

Article

Leakage Quantification in Metallic Pipes under Different Corrosion Exposure Times

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Abstract: The combined effects of aqueous corrosion, stress factors, and seeded cracks on leakage in cast iron pipes have not been thoroughly examined due to the complexity and difficulty in predicting their interactions. This study seeks to address this gap by investigating the interdependencies between corrosion, stress, and cracks in cast iron pipes to optimise the material selection and design in corrosive environments. Leakage experiments were conducted under simulated localised corrosive conditions and internal pressure, revealing that leakage increased from 0 to 25 mL with crack sizes of 0.5 mm, 0.8 mm, 1 mm, and 1.2 mm, along with corrosion times of 0, 120, 160, and 200 h, and varying stress levels. An empirical model was developed using a curve-fitting approach to map the relationships among corrosion time, crack propagation, and leakage amount. The results demonstrate that the interaction between corrosion, stress, and crack propagation was complex and nonlinear, and the leakage amount increased from 0.7 to 0.10 mm every 15 min, as evidenced by SEM microstructure images and empirical data.

Keywords: leakage; crack; degradation mechanism; crack propagation; pressure; stress; corrosion time; pipe failure



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1. Introduction

Cast iron pipes have been widely used in water distribution systems due to their robustness and cost-effectiveness. However, despite these advantages, the long-term reliability of cast iron pipes is frequently compromised by various factors, including corrosion and mechanical stress. These issues often lead to significant maintenance challenges and potential failures [1,2]. The complex interaction between corrosion and stress, particularly in the presence of cracks, remains inadequately understood.

Corrosion in cast iron pipes, typically increased in aqueous environments, gradually deteriorates the material, increasing the possibility of cracking and eventual failure [3]. Stress arising from either internal pressures or external loads can further deteriorate these conditions by promoting the initiation and propagation of cracks [4–12]. The coupled effects of corrosion and stress complicate the prediction and management of pipe leakage due to their nonlinear interaction [12].

Existing research has explored the individual effects of corrosion and stress on cast iron pipes [4,13–23]. Researchers have documented localised corrosion mechanisms and their impact on material integrity [24]. Similarly, Dzioba et al. have investigated how mechanical stress influences crack growth and pipe failure [25,26]. However, comprehensive studies examining the combined effects of these factors on leakage rates are sparse. The complex interdependencies between corrosion, stress, and cracks necessitate a comprehensive understanding of their impact on pipe leakage.

This study aims to address this research gap by investigating the combined effects of corrosion, stress, and cracks on the leakage behaviour of cast iron pipes. By simulating localised corrosive conditions and applying varying stress levels, the aim is to demonstrate

how these factors influence leakage rates. The experimental variables involve crack sizes from 0.5 mm, 0.8 mm, 1 mm, and 1.2 mm and corrosion times from 0 to 160 h under different stress levels. The empirical model developed through a curve-fitting approach will map the relationships among these variables and leakage amount. They will provide a deeper understanding of the mechanisms driving leakage in cast iron pipes, with the optimal selection and design of materials in corrosive environments. Ultimately, this study seeks to improve the maintenance and design of water distribution systems [26].

2. Methodology

The experimental methodology was designed to investigate the combined effects of aqueous corrosion, stress, and cracks on cast iron pipes. The preparation of the samples for the corrosion tests was conducted to ensure the reliability and relevance of the findings. In this study, CI pipes were tested under controlled internal pressures while monitoring the resulting stress. To simulate different levels of structural integrity, these pipes were pre-damaged with cracks of various sizes. Additionally, the duration of exposure to corrosive environments was altered to emulate long-term degradation effects.

2.1. Material

The major chemical constituents of cast iron, which are critical to its corrosion resistance, were analysed and are presented in Table 1.

Table 1. Major chemical constituents of cast iron.

Material	C	S	P	Mn	Si	Fe
HT200 (EN-GJL200) Cast iron	3.2	0.12	0.015	0.9	1.6	93–97%

2.2. Sample Preparation

The experiment used a solution containing 600 parts per million (ppm) of 3.5% NaCl dissolved in redistilled water. This concentration was chosen based on the significant influence of chloride ions on cast iron's corrosion behaviour. The specimens, detailed in Table 2, were prepared with varying crack sizes from 0.5 to 1.2 mm to simulate the realistic damages with different severity. Crack length and depth were constant at 50 and 3 mm, respectively, for convenient machining. All specimens were subjected to different reasonable corrosion durations. In this study, 120 h was determined as the time of appearance of corrosion with a 40 h step to observe the different effects of corrosion over time [26].

Table 2. The details of sample preparation.

Crack Size	Pipe Length	Crack Length	Wall Thickness	Crack Depth	Number of Tubes Needed	Corrosion Time
0.5 mm	200 mm	50 mm	4 mm	3 mm	3	0, 120, 160 and 200 h
0.8 mm	200 mm	50 mm	4 mm	3 mm	3	0, 120, 160 and 200 h
1.0 mm	200 mm	50 mm	4 mm	3 mm	3	0, 120, 160 and 200 h
1.2 mm	200 mm	50 mm	4 mm	3 mm	3	0, 120, 160 and 200 h

The specimens were immersed in a NaCl solution for varying durations (0, 120, 160, and 200 h) to allow sufficient interaction time for the NaCl to initiate the corrosion process.

