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Finite Element Analysis (FEA) Study on Glass Fiber Reinforced Epoxy (GRE) Pipes Used in Oil and Gas Industry

Muhammad Khairulanwar Muhammad Faris[1], RD Khairilhijra' Khirotdin[1]*

[1]Faculty of Mechanical and Manufacturing Engineering,
Universiti Tun Hussein Onn Malaysia, Johor, 86400, MALAYSIA,

*Corresponding Author Designation

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Abstract: The requirement to describe and comprehend the engineering performance of GRE pipes becomes more crucial as applications spread, and a better understanding of the performance of glass fibre-reinforced epoxy (GRE) pipe also needs to be considered due to the improvement of this material for oil and gas industry pipes. Furthermore, GRE has been considered an alternative to carbon steel. Therefore, this research objective is to analyse the tensile strength, fatigue behaviour, and corrosion behaviour of the GRE and then to determine by comparing the analysis result of GRE with a carbon steel pipe. The research has been completed by conducting an analysis using ANSYS software to analyse tensile strength, fatigue behaviour and corrosion behaviour by using three different geometries, which are minimum, medium, and maximum, to see the outcomes differences for both GRE and carbon steel pipes. The outcome from the analysis shows the percentage of differences between GRE and carbon steel just shows a small value, which is for tensile strength; the total deformation and elastic strain of GRE is 3% longer than carbon steel with von Mises stress of GRE just 0.003% behind the carbon steel. However, the fatigue behaviour analysis result shows that for minimum and medium geometry shows, GRE has a low cycle of 1% behind carbon steel, while for maximum geometry, it shows no difference for both pipes. Therefore, the GRE and carbon steel have their own strength, which means it depends on the application or situation whether to choose the GRE or carbon steel as the pipe material, and GRE can be an alternative to carbon steel to use for oil and gas industry pipe. Some suggestions for the future are the outcomes from this research can be validated by doing an experiment for the tensile strength, fatigue behaviour and corrosion behaviour on GRE pipes.

Keywords: Finite Element Analysis (FEA), Glass fibre Reinforced Epoxy (GRE) Pipe, Oil and Gas

**Corresponding author: khairil@uthm.edu.my*

1. Introduction

Oil and gas are significant players in the energy sector and have an impact on the global economy as the world's main fuel source. Oil and gas production and distribution processes and systems are highly complicated, capital-intensive, and dependent on cutting-edge technology. Therefore, technological progress is indisputable because one material that has become more popular is Glass Fiber Reinforced Epoxy (GRE) due to its lightweight, high strength, and chemical/corrosion resistant qualities [1]. Furthermore, corrosion has long been a major concern in the oil and gas sectors, with effects resembling those of natural disasters due to the pipe affected by corrosion. One of the effects that will happen because of corrosion is pipe damage or cracks in the corrosion area. Pipelines carrying oil and gas typically experience corrosion. Since the pipelines are responsible for moving gas and oil from wellheads. From the time that the processing facilities are put into service until they are decommissioned or abandoned, they are constantly at risk from corrosion [2]. However, the requirement to describe and comprehend the engineering performance of GRE pipes becomes more crucial as applications spread, and a better understanding of the performance of glass fibre-reinforced epoxy (GRE) pipe also needs to be considered due to the improvement of this material for oil and gas industry pipes [3]. Furthermore, GRE has been considered as an alternative to carbon steel [4].

Therefore, this study will increase an understanding by giving more information about GRE pipe and will be proof of whether the GRE pipe is better than the carbon steel pipe in terms of results by analysis. The objective is to determine the tensile strength, fatigue behaviour, and corrosion behaviour of the GRE and then to analyse it by comparing the analysis result of GRE with a carbon steel pipe. The expected outcome shows the result from an analysis that GRE has the potential to replace carbon steel pipe in oil and gas industry applications. Besides, GRE pipe has better properties compared to carbon steel for oil and gas industry applications. Finally, the result from this study will give extra information as a guide for future studies about Glass Fiber fibre-reinforced epoxy (GRE) filament winding pipe.

2. Materials and Methods

The materials and methods will be illustrated in this section to show a clearer vision to understand the flow of this study and achieve the objective.

2.1 Materials

There are different materials that have been used during conducting this study analysis which are GRE and carbon steel. First, the GRE pipe consists of two materials: E-glass type as fibre and epoxy as resin, with a ratio of 70% for glass fibre and 30% for resin. Table 1 below shows the mechanical properties of E-glass fibre and epoxy resins [5].

