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Structural Rehabilitation of API Steel Pipes Using GFRP Under Dynamic Condition

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ABSTRACT

Corrosion of steel pipes significantly challenges industries such as oil and gas, water transport, and chemicals, where pipeline integrity is paramount. Degradation due to corrosion leads to reduced efficiency, heightened risk of catastrophic failure, and substantial economic and safety concerns. This study investigates the effectiveness of Glass Fiber-Reinforced Polymer (GFRP) wrap in restoring and enhancing the performance of corroded API 5L X42 steel pipes. Through controlled corrosion induction, application of GFRP wrapping, and cyclic loading tests, this study offers a comprehensive understanding of the initial response and performance under dynamic condition. For unrepaired pipes, maximum force applied ranged from 67.84 kN to 404.8 kN as stroke increased from 1mm to 12mm, with corresponding maximum deformation from 0.8mm to 9.01mm. In contrast, GFRP-rehabilitated pipes demonstrated applied force ranging from 28.98 kN to 452.87 kN, with maximum deformation from 0.65mm to 14.41mm. These findings underscore the efficacy of GFRP patches in mitigating corrosion effects, extending pipeline service life, and reducing failure risk. This study validates theoretical models and offers practical guidance for adopting resilient materials in engineering, enhancing pipeline integrity in critical industrial applications.

Keywords: Corroded; GFRP; Cyclic Loading; Pipeline Integrity; Rehabilitation

INTRODUCTION

The degradation of American Petroleum Institute (API) steel pipes due to corrosion significantly impacts the operational integrity of infrastructure within various sectors, such as oil and gas, water transport, and chemical industries. Environmental exposure, alongside chemical and mechanical deteriorations, diminishes the structural integrity of these pipelines, leading to decreased efficiency, heightened risk of failure, and consequential economic and ecological detriments (Shahid et al. 2023). Given the critical role these pipelines play in industrial operations, finding effective and efficient methods for their repair and reinforcement is of paramount importance. Within this context, composite Fiber-Reinforced Polymers (FRP), particularly Glass Fiber-Reinforced Polymers (GFRP), have been identified as promising materials for the restoration and enhancement of these critical assets (Shamsuddoha et al. 2013). The corrosion of steel pipelines, an inevitable consequence of their exposure to aggressive environments, significantly undermines the mechanical and structural integrity of these conduits (Belarbi et al. 2016; Rajak et al. 2021; Shamsuddoha et al. 2013). Various studies have documented the multifaceted nature of corrosion processes, highlighting electrochemical reactions, environmental factors, and material susceptibilities as key contributors (Hussein Farh et al. 2023; Rubino et al. 2020; Zhu et al. 2018). The loss of wall thickness and the emergence of localized defects not only reduce the pipeline's carrying capacity but also elevate the risk of catastrophic failures (Muda et al. 2022). In response to the limitations of traditional steel repair methods, the use of GFRP has emerged as a viable alternative, offering significant advantages in terms of strength, weight, and resistance to environmental degradation (Chandra Das & Haque Nizam 2014; Ong et al. 2024; Sebaey 2019; Sulu & Temiz 2018). GFRP's