STRESS ANALYSIS OF FLEXIBLE THERMOSETTING PIPE

by

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14447

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CERTIFICATION OF APPROVAL

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Approved by,

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(Name of Main Supervisor)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH PERAK

January 2006

SAMPLE OF CERTIFICATION OF ORIGINALITY

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 that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ALI BIN AKRAM

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Praise to god, thanks for all his blessing. First and foremost, I would like to give thanks for His amazing love that knows no boundaries and endures forever. Through the experience of life, I have learnt and am still learning that I am strong when I am strong when I am on his shoulders. I want to thank Him for all his wonderful thoughts of me and for raising me up to so much more than I can be.

I would like to express my greatest gratitude to my supervisor, Dr. Zahiraniza Binti Mustaffa, for her kind guidance throughout this research. It was her advice which ensured the success of this research. I can honestly say that I have benefited a lot under her supervision.

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Last but not least, my greatest appreciation goes to those who have assisted me directly or indirectly starting from the beginning of the research. Your cooperation is highly appreciated and may God repay your kindness.

Thanks.

ABSTRACT

Carbon steel pipeline is widely used in the offshore industry to transport oil and gas from offshore platforms to onshore. However, the main concern lies in the corrosion and flexibility of the pipe, which led to the development of a flexible thermosetting pipeline. Although the new pipeline is flexible and resistant to corrosion, its performance in terms of strength is yet to be tested for deep water applications. Therefore, the stress analysis was conducted using ANSYS Finite Element Modelling software to determine the strength of the flexible thermosetting pipeline in terms of stress, strain and deflection. The results were compared using different materials, which are graphite epoxy and glass fiber epoxy, polyethylene and carbon steel. The results showed that, although the carbon steel performs better, the thermosetting pipeline, using glass fiber, has almost achieved the same strength with a difference of 10% in equivalent stress, 7% in equivalent strain and 4% in total deformation. Further modifications is suggested such as by adding more layers to the thermosetting pipeline to improve its strength and adding fatigue tool or stress tool in the analysis.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

As the supplies of hydrocarbon from shallow water reservoir continue to deplete, attention has been diverted to deep water and ultra-deep water for supply of hydrocarbons. However, as the depth increases, so does the difficulty of transporting the crude oil. There are essentially three ways of moving fluid which is to pour the fluid in a tank, move the tank to its destination and unload the fluid. Another alternative is to use pipelines, which is inflexible and requires a large capital cost. However, once placed, the operation and maintenance cost is relatively small. The third option is to transform the fluid into a solid or another type of fluid that is easier to transport. This paper will discuss only pipelines under water.

Carbon-manganese steels are always the popular choice of materials for pipelines for economic reasons. However, the major issue of using this material is the occurrence of corrosion which affects the strength of the pipeline. Weakening of the pipeline by corrosion will reduce the resistance of the pipeline to external forces and will accentuate materials and fabrication weaknesses. Compared to onshore pipelines, offshore pipelines have more incidents related to corrosion since it is in direct contact with water. Table 1 shows the incident for failure of pipes.

Table 1: Incident for Failure of Pipes

Location	Reason for the Incident %			
	Construction	Material	Third Party	Corrosion
Onshore	4	9	40	20
Offshore	6	8	36	41

In order to cater for this problem, a new type of non-metal composite pipe has been recently developed which prevents corrosion from occurring. This research will focus on the stress analysis of the composite pipe using finite element.

1.2 Problem Statement

Catering for the problem of corrosion, a non-metal composite pipe named the thermosetting pipe, has been recently developed as shown in Figure 1.

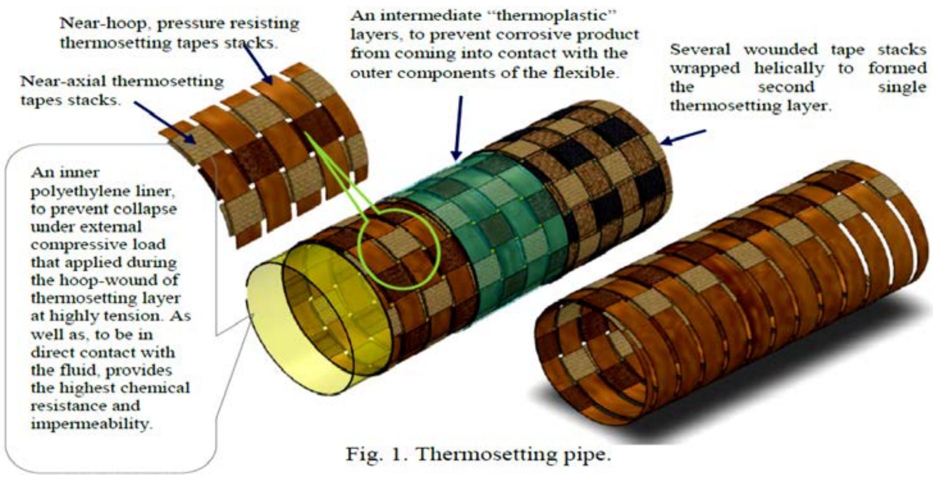


Figure 1: Design of Thermosetting pipe

The existing steel material is replaced with flexible composite pipe for high pressure applications. However, given the harsh condition of deep water environment, the choice of thermoplastic material is yet to be analysed under high pressure internally and externally. Thus the need of a stress analysis is required. In this research, a stress analysis will be conducted using finite element modelling method to ensure the structural integrity of the non-metal composite pipeline.

1.3 Scope of study and Objective

The objective of this research is:

a) To numerically model the stress analysis of the thermosetting pipeline using ANSYS Finite Element Model.
b) To implement several materials in the thermosetting pipeline model using ANSYS Finite Element Model.
c) To determine the best material to be used for the flexible thermosetting pipe.

In general, the scope of this research is to design and assess the integrity of the flexible thermosetting pipe using Finite Element Modelling (FEM) method. Therefore, the scope of work for this research includes:

a) Deepwater application
b) To numerically check the stress analysis of a newly developed Flexible Thermosetting Pipeline
c) To assess the existing newly developed thermosetting pipeline without any modifications.

1.4 Relevancy of research

The proposed model of the non-metal pipe uses thermoplastic material which is a very sturdy material. However, given the harsh conditions of deep water, it is unsure whether the material will be able to withstand the high pressure and the external forces. Thus, ANSYS is used to conduct a stress analysis on the pipe and determine its suitability. ANSYS is a powerful Finite Element Modelling tool which can provide the required data for this research. The data will be written into files during each analysis and can be depicted graphically immediately afterwards. Therefore, this research is relevant.

1.5 Feasibility of research

Based on the scope of work, this research involves modelling a non-metal composite pipeline as well as a stress analysis. Thus, there will be numerous simulations and documentation during this research. The software that will be used is ANSYS which is provided by the university in the software lab. Thus, this research is feasible and can be completed.

CHAPTER 2

LITERITURE REVIEW

2.1 Carbon Steel

Carbon steel pipe is widely used for oil and gas pipelines due to its strength. However, a pipeline steel must have high strength while retaining ductility, fracture toughness and weldability:

- Strength : resist the longitudinal and transverse tensile forces.
- Ductility : absorb overstressing by deformation
- Toughness : withstand impacts and shock loads
- Weldability : ease of production of a quality weld with adequate strength and toughness.

Balancing these criterias depends on the intended use of the pipeline. In the design of carbon steel pipe, yield strength is the primary design parameter where it controls the wall thickness (Palmer and King, 2008). However, different thicknesses of wall have their own complications. Table 2 shows the advantage and disadvantage for pipe wall thickness.

Table 2 : Advantage and disadvantage for pipe wall thickness

	Advantage	Disadvantage
Thick wall	• Higher strength	• Higher operating costs • Welding difficulty
Thin wall	• Reduce material, transportation, loading and welding costs	• Cannot operate at high pressures

The strength of steel pipe can be improved by several methods. The most common and oldest method used is to increase the alloying elements (solid solution strengthening). Table 3 shows the effects of solid solution strengthening.