Table 1: Mechanical properties of E-glass fibre and epoxy resin

Property	Unit	E-Glass	Epoxy Resin
Elastic modulus	E (GPa)	73	3
Shear modulus	G (GPa)	29.7	1.1
Tensile strength	σ_{Ts} (MPa)	2500	79
Poison ratio	$\mathcal{V}$ (-)	0.23	0.35
Density	ρ (g/cm^3)	2.6	1.16

Meanwhile, high carbon steel has been applied on the carbon steel pipe for the analysis due to the mechanical properties of high carbon steel material, the same as ASTM A106 carbon steel that is widely used in oil and gas industry pipe materials. The following below table 2 shows the high carbon steel mechanical properties [6].

Table 2: Mechanical Properties of E-Glass Fiber and Epoxy Resin

Property	Unit	High Carbon Steel
Elastic modulus	E (GPa)	205
Shear modulus	G (GPa)	80
Tensile strength	σ_{Ts} (MPa)	480
Poison ratio	$\mathcal{V}$ (-)	0.29
Density	ρ (g/cm^3)	7.85

2.2 Methods

First and foremost, the methods of the study have been determined and clear in advance to fully understand the purpose of the study and their relationship with the study goals. In the beginning, the geometry and material properties that have been used for this study analysis have been determined. Geometry has been set to three different types of geometry: minimum, medium, and maximum, as shown in Table 3 below.

Table 3: Details of All Geometry Types

Geometry	Outer Diameter (OD)	Inner Diameter (ID)	Wall Thickness (Wt)
Minimum	60.3mm	46.09mm	14.21mm
Medium	323.9mm	290.47mm	33.43mm
Maximum	609.6mm	590.47	19.13mm

Then, the material properties were determined for GRE and Carbon Steel pipes. For GRE pipes, the E-glass type has been used as fibre and epoxy as resin, which has been set. The ratio of the mixture is 70% for fibre and 30% for resin. For carbon steel, High Carbon Steel (AISI 106) has been used for this study as a carbon steel pipe material.

Furthermore, boundary conditions have been determined to determine the best and most suitable boundary conditions for each analysis conducted in this study. Furthermore, ANSYS Workbench has been used as an analysis tool to analyse the tensile strength, fatigue behaviour, and corrosion behaviour to achieve the main objective of this study. The analysis has been conducted by using the geometry, material properties, and boundary conditions that have been determined at the beginning of the study.

After the analysis has been done for all types of analysis of this study, the outcomes from the analysis will be discussed, and then a comparison between the GRE and Carbon Steel based on the results gained for each type of analysis and directly the second objective has been achieved by making a conclusion based on a discussion of the result and the overall outcomes from this study. Figure 1 below shows the flowchart to show a clear route for this study.