compatibility with steel substrates, coupled with its ease of application, presents a cost-effective and efficient approach to extending pipeline service life (Teng et al. 2012). Comparative studies have shown that GFRP-wrapped pipes exhibit enhanced bending stiffness, improved fatigue resistance, and a marked increase in load-bearing capacity (Rafiee 2017). Furthermore, GFRP's high tensile strength and corrosion resistance make it particularly suitable for environments that impose dynamic loading conditions, such as those from seismic activity, traffic loads, waves, current, and internal pressure fluctuations (Chan et al. 2015; Rafiee 2017; Tafsirojjaman et al. 2019; Yu et al. 2015). The resilience of repaired and reinforced pipelines under such conditions is critical to ensuring the reliability of the infrastructure network. While extensive research exists on the application of GFRP in static conditions, studies exploring its efficacy on API steel pipes under dynamic loading remain limited (Abdul Shahid et al. 2023). There is a pressing need for empirical studies addressing the performance of corroded and repaired pipes under dynamic stresses to validate theoretical models and provide a foundation for practical applications. This research meticulously evaluates the efficacy of GFRP patches in restoring and enhancing the bending capacity of corroded API steel pipes under dynamic loading conditions. Specifically, it seeks to ascertain the comparative bending resilience of both unrepaired corroded and GFRP-rehabilitated API steel pipes when subjected to cyclic dynamic stresses simulating real-world environmental and operational conditions. Through controlled corrosion induction, precise application of GFRP patches, and rigorous cyclic loading tests, this study provides empirical evidence and analytical insights into the structural integrity and performance of patched pipes. Compared to other potential rehabilitation materials, GFRP offers distinct advantages that justify its selection for pipeline repair. Traditional repair methods, such as steel sleeves and welded patches, often add significant weight and complexity to the pipelines, potentially exacerbating corrosion issues and increasing maintenance costs (Salemi 2020; Shamsuddoha et al. 2013; Tafsirojjaman et al. 2022; Watanabe et al. 2017). Moreover, materials like carbon fibre-reinforced polymers (CFRP), although offering cheaper and available, are significantly lower strength and less flexible than GFRP (Ong et al. 2024). CFRP's brittleness make it less practical for large-scale pipeline repairs where flexibility and cost-effectiveness are crucial. In contrast, GFRP is provides excellent mechanical properties that enhance the structural performance of rehabilitated pipelines. Its ease of application allows for efficient and rapid repairs, minimizing downtime and disruption to pipeline operations. Additionally, GFRP's ability to conform to various pipeline shapes and sizes without compromising strength or durability makes it an ideal choice for diverse repair scenarios as mentioned in a study by Lim et. al. (2017). Ultimately, this investigation aims to advance the field of pipeline rehabilitation, offering a scientifically grounded foundation for developing more reliable, efficient, and durable repair strategies for critical infrastructure in various industries. The study's findings are expected to contribute valuable insights into the practical application of GFRP for extending the service life of corroded pipelines while minimizing failure risks.

