and comparison with the ultimate tensile strength of the pipeline's material which varied from X42, X46, X52, and X56. The pipeline was considered 'burst' when the maximum equivalent stress induced was equal or larger than the ultimate strength and the corresponding applied pressure was recorded, and the pressure was named as burst pressure which the pipeline could take.

### 3.9 Thinned Wall Setup

All models were designed to be a thinned wall pipeline. For this, there was a criterion that must be adhered which the aspect ratio of D/t must be more than 20. All the pipeline modelled fulfilled this requirement. A. Keith Escoe (2006) mentioned in his paper that the vast majority of standard piping schedules are thin walled. This became the basis of the study on why thinned wall pipeline was considered throughout the analysis. Since most of the pipeline is thinned wall, it is important to adhere to the common pipeline designs and parameters.

## 3.10 Pressure Application

Pressure application for this analysis was manually incremented. The internal pressure was applied starting from 2 MPa and then gradually increased by 2 MPa each step. From each load step, the corresponding maximum equivalent stress was retrieved and inserted in the excel sheet. To ease the analysis, the function “IF()” was used in determining whether the maximum equivalent stress has exceeded the burst limit for each degree of embrittlement or not. For example, the code used for the shown table was IF(I40>$B$23,"Burst","Safe"), where I40 and $B$23 was the column and row location of the burst limit.

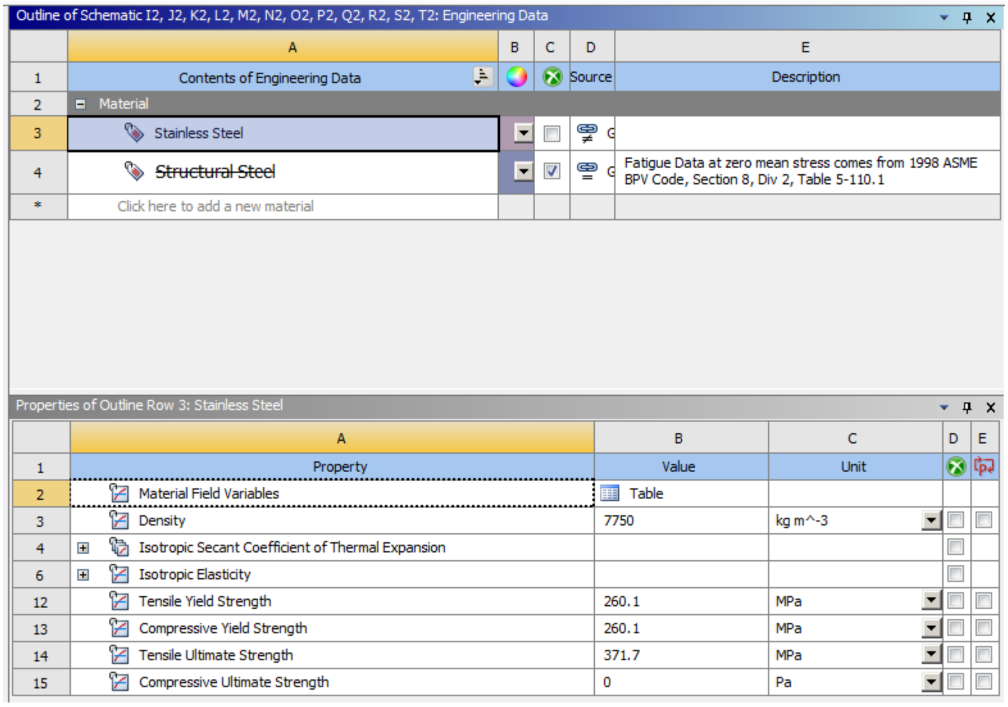
TABLE 3.5 Pressure Application Method Using Excel

| Thickness (mm) | 10 | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Applied Pressure (MPa) | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 15 | 16 | 17 | 18 |
| Max. Pressure (MPa) | 48.3 | 96.6 | 145 | 1.93 | 241 | 290 | 338 | 362 | 386 | 410 | 435 |
| Burst or Not (0%) | Safe | Safe | Safe | Safe | Safe | Safe | Safe | Safe | Safe | Safe | Burst |
| Burst or Not (10%) | Safe | Safe | Safe | Safe | Safe | Safe | Safe | Safe | Burst | Burst | Burst |
| Burst or Not (15%) | Safe | Safe | Safe | Safe | Safe | Safe | Safe | Burst | Burst | Burst | Burst |

## 3.11 Material and Strength Assignment

The material chosen for the pipeline models was purely stainless steel. The material was already available in the engineering data where it was accessible and easily adopted. The selection of this material was based on study from Zhanfeng et. al (2020) who adopted stainless steel pipe such as ASTM A312/A358 TP 304/304 in failure pressure analysis of hydrogen storage pipeline under low temperature and high pressure considering the analysis was done in cryogenic environment. The grade of pipeline used in this analysis was X42, X46, X52, and X56.

For the mentioned grade of pipeline models, the strength of each pipeline was manually modified in the engineering data under material property’s section. The yield strength and ultimate tensile strength was changed to according to pipeline’s grade. The properties for embrittled pipelines also were changed at the same section.



Outline of Schematic I2, J2, K2, L2, M2, N2, O2, P2, Q2, R2, S2, T2: Engineering Data

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Contents of Engineering Data | | | Source | Description |
| 2 | Material | | | | |
| 3 | Stainless Steel | | ☐ | G | |
| 4 | ~~Structural Steel~~ | | ☑ | G | Fatigue Data at zero mean stress comes from 1998 ASME BPV Code, Section 8, Div 2, Table 5-110.1 |
| * | Click here to add a new material | | | | |

Properties of Outline Row 3: Stainless Steel

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Property | Value | Unit | | |
| 2 | Material Field Variables | Table | | | |
| 3 | Density | 7750 | kg m^-3 | ☐ | ☐ |
| 4 | Isotropic Secant Coefficient of Thermal Expansion | | | ☐ | |
| 6 | Isotropic Elasticity | | | ☐ | |
| 12 | Tensile Yield Strength | 260.1 | MPa | ☐ | ☐ |
| 13 | Compressive Yield Strength | 260.1 | MPa | ☐ | ☐ |
| 14 | Tensile Ultimate Strength | 371.7 | MPa | ☐ | ☐ |
| 15 | Compressive Ultimate Strength | 0 | Pa | ☐ | ☐ |

FIGURE 3.4 Engineering Data Material Properties

## 3.12 Chapter Summary

This chapter discussed about the method and analysis that were carried out using ANSYS Software and Microsoft Excel starting from the early stage of the study until the end. This section highlights the material selection, material strength set up, meshing size selection, modelling, method of analysis, and the result validation. All data presented in this chapter were adopted from the software itself and some from published literatures.

# CHAPTER 4

# RESULT AND DISCUSSION

## 4.1 Elimination of parameters

Initially, the parameters to be studied in this project are the wall thickness, diameter, length, material strength, and boundary condition of the pipeline. While performing the analysis, other than time constraint factor, it has been observed that the length of the pipeline and the boundary condition such as the type of end supports, give no significant effect towards the burst pressure of the pipeline.

The decision of eliminating these two parameters was made based on the equivalent stresses (Von-Mises Stress) developed in the internal surface of the pipeline with 12 m length and 4 m length. It must be noted that while comparing these two models, the other attributes such as size of elements, diameter, thickness, end supports, and material strength is maintained for both models.

From the analysis conducted, the maximum equivalent stresses developed for both models are almost similar to one another. As shown in the result that was retrieved from ANSYS below, the maximum equivalent stresses developed in model with L = 4 m is 4.0241 Pa while the maximum equivalent stresses developed in model with L = 12 is 4.0293 Pa. The difference between the two values is 0.0052 MPa which is about 0.13 %. From here, it was concluded that the length of pipeline does not give a significance difference in determining the burst pressure.

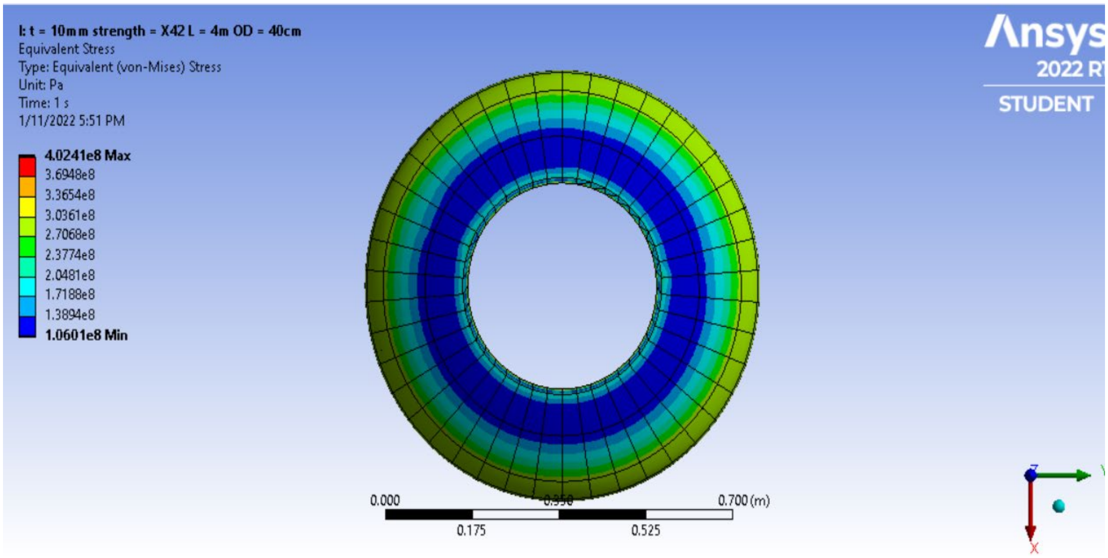


FIGURE 4.1 X42 Pipeline with L = 4m

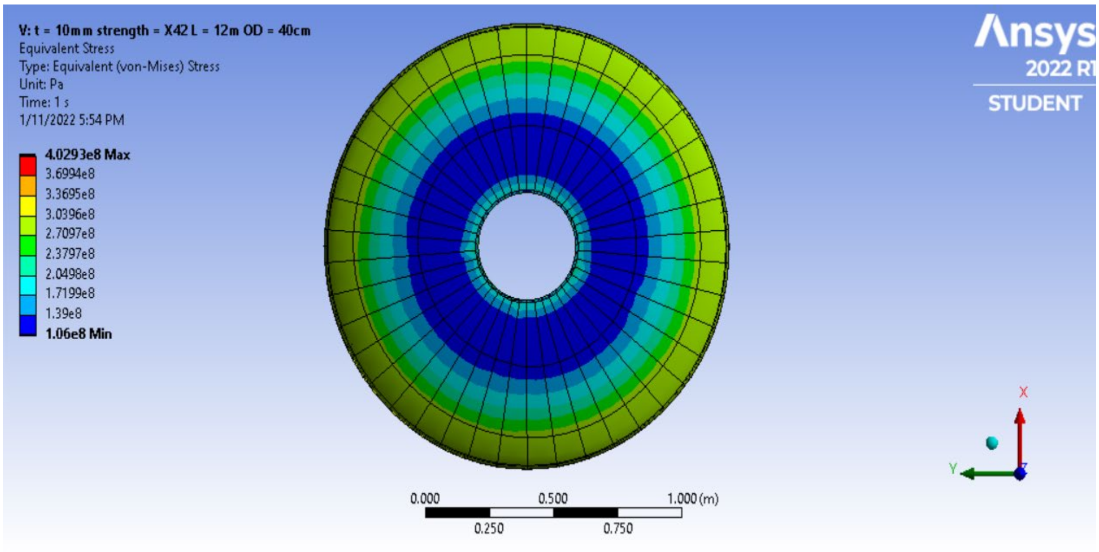


FIGURE 4.2 X42 Pipeline with L = 12m

## 4.2 Combined Loading Analysis

The analysis also studied the effect of combined loadings toward the largest pipeline geometry. The largest pipeline modelled was having a diameter of 1200 mm, 17.5 mm thickness and 4000 mm length. Since the study is about burst stress analysis of large hydrogen pipeline, only the largest pipeline is considered for the combined loading analysis. The load combination used in the analysis are axial stress and hydrostatic pressure.

TABLE 4.1 Parameters for Hydrostatic Pressure Calculation

| | | |
|---|---|---|
| Water depth | 60 | m |
| Gravity | 9.81 | m/s2 |
| Seawater Density | 1025 | kg/m2 |
| Pressure | 0.603315 | MPa |

There is a certain criterion was fixed before proceeding with the analysis in which, the depth of the pipeline was assumed to be z = 60 meters under the sea to ease the analysis. Using the parameter shown in the table, hydrostatic pressure can be simply calculated using formula :

$$P = \gamma z \tag{4}$$

Where

$\gamma$ = specific weight density = 10.05kN/m$^3$

From the equation, the hydrostatic pressure obtained was 0.603315 MPa. From this hydrostatic pressure obtained, it was then increased by percentage with 10% increment to demonstrate a greater hydrostatic pressure on the pipeline. The result shown below consisting of the maximum equivalent stresses (von-mises stress) before and after the application of hydrostatic pressure and the effect of this pressure was evaluated by percentage difference of the two conditions, before and after the application.

TABLE 4.2 Effects of Hydrostatic Pressure Toward Max. Equivalent Stress

| Hydrostatic Pressure | | | |
|---|---|---|---|
| Applied Force | Max. Equivalent Stress (Pa) - Before | Max. Equivalent Stress (Pa) - After | Difference (%) |
| 100% | 416640000 | 391260000 | 6.09 |
| 110% | 416640000 | 388720000 | 6.70 |
| 120% | 416640000 | 386190000 | 7.31 |
| 130% | 416640000 | 383650000 | 7.92 |
| 140% | 416640000 | 381110000 | 8.53 |
| 150% | 416640000 | 378570000 | 9.14 |
| 160% | 416640000 | 376040000 | 9.74 |
| 170% | 416640000 | 373500000 | 10.35 |
| 180% | 416640000 | 370960000 | 10.96 |
| 190% | 416640000 | 368420000 | 11.57 |
| 200% | 416640000 | 365890000 | 12.18 |

From the result, the hydrostatic pressure did affect the equivalent stress developed in the internal wall of the pipeline. This means that from the result, the hydrostatic pressure can reduce the burst pressure of pipeline and the significant of the reduction is dependent on how deep the pipeline is located and how strong the hydrostatic pressure. Other than the depth of the pipeline location, seawater density also can affect the strength of hydrostatic pressure. Simply said, the denser a fluid is, the greater the pressure is even though it is located at the same depth.

Next, for the axial stress, the value of stresses was determined by using longitudinal stress formula given by :

$$fa = \frac{PD}{4t} \tag{5}$$

By consuming the formula, the longitudinal stress obtained was 10.34 MPa. The reason of using longitudinal stress to determine the axial stress that is imposed onto the pipeline is to set the basis of the study conducted. Since the magnitude of axial stresses can vary from location to location, and the value can be arbitrary, using the longitudinal stress formula can be simpler yet still logical.