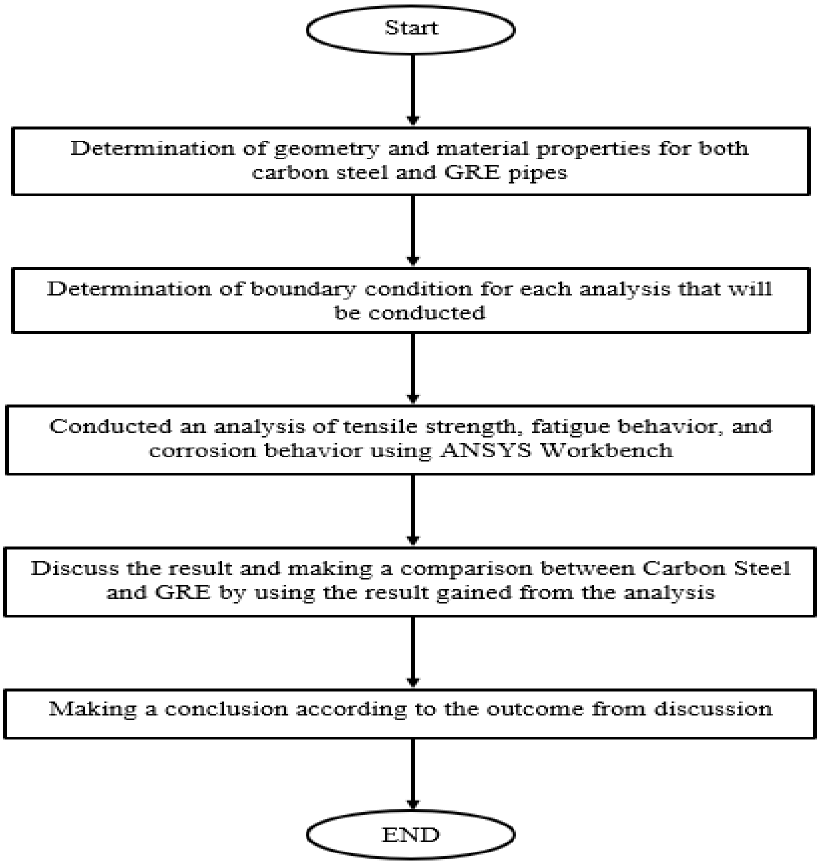

Figure 1: Flowchart of Study

3. Results and Discussion

The results gained from the tensile strength analysis, fatigue behaviour analysis, and corrosion behaviour analysis will be shown in this section. Then, the discussion will be based on the results gained to better understand this study's outcome.

3.1 Tensile Strength Analysis Result

Tensile strength analysis has been conducted to gain the total deformation, equivalent (von Mises) stress, equivalent elastic strain, and safety factor for both GRE and carbon steel pipe. It uses a static structural system, and the geometry has been applied, consisting of minimum, medium, and maximum geometry. The boundary condition has been set as a fix at point A, and at point B, force, which is about 300KN, has been applied, as shown in Figure 2.

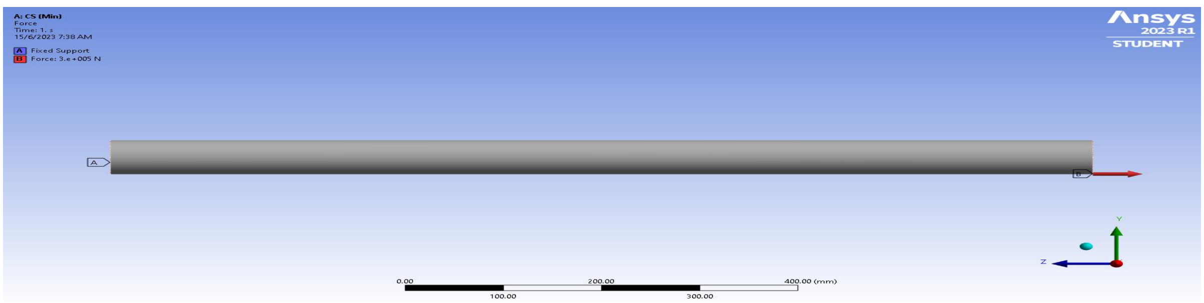

Figure 2: Boundary Conditions for Tensile Strength Analysis

The analysis has been conducted, and the result that has been gained shows for the minimum geometry, the total deformation of pipes for carbon steel pipe is 1.1884mm while GRE pipe is 4.8551mm. Then, the medium geometry shows that the total deformation of pipes for carbon steel is 0.0873mm and GRE is 0.3569mm. For the maximum geometry, it is shown that the result for the total deformation for carbon steel pipes is 0.0784mm while GRE pipes are 0.3200mm. Figure 3 below shows carbon steel and GRE's total deformation comparison graph for all geometry.

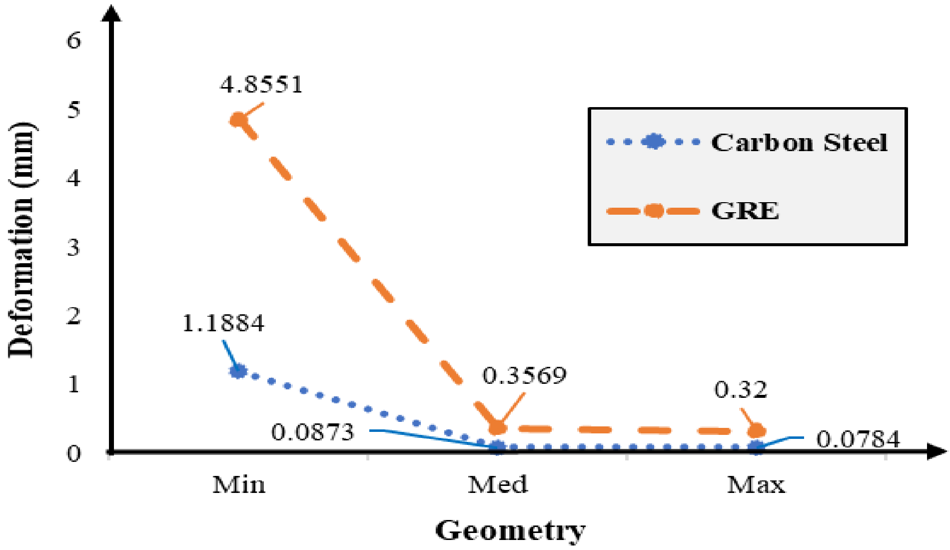

Figure 3: Total Deformation Comparison Graph of Both Carbon Steel and GRE for All Geometry

