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# A Comparative Analysis on the Optimization of Carbon Fibre Reinforced Polymer and Glass Fiber Reinforced Polymers as Wrapping Structures on Defected Piping System using Computational Simulation Approach

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**ABSTRACT**

This study examined the application of carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP) as wrapping structures for defective pipe systems. The structural behavior and performance of the CFRP and GFRP wrapping structures were assessed using computational simulation methodologies. The goal of the study was to determine the best wrapping material for strengthening the integrity and reliability of piping systems with defects by comparing the results of the simulations. The study evaluated the capability of the proposed composite wrapping structure through CAD simulation. The simulations provided preliminary analysis and visually depicted deformations, aiding in the selection of an optimized lamination orientation for the composite wrapping structure in real-world applications. Eventually, this approach could have alleviated two primary failure modes that were common in composite repair: composite overloading due to excessive thickness and composite delamination from the substrate. The results of this study would have helped enhance effective and efficient pipe repair techniques in a variety of industries by offering useful insights into the selection and use of suitable wrapping structures for repairing defective pipes.

## 1. Introduction

In today's modern working culture, sustainable technologies that prioritize competitive production rely on robust infrastructure systems consisting of software, communications, machines, instruments, tools, and structures. Critical Infrastructure (CI), particularly the strategic infrastructures (SIs), play a crucial role in supporting these systems [1]. Among the essential components of CI, pipeline systems are widely utilized for the transportation of various substances, such as oil, gas, water, and more. Ensuring the safety, reliability, and continuous flow of products in these pipeline systems is of utmost importance. One method to address pipeline failures is by pipe insulation, which enhances hydraulic efficiency and stability across diverse applications, including oil and gas pipelines, water pipes, and manufacturing tanks [1].

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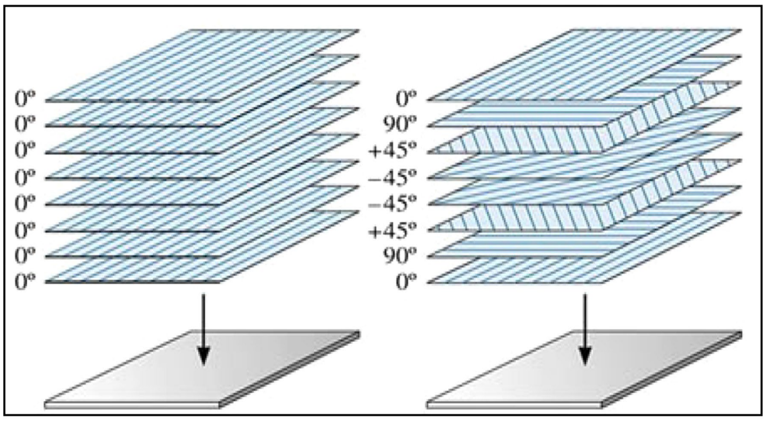
The focus of this research is to assess the structural behavior and performance of the CFRP and GFRP wrapping structures using computational simulation methodologies. Besides the goal of the study is to determine the best wrapping material for strengthening the integrity and reliability of piping systems with defects by comparing the results of the simulations. Composite materials, such as Carbon Fiber Reinforced Polymer (CFRP) and Glass Fibre Reinforced Polymer (GFRP), have gained prominence in the oil and gas sector due to their unique properties, including low density, corrosion resistance, and superior mechanical characteristics [2,3]. By employing composite wrapping, the need for costly and time-consuming pipe replacements, caused by defects like gouges, pits, and splits, can be mitigated [4,5].

While various wrapping methods exist, this research aims to address the orientation of layers and wrapping materials through simulation, providing valuable insights for consumers to choose the appropriate material and orientation based on specific conditions. By employing SOLIDWORKS simulation, the study also advances layer optimization for composites with different angle of laminations referring to Figure 1 [25]. Previous studies have primarily focused on different wrapping materials, with limited research conducted on various laminations [6,7].




(a) (b)

**Fig. 1.** (a) Unidirectional quasi-isotropic (b) cross-piled quasi-isotropic lamination [8]

Given the critical nature of pipeline systems and their role in the transportation of flammable and inflammable liquids over vast distances, safety is paramount. However, the long-term sustainability of pipelines poses challenges, with defects classified into multiple categories based on the nature of causes, technological processes, location, and configuration [9]. Wrapping, or lamination, serves as a temporary and long-term solution to address these complications.

The goal of this research is to provide a comprehensive analysis of CFRP and GFRP as a wrapping material for pipe structures, determining the optimized lamination thickness and sustainable effects to maintain strength. By characterizing composites and exploring their potential as a solution for pipeline defects, this study aims to offer a breakthrough in selecting the appropriate wrapping material and optimized lamination orientation. Overall, this journal focuses on the simulation and optimization of carbon fiber reinforced polymer wrapping for pipeline systems, contributing to the development of sustainable technologies, and enhancing the performance of critical infrastructure in modern competitive production environments.