From the result obtained, the axial stress did not affect both maximum equivalent stress and the total deformation of the pipeline. The maximum equivalent stress before and after the axial stress application was the same and the total deformation also did not change throughout the analysis. The reason for this might be due to the location of the axial stress application. The axial stress was applied parallel to the pipeline length (axial direction) . The point of application was at the wall thickness of the pipeline which was set to be fixed throughout the analysis. Fixing both ends means to prevent any movement in any direction. Because of that, there was no displacement took place and no deformation was allowed. As the conclusion from these combined loadings analysis, the significant reduction in the equivalent stresses was caused by the hydrostatic pressure only since there is no changes occur when only axial stresses being subjected to the pipeline.

TABLE 4.3 Effects of Axial Stress Toward Max. Equivalent Stress

| Axial Stress | | | |
|---|---|---|---|
| Applied Force | Max. Equivalent Stress (Pa) - Before | Max. Equivalent Stress (Pa) - After | Total Deformation (m) |
| 100% | 416640000 | 416640000 | 9.78E-04 |
| 110% | 416640000 | 416640000 | 9.78E-04 |
| 120% | 416640000 | 416640000 | 9.78E-04 |
| 130% | 416640000 | 416640000 | 9.78E-04 |
| 140% | 416640000 | 416640000 | 9.78E-04 |
| 150% | 416640000 | 416640000 | 9.78E-04 |
| 160% | 416640000 | 416640000 | 9.78E-04 |
| 170% | 416640000 | 416640000 | 9.78E-04 |
| 180% | 416640000 | 416640000 | 9.78E-04 |
| 190% | 416640000 | 416640000 | 9.78E-04 |
| 200% | 416640000 | 416640000 | 9.78E-04 |

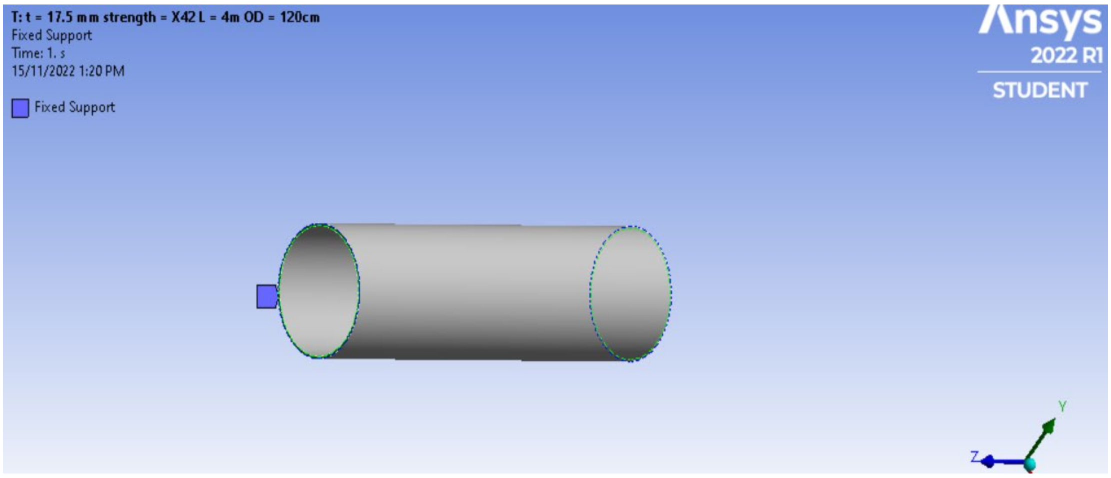


FIGURE 4.3 Fixed End

The pipeline was then subjected to the combination  of hydrostatic pressure and axial stress. From this combination of loadings, it was shown that only hydrostatic pressure affects the maximum equivalent stress in the internal wall of the pipeline. Same goes to deformation, it was purely caused by the hydrostatic pressure that was subjected onto the outer diameter wall of the pipeline model. Though, the deformation is too small and almost insignificant. The highest deformation was 0.000918 m which is very small. However, as the hydrostatic pressure increased, the deformation decrease. This means that the internal pressure subjected to the internal wall was greater than the hydrostatic pressure. The deformation observed was actually caused by the internal pressure. Here, increment in hydrostatic pressure has caused a resisting effect towards the deformation. Simply said, the hydrostatic pressure against the direction of the deformation, thus reducing the total deformation of the pipeline.

TABLE 4.4 Effects of Axial Stress and Hydrostatic Pressure Toward Max. Equivalent Stress

| Hydrostatic Pressure + Axial Stress | | | | |
|---|---|---|---|---|
| Applied Force | Max. Equivalent Stress (Pa) - Before | Deformation - Before (m) | Max. Equivalent Stress (Pa) - After | Deformation - After (m) |
| 100% | 416640000 | 9.78E-04 | 391260000 | 9.18E-04 |
| 110% | 416640000 | 9.78E-04 | 388720000 | 9.12E-04 |
| 120% | 416640000 | 9.78E-04 | 386190000 | 9.06E-04 |
| 130% | 416640000 | 9.78E-04 | 383650000 | 9.00E-04 |
| 140% | 416640000 | 9.78E-04 | 381110000 | 8.94E-04 |
| 150% | 416640000 | 9.78E-04 | 378570000 | 8.88E-04 |
| 160% | 416640000 | 9.78E-04 | 376040000 | 8.82E-04 |
| 170% | 416640000 | 9.78E-04 | 373500000 | 8.76E-04 |
| 180% | 416640000 | 9.78E-04 | 370960000 | 8.70E-04 |
| 190% | 416640000 | 9.78E-04 | 368420000 | 8.64E-04 |
| 200% | 416640000 | 9.78E-04 | 365890000 | 8.58E-04 |

## 4.3 Revised Combined Loading Analysis

Since the axial stress in the previous analysis did not affect the result that much due to the fixed end support at both ends, for clarification of study, the support was made fixed only at one end. This time, it can be seen that the how significant the axial stress was to both maximum equivalent stresses and deformation. T. Neil et al. (2015) discussed on the effect of bending and axial compression on pipeline burst capacity and the authors found that as cross-section plasticity and the associated stiffness reduction occur due to the presence of combined loadings, the shape of the imperfection changed significantly to satisfy the loading condition which lead to reduction of burst pressure. Due to the significant reduction of the burst pressure, the authors also mentioned that the analytical equation was no longer valid. Since the revised pipeline were set as fixed-free supported, the applied axial stress has caused one of the pipeline’s ends to freely move. This elongation has caused a reduction in stiffness of the pipeline itself which also lead to reduction of burst pressure. To conclude, this study and the author’s research of the effects of combined loadings to the burst pressure has found an agreement.

TABLE 4.5 Revised Effects of Axial Stress and Hydrostatic Pressure Toward Max. Equivalent Stress

| Hydrostatic Pressure + Axial Stress (Revised) | | | | |
|---|---|---|---|---|
| Applied Force | Max. Equivalent Stress (Pa) - Before | Deformation - Before (m) | Max. Equivalent Stress (Pa) - After | Deformation - After (m) |
| 100% | 371220000 | 2.31E-03 | 422960000 | 1.58E-03 |
| 110% | 371220000 | 2.31E-03 | 428260000 | 1.88E-03 |
| 120% | 371220000 | 2.31E-03 | 433340000 | 2.19E-03 |
| 130% | 371220000 | 2.31E-03 | 438900000 | 2.50E-03 |
| 140% | 371220000 | 2.31E-03 | 444240000 | 2.82E-03 |
| 150% | 371220000 | 2.31E-03 | 449610000 | 3.15E-03 |
| 160% | 371220000 | 2.31E-03 | 454990000 | 3.48E-03 |
| 170% | 371220000 | 2.31E-03 | 460380000 | 3.81E-03 |
| 180% | 371220000 | 2.31E-03 | 465790000 | 4.15E-03 |
| 190% | 371220000 | 2.31E-03 | 471210000 | 4.48E-03 |
| 200% | 371220000 | 2.31E-03 | 476650000 | 4.82E-03 |

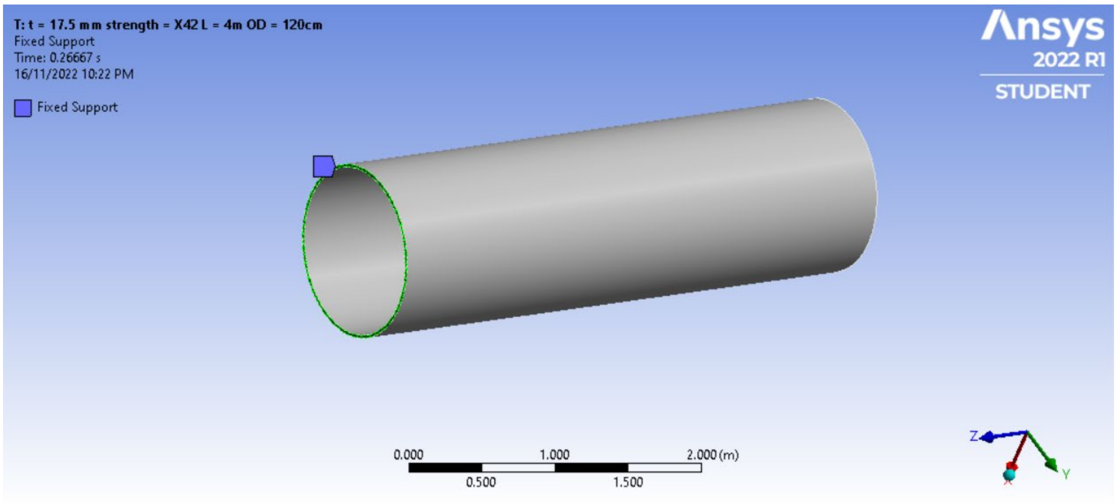


FIGURE 4.4 X42 Pipeline Fixed-Free Ends

## 4.4 Equivalent Stress (Von-Mises)

Equivalent stress or Von-mises stress behavior was observed in this analysis. Throughout the analysis, the equivalent stress response to the magnitude of the applied load with different wall thickness, diameter and the strength of the material are also different. These are very important aspects to be observed in order to study how the parameters affect the burst stress of a pipeline or a pressure vessel in general.

## 4.5 Equivalent Stress with Different Wall Thickness

The equivalent stresses for three different wall thickness are different. The applied pressure for the three models was 2 MPa. However, the applied pressure has induced the maximum equivalent stress of 38.2 Mpa, 31.5 Mpa, and 27.1 Mpa for t = 12.5 mm, t = 15 mm, and t = 17.5 mm respectively. As shown, the thicker the wall thickness, the lesser maximum equivalent stresses induced in the internal wall of the pipeline if the applied internal pressure is constant. In terms of aspect ratio, the smaller the aspect ratio (D/t), the maximum equivalent stresses induced when internal pressure is applied is also increased. Thus, thicker pipeline can take more internal pressure before it burst.

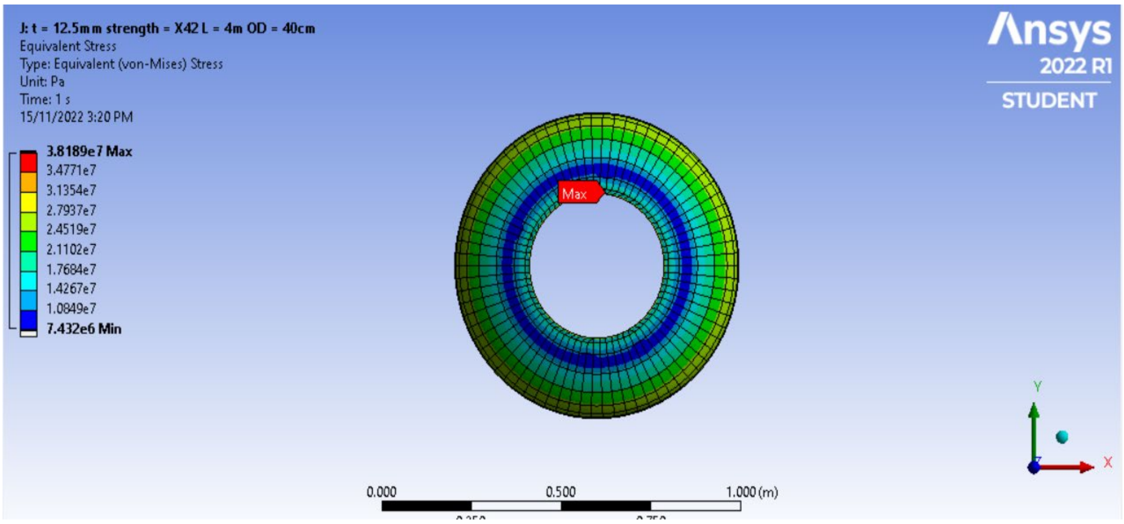

**J: t = 12.5mm strength = X42 L = 4m OD = 40cm**
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1 s
15/11/2022 3:20 PM