2.3. Data Collection and Analysis

The physical effects of corrosion, such as changes in crack propagation and leakage amount, were measured and analysed using a multi-linear regression approach. This

empirical model mapped the relationships among corrosion time, stress, crack propagation, and leakage amount.

By following this methodology, this study aimed to produce reliable and transferable results that could enhance the understanding of corrosion behaviour in cast iron pipes and inform the material selection and design in corrosive environments.

2.4. Experimental Setup

Figure 1 illustrates the experimental setup used in this study. The test arrangement comprised two removable end sections attached to a corroded pipe section using couplings. One end section was connected to the water supply network via a combination turbine flow meter from GPI® (Enfield, UK), and the downstream section was equipped with a calibrated pressure transducer from Baker Hughes (Houston, TX, USA). Threaded cast iron rods and end supports were used to maintain the system intact. Data collection was facilitated through a data logger, which recorded readings from the flow meter and pressure transducer. Pressure readings were recorded every second, while the flow rate was measured by the pulse generated by the flow meter for every minute of flow.

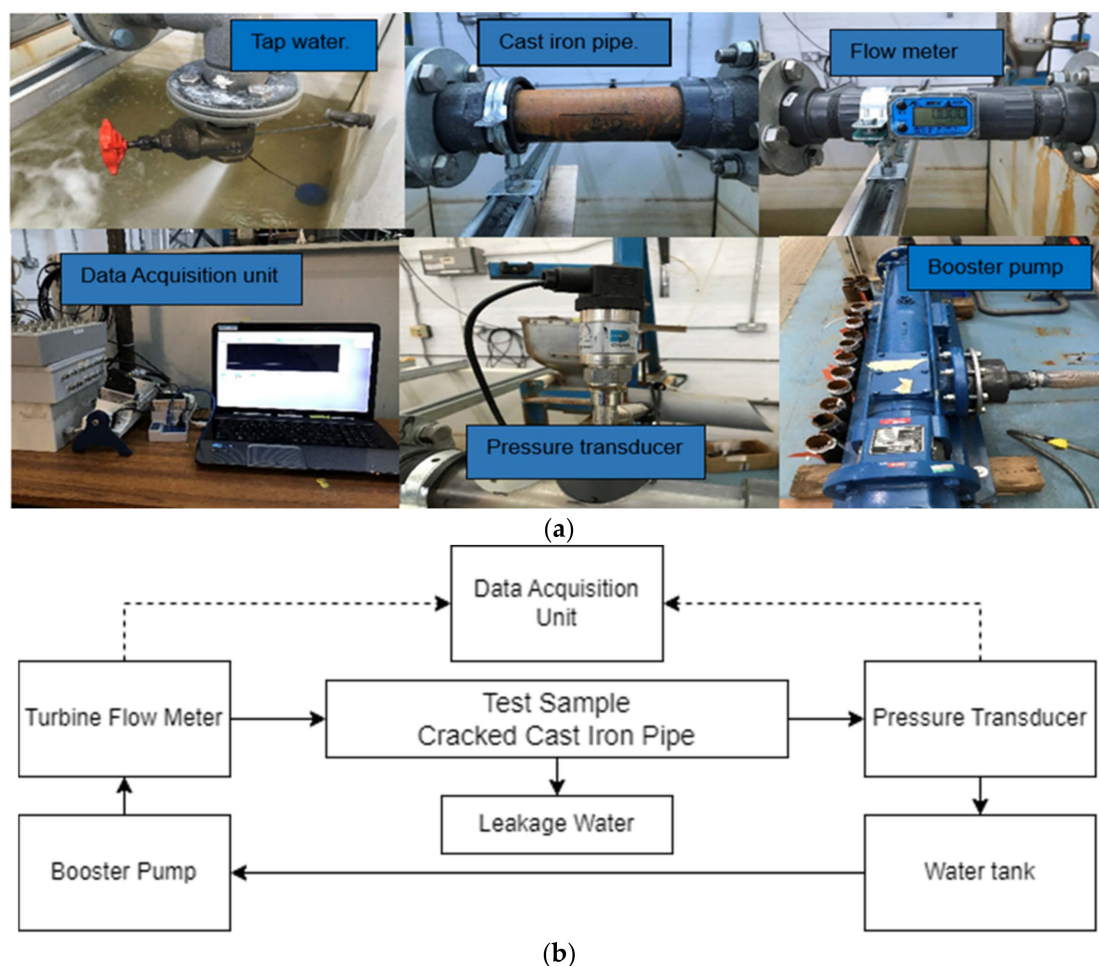


Figure 1. (a) Experimental setup; (b) conceptual diagram showing the whole equipment system connection.