## 2. Methodology

The methodology for this research project consists of several key steps. Firstly, a thorough literature review is conducted to gather relevant information and establish a strong foundation for the study. This includes reviewing previous studies on repairing defected pipes using CFRP and GFRP wrappers and referring to standards such as ASME-PCC-2-2018 and LANL Engineering Standard Manual for parameter references. Design parameters for the defected pipe, including test pressure, wall thickness, yield strength, and temperature limits, are determined based on these references.

The research is divided into two parts, each aligned with a specific objective. In the first part, the focus is on designing the wrapper for the defected pipe. This involves assembling the pipe with a defect, the composite wrapper with different lamination orientations, and the repaired pipe with the wrapping material. The design takes into account the specifications of the chosen pipe, such as its outside diameter, wall thickness, NPS, and ID, as well as the specific defect geometry, assuming a crack-type defect. Table 1 and Table 2 are the parameters that has been set for the pipe structure and design parameters.

**Table 1**
Parameter Set up for Pipe Specification

| Parameters | Specimen Specifications | Parameter References |
|---|---|---|
| Type of pipeline | Crude oil pipeline, operating | NA |
| Outer Diameter (mm) | 168.3 | Minimum 150mm (ASME B36.10M) |
| Wall thickness (mm) | 7.11 | ASME B36.10M |
| Nominal Pipe Size (mm) | 150 | NPS range in between 1/8” – 12” (ASME B36.10M) |
| Pipe Schedule | 40 | (ASME B36.10M) |
| Internal Diameter (mm) | 161.19 | [7] |
| Length (mm) | 1200 | [7] |
| Seamless Pipe Minimum Yield Strength (MPa) | 245 | Table A-1 ASME B31.3 |
| Seamless Pipe Tensile Strength (MPa) | 415 | Table A-1 ASME B31.3 |
| Material grade | API 5L Grade B Carbon Steel Seamless | LANL Engineering Standard Manual |
| Fluid Service | Normal | LANL Engineering Standard Manual |
| Fluid Velocity | 2 to 10 m/s | NA |
| Pressure Rating | Class 150 | ASME B36.10M |
| External Pressure Rating (MPa) | 0.103421 | ASME B36.10M |
| Corrosion Allowance (For 6-inch pipe) | 0.063 | 0.00, 0.031, 0.063, 0.125 (ASME B36.10M) |
| Type of pipe thickness | Thin wall structure (23.67) | If ratio of pipe diameter to thickness is greater than 20 (D/t > 20) thin wall structure is considered [10]. |

**Table 2**
Design Parameters [11]

| Piping Specification | | Corrosion Allowance (0.000, 0.031, 0.063, 0.125) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Metric System | Design Pressure (MPa) | 1.97 | 1.79 | 1.59 | 1.38 | 1.17 | 0.97 | 0.86 |
| | Design Temperature (°C) | 37.78 | 93.33 | 148.89 | 204.44 | 260.0 | 315.56 | 343.33 |
| | Minimum Temperature (°C) | -6.67 | -6.67 | -6.67 | -6.67 | -6.67 | -6.67 | -6.67 |
| | Minimum Test Pressure (MPa) | 2.96 | 2.69 | 2.38 | 2.07 | 1.86 | 1.69 | 1.52 |
| | Maximum Test Pressure (MPa) | | | | 5.65 | | | |

Next, material properties are established for the pipe, sealer, and CFRP wrapper. The pipe and sealer are considered isotropic materials, while the composite wrapper is treated as an orthotropic material due to its layered structure. These material properties are then declared in SOLIDWORKS, the simulation software used for analysis [23].

In the second part of the research, the performance of the composite wrapper is evaluated through static analysis. Static analysis is conducted to assess the wrapper's ability to withstand various internal pressures by analyzing stress, strain, factor of safety (FOS), and displacement. Referring to Figure 2 the geometry and connection fixtures, including fixed geometry at the holes where bolts connect the pipe, are defined. Contact settings between the CFRP wrapper, sealer, and defected pipe at the defected region are also established. The internal pressure is applied throughout the pipe, and the analysis parameters specified in the provided tables are used.