METHODOLOGY

In this research, a dynamic pipeline test was conducted on an API 5L X42 steel pipe with localized corrosion defects. The methodology comprises three main stages: material specification, corrosion induction process, and GFRP patching procedure, followed by dynamic loading testing. The overall research approach is illustrated in Fig.1.

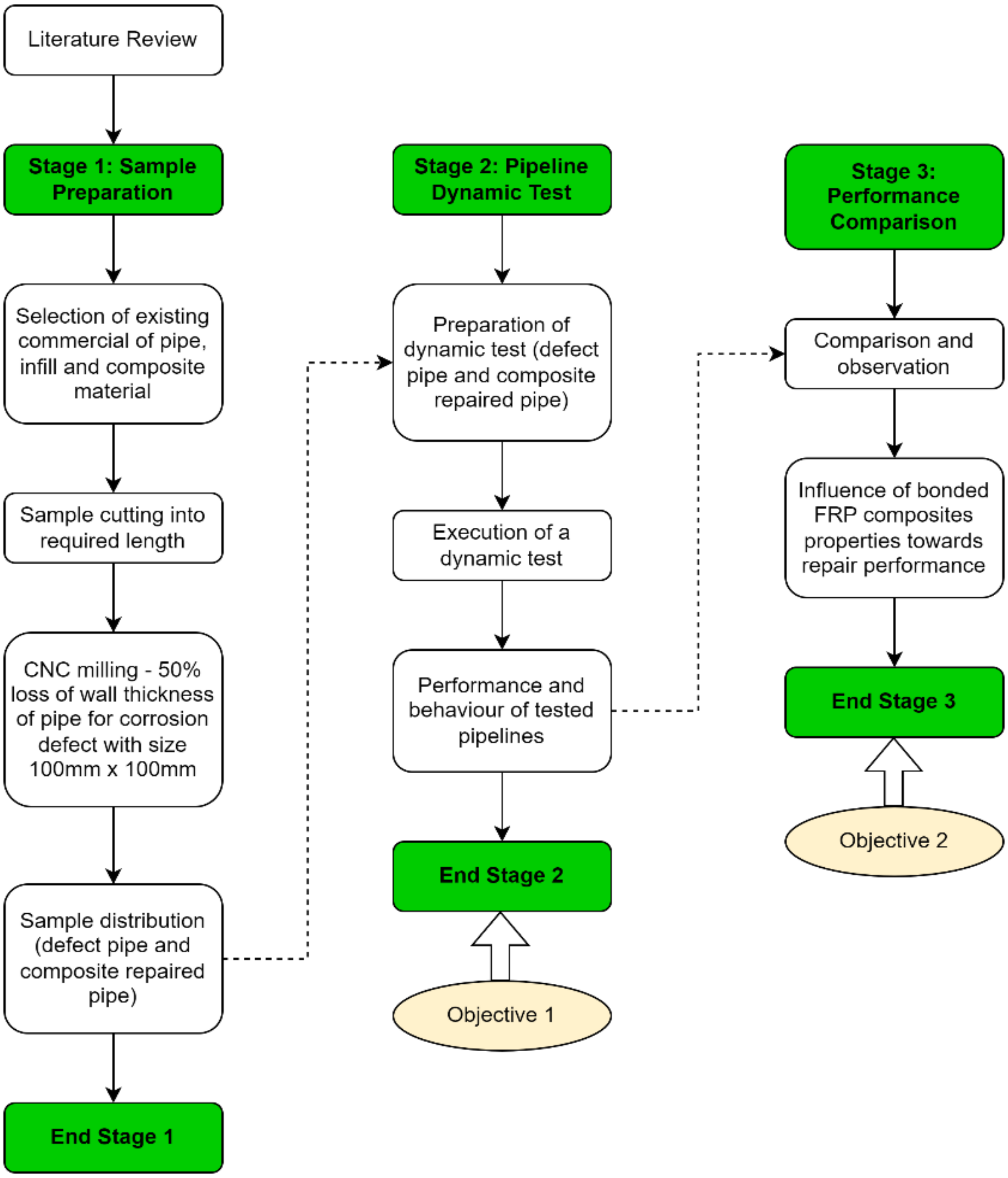

FIGURE 1. Flow chart of overall research methodology.

MATERIAL SPECIFICATION

This study utilizes API 5L Grade X42 steel pipes, adhering to American Petroleum Institute standards for oil and natural gas pipelines. The pipes selected have a nominal diameter of 168.3mm and a wall thickness of 10.97mm. For the rehabilitation process, GFRP sheets embedded with an epoxy resin matrix were employed. The GFRP material was chosen for its high tensile strength, corrosion resistance, and compatibility with the steel substrate. Detailed specifications of the API pipe are provided in Table 1.

CORROSION INDUCTION PROCESS

To simulate real-world corrosion, a Computer Numerical Control (CNC) cutting process was applied to the steel pipes, creating 100mm x 100mm x 5.485mm artificial defects on their external surface to simulate 50% external corrosion. These specific dimensions were selected based on previous research (Lim 2017; Muda et al. 2022) to represent significant yet manageable defects for rehabilitation. A corrosion level of 50% was chosen to replicate severe, but not catastrophic, damage that would typically necessitate repair, thereby providing a stringent test of the GFRP patching method's effectiveness. This level of corrosion is representative of advanced degradation commonly observed in ageing pipelines within the industry, ensuring the study's findings are relevant to real-world conditions. The defects were located at the mid-length of the pipes, as depicted in Figure 2.

TABLE 1. API 5L X42 parameters specification

Type	Pipe Diameter (mm)	Pipe Length (mm)	Thickness (mm)	Corrosion Level (%)	Defects (mm)	
					Length	Width
API 5L X42	168.3	1200	10.97	50	100	100