FIGURE 4.5 Maximum Equivalent Stress of t = 12.5 mm

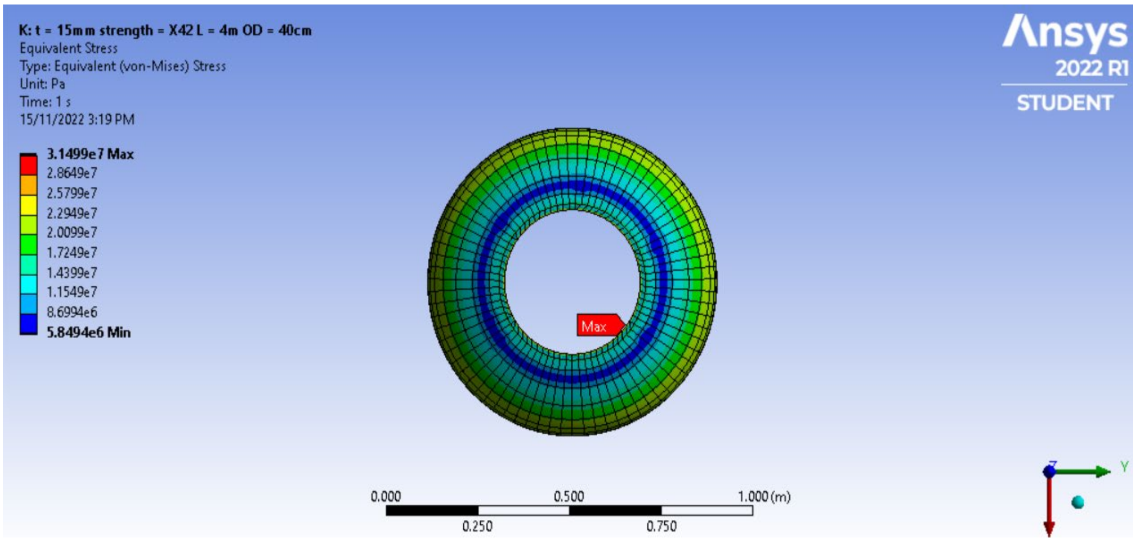


FIGURE 4.6 Maximum Equivalent Stress of t = 15 mm

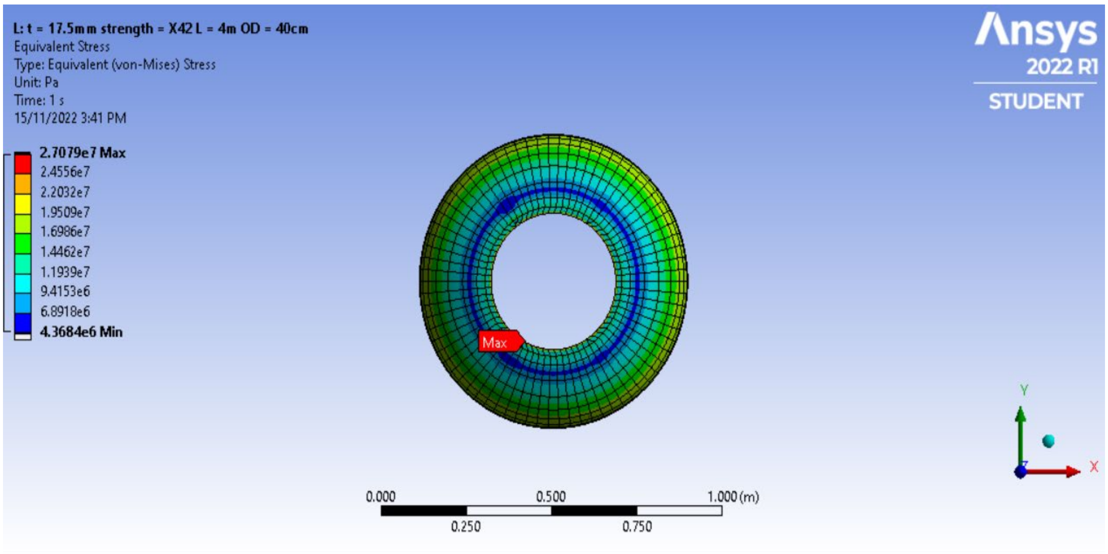


FIGURE 4.7 Maximum Equivalent Stress of t = 17.5 mm

## 4.6 Equivalent Stress with Different Diameter

Other than thickness, the diameter of the pipeline model also affected the induced equivalent stresses in the internal wall. From the result obtained through ANSYS below, the same magnitude of applied pressure has induced the maximum equivalent stress of 27.1 Mpa, 55.2 Mpa, and 8.3 Mpa for D = 40 mm , D = 80 mm, and D = 120 mm respectively. Different from previous one, for this case, the larger the diameter was, the larger the maximum equivalent stresses induced even though the magnitude of applied pressure was constant for all cases. D. Han Oh (2020) studied the development of a burst pressure prediction model for flawless and dented pipeline and found that when the aspect ratio increased, the burst pressure decreased. Relatively, in this section, only the diameter of the pipeline model was increased, and this means that the aspect ratio (D/t) also increased. As the aspect ratio (D/t) became larger, the maximum equivalent stresses induced when internal pressure is applied was also increased which resulted in smaller burst stress. The pipeline model can be said that it failed faster if the diameter is larger with the condition that the thickness is constant.

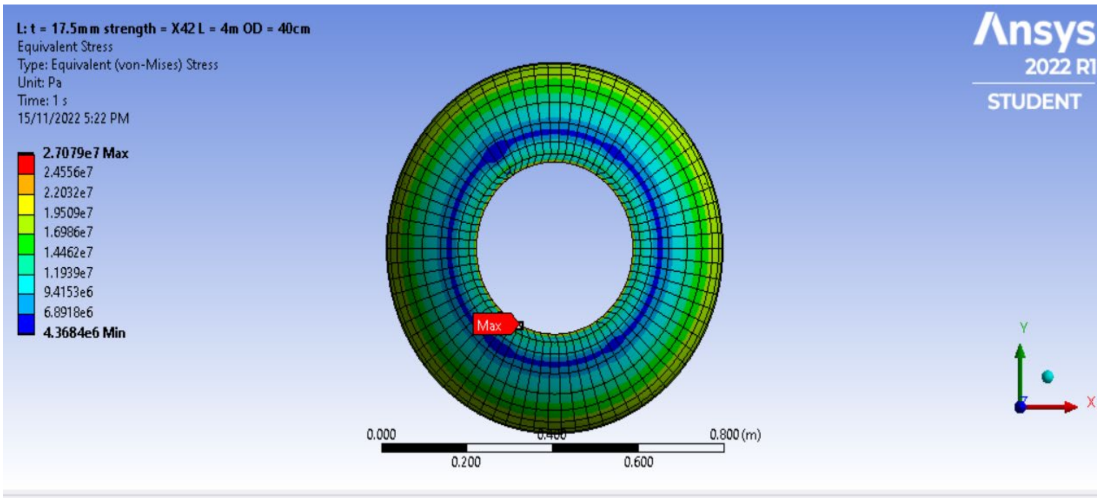


FIGURE 4.8 Maximum Equivalent Stress for D = 40 cm

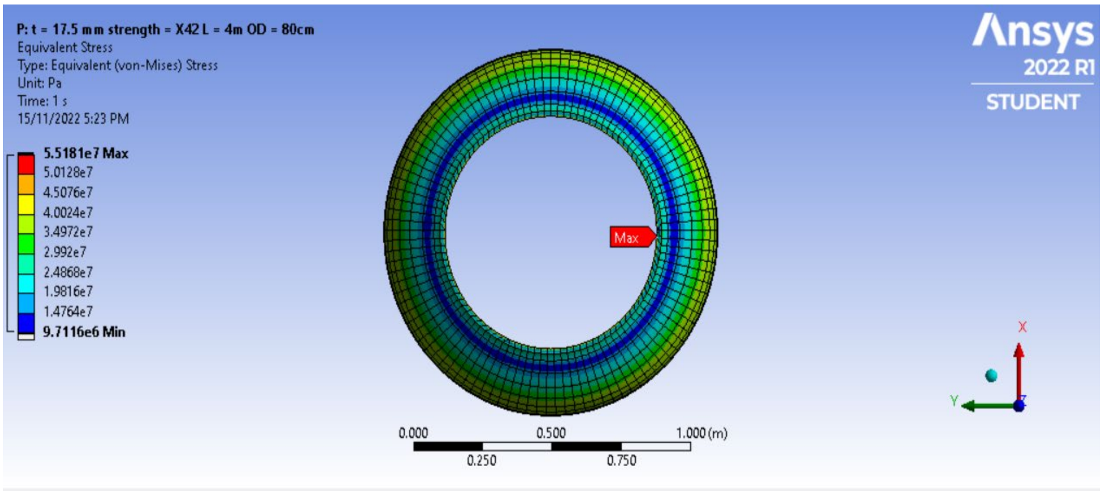


FIGURE 4.9 Maximum Equivalent Stress for D = 80 cm

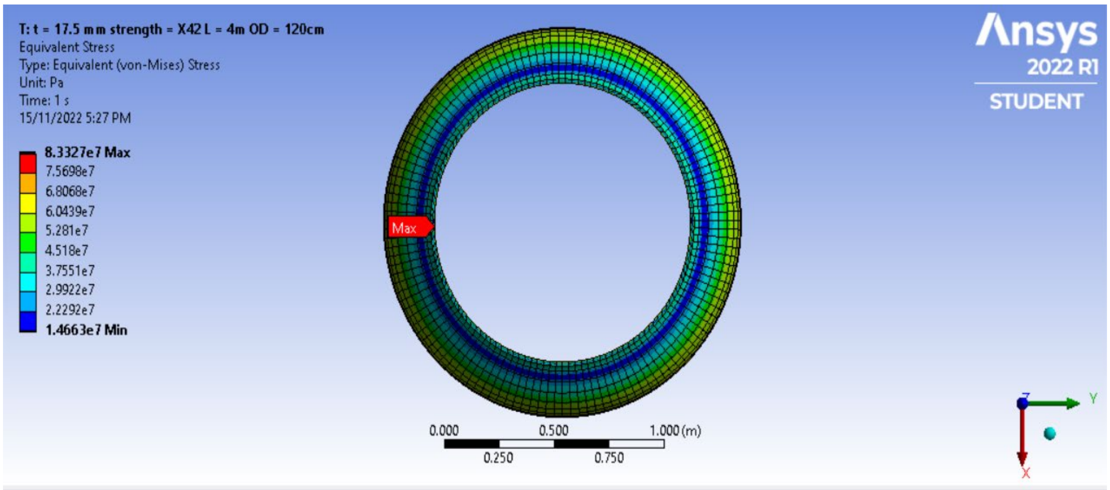
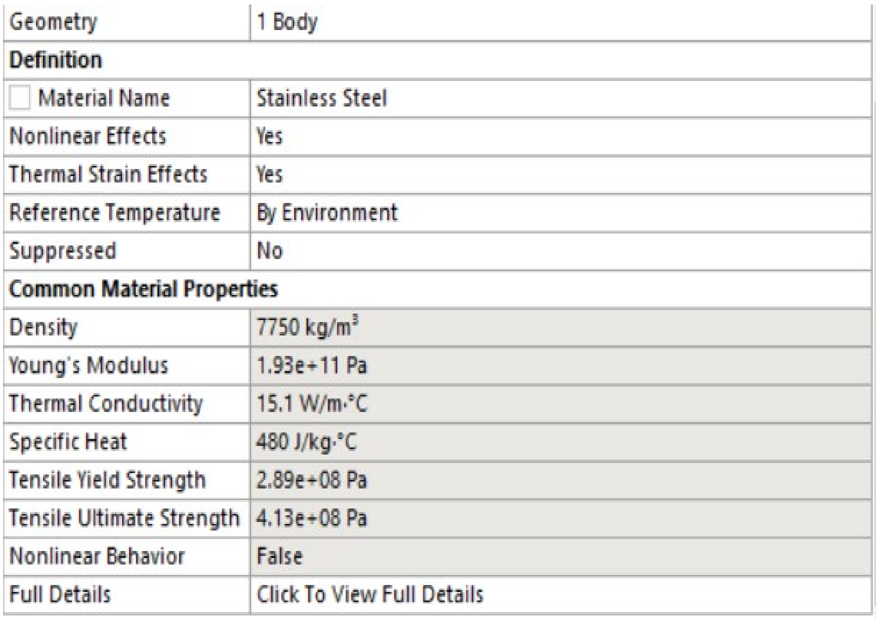


FIGURE 4.10 Maximum Equivalent Stress for D = 120 cm

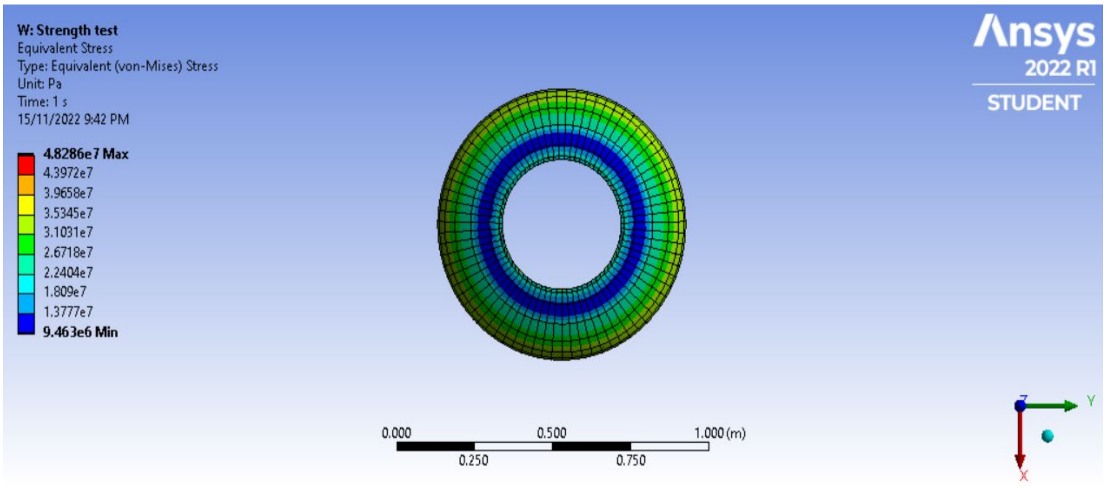
## 4.7 Equivalent Stress with Different Material Strength

During the observation, the thickness and the diameter of this modelled pipeline is made sure to be constant throughout the process. It is very important to observe and study how the applied pressure can affect the induced equivalent stress in different strength of pipeline. From the analysis conducted and as from the result below, maximum equivalent stresses induced does not effected by the different strength of material used, as long as other properties such as the material, which stainless steel was used, the diameter, and thickness were maintained. This means that if two identical pipelines with different strength is being imposed with 2 Mpa of internal pressure, both will be resulting in causing maximum equivalent stress of 48.3 Mpa (as per figure below). However, different material strength did give different burst pressure since the burst pressure is determined by the ultimate tensile yield strength, and different material strength will definitely have different tensile yield strength.