Next, the equivalent (von Mises) stress for all geometry shows that the stress on carbon steel pipe is slightly higher than on GRE pipes. For minimum geometry, it shows the value is 333.68MPa for carbon steel and 327.24MPa for GRE. Then, the equivalent von Mises stress of medium geometry shows that for carbon steel, it is 22.14MPa and 20.66MPa for GRE pipes. For maximum geometry, the equivalent von Mises stress for the carbon steel is 20.37MPa, and for GRE, it is 20.196MPa. Figure 4 shows the equivalent (von Mises) stress comparison graph of carbon steel and GRE for all geometry.

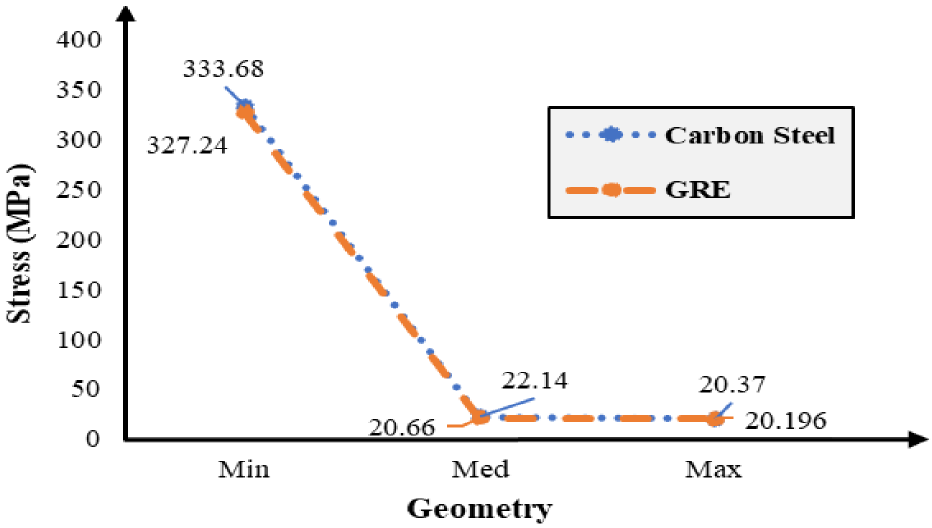

Figure 4: Equivalent (Von-Mises) Stress comparison Graph of Both Carbon Steel and GRE for All Geometry

Furthermore, the equivalent elastic strain of minimum geometry shown for carbon steel is 0.0016mm/mm, and for GRE, it is 0.0063mm/mm. Besides, the equivalent elastic strain of medium geometry for carbon steel is 0.00001mm/mm, and for GRE, it is 0.00043mm/mm. Finally, the equivalent elastic strain shows that carbon steel is 0.00001mm/mm and for GRE is 0.00039mm/mm for maximum geometry. Figure 5 below shows the equivalent elastic strain comparison graph of both carbon steel and GRE for all geometry, and Table 4 shows the full result of tensile strength analysis for all Geometry.