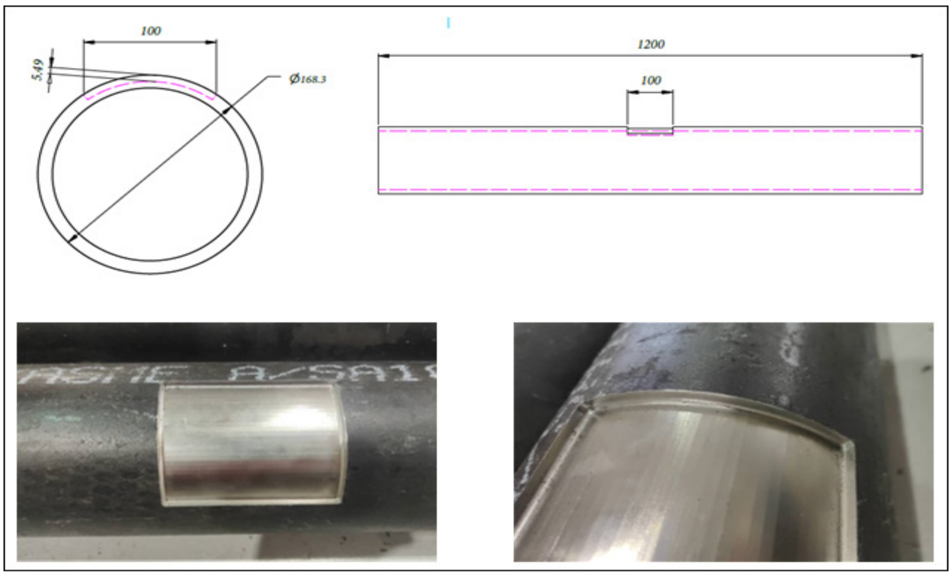

FIGURE 2. The defect was made by a specialist company in Shah Alam, Malaysia.

GFRP WRAPPING PROCEDURE

Following corrosion induction, selected pipes underwent rehabilitation using GFRP patches. Surface preparation involved abrasive blasting to remove rust and create a profile conducive to adhesion. An epoxy putty was used to fill the corrosion void and allowed to cure for 24 hours at room temperature before applying the composite wrap. Subsequently, an epoxy primer was applied, followed by the placement of GFRP sheets cut to predetermined sizes. The patches were applied using a wet layup method, ensuring thorough impregnation of the fibres with the epoxy resin. The curing process was conducted at ambient temperature for five days. The wrapping process is illustrated in FIGURE 3. The selection of the type and number of GFRP layers was guided by the dual objectives of restoring the corroded portion of the pipe and enhancing its overall structural integrity beyond the original strength. Specifically, three layers of GFRP were applied to ensure sufficient strength and durability. Furthermore, this approach has been suggested by Lim et al. (2019) & Muda et al. (2022). This approach not only addresses the immediate need to repair the corroded sections but also provides additional reinforcement, potentially increasing the load-bearing capacity and bending stiffness of the pipe, thus extending its service life.

FIGURE 3. Application of composite wrap.

CYCLIC LOADING TEST

Cyclic loading testing focused on applying cyclic loads to both unrepaired and repaired pipes. A servo-hydraulic testing machine was used to apply a sinusoidal load with an amplitude correlating to 50% of the pipe's predicted yield strength at a frequency of 0.5Hz. Testing was executed starting from 1mm, 2mm, and 3mm increments until failure for unrepaired pipes, and 1mm, 3mm, and 3mm increments until failure for repaired pipes. Each amplitude increment was tested for two cycles to ensure repeatability and reliability of the results. This regimen mimics the fluctuating stress conditions encountered in service. Linear Variable Differential Transformers (LVDT) were strategically placed to capture deformation behaviour and stress concentration points, facilitating a comprehensive analysis of the pipes' dynamic response. The testing setup is shown in Figure 4 shows the process before the execution of dynamic test.