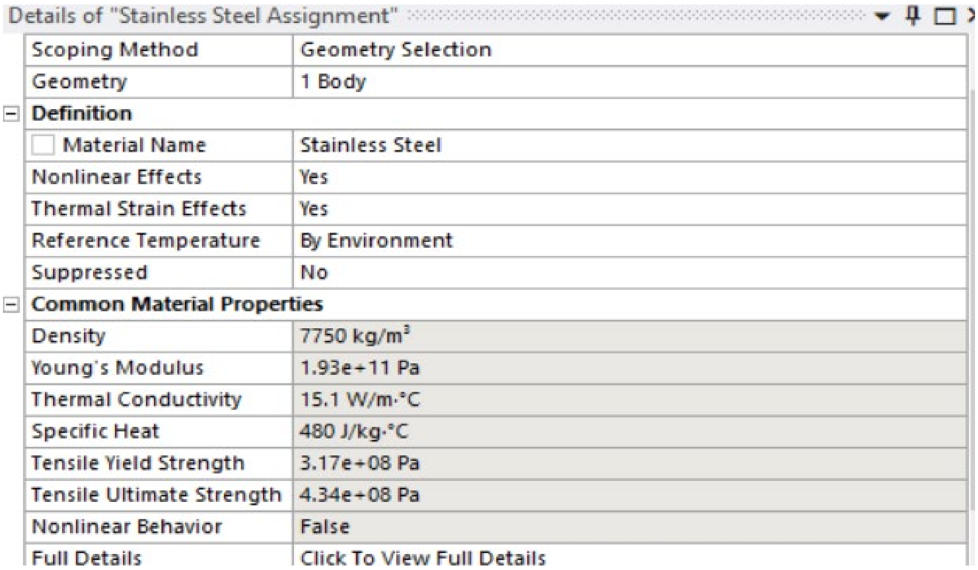
| | |
|---|---|
| Geometry | 1 Body |
| **Definition** | |
| ☐ Material Name | Stainless Steel |
| Nonlinear Effects | Yes |
| Thermal Strain Effects | Yes |
| Reference Temperature | By Environment |
| Suppressed | No |
| **Common Material Properties** | |
| Density | 7750 kg/m$^3$ |
| Young's Modulus | 1.93e+11 Pa |
| Thermal Conductivity | 15.1 W/m·°C |
| Specific Heat | 480 J/kg·°C |
| Tensile Yield Strength | 2.89e+08 Pa |
| Tensile Ultimate Strength | 4.13e+08 Pa |
| Nonlinear Behavior | False |
| Full Details | Click To View Full Details |

FIGURE 4.11 YS and TS of X42 Pipeline



**W: Strength test**
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1 s
15/11/2022 9:42 PM

FIGURE 4.12 Maximum Equivalent Stress of X42 Pipeline



Details of "Stainless Steel Assignment"

| | |
|---|---|
| Scoping Method | Geometry Selection |
| Geometry | 1 Body |
| **Definition** | |
| ☐ Material Name | Stainless Steel |
| Nonlinear Effects | Yes |
| Thermal Strain Effects | Yes |
| Reference Temperature | By Environment |
| Suppressed | No |
| **Common Material Properties** | |
| Density | 7750 kg/m$^3$ |
| Young's Modulus | 1.93e+11 Pa |
| Thermal Conductivity | 15.1 W/m·°C |
| Specific Heat | 480 J/kg·°C |
| Tensile Yield Strength | 3.17e+08 Pa |
| Tensile Ultimate Strength | 4.34e+08 Pa |
| Nonlinear Behavior | False |
| Full Details | Click To View Full Details |

FIGURE 4.13 Yield and Ultimate Strength of X46 Pipeline

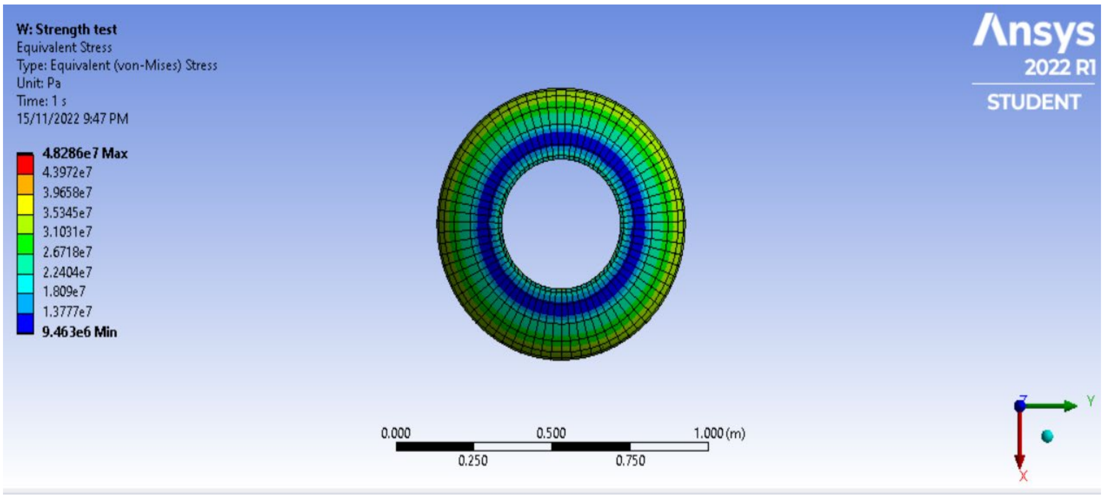


FIGURE 4.14 Maximum Equivalent Stress of X46 Pipeline

## 4.8 Burst Pressure Plot with Embrittlement

In general, the analysis of burst pressure involved in applying internal pressure and the pressure was increased gradually until the maximum equivalent stress until it reached the burst pressure limit that already reduced due to embrittlement effect. In this analysis, there are three things were plotted together in one graph each which are maximum equivalent stress (Pa), applied pressure (Mpa), and the ultimate tensile strength limit post embrittlement effect (Pa).

### 4.8.1 Same Material Strength with Different Diameter and Thickness

The three plots shown below illustrate the burst pressure of three pipeline models having different thickness and diameter but shared same yield and ultimate stress. From the plots, it can be seen that each one of the pipeline models have different burst pressure, depending on the diameter and thickness. The smallest burst stress for X42 pipeline was the one with 40 cm outer diameter and 10 mm thickness which were 15 Mpa, 16 Mpa, and 18 Mpa for different degree of embrittlement. On the other hand, the largest burst stress for X42 pipeline was the one with 120 cm diameter and 17.5 mm thickness which were 27 Mpa, 28Mpa, and 31 Mpa.

As discussed in the previous section, different thickness and diameter caused variation in the maximum equivalent stress induced in the internal wall of the pipeline. Referring to this model, the burst limit for the three plots was at the same point which were 413 Mpa, 371.7 Mpa, and 351.1 Mpa for 0%, 10%, and 15% embrittlement respectively. Due to the changes in wall thickness and diameter, each one of the models failed at different pressure. Note that at the x-axis each plot, the failure, which is defined as the point where the applied pressure intercepts the burst limit line, occurred at different point of applied pressure magnitude and on top of that they were significantly different from one another for different diameter and thickness which showed that how critical the variation of thickness and diameter of pipeline affected the burst stress.

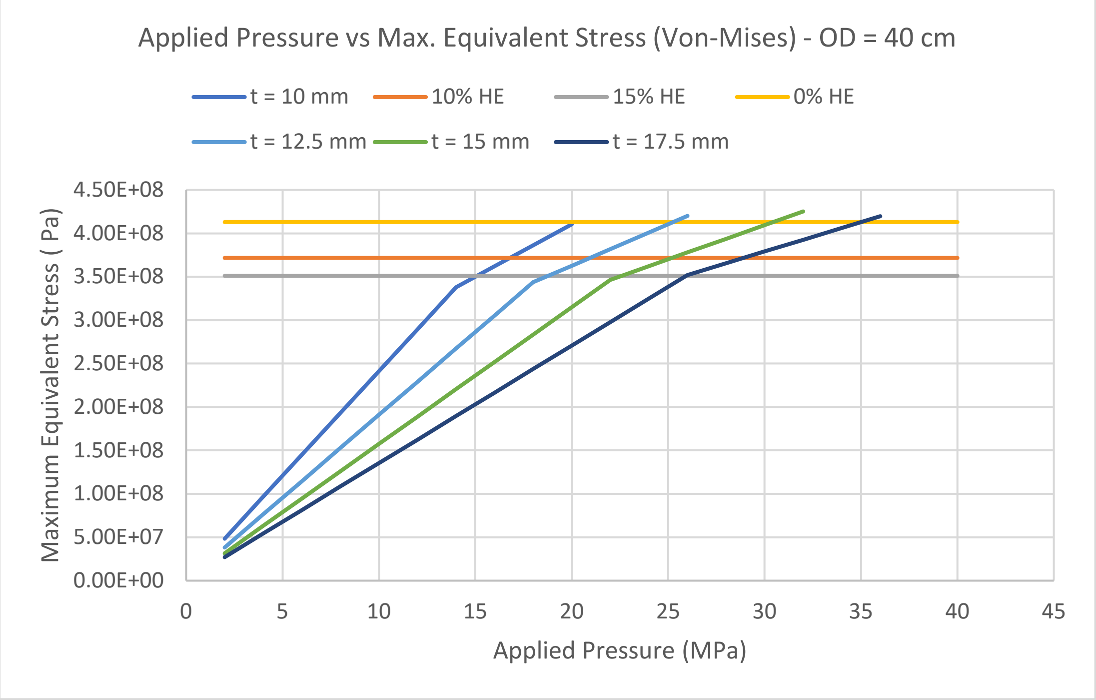


FIGURE 4.15 Maximum Equivalent Stress vs Applied Pressure for X42 Pipeline (OD = 40cm)

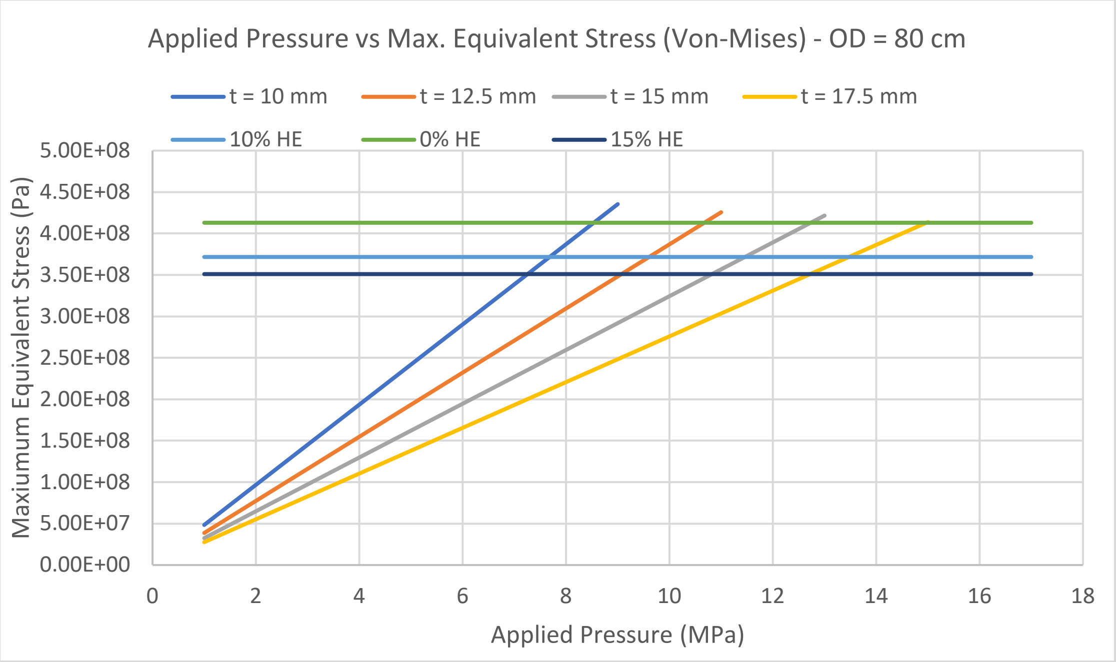


FIGURE 4.16 Maximum Equivalent Stress vs Applied Pressure for X42 Pipeline (OD = 80cm)

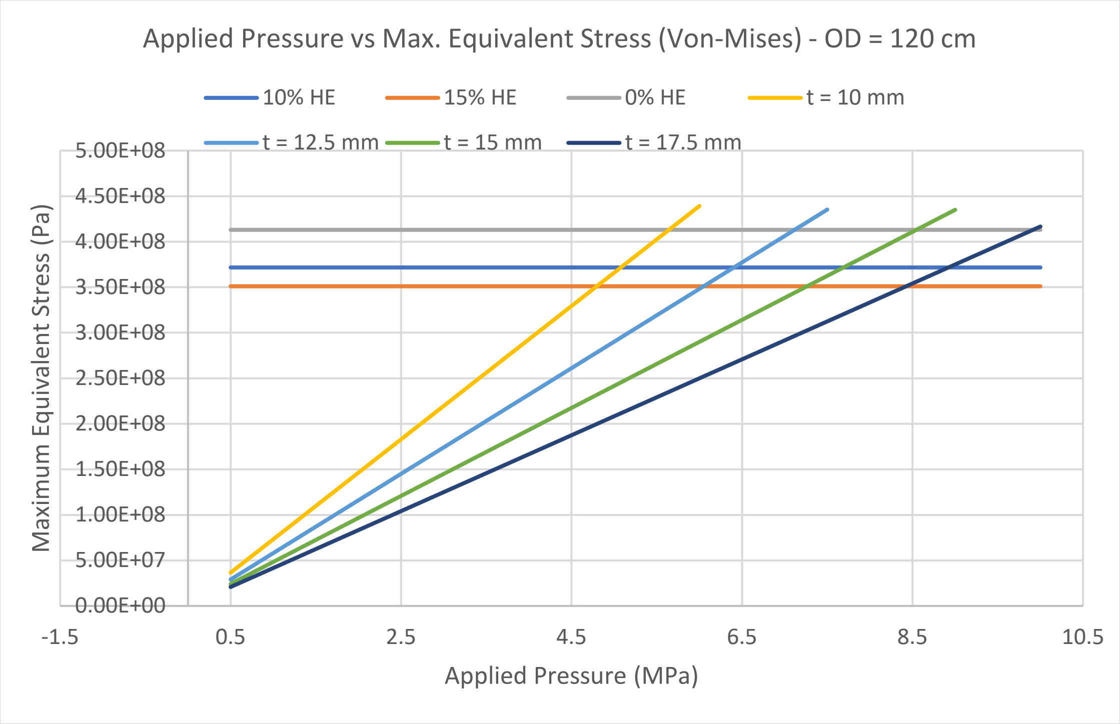


FIGURE 4.17 Maximum Equivalent Stress vs Applied Pressure for X42 Pipeline (OD = 120cm)

### 4.8.2 Identical Thickness and Outer Diameter with Different Strength

For this plot, the pattern for the four graphs might seem alike from one another. But each one of the plots illustrate different results which were very important to understand. As shown in in the four plots, the relationship between applied pressure and the equivalent stress is directly proportional which means, as the applied internal pressure increased, the maximum equivalent stress also increased. The similarity between all four plots is the application of pressure for every different thickness was stopped when each of the line representing them intercepted with all three burst limit line that represent the ultimate tensile strength of 0%, 10%, and 15% degree of embrittlement.

The major difference for all four plots can be seen at the x-axis which the values of applied pressure were slightly different from one another. This is because the only difference between the four plots is the burst limit of the pipeline models. From the plots shown, the three horizontal lines representing burst limit at different degree of embrittlement got higher as the ultimate tensile strength of the material increased. Since the burst limit or ultimate tensile strength increased, the internal pressure required for the equivalent stress to match the ultimate strength also increased. Though, this increased in burst limit just slightly changed the burst stress of each pipeline models.