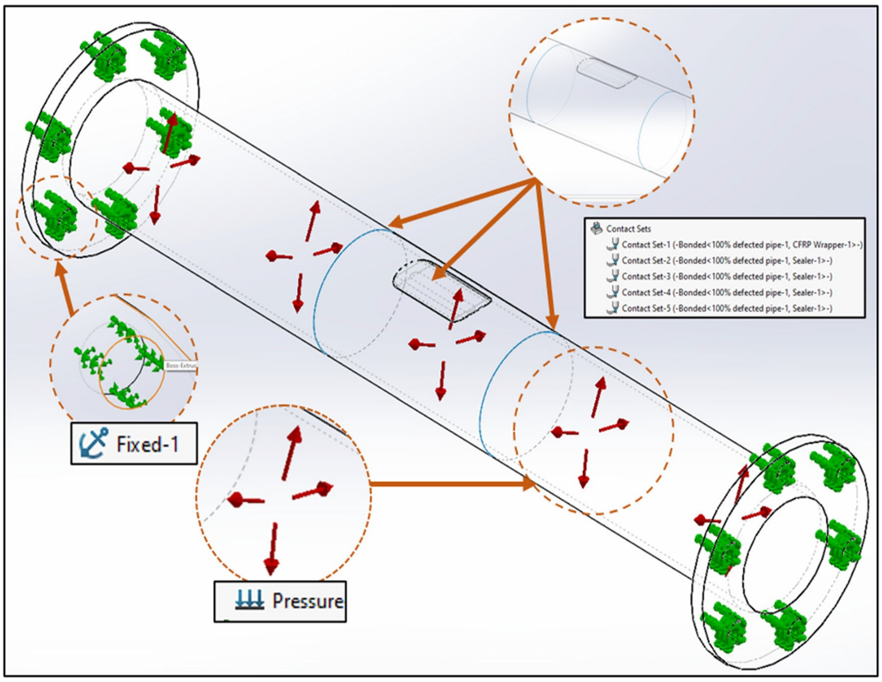



**Fig. 2.** The assembled components were then defined with fixed geometry, contact set and internal pressure for static analysis

A finite element model is developed by meshing the geometries of the individual parts (pipe, sealer, and composite) and assigning material properties to each part. The assembled structure is then analyzed as an integrated entity. Meshing is performed using suitable mesh sizes, including a control mesh for critical geometries [12]. The static analysis is run with the defined boundary conditions and loading, and the results are analyzed, including stress, strain, displacement, deformed shape, and FOS as can be referred from Figure 3.

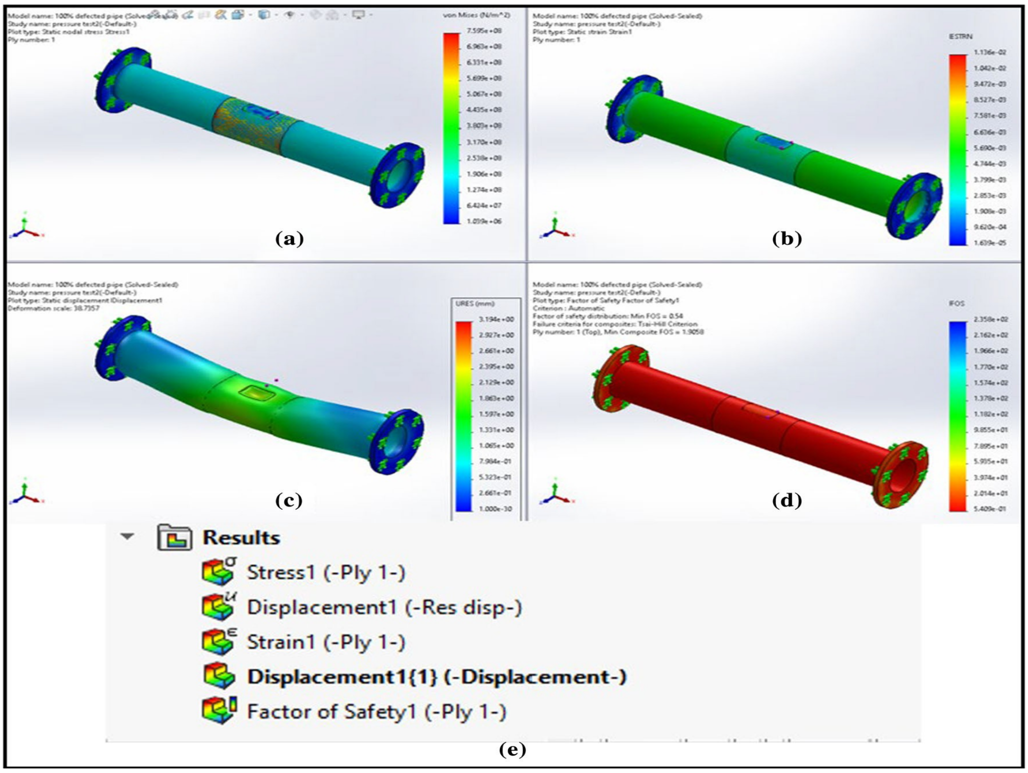



**Fig. 3.** (a) The sample stress results (b) the sample strain results (c) the sample displacement results (d) the sample factor of safety results (e) the list of results that could be achieved by static analysis

Throughout the research process, proper documentation and reporting of the results are maintained. The methodology described aims to achieve the two objectives of designing the wrapper for the defected pipe and evaluating its performance through simulation, ultimately contributing to the understanding and improvement of the repair process for defected pipes using composite wrappers [13]. The study involves analyzing a dataset comprising average minimum factors of safety for CFRP and GFRP repaired pipes. The dataset encompasses various wrapper orientations, such as $(0°)_2$, $(0°)_4$, $(0°)_6$, $(0°)_8$, $(45°/-45°/45°)_s$, $(45°/0°/45°)_s$, $(90°/-90°/90°)_s$, $(90°/0°/90°)_s$, $(45°/-45°/0°/45°)_s$, $(45°/90°/0°/45°)_s$, $(0°/90°/45°/-45°)_s$, and $(0°/-45°/90°/45°)_s$.