Table 3 : Solid Solution Strengthening

Element Strengthening	(MPa per wt%)	Element Strengthening	(MPa per wt%)
Carbon	5,500	Copper	40
Nitrogen	5,500	Manganese	30
Vanadium	1,500	Molybdenum	11
Phosphorus	700	Nickel	0
Silicon	80	Chromium	-11

The main issue however with carbon steel, as with all metal, is that it is prone to corrosion.

2.1.1 Corrosion

Corrosion is the result of two separate reaction processes on a metal surface (Palmer and King, 2008):

- Loss of metal and production of electrons at anodic areas.
- Consumption of these electrons at cathodic areas.

Corrosion can weaken the structural integrity of pipelines and make them an unsafe vehicle for transporting potentially hazardous materials (Chaves and Melchers, 2012). For offshore pipelines, there are two types of corrosion:

- External corrosion
- Internal corrosion

2.1.1.1 External corrosion

The corrosion process is the dissolution of the iron of the pipeline at the anodic areas as charged positive ions into the seawater or seabed sediment. The corrosion reactions are as follow:

$$Fe \longrightarrow Fe^{++} + 2\ \text{electrons} \qquad \text{anodic reaction} \qquad (2.1)$$

$$O_2 + 4H_2O + 4\ \text{electrons} \longrightarrow 4\,(OH)^- \qquad \text{cathodic reaction} \qquad (2.2)$$

The overall reaction is:

$$2Fe + O_2 + 4H_2O \longrightarrow 2Fe(OH)_2 \qquad (2.3)$$

External corrosion is prevented by applying coatings to the pipeline such as Polyethylene, Fusion Bonded Epoxy (FBE) and polypropylene. Theoretically, the risk of corrosion after applying coatings is very small unless caused by external damage which create holes in the coating. Cathodic protection is applied to prevent corrosion on damaged areas (Guo et al., 2005).

2.1.1.2 Internal Corrosion

It should be noted that crude oil by itself is not corrosive at pipeline conditions, but water can drop out of the crude oil and allow corrosion to occur where it accumulates (Larsen et al., 2013). However, crude oil can carry various high-impurity products which are inherently corrosive. The substances are carbon dioxide (CO_2) which is called sweet corrosion, and hydrogen sulfide (H_2S) which is sour corrosion. Figure 2 and Figure 3 below shows sour corrosion and sweet corrosion respectively.

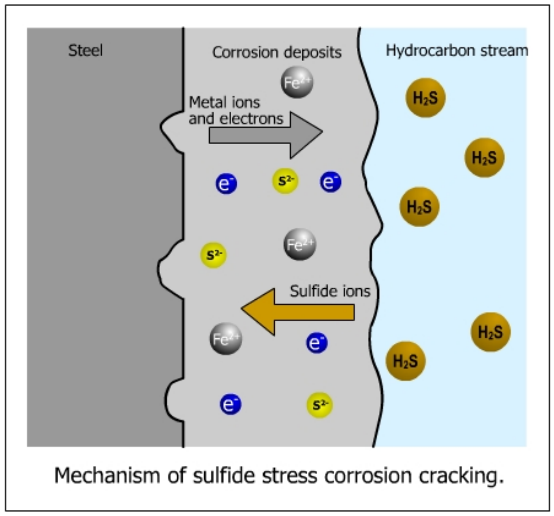


Figure 2 : Sour Corrosion

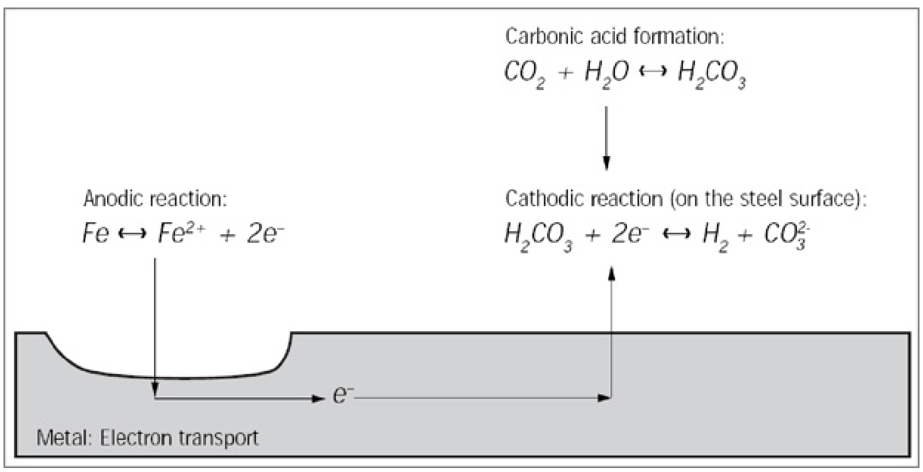


Figure 3 : Sweet Corrosion

Inhbitors are injected into the pipeline to prevent internal corrosion. However, the efficiency of the inhibitor depends on several factors such as flow rate and cleanliness (Palmer and King, 2008). Another alternative to prevent corrosion is by adding a composite material in the design of the pipe.

2.2 Composite Flexible Pipeline

The earliest flexible pipelines were constructed across the English Channel during World War II. It was used to transport fuel from England to France and support the D-day landings. They were based on telegraph cable technology and were composed of a lead tube protected by tape, armoring wires, and an outer sheath. It was only in 1970 that modern type of flexible pipeline was developed (Palmer and King, 2008).

The advantage of using flexible pipeline is it reduces the amount of spans that is usually experienced by stiff steel pipelines. This reduces the stress in the pipelines. Furthermore, it is easier to install and can be laid from modified barges or drill ships. According to Palmer and King (2008), the pipeline material is high, about five to six times the cost of an equivalent steel pipeline which might be true for conventional flexible pipelines. However, current flexible pipelines that have been developed is stated to have a cheaper cost than steel pipelines as much as 50% less (Catha et al., 2011). However, despite the promised advantages, composite materials have historically been slow in gaining acceptance in structural applications within the oil and gas industry (Jha et al., 2014). The reason is due to the lack of unified testing procedures and standards, and concern related to failure models and exposure to harsh chemical environments. Table 4 shows the advantages and disadvantages of flexible composite pipe.

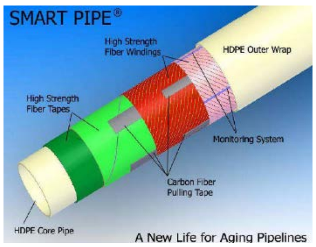
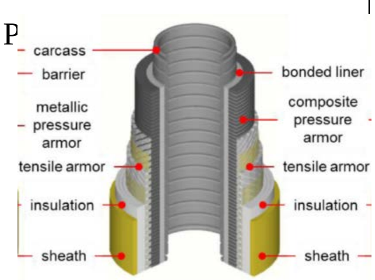
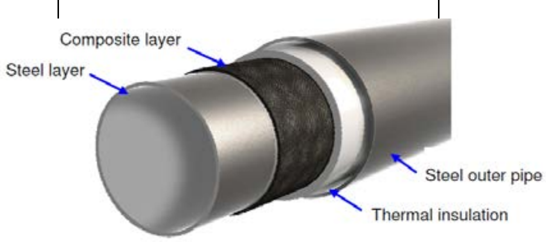
Table 4 : Advantage and Disadvantage of Flexible Composite Pipe

Advantage	Disadvantage
- Stronger than Steel pipe. - Flexible, reducing stress. - Cheaper compared to steel.	- Slow to be recognized due to lack of standards and testing procedures. - Lack of material production.

The design and fabrication of flexible pipelines are different than the steel pipes. Flexible pipes are composites constructed from sequential layers of metals and polymeric thermoplastic materials. Each layer has their specific functions which depends on the nature of the pipe, either bonded or non-bonded.