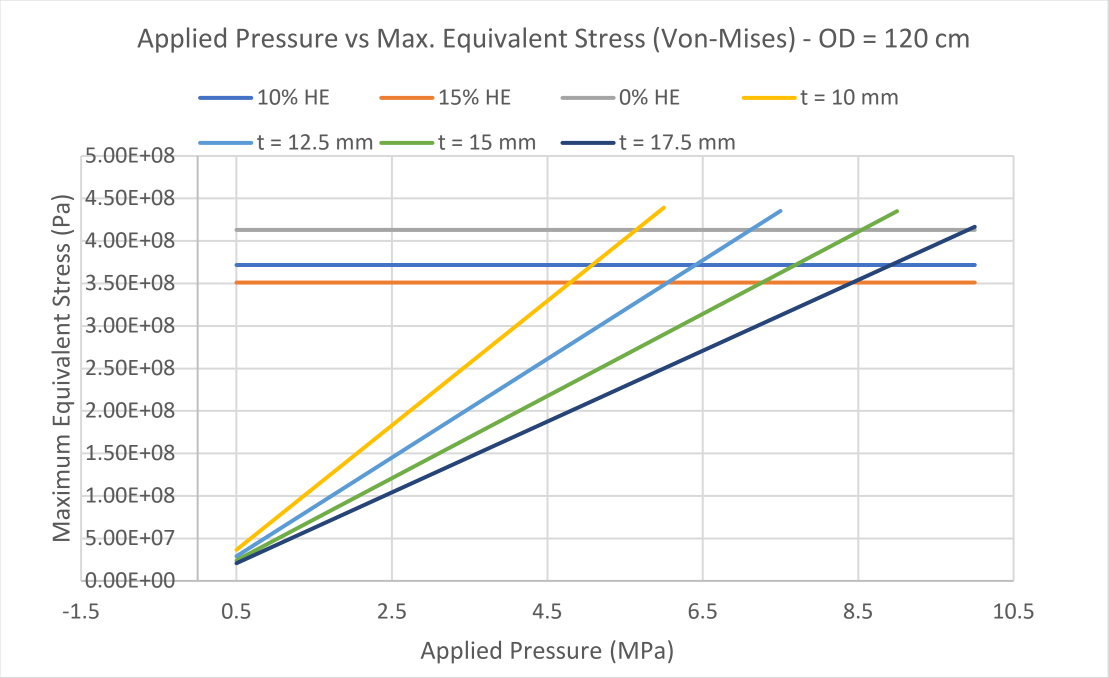


FIGURE 4.18 Maximum Equivalent Stress vs Applied Pressure for X42 Pipeline (OD = 120cm)

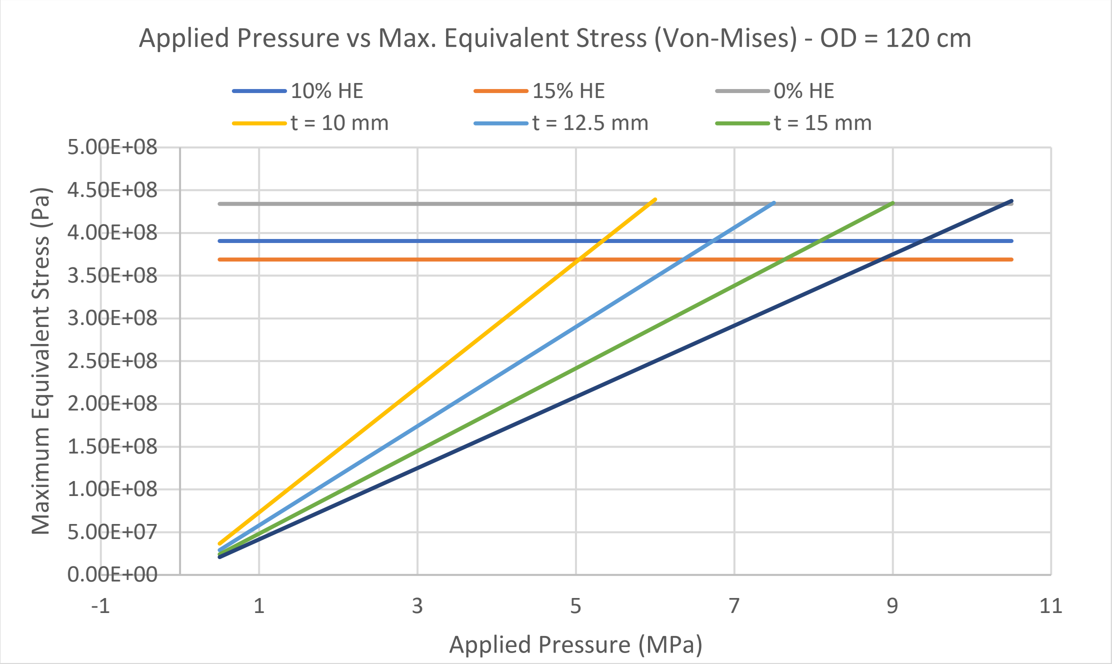


FIGURE 4.19 Maximum Equivalent Stress vs Applied Pressure for X46 Pipeline (OD = 120cm)

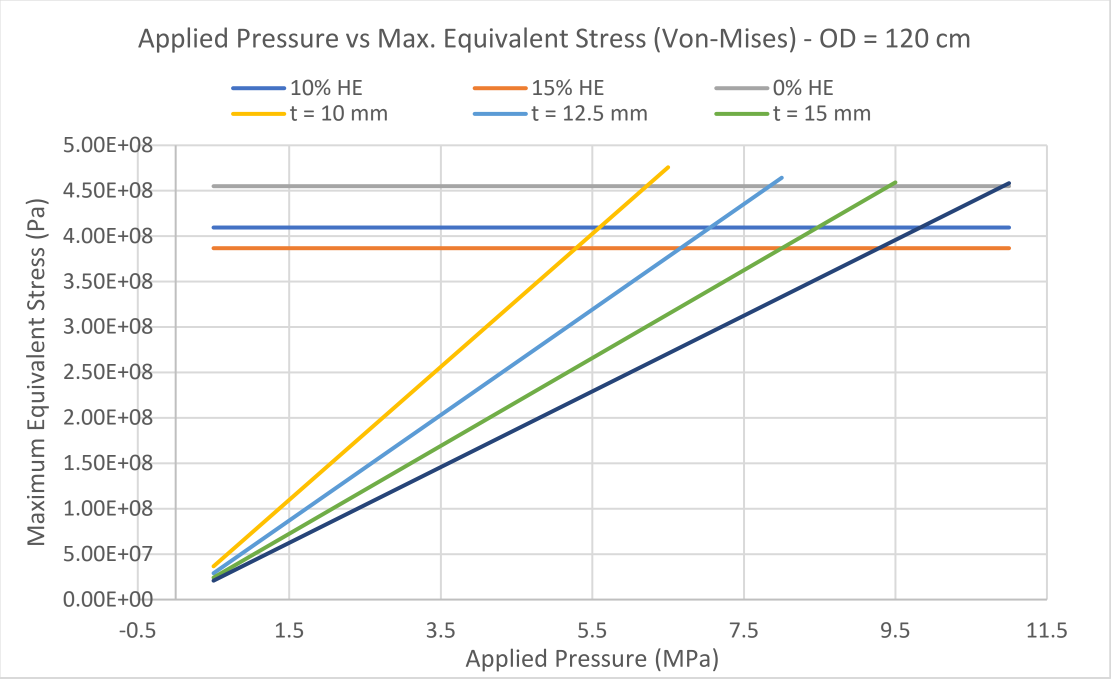


FIGURE 4.20 Maximum Equivalent Stress vs Applied Pressure for X52 Pipeline (OD = 120cm)

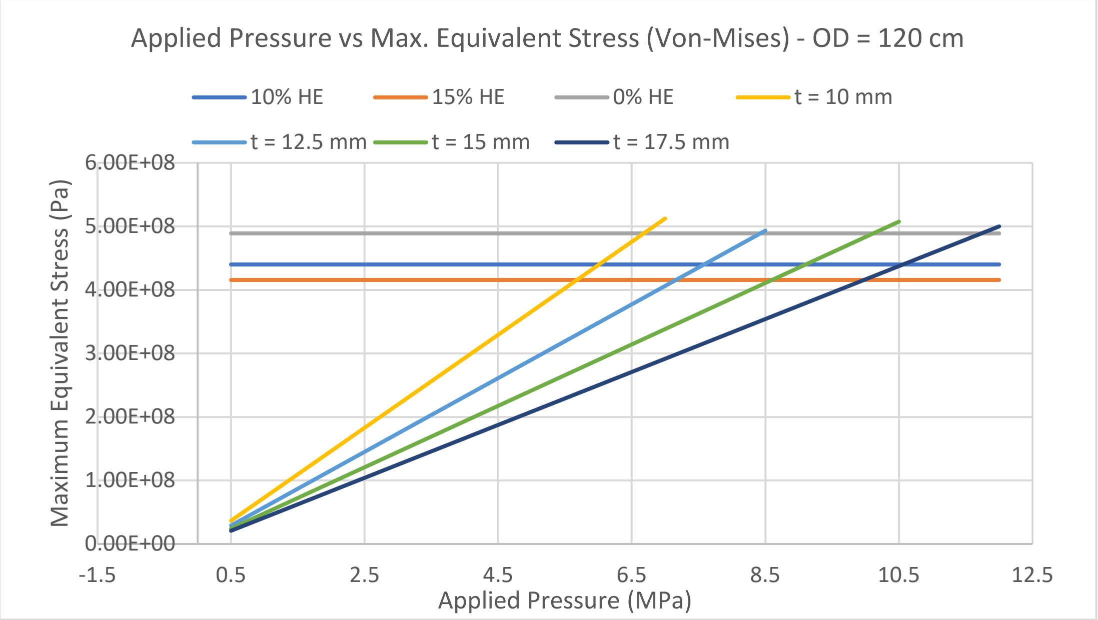


FIGURE 4.21 Maximum Equivalent Stress vs Applied Pressure for X56 Pipeline (OD = 120cm)

## 4.9 Validation of Finite Element Result

To justify this study, the result obtained was validated through numerical equation. There were three numerical equations used in this analysis which are Faupel's Burst Pressure (1956) , Barlow's Equation (1836) and DNV (2013). From these equations used, the result was only validated with DNV (2013) equation which the percentage error falls within acceptable range. The summary of percentage error is summarized in the table below. Note that the shown percentage error was only for largest X56 pipeline having 1200 mm diameter and 17.5 mm thickness. The validation process was also repeated for other parameters.

The acceptable range of percentage error is 10% and below. By referring the summary below, using Faupel's Burst Pressure equation, the percentage error was beyond 20% which was unacceptable. Since it was very high, the validation then was being compared with another equation which was Barlow's Equation. Using this equation, the percentage error obtained was below 20% but still more than 10%. Even though the error this time slightly better, it was still unacceptable to justify the result obtained. For the third formula, DNV equation was adopted. This time the percentage error obtained was below 10%, which the desired one. From DNV equation, it can be interpreted that the result of analysis only deviated maximum of 10% from theoretical value.

TABLE 4.6 Percentage Error of 0% Embrittlement

| Burst Pressure for 0% Embrittlement (MPa) | | | |
|---|---|---|---|
| | Numerical | Analytical | Percentage Error |
| Faupel | 12 | 15.97 | 24.86 |
| Barlow | 12 | 14.3 | 16.08 |
| DNV | 12 | 13.2 | 9.09 |

TABLE 4.7 Percentage Error of 10% Embrittlement

| Burst Pressure for 10% Embrittlement (MPa) | | | |
|---|---|---|---|
| | Numerical | Analytical | Percentage Error |
| Faupel | 11 | 14.375 | 23.48 |
| Barlow | 11 | 12.8 | 14.06 |
| DNV | 11 | 11.9 | 7.56 |

TABLE 4.8 Percentage Error of 15% Embrittlement

| Burst Pressure for 15% Embrittlement (MPa) | | | |
|---|---|---|---|
| | Numerical | Analytical | Percentage Error |
| Faupel | 10 | 13.576 | 26.34 |
| Barlow | 10 | 12.1 | 17.36 |
| DNV | 10 | 11 | 9.09 |

## 4.10 Chapter Summary

This chapter discussed about the results that were obtained from each step analysis, starting from parameters elimination until the burst pressure variation based on different parameters. Other than that, some result that did not meet the criteria were also discussed and justified in this chapter. To tackle the undesired results, modification and improvement were done to the model and the result obtained from the modifications were satisfied. For better visualization, the result from ANSYS Software were included in this chapter on every discussion made.

# CHAPTER 5

# CONCLUSION AND RECOMMENDATION

In conclusion, Burst Stress Analysis of Large Green Hydrogen Offshore Pipeline Under Combined Loads is a parametric study that concerns over pipeline burst stress when diameter, wall thickness, and strength were changed while considering the embrittlement caused by the hydrogen diffusion into the pipeline steel layers took place. Some parameters used in this study are within PETRONAS Technical Standard (PTS) acceptability. From several literature review conducted, the gap of studied are identified and this paper intended to create a new type of parametric study. The objective of this research which were to conduct a parametric study on hydrogen pipeline by determine its effects on the burst stress and to validate FEA result using analytical method was successfully achieved. This analysis was validated using DNV (2013) formula due to non-acceptable range of percentage error given by Faupel Burst Pressure Formula and Barlow's Equation. Using the DNV(2013) the percentage error falls within 10%, which was acceptable.

From the analysis conducted, there are a few conclusions that was made from this project which includes :

1. Maximum Equivalent Stress or Von-Mises Stress affected significantly with the change of diameter and thickness but not with the change of material strength.
2. Different diameter and thickness have greatly affected the burst stress of the pipeline, but different material strength only cause a small change in burst stress of the pipeline.
3. Combined loadings such as axial stress and hydrostatic pressure have a huge potential in affecting the magnitude of burst stress, depending on the depth of pipeline in the sea, end condition, and the density of the seawater.

4. When the length of the pipeline was changed, it was observed that there was no difference in induced equivalent stresses. It was from this observation that the decision to eliminate the parameter was made.
5. Increase in D/t ratio will increase the equivalent stress induced in the internal wall of the pipeline and thus reduce its burst stress.
6. The failure can be estimated based on the value of maximum equivalent stress or Von-Mises stress developed in the pipeline's internal wall

There are certain limitations while conducting this study which firstly, the total number of elements that can be analyzed was below 22 000 elements. Having a smaller size of meshing and greater number of total elements can produce a more accurate result. However, a mesh sensitivity analysis was performed to justify the accuracy and reliability of this study. Next, the effect was represented by percentage of strength reduction. The percentage of hydrogen embrittlement used was 10% and 15% which was general value adopted from previous study. In real life cases, degree hydrogen embrittlement depends on the type of pipeline materials where it was not considered in this study. The pipeline material used in this study was purely stainless steel where in real life, there would be a combination of certain element such as Carbon, Manganese, Aluminum, Nickel, Copper, and more.

For future works, it is recommended to :

1. Use a full version of ANSYS Workbench software so that the mesh convergence test can be done for even smaller size of element and a larger total number of elements.
2. Bending moment also should be included in the study of combine loadings since pipeline more tend to expose to bending loadings.
3. For more efficient analysis, an automatic load step should be used so that the time taken to perform the analysis would reduce.
4. To further validate the result, experimental works and result would be a great addition to the study to further the study the burst stress.
5. To study the lifespan of the pipeline considering that the hydrogen embrittlement occurs different types of materials such as carbon steel or carbon manganese is used.
6. To study the effects of different types of materials to the burst strength of the pipeline.