## 3. Results

As was already indicated, the static analysis is crucial in determining the proper wrapping structure for the entire pipe structure when there is constant pressure loading. Table 3 shows the maximum Stress on CFRP wrapped defected pipe while the Table 4 shows the Maximum Stress on GFRP Wrapped Pipe.

**Table 3**
Maximum Stress on CFRP Wrapped Defected Pipe

| CFRP Wrapper Orientations | Maximum Stress on Repaired Pipe (MPa) | | | | | Average Maximum Stress on CFRP Wrapped Pipe (0.86 – 19.65) |
|---|---|---|---|---|---|---|
| | Minimum thickness of 1 layer | 0.02mm | 0.05mm | 0.13mm | 0.47mm | |
| | Ply | Pressure (MPa) | | | | |
| | | Min. Design 0.86 | Max. Design 1.97 | Max. Test (exp) 5.65 | Max. Test (Theory) 19.65 | |
| $(0^{\circ})_2$ | 2 | 25.70 | 55.66 | 280.3 | 786.2 | 286.965 |
| $(0^{\circ})_4$ | 4 | 24.17 | 51.98 | 259.3 | 652.9 | 247.0875 |
| $(0^{\circ})_6$ | 6 | 23.74 | 51.46 | 242.4 | 572.0 | 222.4 |
| $(0^{\circ})_8$ | 8 | 23.84 | 50.98 | 225.8 | 521.1 | 205.43 |
| $(45°/-45°/45°)_s$ | 6 | 25.01 | 55.70 | 140.1 | 427.0 | 161.9525 |
| $(45°/0°/45°)_s$ | 6 | 24.85 | 54.39 | 137.6 | 399.1 | 153.985 |
| $(90°/-90°/90°)_s$ | 6 | 45.33 | 51.46 | 141.8 | 434.7 | 168.3225 |
| $(90°/0°/90°)_s$ | 6 | 46.26 | 62.65 | 155.8 | 377.6 | 160.5775 |
| $(45°/-45°/0°/45°)_s$ | 8 | 25.49 | 54.16 | 132.0 | 404.2 | 153.9625 |
| $(45°/90°/0°/45°)_s$ | 8 | 27.01 | 54.15 | 131.6 | 387.6 | 150.09 |
| $(0°/90°/45°/-45°)_s$ | 8 | 27.36 | 102.1 | 259.6 | 695.4 | 271.115 |
| $(0°/-45°/90°/45°)_s$ | 8 | 27.49 | 102.1 | 259.4 | 618.5 | 251.8725 |

**Table 4**
Maximum Stress on GFRP Wrapped Defected Pipe

| CFRP Wrapper Orientations | Maximum Stress on GFRP Wrapped Repaired Pipe (MPa) | | | | | Average Maximum Stress on GFRP Wrapped Pipe (0.86 – 19.65) |
|---|---|---|---|---|---|---|
| | Minimum thickness of 1 layer | 0.02mm | 0.05mm | 0.13mm | 0.47mm | |
| | Ply | Pressure (MPa) | | | | |
| | | Min. Design 0.86 | Max. Design 1.97 | Max. Test (exp) 5.65 | Max. Test (Theory) 19.65 | |
| $(0^{\circ})_2$ | 2 | 23.18 | 52.82 | 149.5 | 506.7 | 183.05 |
| $(0^{\circ})_4$ | 4 | 23.16 | 52.37 | 146.3 | 486.6 | 177.1075 |
| $(0^{\circ})_6$ | 6 | 51.94 | 51.94 | 142.7 | 468.7 | 178.82 |
| $(0^{\circ})_8$ | 8 | 23.06 | 51.52 | 139.2 | 450.5 | 166.07 |
| $(45°/-45°/45°)_s$ | 6 | 23.11 | 52.41 | 146.4 | 456.0 | 169.48 |
| $(45°/0°/45°)_s$ | 6 | 23.11 | 52.20 | 144.8 | 459.4 | 169.8775 |
| $(90°/-90°/90°)_s$ | 6 | 23.02 | 52.44 | 146.8 | 414.1 | 159.09 |
| $(90°/0°/90°)_s$ | 6 | 23.04 | 5.221 | 145.0 | 424.0 | 149.3153 |
| $(45°/-45°/0°/45°)_s$ | 8 | 23.06 | 51.93 | 142.6 | 433.60 | 162.7975 |
| $(45°/90°/0°/45°)_s$ | 8 | 23.03 | 51.91 | 142.6 | 415.5 | 158.26 |
| $(0°/90°/45°/-45°)_s$ | 8 | 23.02 | 51.93 | 142.6 | 419.8 | 159.3375 |
| $(0°/-45°/90°/45°)_s$ | 8 | 23.02 | 51.93 | 142.5 | 421.4 | 159.7125 |

The simulation was done for every orientation considering the number of layers and thickness. This is done to study on the effectiveness of the lamination orientation alterations that sustain or control the maximum stress after the pipe repair has been done [14]. For the maximum stress, the orientation that could sustain maximum stress value before and after the pipe repair are considered the effective wrapping structure [15,16]. However, these findings may vary according to the operating pressure that are used. Not all applications utilize the theoretical maximum test pressure of 19.65 MPa [20]. Therefore, it is important to identify a wrapping structure and a wrapping material that could sustain the maximum stress after the repair on an average basis that covers from 0.86MPa till 19.65MPa. Table 5 shows the comparison in between the average maximum stress of CFRP and GFRP repaired pipe structure and Figure 4 is the graph comparison that is tabulated based on Table 3 and 4 to find the comparison in between CFRP and GFRP as wrapping structure.