Currently there are many designs for composite pipes. Table 5 shows several existing designs.

Table 5 : Designs of Flexible Composite pipe

	Author	Advantage
SMART PIPE 	Catha et al., (2011)	- Transportable factory to manufacture and deploy pipe - 24/7 monitoring capabilities in the pipe - Minimal coefficient of thermal expansion. - Lower costs (50% lower than steel)
HYBRID COMPOSITE P 	Jha et al., (2014)	- Metallic armor is substituted with a carbon fiber layer. - High resistance to fatigue
PIPE IN PIPE  Fig 1: Multi-layered pipe-in-pipe cross section	et al., 09)	- Reduction in weight by 35% compared to standard carbon steel pipe. - Depth of water up to 3500m could be reached with this design.

2.3 Finite Element Analysis

Finite element analysis (FEA) is a numerical method used to find approximate solutions to boundary value problems. The concept of FEA is to divide an area or solid into multiple subdomains where each subdomain is analyzed. The area where FEA is applied includes structure analysis, solid mechanics, dynamics, thermal analysis and electrical analysis.

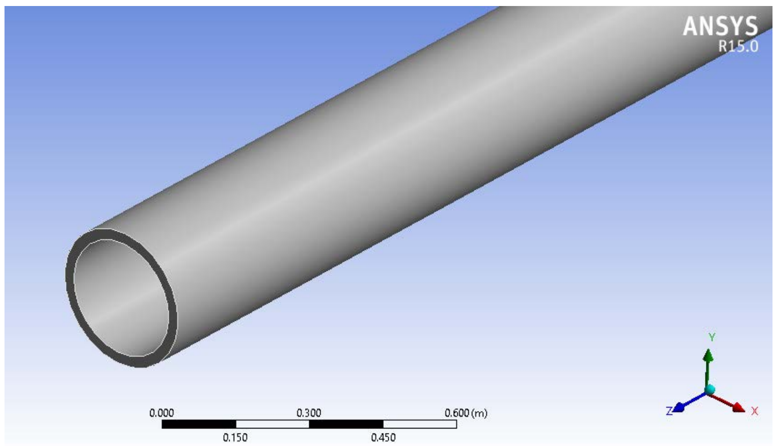


Figure 4 : 3D Pipe Model

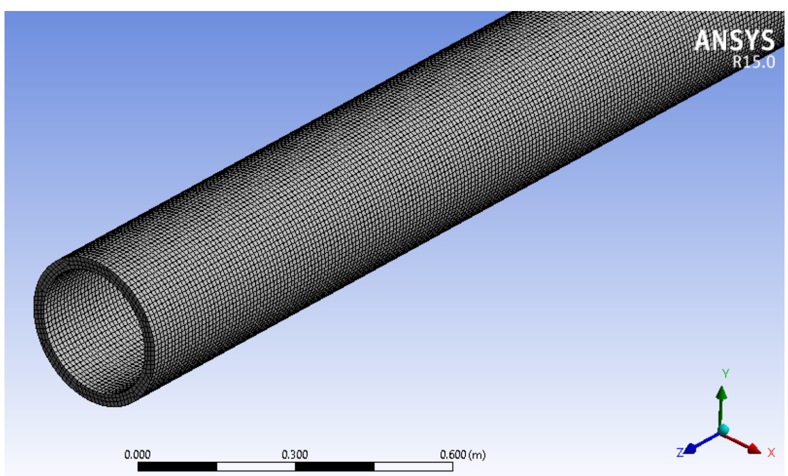


Figure 5 : Meshing of the 3D pipe model

In subsea pipeline, FEA is used for various reasons. Table 6 shows several examples of the application of FEA in subsea pipeline.

Table 6 : Application of FEA in subsea pipeline

Research title	Author	Objective
Application of Finite Element Analyses for Assessment of Fracture Behavior of Modern High Toughness Seamless Pipeline Steels	Nonn et. al., (2013)	To study the fracture behavior of seamless pipeline material X56Q according to API 5L at different loading conditions and temperatures.
Pipeline Mechanical Damage Assessment Using Finite Element Methods	Hanif and Kenny, (2012)	To highlight the effect of plain dents and interaction of plain dents with girth weld on pipe mechanical response.
Finite Element Analysis of Propagating Buckles in Deepwater Pipelines	Tassoulas et. al., (1990)	To analyze the propagating buckles in deep-water pipelines by taking into account the large deformation of the pipe, the elastoplastic behavior of the pipe material and the contact between regions of the interior wall of the pipe during buckle propagation.
Buckle Interaction in Deep Subsea Pipelines	Karampour et. al., (2013)	To simulate buckle interaction in deep subsea pipeline.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This research involves several stages with the first stage to compare the thermosetting pipe using different materials. The purpose of comparing the thermosetting pipe using different materials is to establish the best material to be used. After the comparison, the next stage will be to implement modifications to the thermosetting pipeline in order to achieve better results.

Four materials will be used for the thermosetting pipeline which are glass fiber epoxy, graphite epoxy, polyethylene, and carbon steel. The former three materials are chosen due to their corrosion resistant property.

This research involves a numerical model for stress analysis using ANSYS Finite Element Model. However, further study has to be conducted beforehand to provide better understanding. Therefore, the research method and activities planned are conducted as follow.

1. Research and Literature Review

   The aim of this activity is to study previous research conducted by other people thus creating awareness of the current situation relating to this research. The method of this activity is by reading journal articles, online resources, books and other sources of reading materials.
2. Numerical Modeling Stress Analysis.

   In this activity, the thermosetting pipe will be modelled for stress analysis. The model will be based on studies to ensure its effectiveness. The modelling and simulation will be conducted using ANSYS Finite Element Modelling, which is provided in the computer laboratory.
3. Result analysis and Comparison

   The objective of this activity is to compare the results obtained from the different materials used in the newly developed thermosetting pipe.

4. Model Improvement and Modification

   Depending on the results of the simulations, modifications will be made to increase the effectiveness of the original model. This will be done repeatedly until the results obtained is satisfactory.

3.2 Numerical Modeling Stress Analysis.

The Finite Element Method is often applied for various shapes of model. The ANSYS® Workbench™ version 15.0 allows users to model the pipe and perform necessary analysis. Modelling of a carbon steel pipeline involves several stages before proceeding to the analysis:

- Pipe model properties
- Analysis system
- Modelling
- Meshing
- Defining loads
- Solution

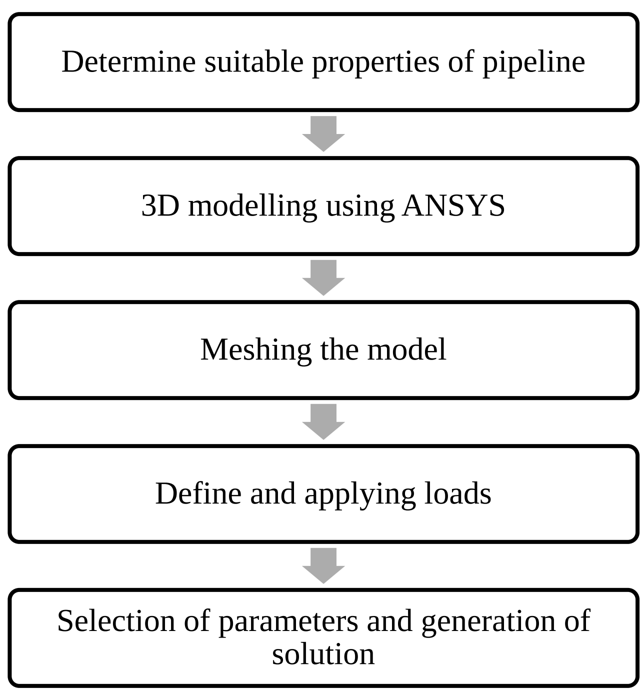


Figure 6 : Steps in numerical modelling

3.3 Pipe model Properties

There will be 4 (four) materials used in the stress analysis of the flexible thermosetting pipe which are:

- Glass fiber epoxy
- Graphite epoxy
- Polyethylene
- Carbon steel

3.4 Analysis System

3.4.1 Static Structural

A static structural analysis is used to determine the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. The loading is assumed to occur immediately with respect to time.