The system was pressurised using a booster pump operating at 6 bars, regulated by a pressure regulator set at 4 bars. Additionally, a booster pump was equipped with an expansion vessel to reduce the frequency of pump starts. Any leakage from the system was discharged into the atmosphere, and aside from the leakage flow rate, there was no other flow present in the system. The pressure transducer and leakage observation point were at the same horizontal level. The experimental procedure involved incrementally

increasing and decreasing flow and pressure. By doing so, the stress factor of the pipeline was calculated under varying durations of corrosion when subjected to internal pressure. The stress factor, denoted as K , refers to the stress distribution around a crack. It represents the measurement of stress and deformation at the crack tip [27]. Griffith's strength and energy theory postulates that the stress intensity factor, K , can be linked to the energy released during crack growth, expressed by Equation (1) [28].

$$K = Y\sigma\sqrt{\pi a} \quad (1)$$

where K = stress intensity factor for a particular mode of cracking;

a = initial crack length;

σ = remote stress;

Y = a geometric factor.

In the experiment, seeded cracks of specific sizes were introduced into each specimen pipeline. These cracks, consistently sized at 0.5, 0.8, 1.0, and 1.2 mm, were placed at similar positions within each pipe, after which the water source was connected, and the pump was used to pressurise the pipes. The experiment continued with the gradual increase in water pressure, which increased the stresses at the tips of the pre-existing cracks, leading to their propagation. This development led to leakage, which was quantitatively measured by collecting the escaped water in a container. This process was repeated at different pressure intensities, enabling the analysis of the impact of varying pressures on crack growth and associated leakage rates. Initially focusing on specific crack dimensions, the experiment was methodically repeated with progressively larger cracks to amass extensive data on leakage rates across diverse crack sizes and pressure magnitudes. These compiled data were then carefully evaluated, and the insights are methodically organised and summarised in the next section, with the objective of deriving significant conclusions from the experimental observations.

2.5. Data Collection and Analysis

The physical effects of corrosion, such as changes in crack propagation and leakage amount, were measured and analysed using a curve-fitting approach, namely multi-linear regression (MLR). This method is used to analyse the relationships between a dependent variable and multiple independent variables. It minimises the differences between the observed and predicted outcomes based on the least-square principle.

In this study, an MLR model was applied to investigate how parameters like corrosion time, crack size, and content affect the mechanical properties of cast iron pipes [29].

3. Results and Discussion

3.1. Calculation of the Stresses at the Tips of the Cracks

The results from stress calculations using Equation (2) are presented in Tables 3–6. These tables display the stress intensity factors for various crack lengths under different applied stresses.

$$\begin{aligned} Kc &= Y\sigma_s\sqrt{\pi a} \\ \sigma_s &= Kc/(Y\sqrt{\pi a}) \end{aligned} \quad (2)$$

Table 3. Results of stress at the crack tip for corrosion time 0 h.

Corrosion Time 0 h		
Initial Crack Size (a) (mm)	Load (N)	Stress σ (MPa)
0.5	10,200	510
0.8	9900	495
1.0	9800	490
1.2	6000	300

Table 4. Results for stress at the crack tip for corrosion time 120 h.

Corrosion Time 120 h		
Initial Crack Size (<i>a</i>) (mm)	Load (N)	Hoop Stress σ (MPa)
0.5	9100	455
0.8	9000	450
1.0	8000	400
1.2	7900	395

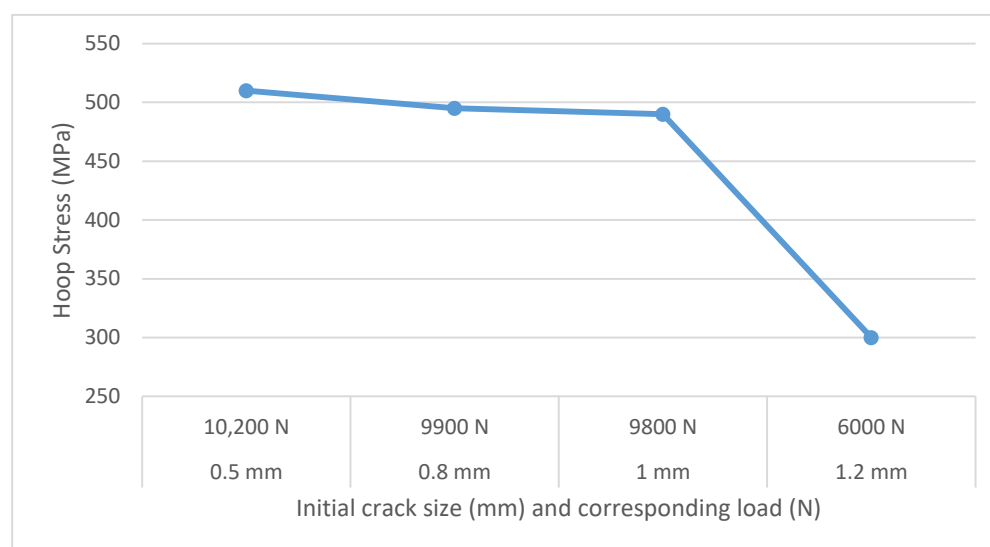
Table 5. Results of stress at the crack tip for corrosion time 160 h.