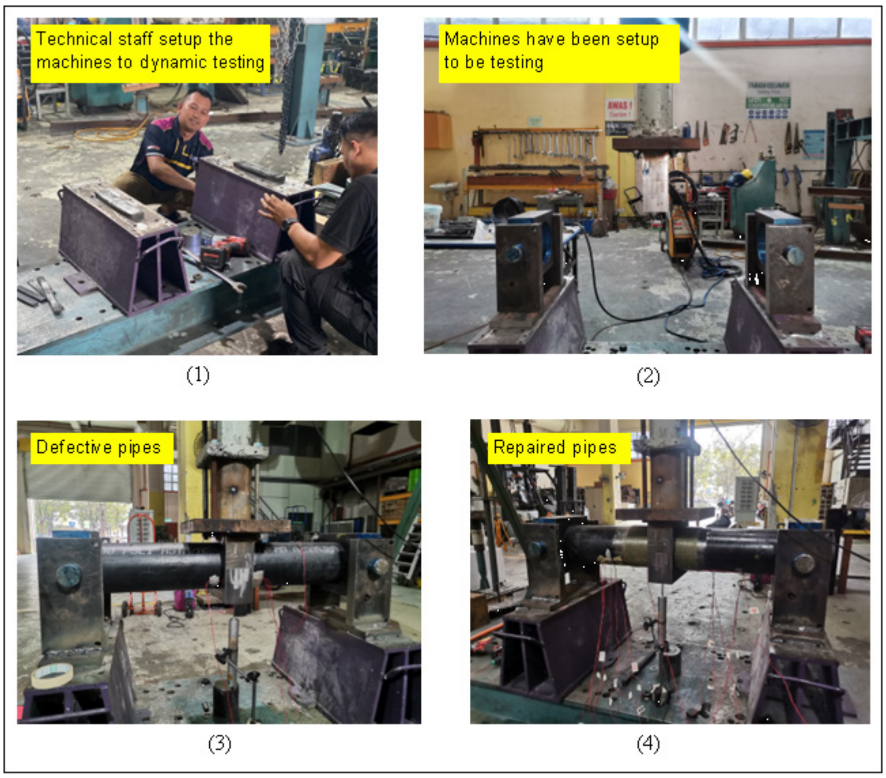

FIGURE 4. Dynamic test specimens.

RESULTS AND DISCUSSION

This section provides an investigation and assessment of the findings from the cyclic loading experiments performed on API 5L X42 steel pipes, both those that were repaired and unrepaired. It presents a thorough analysis of the different situations, emphasizes the enhancements resulting from GFRP rehabilitation, and examines the initial performance of the pipes before and after repair.

UNREPAIRED PIPES

Referencing in Table 2 the cyclic loading tests on the unrepaired API 5L X42 pipes reveal a progressive increase in both the maximum force applied and the corresponding deformation as the stroke length increases. At an initial stroke of 1mm, the maximum force applied is 67.84 kN with a deformation of 0.8 mm.

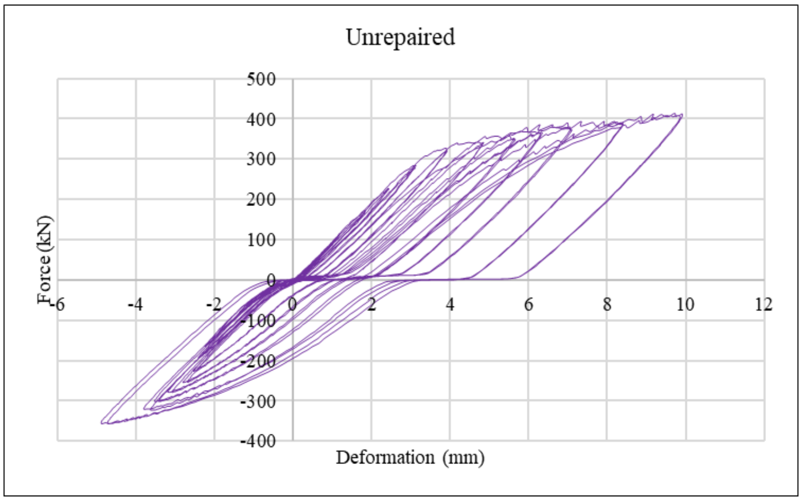

FIGURE 5. Force vs displacement curve – unrepaired

This force escalates to 404.8 kN at a 12mm stroke, with a corresponding deformation of 9.01 mm. The data indicates that the unrepaired pipes exhibit significant deformation under increasing load, suggesting a reduced structural integrity and an increased likelihood of failure under dynamic loading conditions. The force vs. displacement curve in Figure 5 clearly illustrates this trend, showing a near-linear relationship initially, followed by a plateau as the material approaches its yield strength.