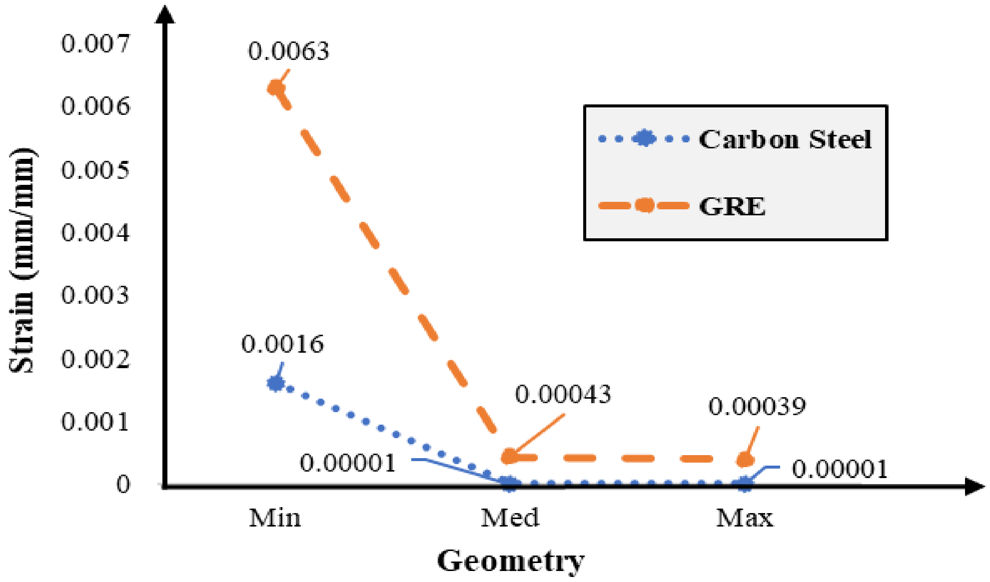

Figure 5: Equivalent Elastic Strain Comparison Graph of Both Carbon Steel and GRE for All Geometry

Table 4: Result of Tensile Strength Analysis for All Geometry

Result	**Minimum Geometry**		**Medium Geometry**		**Maximum Geometry**	
	Carbon Steel	**GRE**	**Carbon Steel**	**GRE**	**Carbon Steel**	**GRE**
Total Deformation (mm)	1.1884	4.8551	0.0873	0.3569	0.0784	0.3200
Equivalent (von-Mises) Stress (MPa)	333.68	327.24	22.14	20.66	20.37	20.196
Equivalent Elastic Strain (mm/mm)	0.0016	0.0063	0.00001	0.00043	0.00001	0.00039
Safety Factor	1.0975	0.9473	15	14.003	15	15

Table 4 shows that the GRE pipes are more elastic than carbon steel pipes due to their total deformation, whether for the minimum, medium or maximum geometry. For the minimum geometry, it shows the values are extremely different and higher for GRE compared to carbon steel. It shows that GRE pipes are unsuitable for application with 300KN on the minimum geometry for this tensile strength analysis due to their safety factor, as shown below: 1. Then, the result shows equivalent (von-mises) stress for carbon steel has slightly higher stress value compared to GRE which mean that GRE can hold the stress almost same with carbon steel even the deformation on GRE more than the carbon steel. Furthermore, we can see the equivalent elastic strain result shows that the value for GRE is higher than carbon steel due to the total deformation for GRE being more than carbon steel that happens during tensile analysis, as shown in the table of the result above. Finally, the extreme gap between minimum and medium geometry, the same as total deformation, might be caused by the same situation, which is the force applied to it is not suitable for minimum geometry. Finally, the tensile strength analysis results show that GRE can compete with carbon steel.

3.2 Fatigue Behavior Analysis Result

This analysis has been conducted for the fatigue behaviour analysis to gain the alternating stress, life cycle, and safety factors for both carbon steel and GRE pipes. It is also used as a static structural system, and the geometry has been applied the same as tensile strength analysis, which consists of minimum, medium, and maximum geometry. The boundary condition for the fatigue behaviour analysis has been set as a fix at point A, and a force has been applied about 300KN at point B, as shown in Figure 6 below.