**Table 5**
Average Maximum Stress of CFRP And GFRP Repaired Pipe

| Wrapper Orientations | Number of layers | Average Maximum Stress (0.86 MPa – 19.65MPa) | |
|---|---|---|---|
| | | CFRP | GFRP |
| $(0^{\circ})_2$ | 2 | 286.965 | 183.05 |
| $(0^{\circ})_4$ | 4 | 247.0875 | 177.1075 |
| $(0^{\circ})_6$ | 6 | 222.4 | 178.82 |
| $(0^{\circ})_8$ | 8 | 205.43 | 166.07 |
| $(45°/-45°/45°)_s$ | 6 | 161.9525 | 169.48 |
| $(45°/0°/45°)_s$ | 6 | 153.985 | 169.8775 |
| $(90°/-90°/90°)_s$ | 6 | 168.3225 | 159.09 |
| $(90°/0°/90°)_s$ | 6 | 160.5775 | 149.3153 |
| $(45°/-45°/0°/45°)_s$ | 8 | 153.9625 | 162.7975 |
| $(45°/90°/0°/45°)_s$ | 8 | 150.09 | 158.26 |
| $(0°/90°/45°/-45°)_s$ | 8 | 271.115 | 159.3375 |
| $(0°/-45°/90°/45°)_s$ | 8 | 251.8725 | 159.7125 |