Corrosion Time 160 h		
Initial Crack Size (<i>a</i>) (mm)	Load (N)	Stress σ (MPa)
0.5	7500	375
0.8	7300	365
1.0	7000	350
1.2	6800	340

Table 6. Results of stress at the crack tip for corrosion time 200 h.

Corrosion Time 200 h		
Initial Crack Size (<i>a</i>) (mm)	Load (N)	Stress σ (MPa)
0.5	5000	250
0.8	4900	245
1.0	4500	225
1.2	3800	190

Figures 2–5 indicate the crack sizes and the corresponding pressures at which the pipes were tested. Each data point on these graphs represents a stress measurement correlating to a specific state of crack and corrosion severity against the applied internal pressure. It is worth noting that we observed some drastically decreased stress due to the rapidly reduced loading measurements for some experimental conditions.

**Figure 2.** Relationship between initial crack and stress value at corrosion time 0 h.

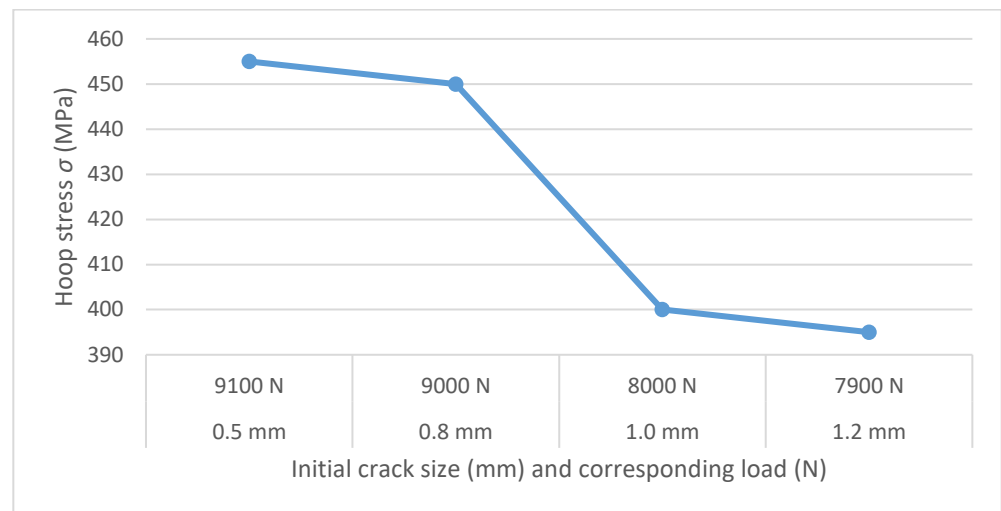


Figure 3. Relationship between initial crack and stress value for corrosion time 120.

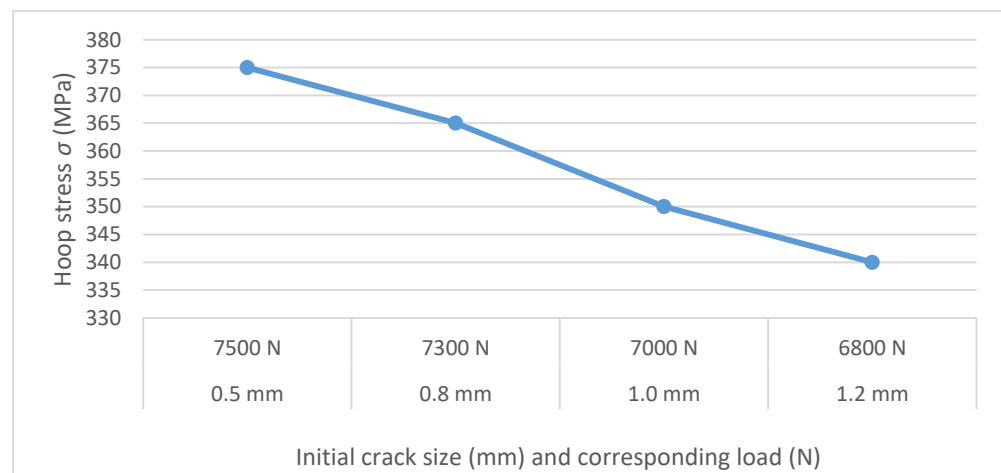


Figure 4. Relationship between initial crack and stress value for corrosion time 160 h.