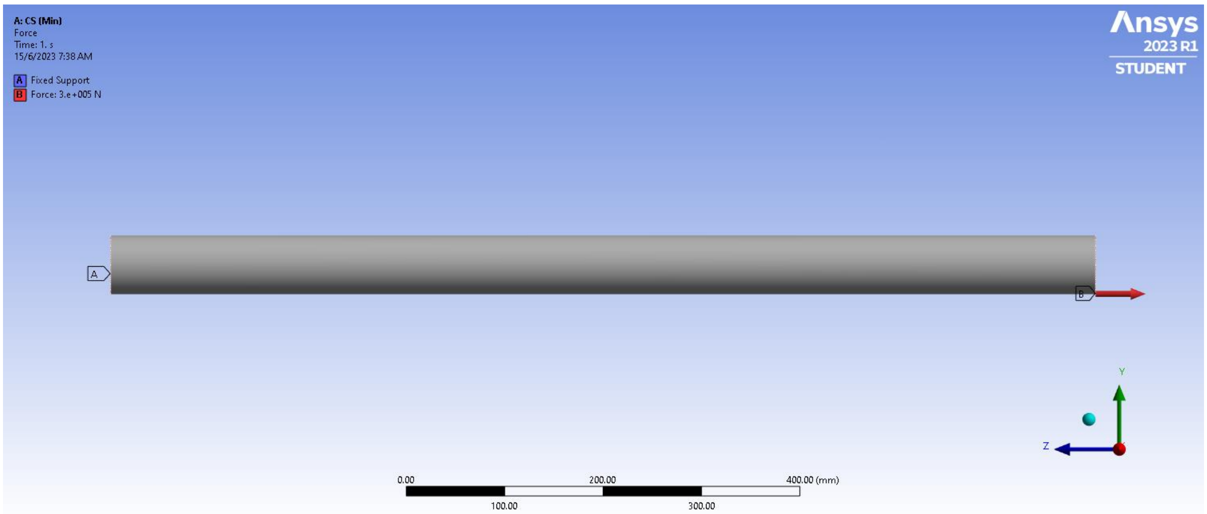

Figure 6: Boundary Condition for Fatigue Behaviour Analysis

The result that has gained from the fatigue behaviour analysis for minimum geometry shows that the stress for carbon steel is 333.68MPa while GRE shows 327.24MPa. It shows that both pipes have extremely high stress at specific area when 300KN force has been applied. Then, for the medium geometry, the result has gained that the carbon steel pipes stress is 22.14MPa while the GRE pipes is 20.66MPa at specific area. However, the maximum geometry result shows that the stress for both carbon steel pipes and GRE pipes is 20.37MPa and 20.20MPa respectively. Following figure 7 below shows the equivalent (von-mises) stress comparison graph of both carbon steel and GRE for all geometry.

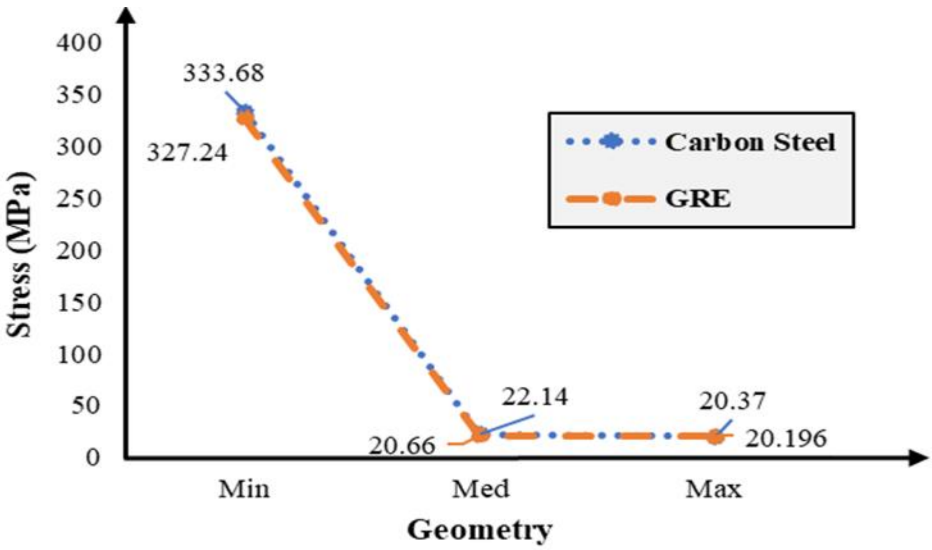

Figure 7: Equivalent (Von-Mises) Stress Comparison Graph of Both Carbon Steel and GRE for All Geometry

The life cycle for both pipes, carbon steel and GRE, shows 4724.1 cycles for carbon steel while GRE has is122.38 cycle to fail, which means both pipes are easily damaged or breaking due to both pipes with this minimum geometry unable to bear the force that has been applied on it and the area to be happen failure also bigger. Then, medium geometry shows that the carbon steel can achieve $1x10^{-6}$ cycles, which means it is safe and will not break when the 300KN force is applied, while GRE pipes can only withstand the force of around 805360 cycles before failure happens. However, for the maximum geometry result, the life of the pipes shows that both carbon steel and GRE pipes are strong because both pipes can withstand the force and can achieve max cycles, which is 1x10^6 cycles. There is no failure will happen on both carbon steel and GRE pipes for maximum geometry. Following below, Figure 8 shows the life cycle comparison graph of both carbon steel and GRE for all geometry, and Table 5 shows the total result of fatigue behaviour analysis for all geometry.