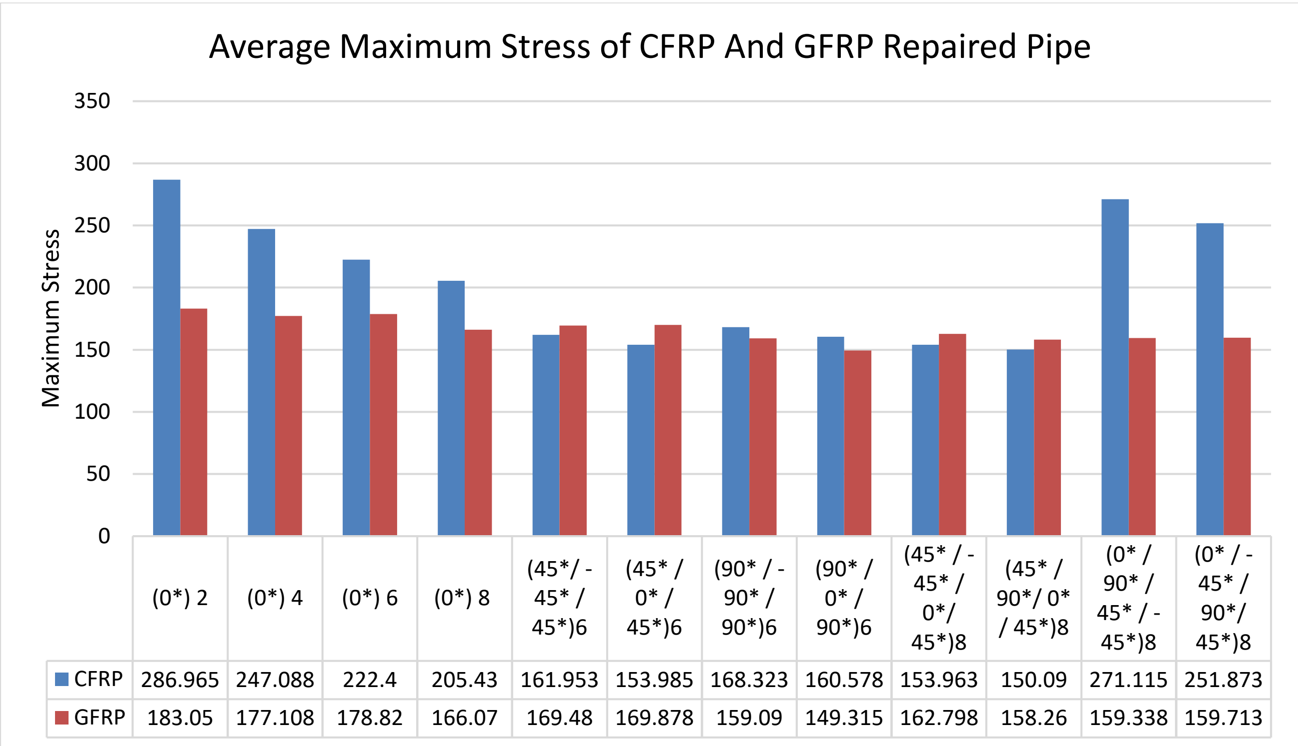



**Fig. 4.** Graph of comparison to compare average maximum stress in between CFRP and GFRP

Looking at the values, CFRP exhibits a range of average maximum stress from 150.09 MPa to 286.965 MPa, with an overall average of approximately 201.74 MPa. On the other hand, GFRP demonstrates a range from 149.3153 MPa to 183.05 MPa, with an overall average of approximately 164.17 MPa. When comparing the two materials, CFRP generally demonstrates higher strength or resistance to maximum stress based on the provided data [23]. CFRP's range of average maximum stress values is greater than that of GFRP, and its overall average maximum stress is slightly higher as well [17]. However, it's essential to consider that this analysis solely relies on the provided data and does not take into account other crucial factors such as manufacturing processes, other geometrical composite design, or specific requirements and standards [22,24]. Additionally, the data lacks information about sample size and statistical significance, which could affect the reliability of the analysis. Table 6 was tabulated to compare the average minimum factor of safety in between CFRP and GFRP repaired pipe structure and Figure 5 is the graph comparison that is tabulated based on Table 6 to compare the average minimum factor of safety between CFRP and GFRP repaired pipe.

**Table 6**
Table of average minimum factor of safety of CFRP and GFRP repaired pipe

| Wrapper Orientations | Number of layers | Average Minimum Factor of Safety (0.86 MPa – 19.65MPa) | |
|---|---|---|---|
| | | CFRP | GFRP |
| $(0^{\circ})_2$ | 2 | 4.3699 | 4.328275 |
| $(0^{\circ})_4$ | 4 | 4.440325 | 4.2636 |
| $(0^{\circ})_6$ | 6 | 4.490225 | 4.285725 |
| $(0^{\circ})_8$ | 8 | 4.533725 | 4.30575 |
| $(45°/-45°/45°)_s$ | 6 | 4.4407 | 4.371325 |
| $(45°/0°/45°)_s$ | 6 | 4.4732 | 4.379825 |
| $(90°/-90°/90°)_s$ | 6 | 4.46315 | 4.3189 |
| $(90°/0°/90°)_s$ | 6 | 4.51645 | 4.3337 |
| $(45°/-45°/0°/45°)_s$ | 8 | 4.519525 | 4.268275 |
| $(45°/90°/0°/45°)_s$ | 8 | 4.542275 | 4.416925 |
| $(0°/90°/45°/-45°)_s$ | 8 | 4.545775 | 4.32245 |
| $(0°/-45°/90°/45°)_s$ | 8 | 4.54635 | 4.328425 |