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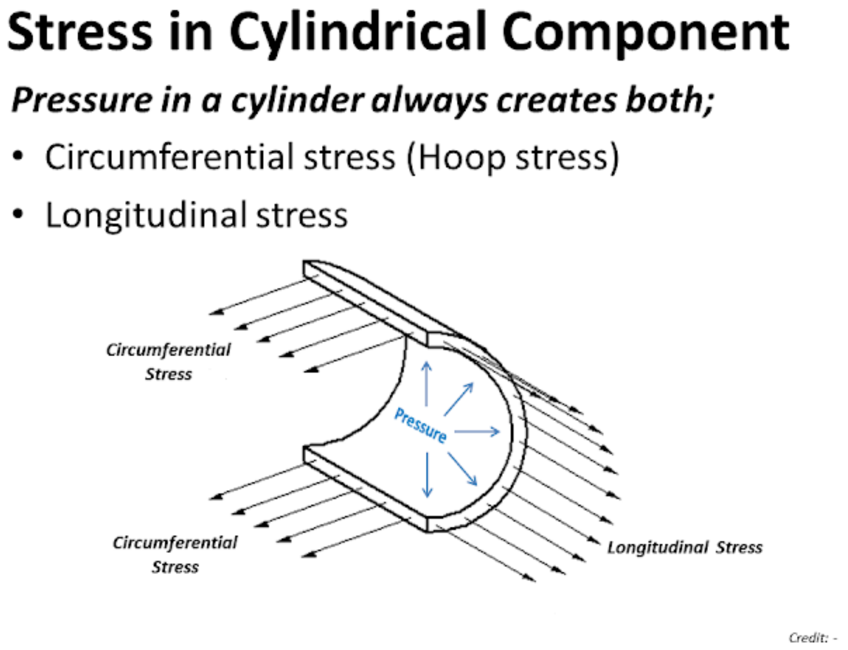
Appendices



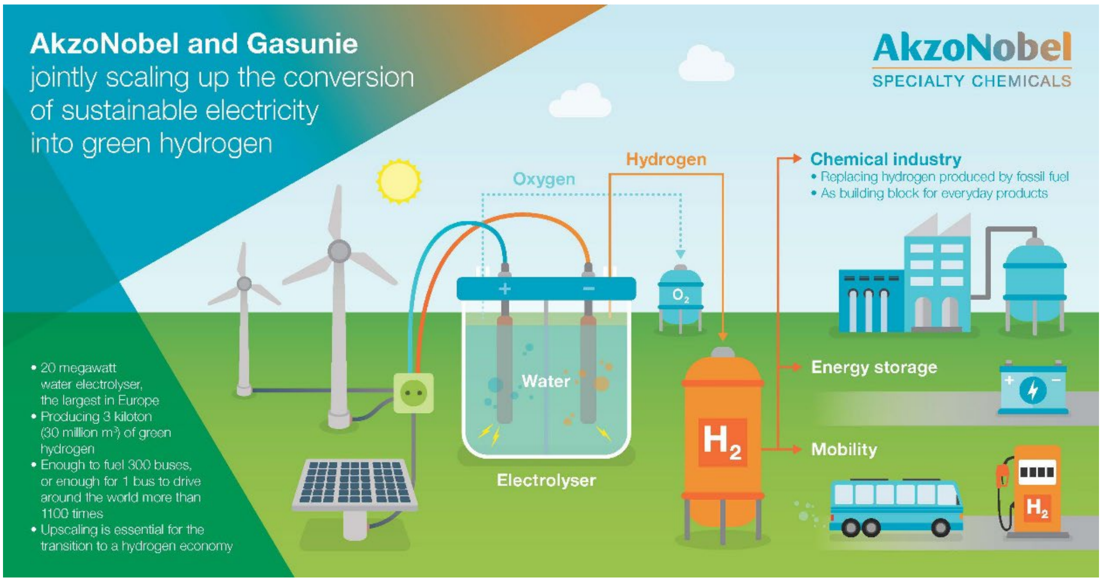
**Stress in Cylindrical Component**

***Pressure in a cylinder always creates both;***

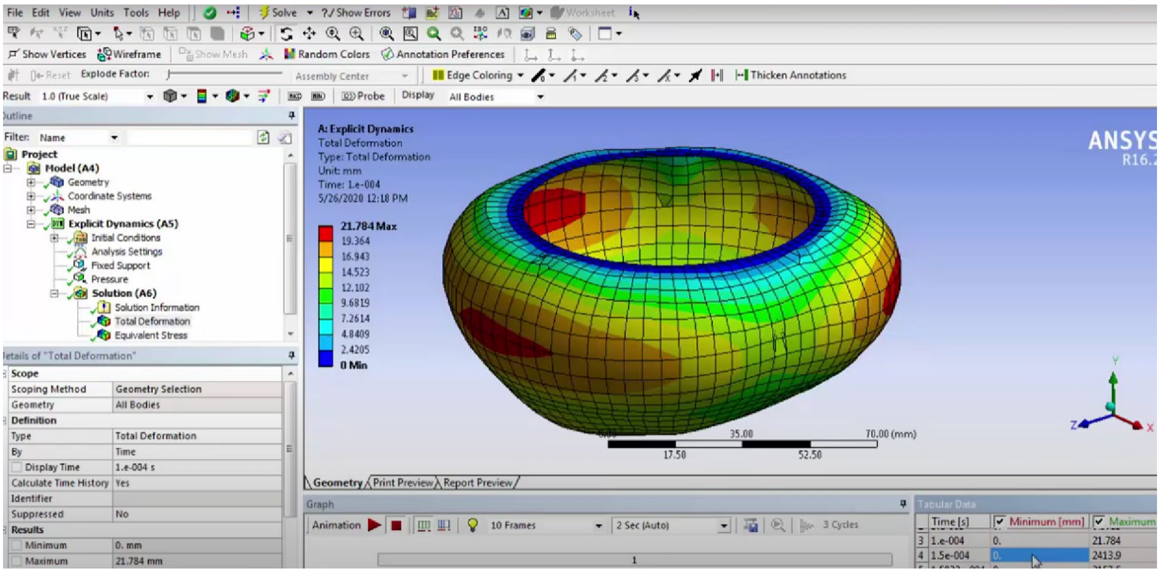
- Circumferential stress (Hoop stress)
- Longitudinal stress

Credit: -

Appendix 1 Stresses in Cylinder



Appendix 2 Green Hydrogen



A: Explicit Dynamics
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1.e-004
5/26/2020 12:18 PM

21.784 Max
19.364
16.943
14.523
12.102
9.6819
7.2614
4.8409
2.4205
0 Min

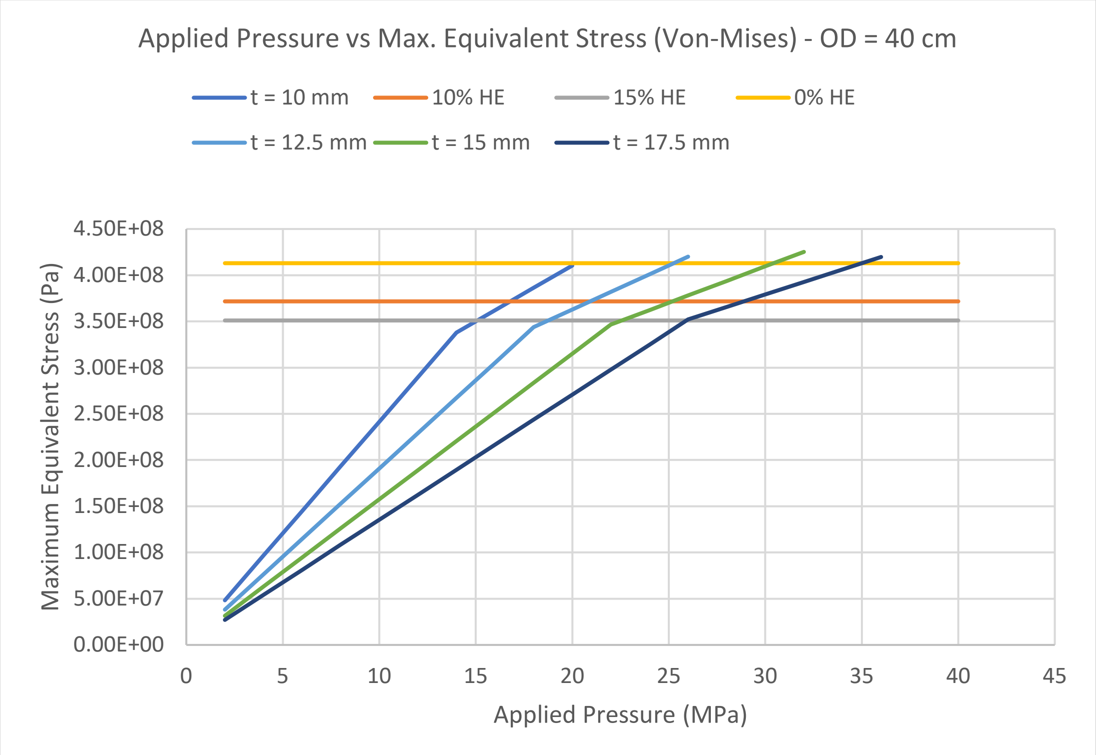
Details of "Total Deformation"

| | |
|---|---|
| **Scope** | |
| Scoping Method | Geometry Selection |
| Geometry | All Bodies |
| **Definition** | |
| Type | Total Deformation |
| By | Time |
| ☐ Display Time | 1.e-004 s |
| Calculate Time History | Yes |
| Identifier | |
| Suppressed | No |
| **Results** | |
| ☐ Minimum | 0. mm |
| ☐ Maximum | 21.784 mm |

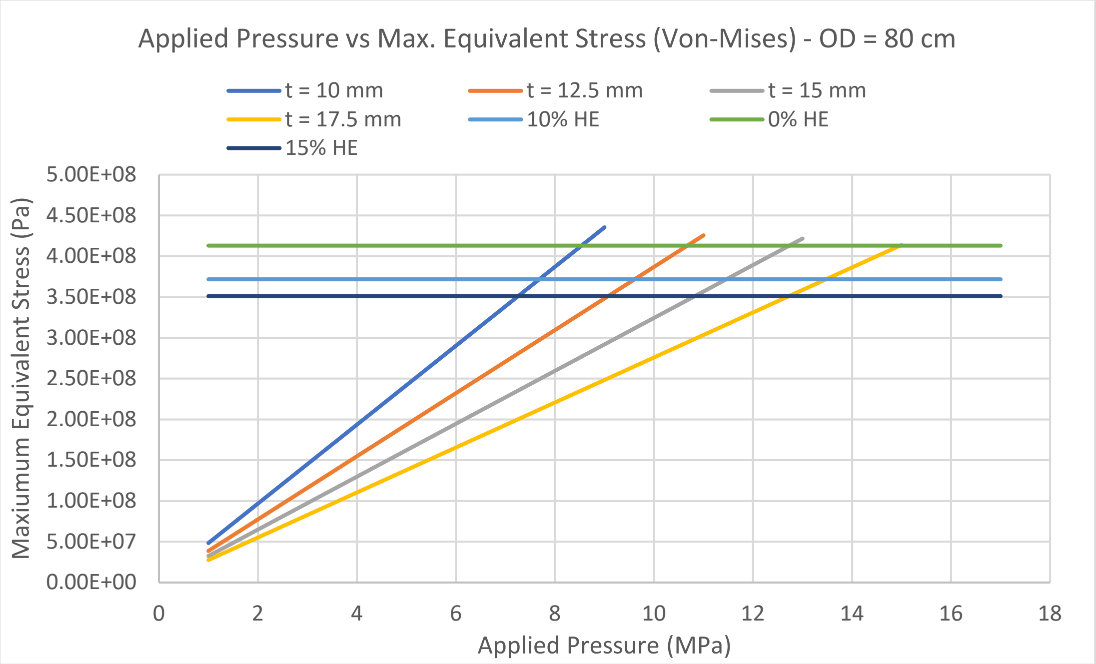
Tabular Data

| | Time [s] | ☑ Minimum [mm] | ☑ Maximum |
|---|---|---|---|
| 3 | 1.e-004 | 0. | 21.784 |
| 4 | 1.5e-004 | 0. | 2413.9 |