TABLE 2. Maximum force and deformation of unrepaired pipes

Unrepaired Pipes		
Stroke (mm)	Max Force Applied (kN)	Max Deformation (mm)
1	67.84	0.8
2	116.59	1.22
3	172.52	1.85
4	227.56	2.44
5	284.62	3.13
6	326.85	3.93
7	341.9	4.85
8	357.18	5.66
9	369.08	6.35
10	379.42	7.1
11	393.79	8.4
12	404.8	9.01

TABLE 3. Maximum force and deformation of repaired pipes

Repaired Pipes		
Stroke (mm)	Max Force (kN)	Max Deformation (mm)
1	28.98	0.65
3	124	1.74
6	294.05	3.71
9	350.34	6.23
12	398.15	8.48
15	433.78	11.69
18	452.87	14.41

REPAIRED PIPES

Conversely in Table 3, the GFRP-repaired pipes demonstrate improved mechanical performance under the same testing conditions. At a 1mm stroke, the maximum force applied is lower at 28.98 kN with deformation of 0.65 mm, reflecting the initial stiffness imparted by the GFRP wrapping. As the stroke increases to 18mm, the maximum force reaches 452.87 kN with a deformation of 14.41 mm. This significant increase in load-bearing capacity and corresponding deformation capacity underscores the effectiveness of GFRP in enhancing the structural integrity of the repaired pipes. The force vs. displacement curve in Figure 6 highlights the enhanced performance, showing a more gradual slope and a higher load-bearing threshold compared to the unrepaired pipes.

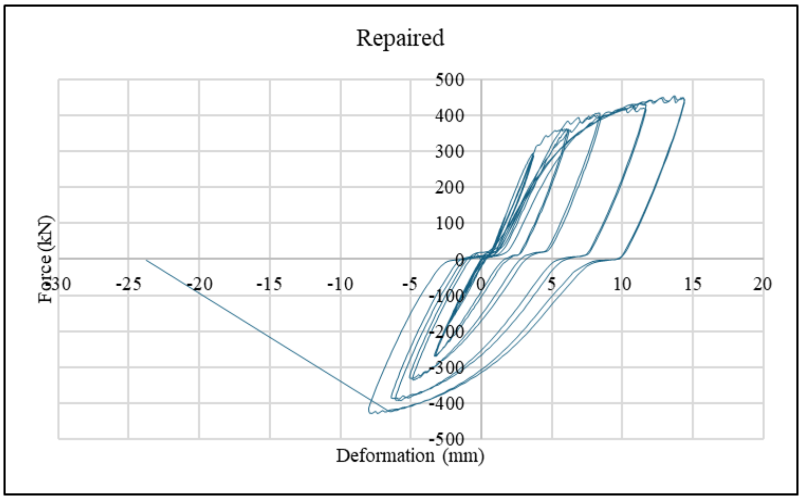

FIGURE 6. Force vs displacement curve – repaired

COMPARATIVE ANALYSIS

Table 4 provides a comparative analysis of the relative error in force and deformation between the unrepaired and repaired pipes. The relative error in force decreases progressively from 0.573 at a 1mm stroke to 0.016 at a 12mm stroke, indicating that the GFRP repair effectively reduces the discrepancy in force handling between the two conditions. Similarly, the relative error in deformation is minimal, ranging from 0.1875 at a 1mm stroke to 0.059 at a 12mm stroke, further validating the improved performance of the repaired pipes.

TABLE 4. Relative error for unrepaired and repaired

Stroke (mm)	Force (kN)		Relative error (%)	Deformation (mm)		Relative error (%)
	Unrepaired	Repaired		Unrepaired	Repaired	
1	67.84	28.98	0.573	0.8	0.65	0.1875
3	172.52	124	0.281	1.85	1.74	0.11
6	326.85	294.05	0.1	3.93	3.71	0.056
9	369.08	350.34	0.0508	6.35	6.23	0.019
12	404.8	398.15	0.016	9.01	8.48	0.059

The experimental results demonstrate the efficacy of GFRP wrapping in restoring and enhancing the structural performance of corroded API 5L X42 steel pipes under dynamic loading conditions. The unrepaired pipes exhibit substantial deformation and reduced load-bearing capacity, reflecting the detrimental impact of corrosion on their structural integrity. In contrast, the GFRP-repaired pipes show a marked improvement in both maximum force and deformation capacity, highlighting the material's potential for effective rehabilitation.