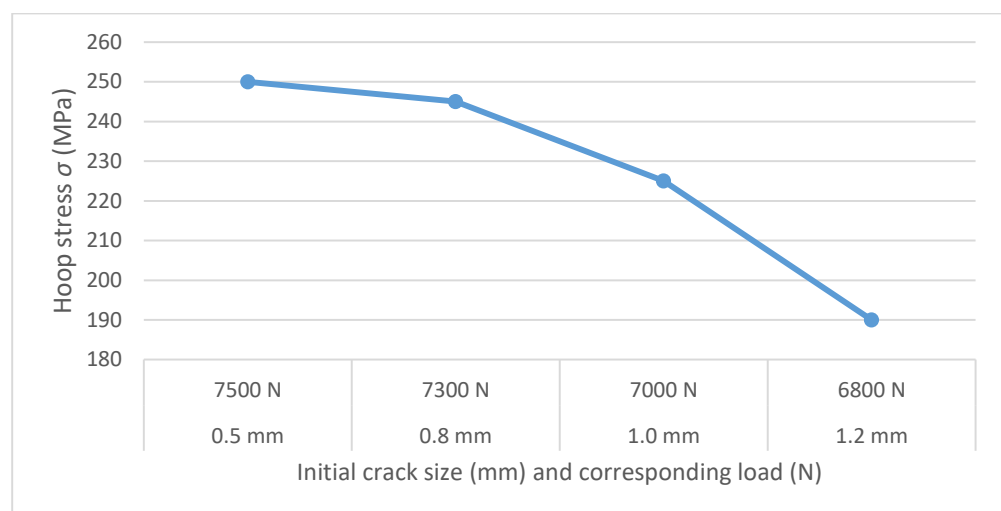


Figure 5. Relationship between initial crack and stress value for corrosion time of 200 h.

Contrary to initial assumptions, we found reduced hoop stress with increased crack size and corrosion exposure, as shown in Tables 3–6. Typically, one would expect larger

cracks and more significant corrosion to compromise the material's strength, potentially increasing stress. However, this anticipated increase in stress was not observed. The reason for this anomaly is linked to the experimental methodology. In this study, the internal pressure within the pipes was deliberately reduced from 6 to 4 bar for specimens with more extensive crack growth. This approach is a standard safety protocol in testing, implemented to prevent the risk of pipe failure. However, this decrease in internal pressure in more damaged pipes influenced the observed stress outcomes.

The findings suggest that the experimental procedures, adjusted based on the severity of pipe damage, produced corresponding modifications to the pressure levels. As a result, the hoop stress, indicative of the circumferential stress within the pipe walls, decreased as the internal pressure was intentionally lowered. This reduction served as a countermeasure to the compromised structural integrity due to increased crack size and extent of corrosion. From a research standpoint, these results are crucial for defining CI pipes' operational limits and failure thresholds. They can be used to develop predictive models to estimate the service life of such pipes and determine the necessary operational pressure adjustments for ongoing safety.

In summary, the experimental outcomes highlight the effects of damage progression on hoop stress in CI pipes and demonstrate the efficacy of pressure modulation as a failure prevention strategy. This information is invaluable for maintaining and safely operating systems that depend on a CI piping infrastructure. By including the variable of crack propagation, the experiment provides a comprehensive understanding of the failure mechanisms in CI pipes. It also assesses how pressure modulation can act as a preventative measure against risks associated with material degradation. The results indicate that adjusting the internal pressure in response to crack propagation can extend pipe life and decrease the leakage of sudden rupture.

3.2. Crack Propagation

In this study, the behaviour of cracks in brittle materials like cast iron was analysed using principles such as the stress intensity factor (SIF), which was employed to quantify the stress conditions near the tips of cracks and predict the onset of crack propagation. The influence of crack propagation in CI pipes was multifaceted, affected by internal pressure variations, exposure to corrosive elements, and different initial crack sizes. The corrosive environmental influences are clearly illustrated in Figure 6.

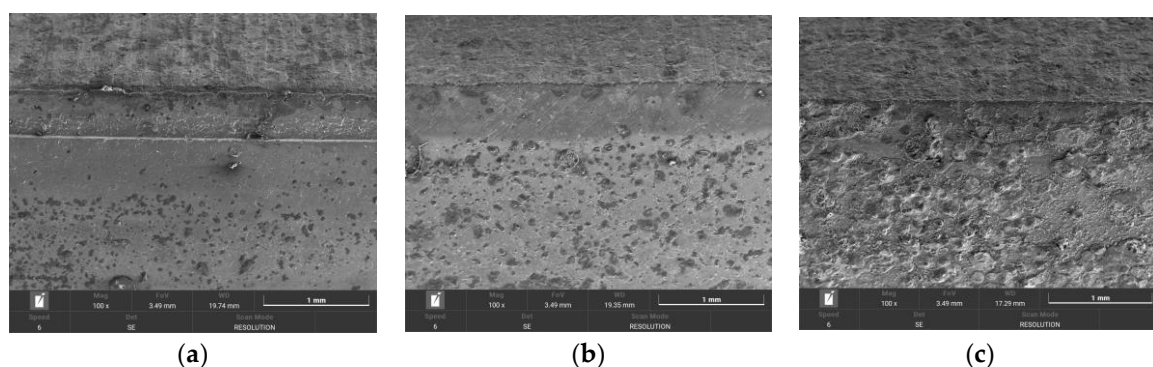


Figure 6. Corrosion conditions of the pipe surfaces after (a) 0 h, (b) 120 h, and (c) 200 h.

These images were captured through scanning electron microscopy (SEM) with $\times 100$ magnification. They show the surface morphology near the cracks on the CI pipe surface. The initial seeded cracks propagate throughout the captured area, as shown in the upper part of the images. Compared with Figure 6a, the pipe surface in Figure 6b exhibits more areas of pitting and roughness, with cracks irregular in shape and varying in depth, indicating the corrosion processes after 120 h. The morphology in Figure 6c shows further

degradation. The surface is covered with a heterogeneous layer of corrosion products. Corrosives penetrate deeper into the substrate.