3.4.2 Modelling

All the 3D models were generated using ANSYS® Workbench™ version 15.0. For this research, eight 3D models were created, each with differing grade, diameter and wall thickness. All the carbon steel pipeline have a length of six meters,

3.4.3 Meshing

Meshing is one of the method used in FEM to run an analysis. It represents field variable such as displacement polynomial function that produce a displacement field compatible with applied boundary condition. For the model in this research, the element size is set to 0.01 to obtain accurate results for stress analysis.

3.5 Defining Loads

3.5.1 Standard Earth Gravity

Standard Earth gravity is set to 9.81 m/s^2 for the model. The purpose of this load is to simulate a realistic environmental load to the pipe system. Table 7 shows the load applied and the direction with respect to the position of the model.

Table 7 : Standard Earth Gravity applied

Definition	
Coordinate System	Global Coordinate System
X Component	0. m/s^2 (ramped)
Y Component	-9.8066 m/s^2 (ramped)
Z Component	0. m/s^2 (ramped)
Suppressed	No
Direction	-Y Direction

3.5.2 External Pressure

The external pressure is manually calculated with respect to depth. The equation used is as follow.

$$\text{Pressure} = \rho \cdot g \cdot h \qquad (3.17)$$

The external pressure is only applied on the outer layer of the model as shown in Figure 7.

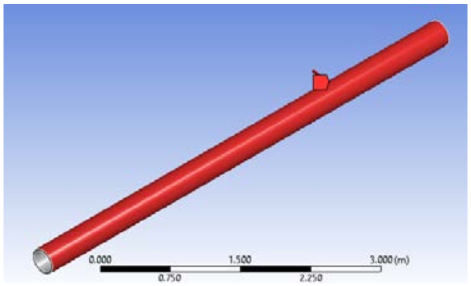


Figure 7 : Area of external pressure applied

3.5.3 Internal Pressure

The internal pressure was set as 34.5 MPa for the models and is applied only in the inner layer of the pipe. The area where the load is applied is shown in Figure 8.

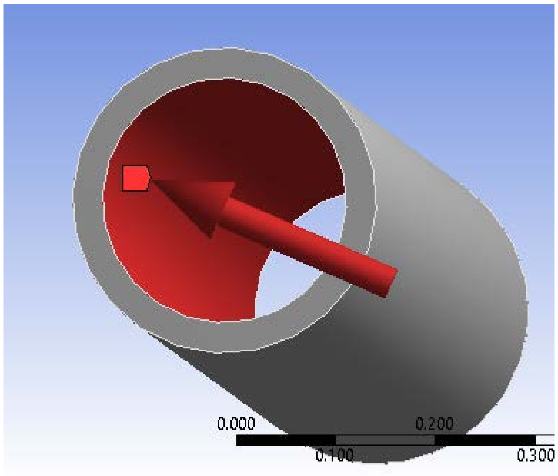


Figure 8 : Area of internal pressure applied

3.5.4 Supports

3.5.4.1 Remote Displacement

The model is assumed to have fix supports in certain axis only, allowing for displacement and rotation to occur in certain directions. Table 8 shows the axis where the model is free (free) and where the model is assumed fixed (0).

Table 8 : Remote displacement

Definition	
Type	Remote Displacement
X Component	0. m (ramped)
Y Component	0. m (ramped)
Z Component	Free
Rotation X	Free
Rotation Y	0. ° (ramped)
Rotation Z	0. ° (ramped)
Suppressed	No
Behavior	Deformable

The remote displacement is applied at both ends of the pipe as shown in Figure 9.

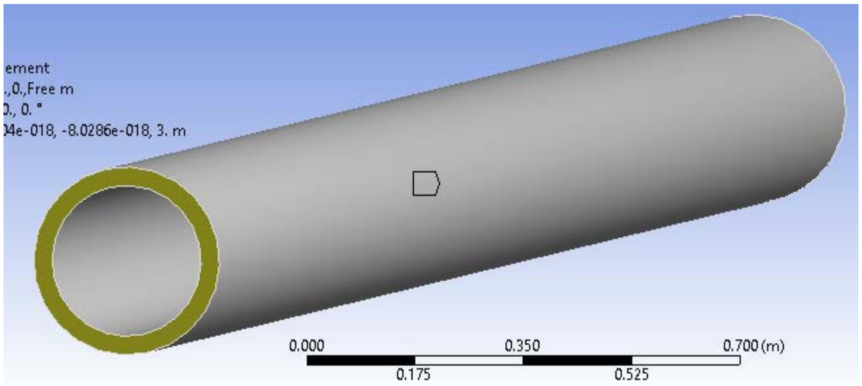


Figure 9 : Area of remote displacement

3.5.5 Temperature

The temperature is set to 35°C to simulate a realistic environment in deep sea. This parameter is considered in the analysis as it affects the expansion of the pipeline. The temperature is applied to the whole model as shown in Figure 10.

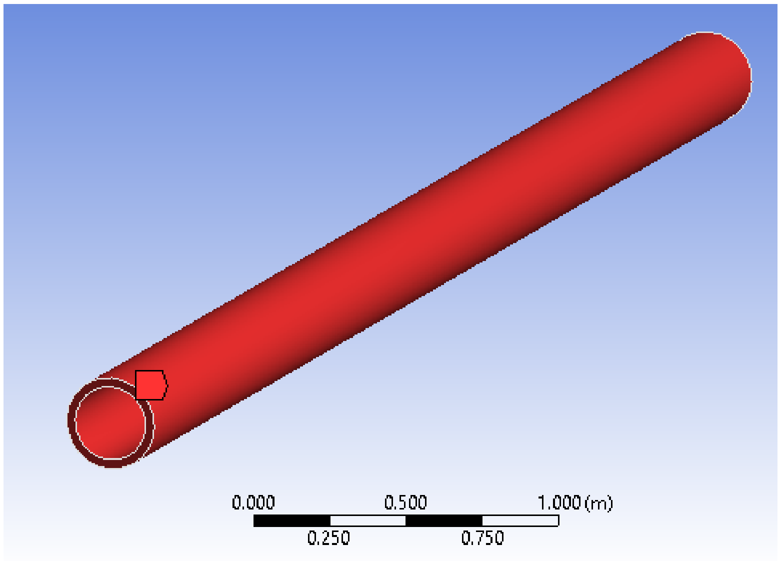


Figure 10 : Area of temperature applied

3.5.6 Summary of Loads

Table 9 shows the summary of loadings applied for the stress analysis.

Table 9 : Summary of loadings

Loading	Value
Specific Earth Gravity	9.8066 m/s^2
Internal Pressure	35 MPa
External Pressure	15 MPa
Applied Tension	500 kN

3.6 Solution

Several parameters are used in the analysis of the carbon steel pipeline which are:

- Total deformation
- Equivalent elastic strain
- Equivalent stress

3.6.1 Total Deformation

The total deformation measures the length of the pipe that is deformed from its original shape. The deformation comes from the combination of self-weight, internal pressure and external pressure. The maximum total deformation was recorded and compared with other pipe models.

3.6.2 Equivalent Elastic Strain

The equivalent elastic strain measures the amount of strain experienced by the pipeline. The maximum strain for a carbon steel pipeline is 0.001 before it fails. The maximum equivalent elastic strain was recorded and compared with other pipe models.