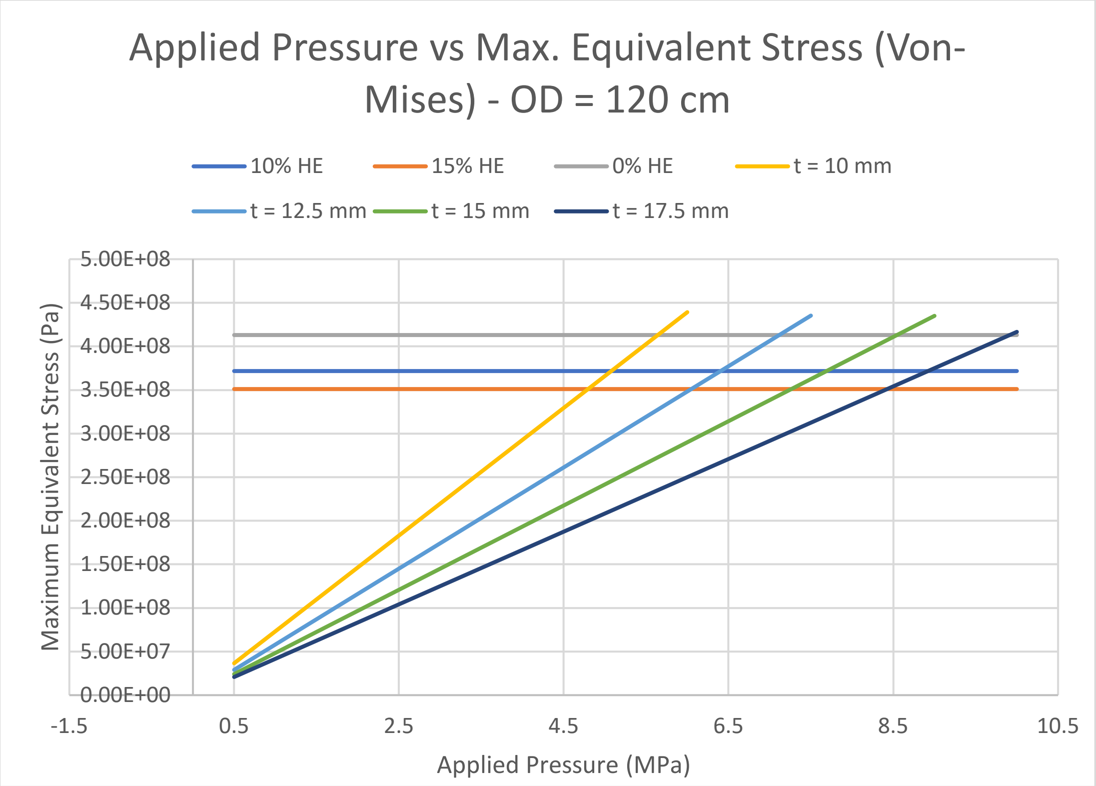
Appendix 3 Ansys Burst Stress



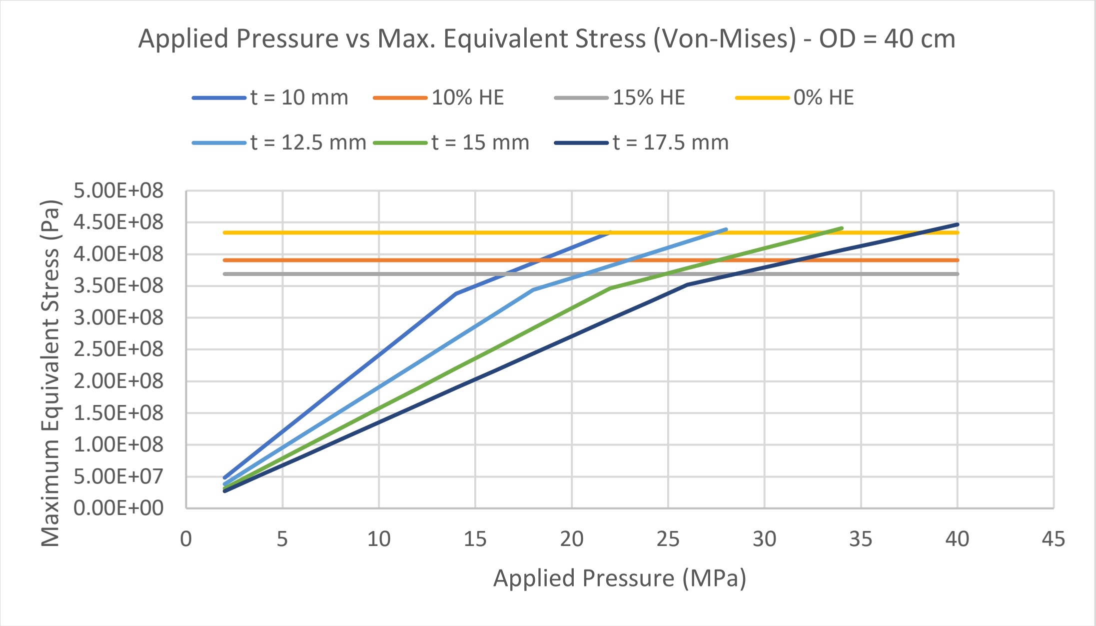
Appendix 4 X42 Pipeline with D = 40 cm



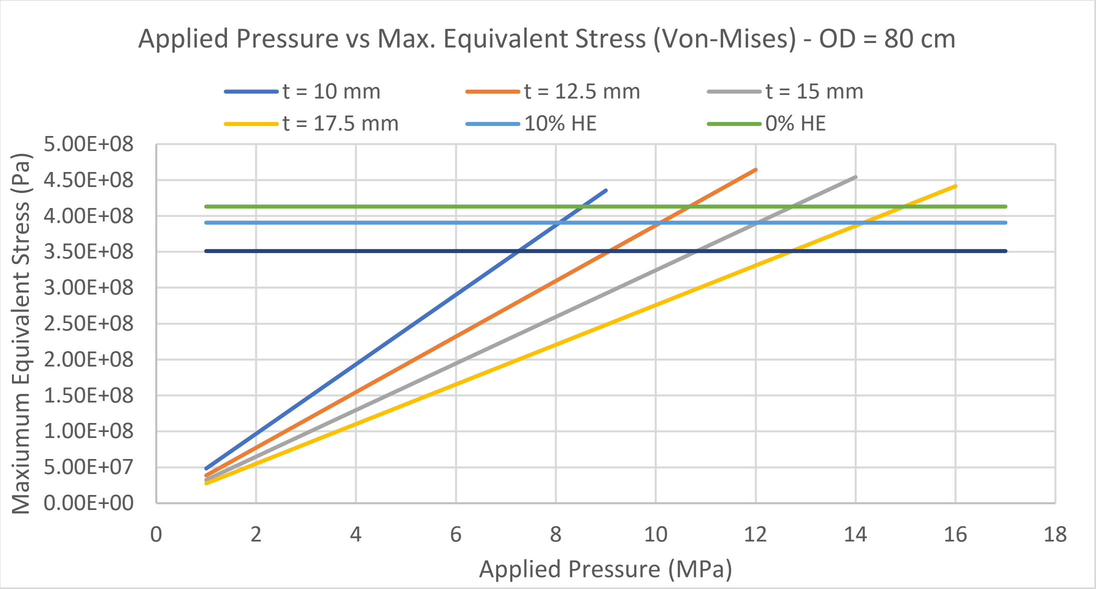
Appendix 5 X42 Pipeline with D = 80 cm



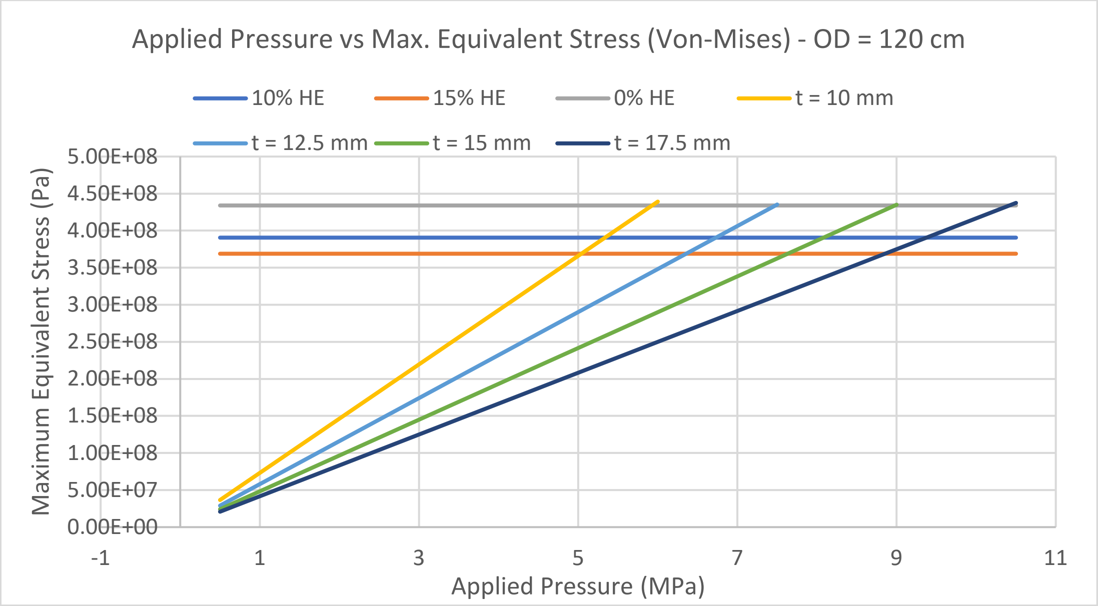
Appendix 6 X42 Pipeline with D = 120 cm



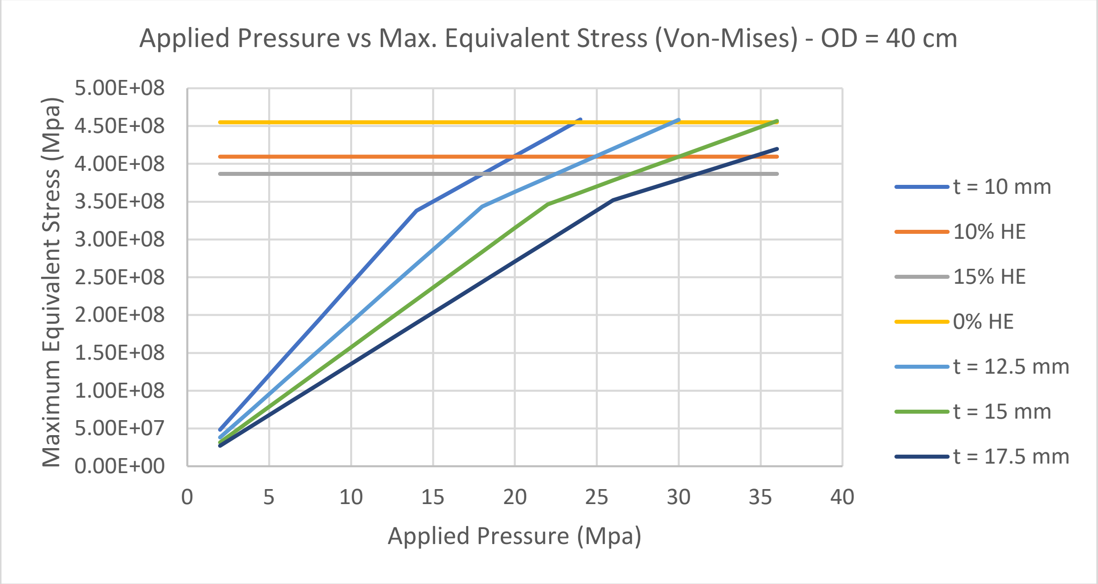
Appendix 7 X46 Pipeline with D = 40 cm



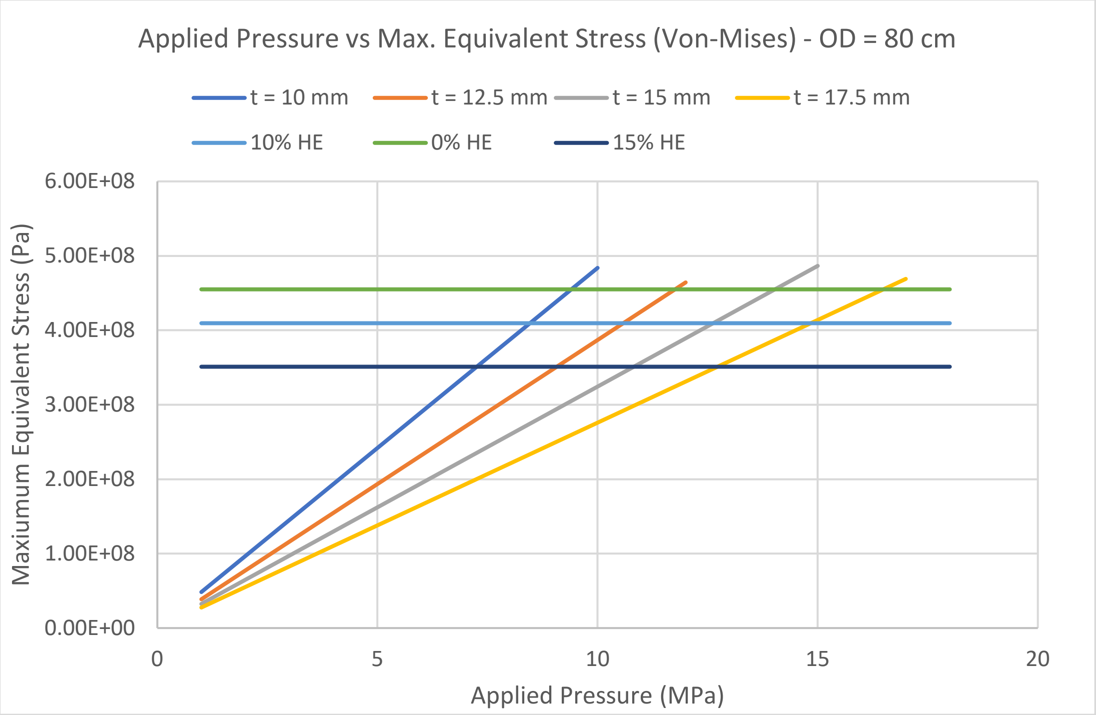
Appendix 8 X46 Pipeline with D = 80 cm



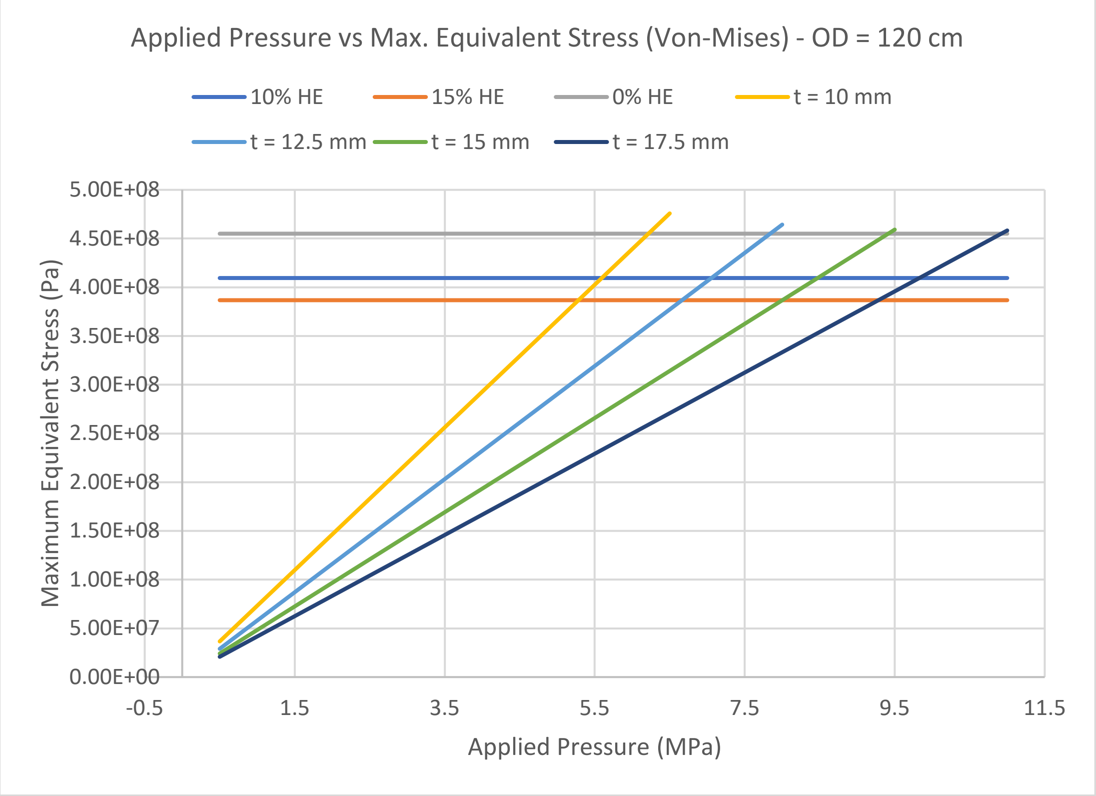
Appendix 9 X46 Pipeline with D = 120 cm



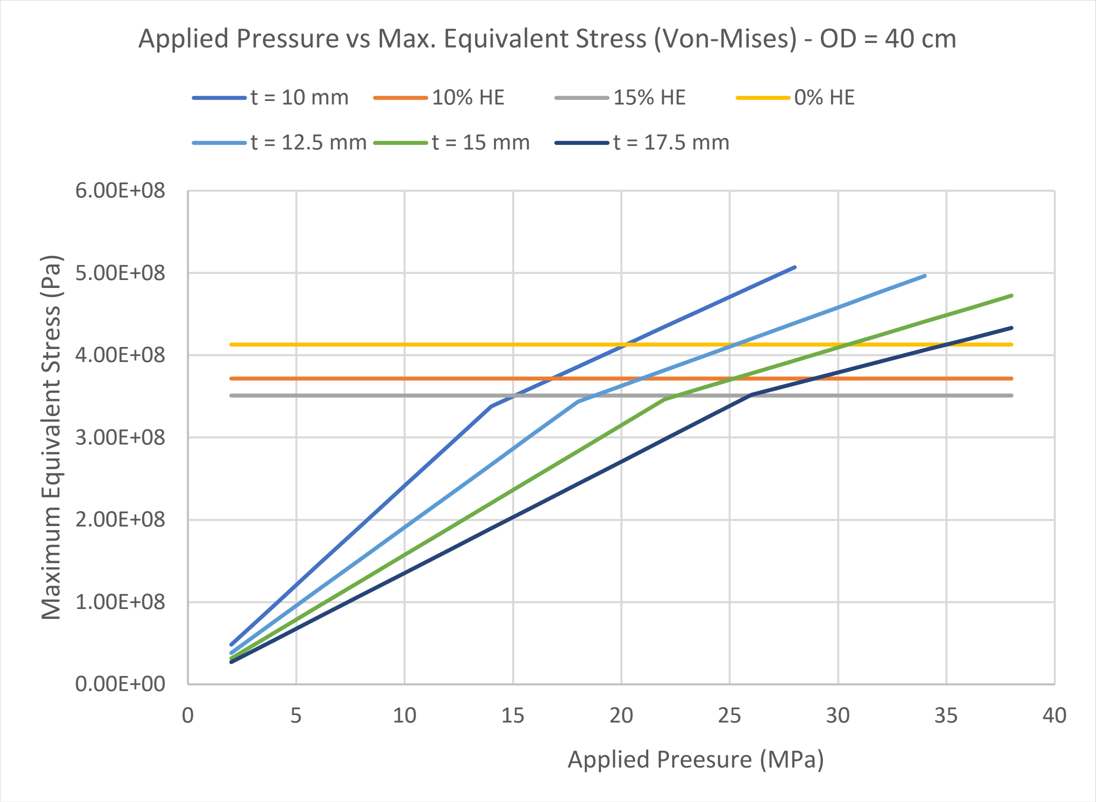
Appendix 10 X52 Pipeline with D = 40 cm



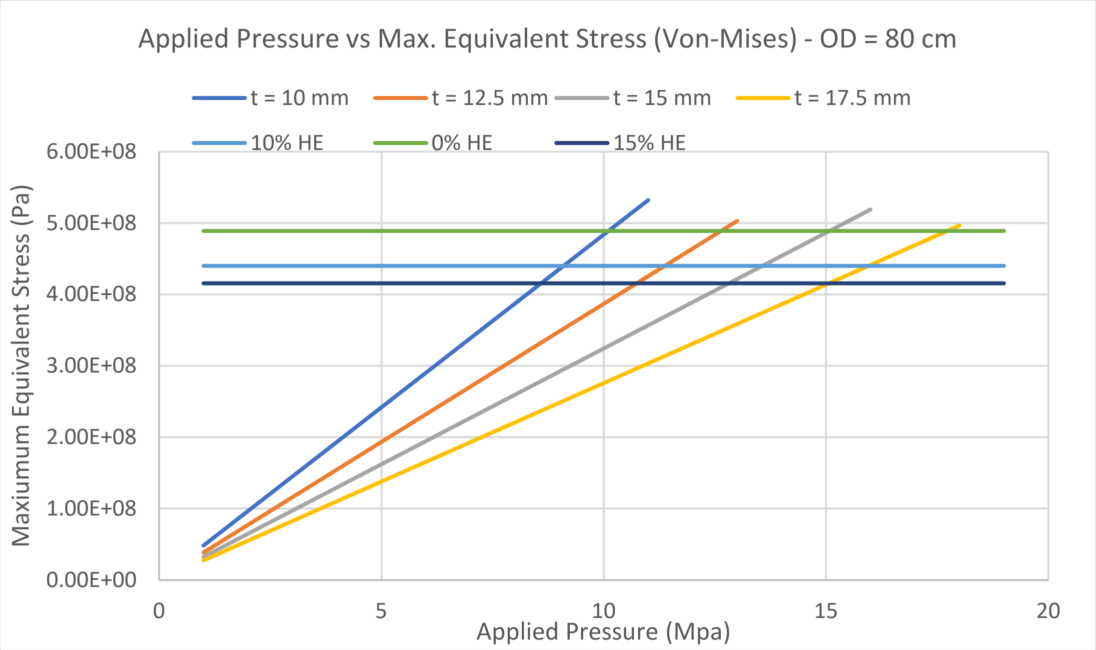
Appendix 11 X52 Pipeline with D = 80 cm



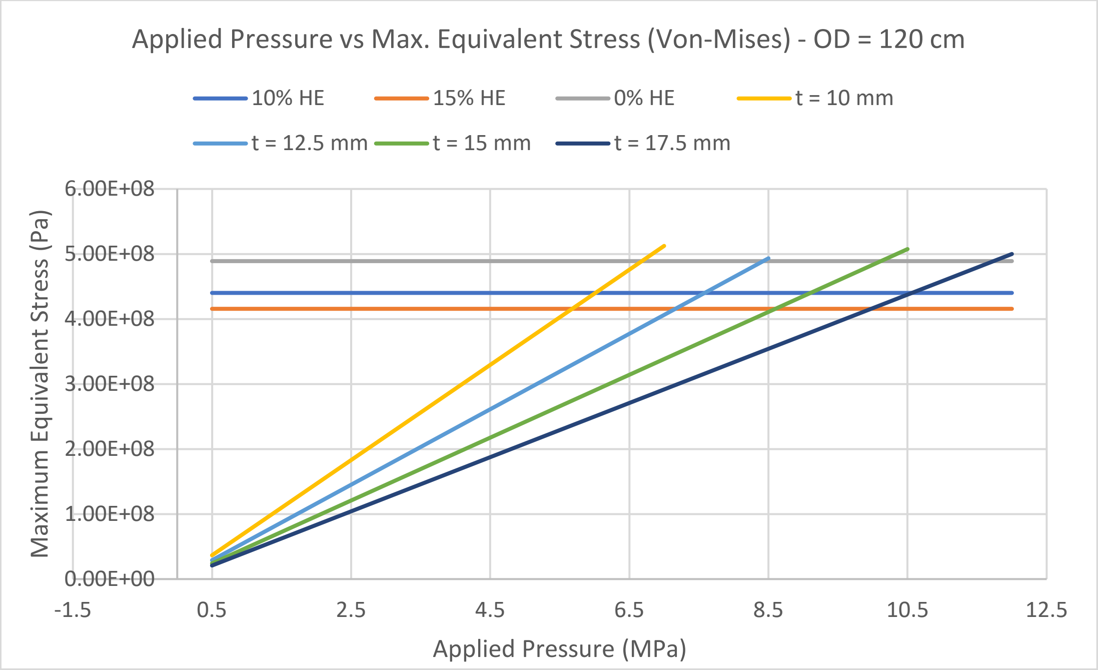
Appendix 12 X52 Pipeline with D = 120 cm



Appendix 13 X56 Pipeline with D = 40 cm



Appendix 14 X56 Pipeline with D = 80 cm



Appendix 15 X56 Pipeline with D = 120 cm

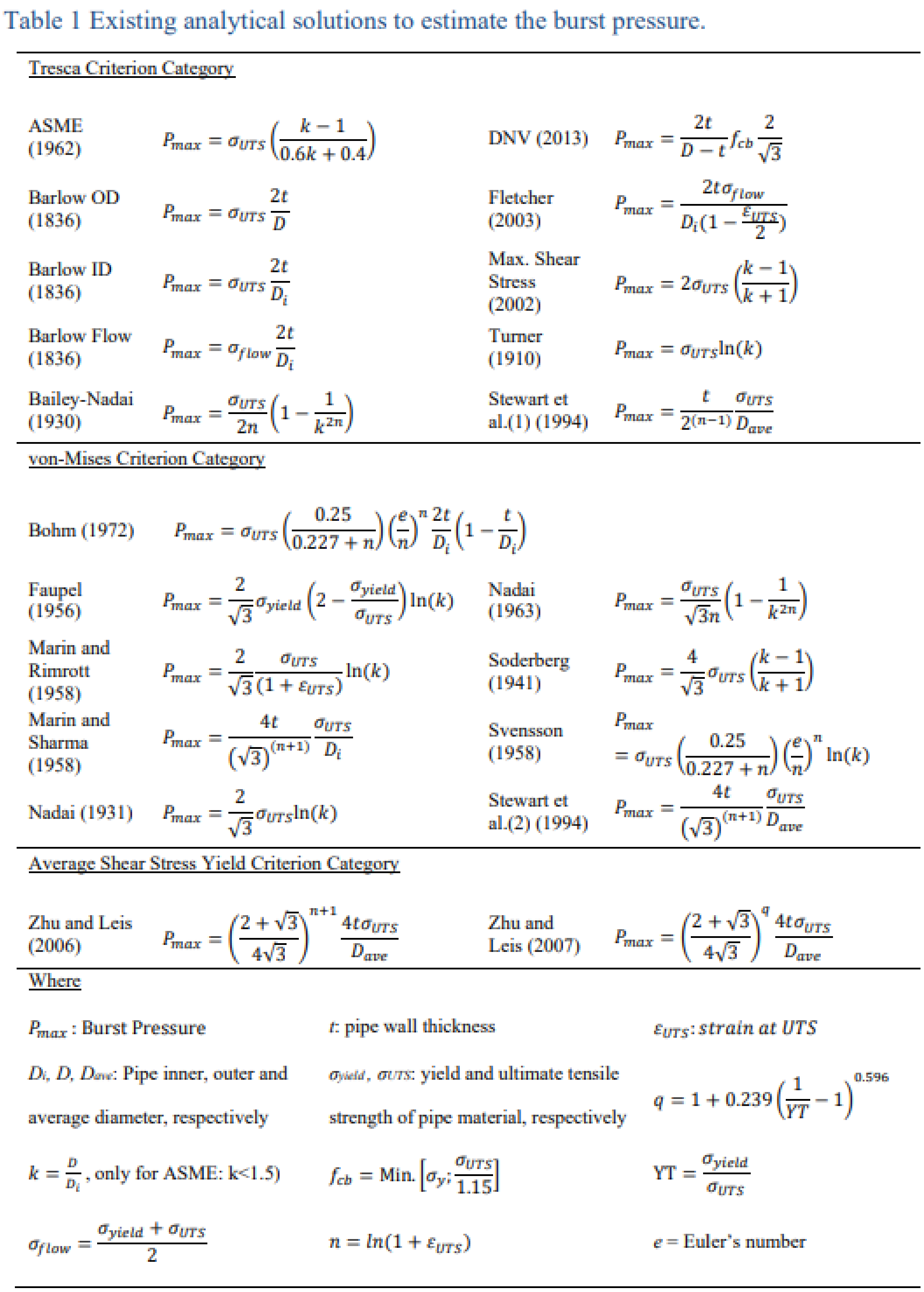


Table 1 Existing analytical solutions to estimate the burst pressure.

| | | | |
|---|---|---|---|
| Tresca Criterion Category | | | |
| ASME (1962) | $P_{max} = \sigma_{UTS}\left(\frac{k-1}{0.6k+0.4}\right)$ | DNV (2013) | $P_{max} = \frac{2t}{D-t} f_{cb} \frac{2}{\sqrt{3}}$ |
| Barlow OD (1836) | $P_{max} = \sigma_{UTS}\frac{2t}{D}$ | Fletcher (2003) | $P_{max} = \frac{2t\sigma_{flow}}{D_i(1-\frac{\varepsilon_{UTS}}{2})}$ |
| Barlow ID (1836) | $P_{max} = \sigma_{UTS}\frac{2t}{D_i}$ | Max. Shear Stress (2002) | $P_{max} = 2\sigma_{UTS}\left(\frac{k-1}{k+1}\right)$ |
| Barlow Flow (1836) | $P_{max} = \sigma_{flow}\frac{2t}{D_i}$ | Turner (1910) | $P_{max} = \sigma_{UTS}\ln(k)$ |
| Bailey-Nadai (1930) | $P_{max} = \frac{\sigma_{UTS}}{2n}\left(1-\frac{1}{k^{2n}}\right)$ | Stewart et al.(1) (1994) | $P_{max} = \frac{t}{2^{(n-1)}}\frac{\sigma_{UTS}}{D_{ave}}$ |
| von-Mises Criterion Category | | | |