The incremental changes in crack length can be visualised and measured under various conditions, as demonstrated in Figure 7. The analysis revealed that crack propagation increased from 0.55 mm to 2.43 mm. It was observed that larger cracks tended to grow more rapidly, as shown in Tables 7–10.

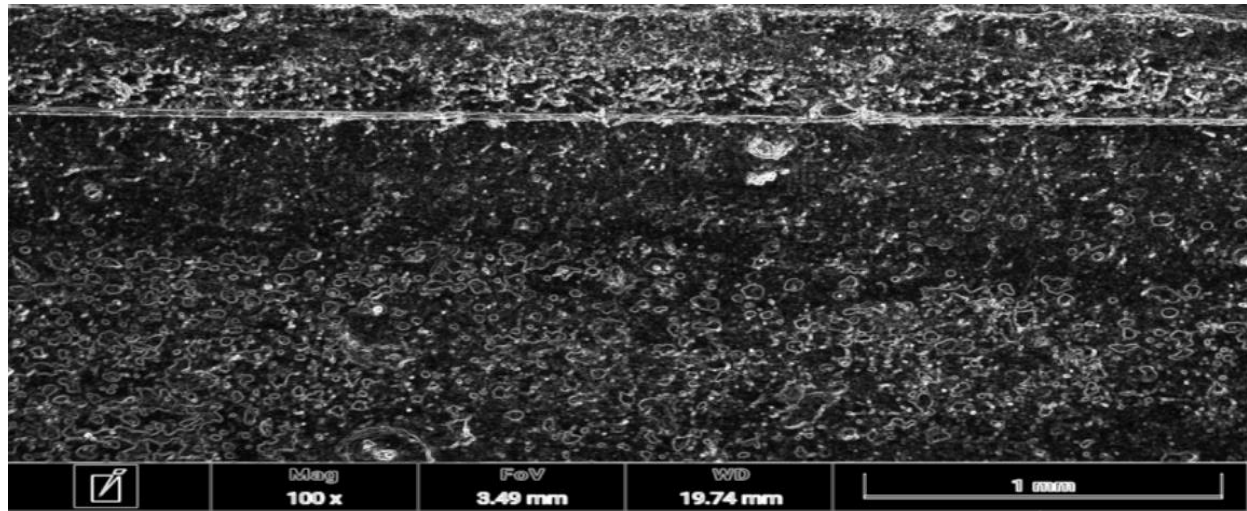


Figure 7. Visualised crack in the image processing software imageJ 1.54i.

Table 7. Crack propagation for the initial crack size of 0.5 mm and corrosion time.

Initial Crack Size 0.5 mm			
Corrosion Time 0 h	Corrosion Time 120 h	Corrosion Time 160 h	Corrosion Time 200 h
Crack Propagation mm/15 min	Crack Propagation mm/15 min	Crack Propagation mm/15 min	Crack Propagation mm/15 min
0.55	0.80	1.20	1.65
0.60	0.95	1.25	1.70
0.63	1.02	1.26	1.78
0.70	1.1	1.30	1.80

Table 8. Crack propagation for the initial crack size of 0.8 mm and corrosion time.

Initial Crack Size 0.8 mm			
Corrosion Time 0 h	Corrosion Time 120 h	Corrosion Time 160 h	Corrosion Time 200 h
Crack Propagation mm/15 min	Crack Propagation mm/15 min	Crack Propagation mm/15 min	Crack Propagation mm/15 min
0.58	1.20	1.35	1.83
0.62	1.23	1.38	1.88
0.64	1.30	1.40	1.93
0.74	1.33	1.44	1.97

Table 9. Crack propagation for the initial crack size of 1 mm and corrosion time.

Initial Crack Size 1 mm			
Corrosion Time 0 h	Corrosion Time 120 h	Corrosion Time 160 h	Corrosion Time 200 h
Crack Propagation mm/15 min	Crack Propagation mm/15 min	Crack Propagation mm/15 min	Crack Propagation mm/15 min
0.75	1.35	1.47	2.10
0.77	1.39	1.50	2.12
0.80	1.42	1.55	2.15
0.84	1.44	1.59	2.25

Table 10. Crack propagation for the initial crack size of 1.2 mm and corrosion time.

Initial Crack Size 1.2 mm			
Corrosion Time 0 h	Corrosion Time 120 h	Corrosion Time 160 h	Corrosion Time 200 h
Crack Propagation mm/15 min	Crack Propagation mm/15 min	Crack Propagation mm/15 min	Crack Propagation mm/15 min
0.77	1.47	1.62	2.30
0.80	1.52	1.70	2.35
0.82	1.55	1.90	2.40
0.85	1.59	2.09	2.43

This study comprehensively details the dynamics of crack propagation in CI pipes, presenting the results across various initial crack sizes (0.5, 0.8, 1.0, and 1.2 mm) as follows:

3.2.1. Initial Crack Size 0.5 mm

The data on corrosion time and crack propagation reveal a gradual increase in crack growth over time, as shown in Table 7. Initially, at 0 h, the crack growth ranged between 0.55 mm and 0.70 mm within 15 min. After 120 h of corrosion, the crack size increased to a range between 0.80 mm and 1.1 mm. This growth continued, reaching a range between 1.2 mm and 1.30 mm at 160 h. By 200 h, the crack size further increased, ranging between 1.65 mm and 1.80 mm. This significant increase in crack size due to prolonged corrosion time notably impacts stress resistance and elevates the risk associated with material failure.