3.6.3 Equivalent Stress

The equivalent stress measures the amount of stress experienced by the pipeline. The maximum amount of stress that can be applied to the pipeline is 207 MPa before it fails. The maximum equivalent stress was recorded and compared with other pipe models.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

The results of the stress analysis for the flexible thermosetting pipe comprises three parts, namely:

- Equivalent stress
- Equivalent deformation
- Total deformation

4.2 Simulation Result

The simulation shows the visual result of the stress analysis. The color signifies the amount of stress, strain, or deformation experienced in an area where blue is the minimum and red is the maximum. The simulation results are shown for:

- Glass fiber epoxy
- Graphite epoxy
- Polyethylene
- Carbon steel

4.2.1 Glass fiber epoxy

Figures 11, 12, and 13 shows the simulation results for the flexible thermosetting pipe using glass fiber epoxy.

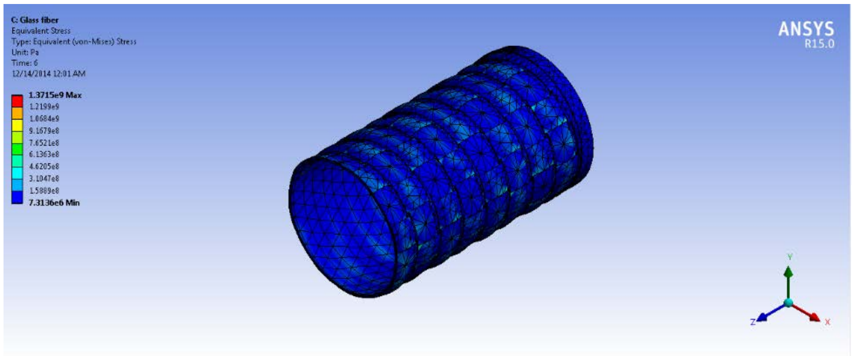


Figure 11 : Equivalent stress for glass fiber epoxy

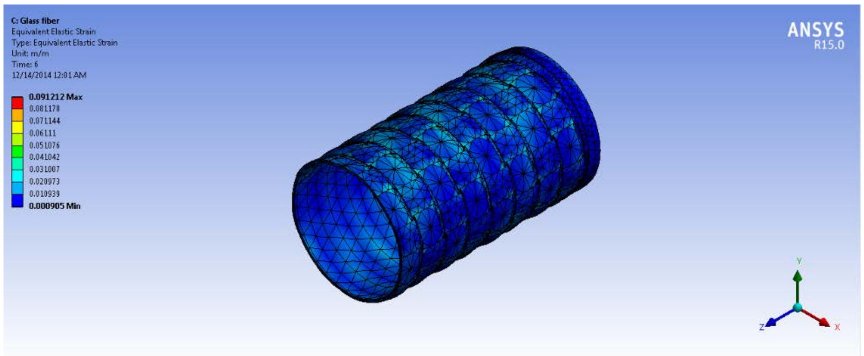


Figure 12 : Equivalent strain for glass fiber epoxy

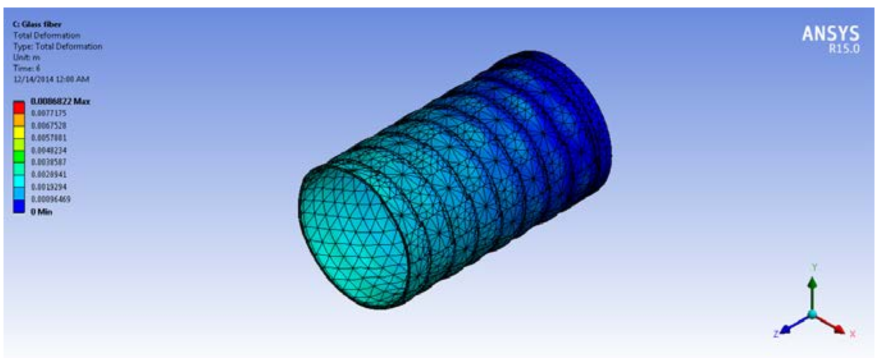


Figure 13 : Total deformation for glass fiber epoxy

Table 10 shows the stress analysis result for the thermosetting pipe using glass fiber epoxy in terms of equivalent stress, equivalent strain and total deformation

Table 10 : Stress analysis result for glass fiber epoxy

Time (sec)	Equivalent stress (Pa)	Equivalent Strain (m/m)	Total deformation
1	6.35E+08	4.04E-02	4.06E-03
2	7.86E+08	5.06E-02	4.97E-03
3	9.32E+08	6.07E-02	5.90E-03
4	1.08E+09	7.09E-02	6.82E-03
5	1.23E+09	8.11E-02	7.75E-03
6	1.37E+09	9.12E-02	8.68E-03

4.2.2 Graphite epoxy

Figures 14, 15, and 16 shows the simulation results for the flexible thermosetting pipe using graphite epoxy.

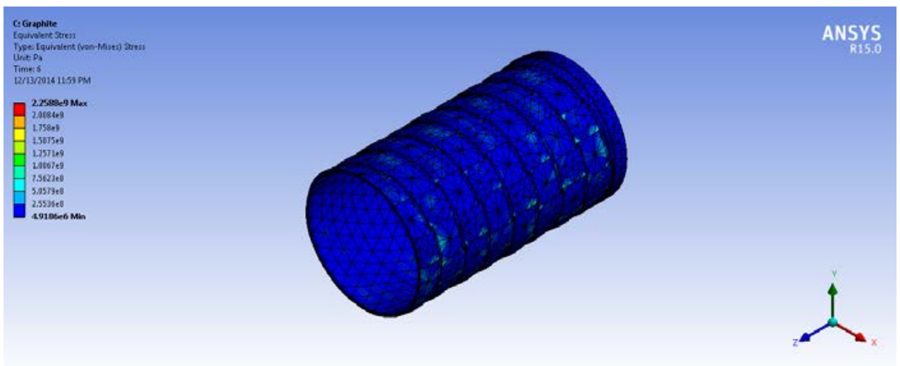


Figure 14 : Equivalent stress for graphite epoxy

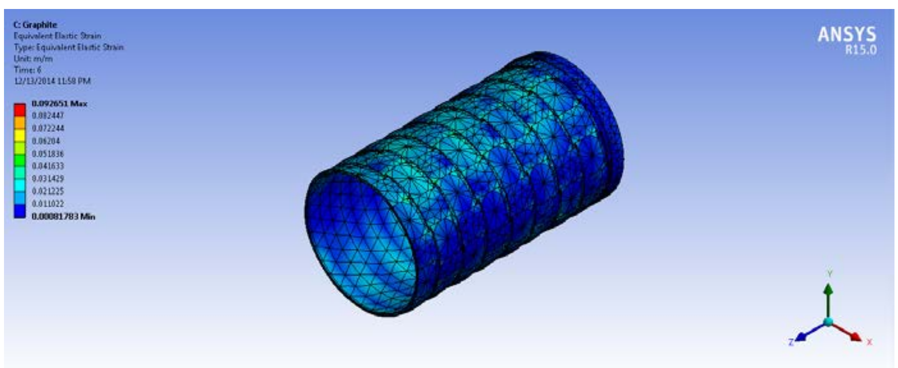


Figure 15 : Equivalent strain for graphite epoxy

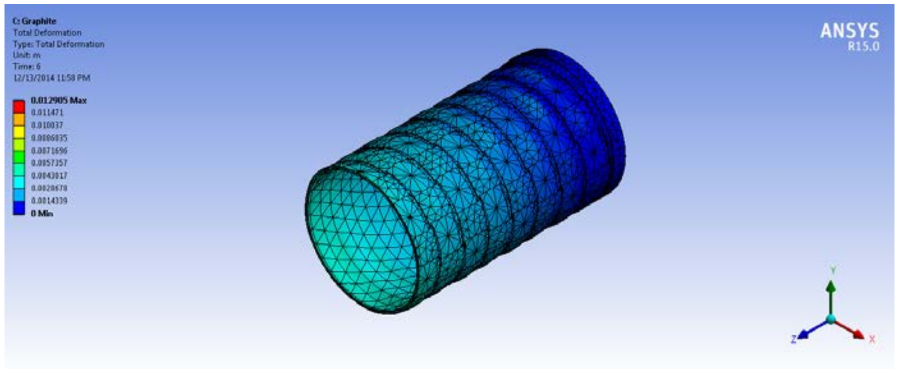


Figure 16 : Total deformation for graphite epoxy

Table 11 shows the stress analysis result for the thermosetting pipe using glass fiber epoxy in terms of equivalent stress, equivalent strain and total deformation.