| Bohm (1972) | $P_{max} = \sigma_{UTS}\left(\frac{0.25}{0.227+n}\right)\left(\frac{e}{n}\right)^n \frac{2t}{D_i}\left(1-\frac{t}{D_i}\right)$ | | |
| Faupel (1956) | $P_{max} = \frac{2}{\sqrt{3}}\sigma_{yield}\left(2-\frac{\sigma_{yield}}{\sigma_{UTS}}\right)\ln(k)$ | Nadai (1963) | $P_{max} = \frac{\sigma_{UTS}}{\sqrt{3}n}\left(1-\frac{1}{k^{2n}}\right)$ |
| Marin and Rimrott (1958) | $P_{max} = \frac{2}{\sqrt{3}}\frac{\sigma_{UTS}}{(1+\varepsilon_{UTS})}\ln(k)$ | Soderberg (1941) | $P_{max} = \frac{4}{\sqrt{3}}\sigma_{UTS}\left(\frac{k-1}{k+1}\right)$ |
| Marin and Sharma (1958) | $P_{max} = \frac{4t}{(\sqrt{3})^{(n+1)}}\frac{\sigma_{UTS}}{D_i}$ | Svensson (1958) | $P_{max} = \sigma_{UTS}\left(\frac{0.25}{0.227+n}\right)\left(\frac{e}{n}\right)^n \ln(k)$ |
| Nadai (1931) | $P_{max} = \frac{2}{\sqrt{3}}\sigma_{UTS}\ln(k)$ | Stewart et al.(2) (1994) | $P_{max} = \frac{4t}{(\sqrt{3})^{(n+1)}}\frac{\sigma_{UTS}}{D_{ave}}$ |
| Average Shear Stress Yield Criterion Category | | | |
| Zhu and Leis (2006) | $P_{max} = \left(\frac{2+\sqrt{3}}{4\sqrt{3}}\right)^{n+1}\frac{4t\sigma_{UTS}}{D_{ave}}$ | Zhu and Leis (2007) | $P_{max} = \left(\frac{2+\sqrt{3}}{4\sqrt{3}}\right)^{q}\frac{4t\sigma_{UTS}}{D_{ave}}$ |

Where

$P_{max}$ : Burst Pressure

$t$: pipe wall thickness

$\varepsilon_{UTS}$: *strain at UTS*

$D_i$, $D$, $D_{ave}$: Pipe inner, outer and average diameter, respectively

$\sigma_{yield}$, $\sigma_{UTS}$: yield and ultimate tensile strength of pipe material, respectively

$q = 1 + 0.239\left(\frac{1}{YT}-1\right)^{0.596}$

$k = \frac{D}{D_i}$, only for ASME: k<1.5)

$f_{cb} = \text{Min.}\left[\sigma_y; \frac{\sigma_{UTS}}{1.15}\right]$

$\text{YT} = \frac{\sigma_{yield}}{\sigma_{UTS}}$

$\sigma_{flow} = \frac{\sigma_{yield}+\sigma_{UTS}}{2}$

$n = ln(1+\varepsilon_{UTS})$

$e$ = Euler's number

Appendix 16 List of Analytical Equation adopted from Do-Han Oh (2020) Development of a Burst Pressure Prediction Model for Flawless and Dented Pipelines