The force vs. displacement curves for both unrepaired and repaired pipes provide visual confirmation of these findings. The unrepaired pipes' curve shows a steep initial slope followed by a plateau, indicating a rapid approach to the material's yield strength and subsequent risk of failure. On the other hand, the repaired pipes' curve demonstrates a more gradual slope and a higher peak force, signifying enhanced load distribution and increased resistance to deformation. The comparative analysis of relative errors further reinforces the benefits of GFRP rehabilitation. The significant reduction in relative error for both force and deformation between the unrepaired and repaired conditions suggests that GFRP wrapping not only restores the pipes' original strength but also provides additional reinforcement, extending their service life and reliability under dynamic loads.

CONCLUSION

This research focused on examining the structural rehabilitation of API 5L X42 steel pipes using three layers of GFRP under dynamic conditions. Through a comprehensive series of cyclic loading tests, this study compares the structural performance of unrepaired and GFRP-repaired pipes, providing valuable insights into the mechanical enhancements achieved through GFRP rehabilitation. The unrepaired pipes, subjected to incremental cyclic loads, exhibited significant deformation and a pronounced risk of structural failure as the load increased. The data clearly indicated a rapid approach to the material's yield strength, resulting in diminished load-bearing capacity and increased susceptibility to failure. In contrast, the GFRP-repaired pipes demonstrated substantial improvements in both maximum force applied and corresponding deformation capacity. Specifically, the repaired pipes, wrapped with three layers of GFRP, showcased enhanced structural integrity, superior load distribution, and increased resistance to dynamic stresses. The comparative analysis of relative errors in force and deformation further validated the effectiveness of the GFRP repair method. The significant reduction in relative errors between the unrepaired and repaired conditions underscored the GFRP's ability to not only restore the original strength of the corroded pipes but also provide additional reinforcement, thereby extending their service life and reliability.The findings of this study highlight the practical benefits of employing GFRP for pipeline rehabilitation. The ease of application, cost-effectiveness, and superior mechanical properties of GFRP make it an ideal choice for repairing and reinforcing corroded pipelines across various industries, including oil and gas, water transport, and chemical sectors. The use of three layers of GFRP, as demonstrated in this study, offers a robust solution for mitigating the adverse effects of corrosion and enhancing the structural performance of critical infrastructure. To build upon the findings of this study, future research should focus on the following specific areas:

1. Investigate the long-term durability and performance of GFRP-repaired pipes under prolonged exposure to dynamic loads and varying environmental conditions. This will help establish the sustainability and reliability of GFRP rehabilitation over extended operational periods.
2. Conduct empirical studies to evaluate the performance of GFRP-repaired pipes in diverse environmental settings, including subsea and offshore conditions. Understanding the material's behavior in different environments will provide a more comprehensive assessment of its practical applications.
3. Explore the effects of varying the number of GFRP

layers and their orientation on the structural performance of repaired pipes. This could lead to optimized repair strategies that balance material usage, cost, and mechanical enhancements.

4. Develop and validate predictive models to accurately forecast the performance of GFRP-repaired pipes under dynamic loading conditions. Such models will be invaluable for engineers in designing and implementing effective rehabilitation strategies.

In conclusion, the application of three layers of GFRP patches significantly enhances the structural performance of corroded API 5L X42 steel pipes, particularly under dynamic loading conditions. This study provides robust empirical evidence supporting the use of GFRP as a viable and effective material for pipeline rehabilitation. By extending the service life and improving the reliability of critical infrastructure, GFRP offers a promising solution to the challenges posed by pipeline corrosion. In further research, will further solidify the role of GFRP in advancing pipeline repair technologies.

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DECLARATION OF COMPETING INTEREST

None.

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