Table 11 : Stress analysis result for graphite epoxy

Time (sec)	Equivalent stress (Pa)	Equivalent Strain (m/m)	Total deformation
1	1.02E+09	4.07E-02	5.78E-03
2	1.27E+09	5.12E-02	7.18E-03
3	1.52E+09	6.16E-02	8.60E-03
4	1.76E+09	7.19E-02	1.00E-02
5	2.01E+09	8.23E-02	1.15E-02
6	2.26E+09	9.27E-02	1.29E-02

4.2.3 Polyethylene

Figures 17, 18, and 19 shows the simulation results for the flexible thermosetting pipe using polyethylene.

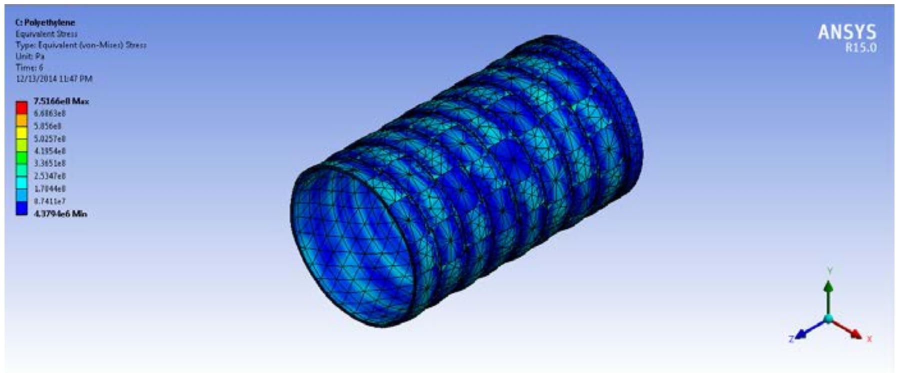


Figure 17 : Equivalent stress for polyethylene

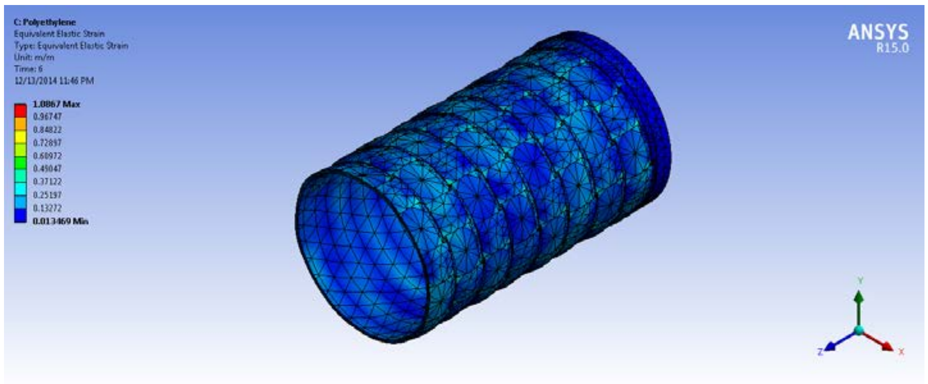


Figure 18 : Equivalent strain for polyethylene

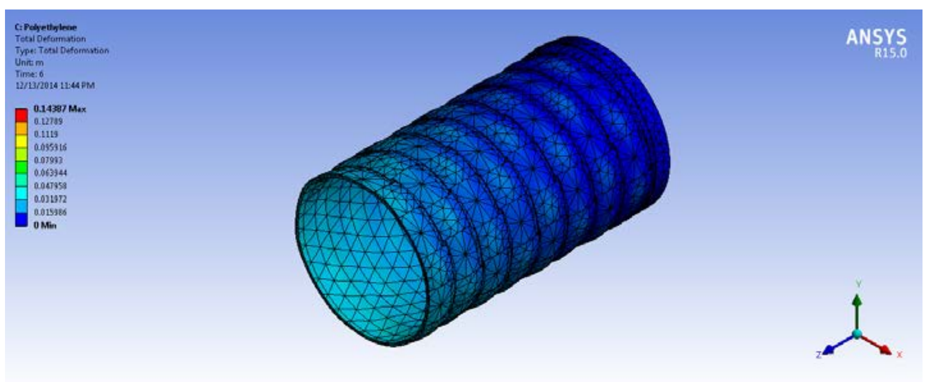


Figure 19 : Total deformation for polyethylene

Table 12 shows the stress analysis result for the thermosetting pipe using glass fiber epoxy in terms of equivalent stress, equivalent strain and total deformation.

Table 12 : Stress analysis result for polyethylene

Time (sec)	Equivalent stress (Pa)	Equivalent Strain (m/m)	Total deformation
1	3.29E+08	0.46575	6.36E-02
2	4.15E+08	0.59182	7.99E-02
3	4.99E+08	0.7155	9.58E-02
4	5.83E+08	0.83922	0.1118
5	6.67E+08	0.96297	0.12783
6	7.52E+08	1.0867	0.14387

4.2.4 Carbon Steel

Figures 20, 21, and 22 shows the simulation results for the flexible thermosetting pipe using carbon steel.