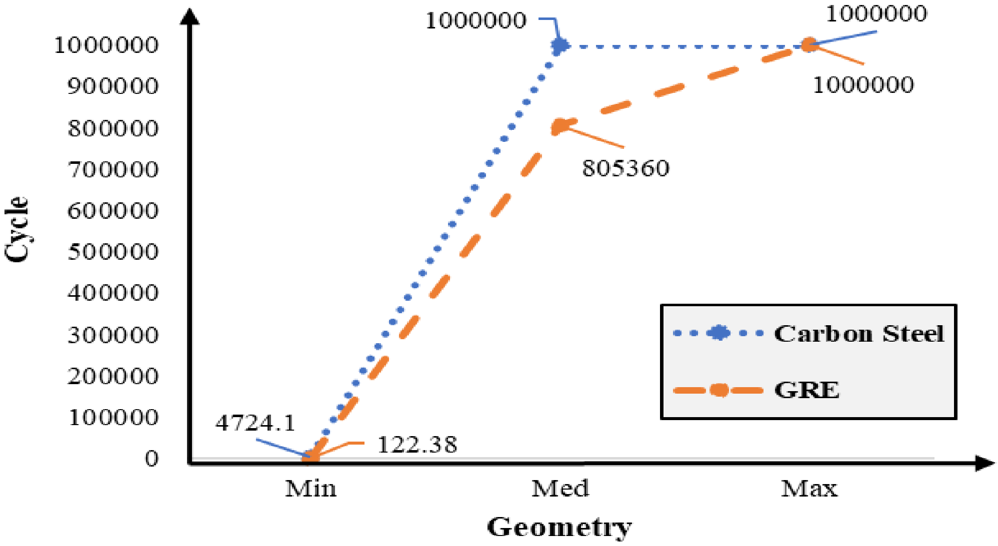

Figure 8: Life Cycle Comparison Graph of Both Carbon Steel and GRE for All Geometry

Table 5: Result of Fatigue Behaviour Analysis for All Geometry

Result	Minimum Geometry		Medium Geometry		Maximum Geometry	
	Carbon Steel	GRE	Carbon Steel	GRE	Carbon Steel	GRE
Stress (MPa)	333.68	327.24	22.14	20.66	20.37	20.20
Life (Cycle to failed)	4724.1	122.38	1000000	805360	1000000	1000000
Safety Factor	0.2552	0.0660	4.1224	0.9759	4.1818	1.0697

Based on the result gained from all types of geometry, Table 5 shows that the stress between GRE and carbon steel is just slightly different, and it shows stress on carbon steel is slightly higher than GRE. According to the life cycle, the carbon steel pipes are still more durable and strong due to their longer life cycles than the GRE pipes in fatigue analysis. However, it shows GRE can compete with carbon steel at minimum and maximum geometries, while the medium geometry shows carbon steel has an extreme gap compared to GRE, which means at medium geometry, carbon steel is a better material to apply as oil and gas pipe. Additionally, carbon steel can achieve maximum cycles for medium and maximum geometry while the GRE just can achieve maximum cycles on maximum geometry, which means the minimum and medium geometry of GRE is not strong enough to bear the 300KN force, which failure, damage, or breaking happen at a specific area on the pipes. Otherwise, the comparison of the result for fatigue behaviour analysis shows that both pipes have their own strength compared based on all geometry used for this analysis, which means at minimum and maximum geometry, GRE pipe can be selected due to their life cycle can compete with carbon steel while for medium geometry can be used carbon steel pipe.

3.3 Corrosion Behavior Analysis Result

Finally, the corrosion behaviour analysis was conducted to determine the corrosion rate for both carbon steel and GRE pipes. However, this analysis uses a different method compared with tensile strength analysis and fatigue behaviour analysis, which is it has been done by using a fluent system while the geometry that has been used for this analysis just minimum geometry due to geometry doesn't give any effect to the corrosion rate [7]. The boundary condition for the corrosion behaviour analysis has been set as the fluid flow inside the pipes. Oil has been set as a fluid that will flow inside the pipes in this analysis [8]. Figure 8 shows the boundary condition that has been set in Ansys for corrosion behaviour analysis.