3.2.2. Initial Crack Size 0.8 mm

The pattern resembles that of the 0.5 mm scenario but with greater increases in crack size over time, as shown in Table 8. Larger initial cracks show faster growth rates, emphasising the importance of monitoring and intervention, especially for larger cracks prone to rapid deterioration.

3.2.3. Initial Crack Size 1 mm

The data on corrosion time and crack propagation reveal a consistent pattern of increasing crack growth over time, consistent with previously observed trends but showing even larger increases in crack size, as shown in Table 9. This substantial growth intensifies durability and safety concerns, as the increasing crack size significantly impacts the material's stress resistance and elevates the risk of failure.

3.2.4. Initial Crack Size 1.2 mm

The data on corrosion time and crack propagation show a marked increase in crack growth rate from 0.77 to 2.43 mm, indicating significant material weakening due to 200 h of corrosion, as shown in Table 10. The rapid growth from the initial crack size underscores the material's high susceptibility to corrosion, intensifying durability and safety concerns.

This study reveals a consistent trend: As the duration of corrosion extended across all specimens (0, 120, 160, and 200 h) with an initial crack size of 0.5 mm, crack propagation increased from 0.55 to 1.80 mm per hour. Similarly, with an initial crack size of 0.8 mm, the crack extended from 0.58 to 1.97 mm, indicating a 4% increase. Likewise, with an initial crack size of 1 mm, the crack size propagated from 0.75 to 2.25 mm, marking a 3% increase. For an initial crack size of 1.2 mm, the crack propagated from 0.77 to 2.43 mm, representing a 5% increase. These findings underscore the significance of factoring in both the initial crack size and environmental conditions in material integrity assessments and lifespan predictions.

4. Empirical Modelling of Leakage, Crack Propagation, and Corrosion

4.1. The Use of Multi-Linear Regression to Identify the Relationships between Corrosion Time, Crack Size, and Leakage Amount

The results in Table 2 are illustrated in a 3D scatter plot, as shown in Figure 8, with a fitted polynomial surface to visualise the relationship between the variables. The independent variables, namely the corrosion time (CT, hours) and crack size (CZ, mm), are plotted along the x- and y-axes, respectively, while the dependent variable, leakage amount (LA), is represented on the z-axis. Each blue dot on the plot signifies an observed data point, correlating specific CT and CZ values to a measured LA value.

$$LA(x,y) = 8.069 + (-30.45)x + 0.01402y + 41.51x^2 + (-0.176)xy + 0.0002779y^2 + (-17.33)x^3 + 0.07944x^2y + 0.0005892xy^2 \quad (3)$$

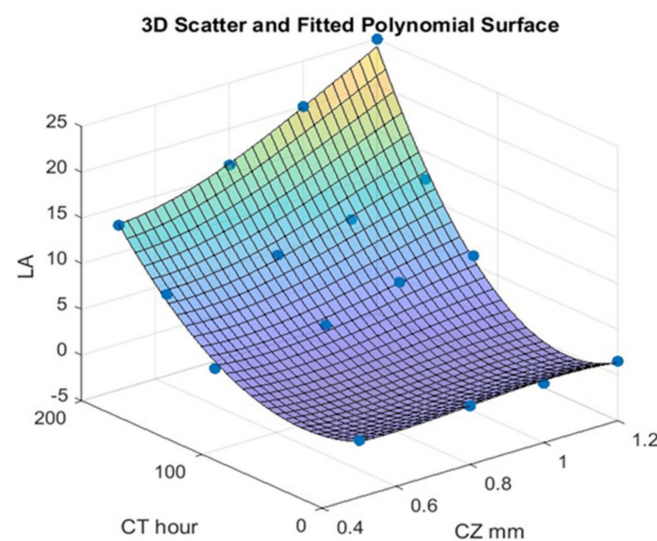


Figure 8. The relationship between crack size (CZ), corrosion time (CT), and leakage amount (LA). Blue dots represent the raw test data.

At lower CT hours and CZ mm, both near zero, LA starts at a negative value, around -0.5 , as indicated by the blue colour at the corner of the surface. As CT hours and CZ mm increase, LA increases, exemplified by a value around 8 mL at CT = 100 h and CZ = 0.6 mm. When CT and CZ approach their maxima, near 200 h and 1.2 mm, respectively, LA becomes positive, potentially reaching 20 mL, showing above the zero plane on the surface. A polynomial surface fitted through these data points visually represents the predicted LA values, colour-coded from 0 to 20, reflecting a relationship between CT, CZ, and LA. This model predicts LA values within the observed ranges, enhancing the understanding of the dynamics between these variables. The analysis examines how crack size and corrosion duration influence leakage amount. It demonstrates that larger cracks and longer corrosion times significantly contribute to the enhancement of leakage.