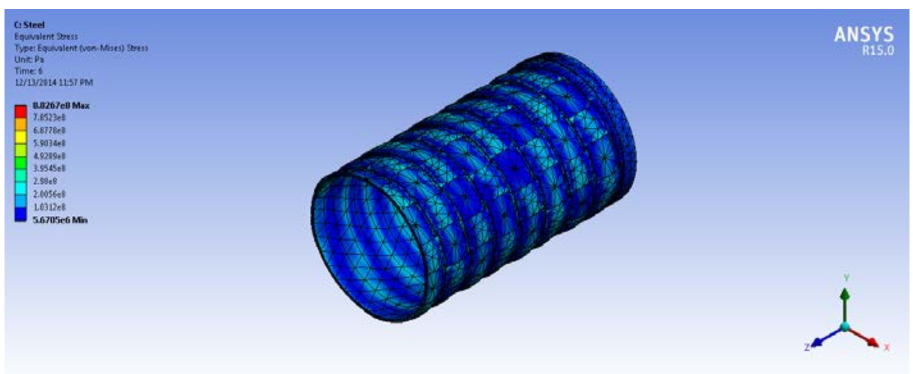


Figure 20 : Equivalent stress for carbon steel

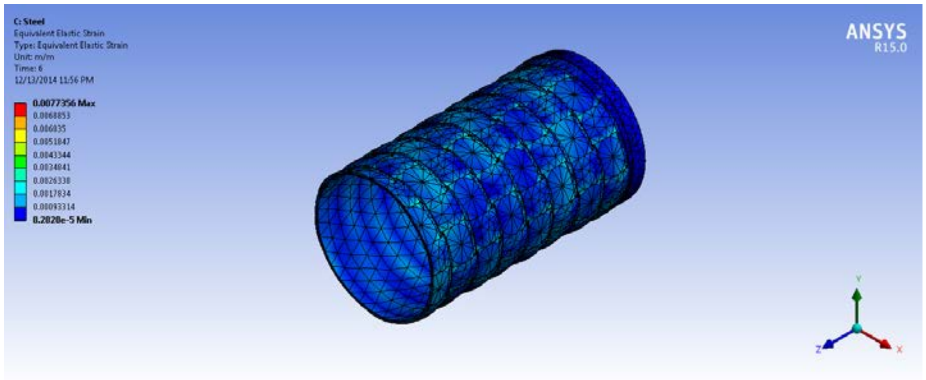


Figure 21 : Equivalent strain for carbon steel

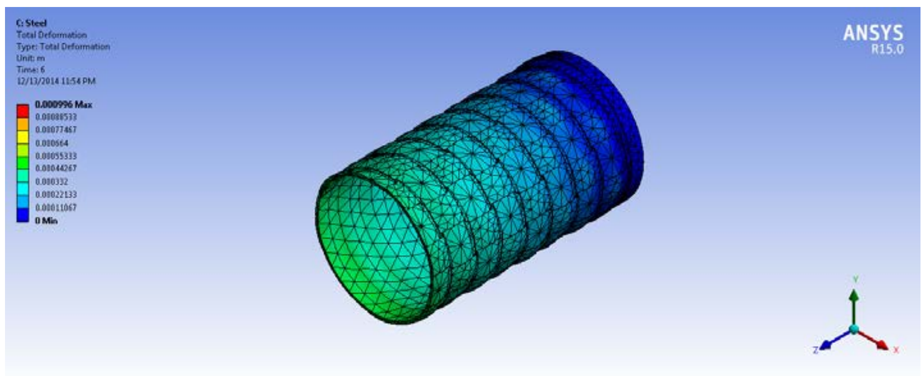


Figure 22 : Total deformation for carbon steel

Table 13 shows the stress analysis result for the thermosetting pipe using glass fiber epoxy in terms of equivalent stress, equivalent strain and total deformation.

Table 13 : Stress analysis result for carbon steel

Time (sec)	Equivalent stress (Pa)	Equivalent Strain (m/m)	Total deformation
1	4.50E+08	3.86E-03	5.81E-04
2	5.37E+08	4.64E-03	6.58E-04
3	6.23E+08	5.42E-03	7.42E-04
4	7.10E+08	6.19E-03	8.26E-04
5	7.96E+08	6.96E-03	9.11E-04
6	8.83E+08	7.74E-03	9.96E-04

4.2.5 Equivalent Stress

Figure 23 shows a graph of equivalent stress experienced by the thermosetting pipe with respect to time.

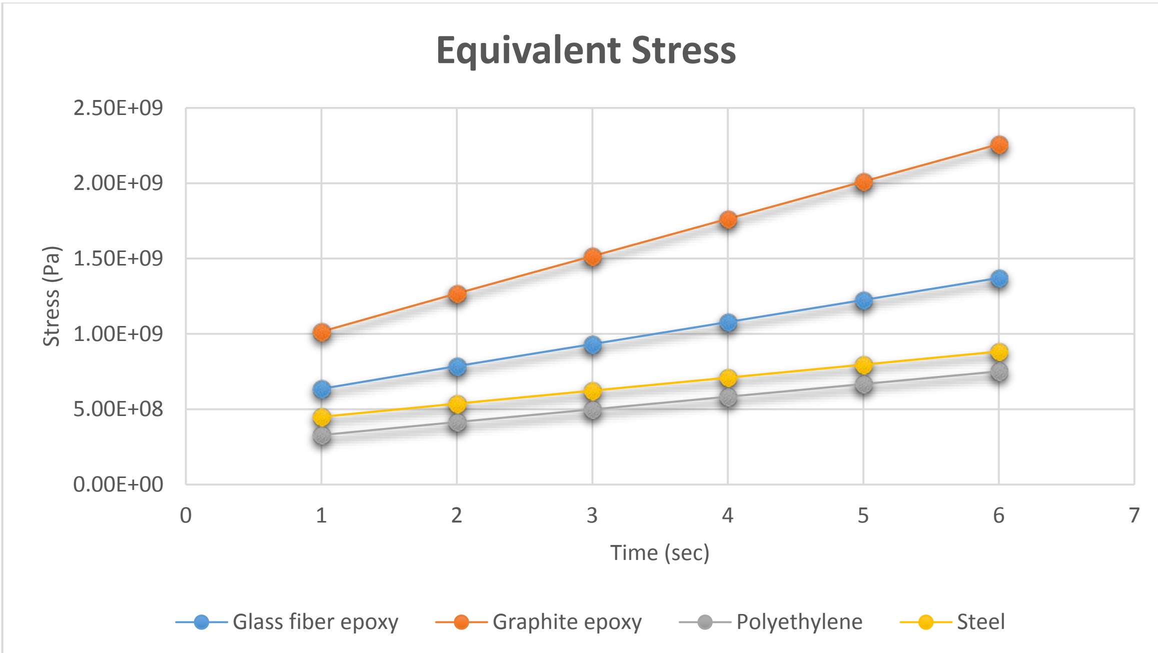


Figure 23 : Graph of Equivalent stress vs Time

From the graph, the highest stress is experienced by graphite epoxy, followed by glass fiber epoxy, and carbon steel. Polyethylene experiences the lowest stress among the four materials used. This is due to the high elasticity of the polyethylene compared to the other materials.

4.2.6 Equivalent strain

Figure 24 shows a graph of equivalent strain experienced by the thermosetting pipe with respect to time.

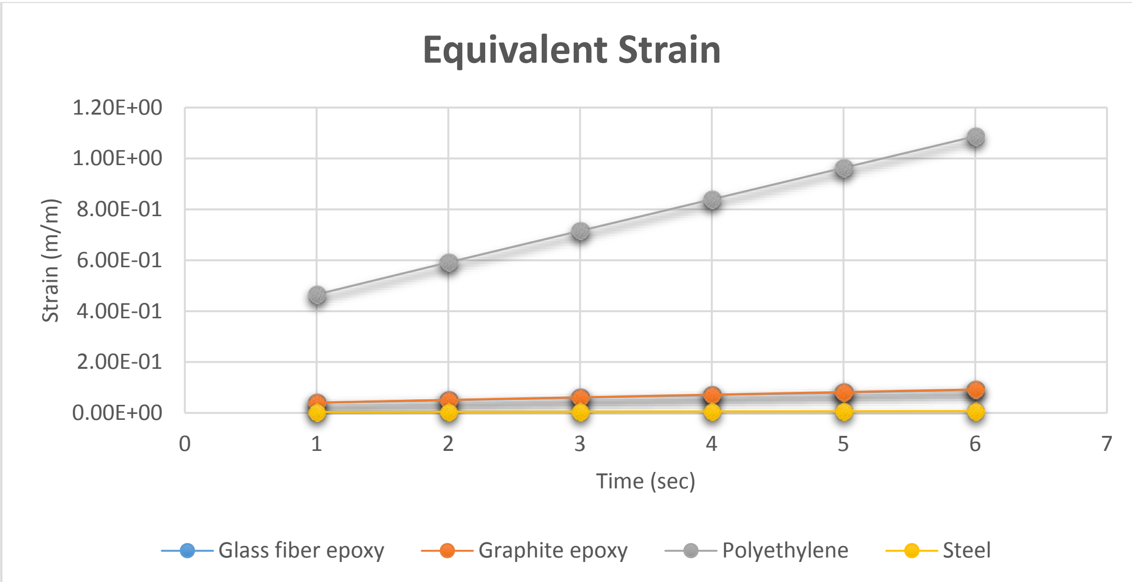


Figure 24 : Graph of Equivalent strain vs Time

From the graph, it can be seen that polyethylene experiences the highest strain among all four materials. This is followed by graphite epoxy and glass fiber epoxy. Carbon steel experiences the least strain. The large difference in strain between polyethylene and other materials may be due to its lower young's modulus and shear modulus, making it more elastic and easier to expand or contract. Carbon steel, on the other hand, has the highest young's modulus and shear modulus.

4.2.7 Total Deformation

Figure 25 shows a pie chart of total deformation experienced by the thermosetting pipe in terms of percentage.