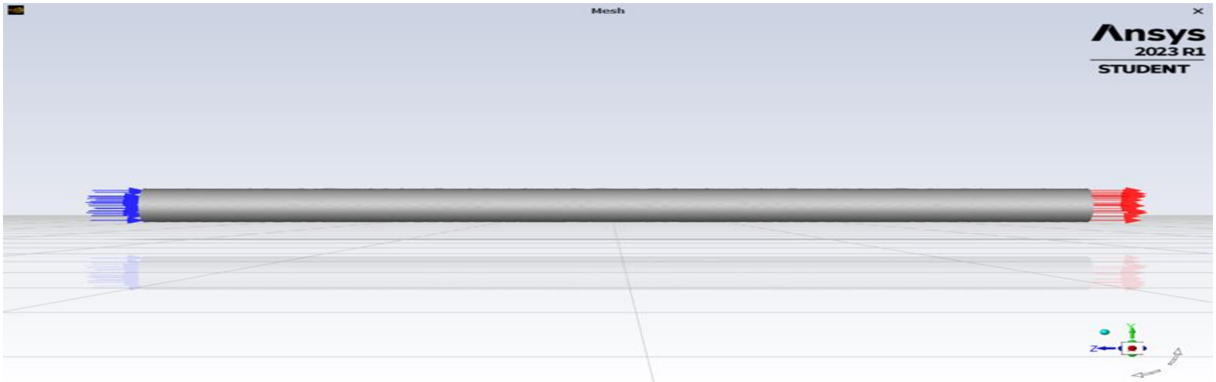

Figure 8: Boundary Condition for Corrosion Behaviour Analysis

The result shown for this analysis is the corrosion rate of both carbon steel and GRE with minimum geometry for both pipes. This geometry will represent the other geometry of this study because it will also give the same result for the corrosion rate for both materials. In this case, the sand has been added as erosion particles to help calculate the corrosion rate during this analysis. This is because erosion during the flow in the pipes can easily cause corrosion.

The GRE shows that there is no corrosion on the pipes for this analysis. However, the carbon steel pipes show the opposite result, and corrosion behaviour occurs on the pipes in this analysis. The result for carbon steel shows the corrosion occurs at the random area, and the value at the critical area shows that the corrosion rate I 12 cap to the, minus 25 end superscript, kg over the superscript base, i $12E^{-25}\ kg/.m^2$. Table 5 below shows the generated result of corrosion rate that occurs for both GRE and carbon steel pipes.

Table 5: Result of Corrosion Behaviour Analysis

Result	GRE	Carbon Steel
Corrosion rate (kg/m^2)	0	$1.62E^{-25}$

Based on the result of the corrosion behaviour analysis, it can be summarised that GRE has an advantage over carbon steel in terms of corrosion resistance. Additionally, there are many sources that say GRE is better than carbon steel for sustaining corrosive surroundings and doesn’t have a corrosion rate because GRE is one of the polymer matrix composites (PMC) materials that do not corrode. Finally, this analysis has proved that GRE is better than Carbon Steel in corrosive conditions.

4. Conclusion

In conclusion, it can be concluded that both objectives of this study were accomplished because all analyses have been done, and the result gained has been discussed by comparing GRE and carbon steel pipe. The main objective is to determine the tensile strength, fatigue behaviour and corrosion behaviour of GRE and carbon steel pipes by doing an analysis. The second objective is to analyse by making a comparison using the result gained between GRE and carbon steel. The tensile strength and fatigue behaviour analysis result shows that carbon steel has a better value compared to GRE. However, it shows that GRE can also hold the stress almost the same as carbon steel while carrying the load. Furthermore, it also shows that the GRE has a better elasticity form due to the total deformation that GRE pipes have achieved during tensile strength analysis, more than carbon steel's total deformation with stress, which is almost the same as carbon steel's. For example, the difference between GRE and carbon steel deformation is about 6.0396 mm, with GRE deformation being 8.0918 mm, while carbon steel is just 2.0522 mm for minimum geometry. Then, the corrosion behaviour result showed that the GRE won over the carbon steel due to no corrosion rate on GRE compared with carbon steel. So, it can be concluded that GRE is better in corrosion resistance material than carbon steel. Finally, the comparison of the results shows that carbon steel is slightly better in terms of strength compared to GRE, while GRE is the best material for corrosion resistance compared to carbon steel. However, the result shows that GRE can be an alternative to carbon steel. It is valid, especially in terms of corrosion resistance to be used in the oil and gas industry, because it can be sustained better than carbon steel to face corrosive surroundings.

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