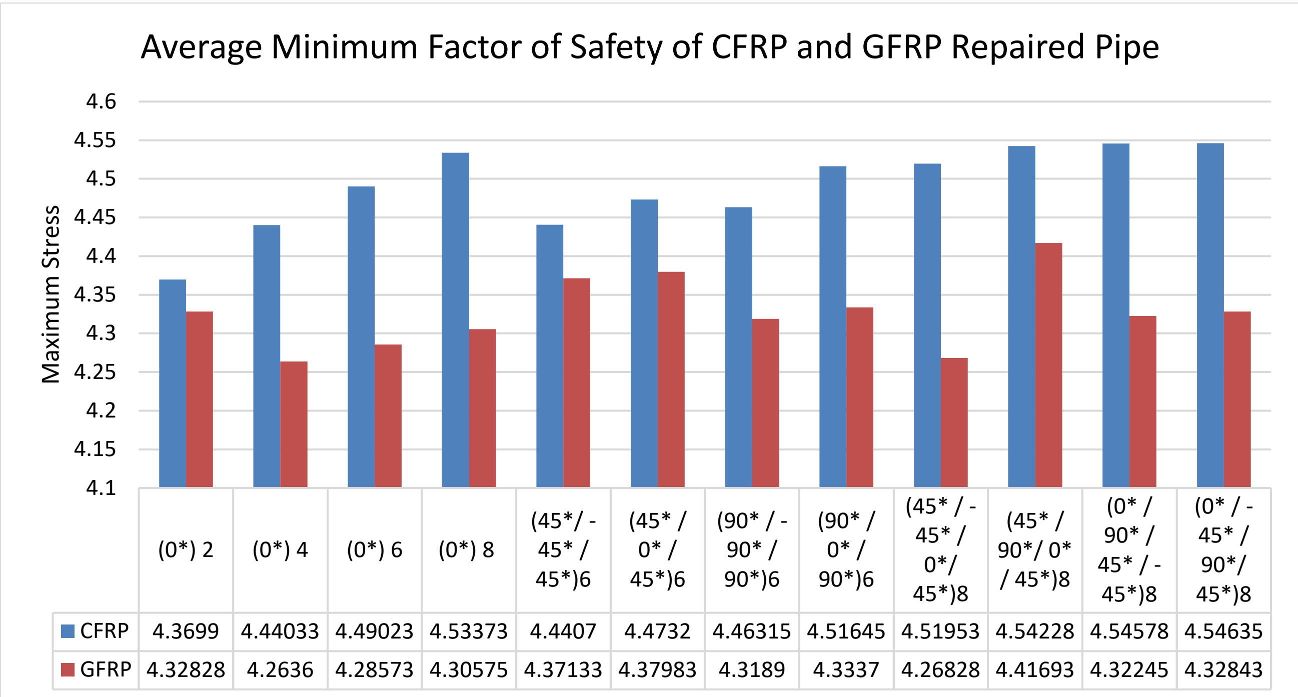



**Fig. 5.** Graph of comparison to compare average minimum factor of safety between CFRP and GFRP repaired pipe

By examining the data, we can draw the following analysis and make a suggestion for the wrapping structure. For CFRP the average minimum factor of safety ranges from 4.3699 to 4.54635 for various wrapper orientations and the number of layers. For GFRP the average minimum factor of safety ranges from 4.2636 to 4.416925 for different wrapper orientations and layer combinations. Comparing both CFRP and GFRP in general, both CFRP and GFRP exhibit relatively high average minimum factors of safety, indicating a good level of safety in the repaired pipes [21,26]. The specific wrapper orientation and number of layers influence the minimum factor of safety for each material. Based on the provided data, CFRP tends to have slightly higher average minimum factors of safety compared to GFRP for most wrapper orientations and layer combinations [18,19]. From the given data, the wrapper orientation of (45°/90°/0°/45°)s with 8 layers appears to provide relatively high average minimum factors of safety for both CFRP (4.542275) and GFRP (4.416925). Therefore, considering the provided information, this wrapping structure may be a suitable option for repairing a defected pipe.

Based on the previous analysis, CFRP (Carbon Fiber Reinforced Polymer) exhibits a slightly higher average minimum factor of safety compared to GFRP (Glass Fiber Reinforced Polymer) for most wrapper orientations and number of layers. Therefore, based on the provided data, CFRP can be considered as the preferred material for repairing a defected pipe. However, it's important to note that this conclusion is based solely on the provided data, and other factors such as cost, availability, specific application requirements, and expert consultation should also be taken into consideration when making the final decision.

## 4. Conclusions

In conclusion, the analysis of maximum stress on the pipe provides important insights into the performance of different materials. Based on the simulated data, Carbon Fiber Reinforced Polymer (CFRP) exhibits a higher range of average maximum stress values (150.09 MPa to 286.965 MPa) compared to Glass Fiber Reinforced Polymer (GFRP), which has a relatively lower range (149.3153 MPa to 183.05 MPa). Moreover, the overall average maximum stress for CFRP is approximately 201.74 MPa, whereas GFRP has an average of approximately 164.17 MPa. These findings suggest that CFRP has a greater capacity to withstand higher stress levels compared to GFRP. Therefore, if the primary concern is the maximum stress endured by the pipe, CFRP may be a more suitable choice due to its ability to provide a higher level of strength and resistance. Besides, the average Minimum Factor of Safety for both CFRP and GFRP exhibit relatively high average minimum factors of safety, indicating a good level of safety in the repaired pipes. Specifically based on the simulated data, CFRP tends to have slightly higher average minimum factors of safety compared to GFRP for most wrapper orientations and layer combinations. This suggests that CFRP may provide better resistance to failure and increased safety margins in repairing defected pipes. Considering the wrapper orientation and number of layers, the specific combination of wrapper orientations and the number of layers significantly influences the minimum factor of safety for both CFRP and GFRP. The data reveals variations in the minimum factor of safety across different orientations and layer combinations. From the given data, the wrapper orientation of (45°/90°/0°/45°)s with 8 layers appears to provide relatively high average minimum factors of safety for both CFRP and GFRP. Therefore, this wrapping structure is recommended as a suitable option for repairing a defected pipe. However, it's essential to consider that the conclusions drawn from this analysis are based solely on the simulated data. Other factors, such as cost, availability, specific application requirements, and expert consultation, should be taken into account before making a final decision on the wrapping structure. To make more accurate and informed choices, it is recommended to gather additional data, conduct further analyses, and consider all relevant factors that could impact the performance and suitability of the wrapping structure for the specific pipe repair application.