4.2. Methods for Evaluating the Accuracy of the Prediction Model

In this study, the effectiveness of the empirical model was assessed by applying evaluation metrics to gauge the model's performance. Specifically, we used the mean-squared error to quantify the accuracy of a model's predictions, as demonstrated in Equation (4). This parameter assesses the variance between the predicted and actual values [30].

$$MSE = (1/n) \times \sum (\text{actual} - \text{forecast})^2 \quad (4)$$

where $\sum$ is the sum, n is the sample size, actual is the actual data value, and forecast is the data value forecast.

4.3. Empirical Analysis and Results

The empirical analysis demonstrates significant degradation in cast iron pipes with larger crack sizes and extended corrosion periods of 0, 120, 160, and 200 h. This degradation is attributed to the increased SIF and the adverse effects of corrosion processes, such as pitting and stress corrosion cracking, causing material degradation. The model's findings are visually represented through a polynomial surface, where transitions in colour hues illustrate the detrimental impact of prolonged corrosion and increased crack dimensions on the pipe, as well as increased leakage amount.

4.4. Validation of the Empirical Model

The validation of the empirical model is presented in this section. Equation (3) models the relationship among crack characteristics, corrosion duration, and leakage quantity. The model was validated using the same material types but with varying crack sizes and corrosion durations. The crack sizes selected for this study were 0.9, 1.5, and 1.7 mm, while the corrosion durations were set at 100, 130, and 180 h, respectively, as presented in Table 11.

Table 11. Crack size and corrosion time values.

Crack Size (mm)	Corrosion Time (h)
0.9	100, 130, and 180
1.5	100, 130, and 180
1.7	100, 130, and 180

The predicted values for corrosion time, crack size, and leakage amount obtained from the model were compared to numerical estimations in the existing papers, as shown in Table 12. This model, formulated from empirical data, is derived from Equation (4).

Table 12. Comparison of leakage amounts.

Corrosion Time 100 h			
Crack Size (mm)	Leakage Quantity (mL/h)		
	Experimental	Empirical	Error %
0.9	3	2.8	0.4
1.5	5	4.7	0.6
1.7	6	6.2	0.2
Corrosion Time 130 h			
Crack Size (mm)	Leakage Quantity (mL/h)		
	Experimental	Empirical	Error %
0.9	8	7.9	4.45
1.5	8.3	9	0.33
1.7	10	10.3	0.5
Corrosion Time 180 h			
Crack Size (mm)	Leakage Quantity (mL/h)		
	Experimental	Empirical	Error %
0.9	17.5	18	0.28
1.5	20	20.24	0.4
1.7	26	25.4	0.21

Good agreement was observed between this model and the numerical models in [31–33]. Furthermore, as documented in Table 12, the MSE was employed to validate the results for leakage amount. A comparison of the MSE results between the empirical and numerical

models indicated an error range of 0.40% to 8% across all parameters. The error in estimating the leakage amount was below 10%, demonstrating the accuracy of the proposed model's predictions. Despite increased error margins in cases of larger cracks or prolonged corrosion, these results emphasise the necessity of establishing validation criteria that are tailored to the application's criticality.

The validation results confirm the empirical model's efficacy in predicting leakage. The low error percentages observed in most scenarios reinforce the model's precision and reliability. However, the noted variations in error rates, especially under conditions of increased crack sizes and prolonged corrosion durations, highlight areas where the model might require further improvement. These variations could be attributed to the complexities inherent in the corrosion process and the behaviour of larger cracks under prolonged exposure to corrosion.

5. Conclusions

Model development plays a crucial role in engineering, especially in assessing structural integrity under various conditions. This study focused on the impact of corrosion and mechanical loads on structural dynamics and crack propagation. An empirical model was formulated to include variables such as crack size, duration of corrosion exposure, and leakage quantity. The validation of the model was achieved through both experimental and numerical methods. The investigation revealed that crack propagation behaviour varied with changes in corrosion duration and crack size, particularly in scenarios involving large cracks and prolonged corrosion exposure.

This study also revealed the crack propagation characteristics in cast iron (CI) pipes exposed to corrosive environments. Our findings indicated a linear progression of crack growth regardless of the crack size and corrosion duration. Multiple cracks were observed on surfaces with pre-existing rectangular-shaped cracks, suggesting the usefulness of analysing crack propagation using pre-seeded cracks of specific geometries. However, future research should consider using naturally occurring cracks for more representative insights.

Experimental observations showed that corrosion progressively undermines material integrity, leading to crack initiation and expansion. As exposure to corrosive conditions extends, cracks tend to grow larger, which accelerates fluid leakage by providing more efficient channels for flow. This results in a significant increase in water leakage. A key finding was the correlation between model parameters and the reduction in material integrity, which decreased with increasing corrosion time and crack size. These results confirm that material strength reduction is an important factor to consider in such studies. The experimental data support this, indicating that longer corrosion duration and larger crack size lead to a decrease in material integrity.

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Leakage quantification in metallic pipes under different corrosion exposure times

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