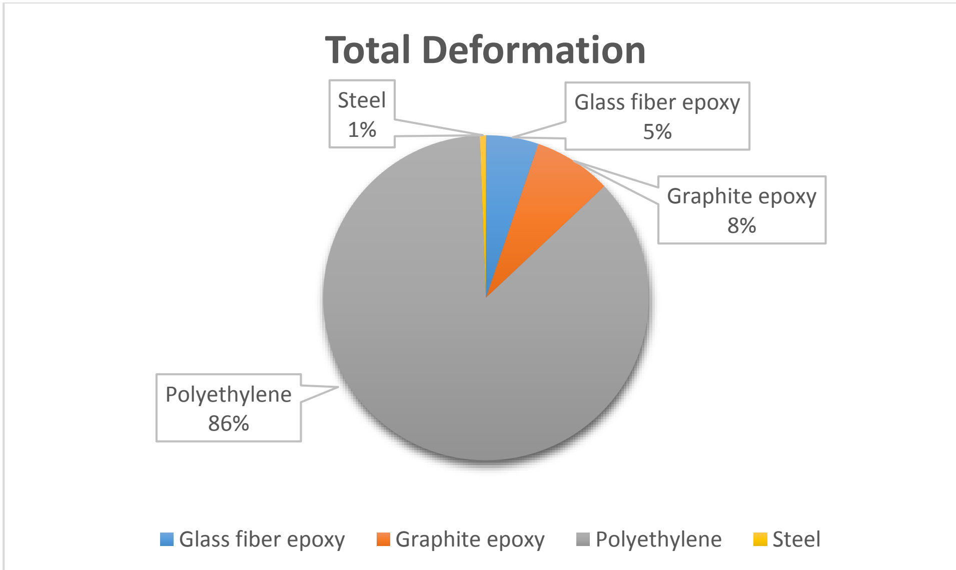


Figure 25 : Total Deformation

From the pie chart, it can be seen that polyethylene has the highest deformation, approximately 80% more than the other three materials. This is followed by graphite epoxy, 8%, glass fiber epoxy, 5%, and lastly carbon steel at 1%. The result of the deformation depends on the elasticity of the material. Polyethylene, being the most elastic, will obviously undergo the most deformation. On the other hand, carbon steel, which is the stiffest material, experiences the lowest deformation.

4.3 Results Summary

Table 14 and 15 shows the summary of simulation results.

Table 14 : Summary of simulation results

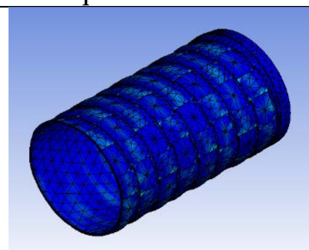
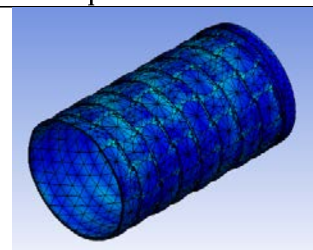
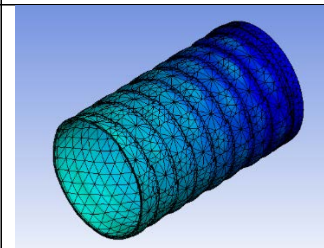
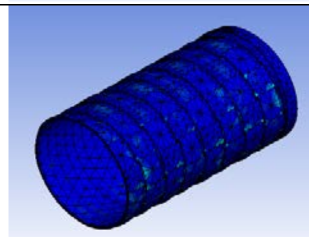
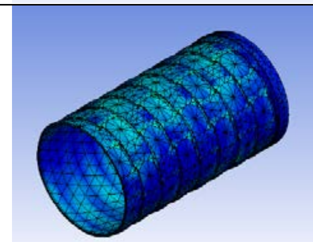
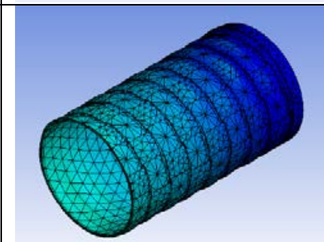
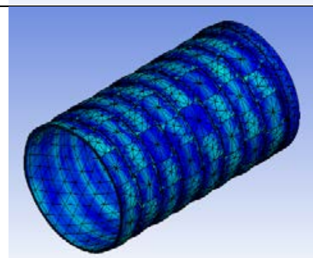
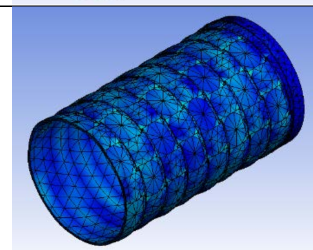
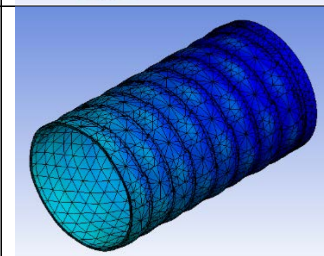
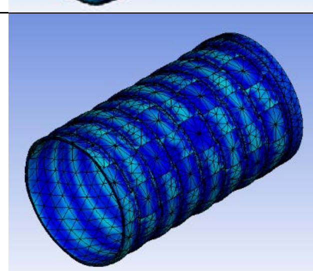
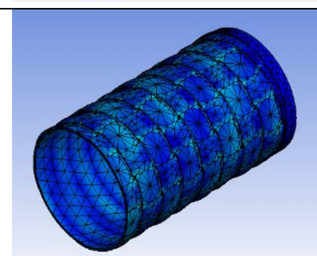
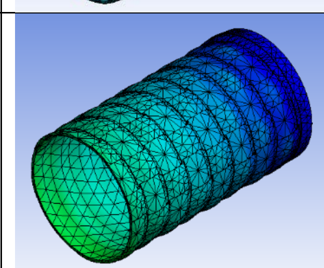
Material	Equivalent stress	Equivalent strain	Total Deformation
Glass fiber epoxy			
Graphite epoxy			
Polyethylene			
Carbon steel			

Table 15 : Maximum stress, strain and deformation

Criteria	Glass fiber epoxy	Graphite epoxy	Polyethylene	Carbon Steel
Equivalent stress (Pa)	1.37E+09	2.26E+09	7.52E+08	8.83E+08
Equivalent strain (m/m)	9.12E-02	9.27E-02	1.0867	7.74E-03
Maximum deformation	8.68E-03	1.29E-02	0.14387	9.96E-04

Based on the results, polyethylene experiences the lowest stress compared to the other three materials. However, it has the highest strain and deformation due to its elasticity, making it unsuitable to be used for the flexible thermosetting pipe as it is prone to buckling. On the other hand, carbon steel has the lowest stress, next to polyethylene, strain and deformation. Unfortunately carbon steel is vulnerable to corrosion, thus also unsuitable. Therefore, the best material to be used is glass fiber epoxy as it has already achieved a close mechanical property with carbon steel.

CHAPTER 5

CONCLUSION

A stress analysis using extensive FEM simulations were conducted in this research for the flexible thermosetting pipe. The stress analysis was conducted to determine the best non-corrosive material to be used for deepwater applications.

From the stress analysis, polyethylene has the lowest equivalent stress but the highest deformation and equivalent strain. Carbon steel on the other hand has the best mechanical property but is not corrosion resistant. Although graphite epoxy has a lower stress, strain and deformation compared to polyethylene, glass fiber epoxy has better mechanical property.

While it is yet to be conclusively proven, the results of the stress analysis indicates that the fiber glass epoxy has the potential to be a viable material for the newly developed thermosetting pipeline.

Recommendation for future work:

a. Incorporate fatigue tools in the stress analysis – The fatigue tool comprises biaxility indication, safety factor, life, damage and equivalent alternating stress. These elements can further increase the accuracy and precision of the data.
b. Modification of model – Further modifications can be made on the model which is by adding more layers. Currently the model only consists of three layers of the thermosetting tapes. It is suggested to have an increment from 30 to 100 layers to increase the performance of the flexible thermosetting pipe.

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