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## References
[1] Timashev, Sviatoslav, and Anna Bushinskaya. *Diagnostics and reliability of pipeline systems*. Vol. 30. New York: Springer, 2016. https://doi.org/10.1007/978-3-319-25307-7
[2] Letchumanan, Shaktivell M., Ahmad Mubarak Tajul Arifin, Ishkrizat Taib, Mohammad Zulafif Rahim, and Nor Adrian Nor Salim. "Simulating the optimization of carbon fiber reinforced polymer as a wrapping structure on piping system using SolidWorks." *Journal of Failure Analysis and Prevention* 21 (2021): 2038-2063.
[3] Timashev, Sviatoslav, and Anna Bushinskaya. *Methods of Assessing Integrity of Pipeline Systems with Different Types of Defects.* Diagnostics and Reliability of Pipeline Systems. Topics in Safety, Risk, Reliability and Quality, Vol 30, pp (2016): 9-43. https://doi.org/10.1007/978-3-319-25307-7_2
[4] Letchumanan, S. M., A. M. T. Arifin, A. E. Ismail, and I. Taib. "A Review on Carbon Fiber Reinforced Polymer as Wrapping Structures For Pipeline." *International Journal of Integrated Engineering* 15, no. 1 (2023): 45-57.
[5] Saeed, Nariman, Hamid Ronagh, and Amandeep Virk. "Composite repair of pipelines, considering the effect of live pressure-analytical and numerical models with respect to ISO/TS 24817 and ASME PCC-2." *Composites Part B: Engineering* 58 (2014): 605-610.
[6] Lim, Kar Sing, Siti Nur Afifah Azraai, Nordin Yahaya, Norhazilan Md Noor, Libriati Zardasti, and Jang-Ho Jay Kim. "Behaviour of steel pipelines with composite repairs analysed using experimental and numerical approaches." *Thin-Walled Structures* 139 (2019): 321-333. https://doi.org/10.1016/j.tws.2019.03.023
[7] Lim Kar Sing (2017). Behaviour Of Repaired Composite Steel Pipeline Using Epoxy Grout As Infill Material. Ph. D Thesis, Universiti Teknologi Malaysia.
[8] Hadj Meliani, M., O. Bouledroua, Z. Azari, A. Sorour, N. Merah, and G. Pluvinage. "The inspections, standards and repairing methods for pipeline with composite: a review and case study." In *Proceedings of the 17th International Conference on New Trends in Fatigue and Fracture 17*, pp. 147-156. Springer International Publishing, 2018. https://doi.org/10.1007/978-3-319-70365-7
[9] Kara, Memduh, Mesut Uyaner, and Ahmet Avci. "Repairing impact damaged fiber reinforced composite pipes by external wrapping with composite patches." *Composite Structures* 123 (2015): 1-8. https://doi.org/10.1016/j.compstruct.2014.12.017
[10] Antaki, G. A. *Piping and Pipeline Engineering: Design, Construction Maintenance, Integrity, and Repair.* Marcel Dekker, Inc., New York, U.S.A. (2003).
[11] Los Alamos National Laboratory. *LANL Engineering Standards Manual PD342,* New Mexico, United States: Los Alamos National Laboratory. (2009).
[12] Solidworks. *Contact Analysis.* (2020).
[13] Duell, J.M. *Characterization and FEA of A Carbon Composite Overwrap Repair System.* Master of Science, The University of Tulsa, Oklahoma. (2004).
[14] Koruche, Uttam S., and Subhas F. Patil. "Application of classical lamination theory and analytical modeling of laminates." *International Research Journal of Engineering and Technology* 2, no. 02 (2015): 958.
[15] Letchumanan, Shaktivell M., Ahmad Mubarak Tajul Arifin, Ishkrizat Taib, and Nor Adrian Nor Salim. "Computational Fluid Dynamic Analysis on Carbon Fibre Reinforced Polymer Wrapped on Defected Oil and Gas Piping System Using Solidwork Flow Simulation." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 101, no. 2 (2023): 197-210. https://doi.org/10.37934/arfmts.101.2.197210
[16] Denso. *Pipeline Tape,* 2021.
[17] Burkov, Petr Vladimirovich, Svetlana Petrovna Burkova, and S. A. Knaub. "Stress and strain state analysis of defective pipeline portion." In *IOP Conference Series: Materials Science and Engineering*, vol. 91, no. 1, p. 012055. IOP Publishing, 2015. https://doi.org/10.1088/1757-899X/91/1/012055
[18] Poutanen, Tuomo, Tim Länsivaara, Sampsa Pursiainen, Jari Mäkinen, and Olli Asp. "Calculation of safety factors of the eurocodes." *Applied Sciences* 11, no. 1 (2020): 208. https://doi.org/10.3390/app11010208
[19] Rajib. *Factor Of Safety,* 2021.
[20] Matthew Fetke. *Solidworks Flow Simulations: Pressure opening explained*, 2019.
[21] Xiaobin Le P.E, Richard L. Roberts, Anthony William Duva P.E. *Teaching Finite Element Analysis for mechanical undergraduate students.* Conference paper of ASEE Annual Conference & Exposition (2019).
[22] Ferràs, David, Dídia IC Covas, and Anton J. Schleiss. "Stress–strain analysis of a toric pipe for inner pressure loads." *Journal of Fluids and Structures* 51 (2014): 68-84. https://doi.org/10.1016/j.jfluidstructs.2014.07.015

[23] Tey, Wah Yen, and Hooi Siang Kang. "Power Loss in Straight Polygon Pipe via CFD Simulation." *Progress in Energy and Environment* (2018): 1-10.
[24] Salleh, Mohd Shukor, Ammar Abd Rahman, Mohd Fairuz Jaafar, and Salah Salman Al-Zubaidi. "Effect of Drilling Penetration Angle on Delamination for One-Shot Drilling of Carbon Fiber Reinforced Plastic (CFRP)." *Malaysian Journal on Composites Science & Manufacturing* 8, no. 1 (2022): 1-10. https://doi.org/10.37934/mjcsm.8.1.110
[25] Azizan, Azisyahirah, Haris Ahmad Israr, and Mohd Nasir Tamin. "Effect of Fiber Misalignment on Tensile Response of Unidirectional CFRP Composite Lamina." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 11, no. 1 (2018): 23-30.