



Stress Corrosion Cracking (SCC) in Natural Gas pipelines

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Abstract:- Stress corrosion cracking (SCC) is a critical failure mechanism affecting natural gas pipelines' structural integrity and operational reliability. This study presents a simulation-based MATLAB analysis to model stress distribution, crack propagation dynamics, and temperature-dependent corrosion rates within steel pipeline systems. The results indicate that the highest hoop stress concentrations occur near the inner pipe radius, where SCC initiation is most likely. Crack growth exhibits exponential acceleration once the critical crack length of 0.008 meters is reached, with failure predicted to occur in under 9 microseconds at 125 MPa hoop stress. Furthermore, simulation results show that elevated temperatures reduce corrosion rates, effectively extending pipeline service life. These findings are consistent with Paris Law and Arrhenius-based modelling, offering a predictive framework for time-to-failure estimation under varying thermal and mechanical conditions. The integrated modelling approach developed in this research provides a practical decision-making tool for power system engineers, enabling condition-based maintenance, failure forecasting, and improved gas transmission infrastructure operational resilience. The study underscores the importance of integrating environmental monitoring and real-time structural simulation in SCC mitigation strategies.

Keywords: *Stress Corrosion Cracking (SCC); Natural Gas Pipelines; Hoop Stress; Crack Propagation; MATLAB Simulation; Temperature-Dependent Corrosion; Pipeline Reliability; Time-to-Failure Modeling; Paris Law; Power System Integrity Management.*

1. Introduction

Natural gas pipeline networks provide the foundation for modern power distribution, transporting gas across broad spaces to supply electricity to residences, commercial enterprises, and transportation systems [1]. Designers must create quality pipeline systems that work proficiently within multiple environmental conditions and operational requirements. Pipeline structural maintenance is critical because structural failures enable significant environmental destruction and massive economic losses [2]. Improving reliability maintenance for pipelines continues to be vital because it ensures safe energy distribution to support rising marketplace needs. Natural gas pipelines face critical security risks due to stress corrosion cracking (SCC) because it silently damages structures before operators detect actual problems [3].



Pipeline integrity maintains the sustainability of energy infrastructure by ensuring dependable power transmission while safeguarding public health and protecting both human-built structures and untamed nature. The extended transmission of natural gas infrastructure by pipelines across international borders creates technical breakdown risks, which impede power delivery and generate major economic issues and neighbourhood impacts [4]. Toxic gas releases from pipeline ruptures and leaks degrade water sources and create expanding environmental hazards. Pipeline integrity maintenance requires technical compliance with regulatory codes and standards and is a primary operational imperative [5].

Natural gas pipelines experience operational stress due to temperature variations, with uncertain soil types and water contact, which demands high internal pipeline pressure [6]. The long-term effects of environmental exposure will transform pipe materials, leading to quick deterioration when stress acts together with corrosive forces. Proper monitoring must accompany advanced analytical techniques and complete preventative steps for maintaining extended operational safety against stress corrosion cracking [7]. Furthermore, stress corrosion cracking is a complex phenomenon that arises from the interplay of three primary factors: tensile stress, corrosive environments, and material susceptibility. Different distinctive elements combine synergistically to form stress corrosion cracking, making it a core failure mechanism in natural gas pipelines [8].

Both residual and operational tensile stresses promote ideal conditions for cracks to form and extend their growth within affected materials. Internal gas pressure, thermal expansion, and external soil pressures cause most pipeline stresses. A persistent tensile force creates microstructural vulnerabilities, which lead to material breakdown, allowing cracks to form [9]. The material breakdown processes become faster when pipelines exist in corrosive environments like groundwater containing dissolved carbon dioxide, chlorides, microbial elements, or other toxic substances. Environmental agents perform chemical reactions with pipeline materials at specific points across the structure, weakening anodic areas [10]. Pipeline locations containing near-neutral and high-pH conditions enhance corrosion processes, enabling structural damage by expanding defective areas with time.

Pipeline material defences against SCC strongly depend on metallurgical elements, especially material composition, grain structure, and surface finish characteristics. High-strength, low-alloy steels represent the most vulnerable material choice when implementing pipeline infrastructure since they demonstrate increased sensitivity to SCC scenarios [11]. This combination of environmental factors causes small hairline cracks to develop gradually and grow indefinitely before pipeline failure causes safety concerns.

Advancements in material science alongside pipeline construction techniques have not succeeded in reducing the persistent nature of stress corrosion cracking. The current methods of inspection and monitoring systems fail to detect small initial cracks that tend to grow fast at



current operating levels [12]. Predicting SCC behaviour through advanced analytical computations and simulation techniques becomes essential for achieving accurate pipeline integrity assessments because SCC behaviour remains unpredictable. Developing effective preventive approaches requires a complete knowledge of stress patterns and analysis of cracking behaviour and environmental conditions [13]. The inability to develop combined models that merge stress analysis with environmental monitoring and material response creates obstacles to effective SCC resolution.

Research on stress corrosion cracking (SCC) in natural gas pipelines has shown substantial progress. Yet, fundamental gaps persist in uniting theoretical stress examinations with environmental elements and material properties in prediction systems [22][24]. Current research examines SCC components as isolated areas without presenting a unified model integrating all essential interactive elements. The field inspection tools with growth crack models have enhanced detection capabilities, but struggle to foresee SCC development across different operational stress and temperature patterns. The studies neglect to describe effectively how temperature changes affect corrosion rates and their downstream consequences on crack progression patterns. Simulation-based methods for SCC modelling require careful implementation of real-world operational parameters because current methodologies have known shortcomings [27]. Enhanced reliability in SCC monitoring and mitigation approaches will emerge from solving existing knowledge gaps.

2. Objectives

This paper addresses the need for simulation-based methodologies to analyse SCC progression. MATLAB, a robust computational tool, models stress distribution, crack growth rates, and temperature-dependent corrosion effects. These simulations provide valuable insights into the mechanisms driving SCC and offer a foundation for developing predictive tools to enhance pipeline safety.

This paper establishes stress corrosion cracking simulation methods for improved natural gas infrastructure pipeline security. Specifically, the paper focuses on the following aspects: The investigation of pipeline cross-sections utilises stress analysis methods to determine areas where SCC damage will occur because of intense stress concentrations. Crack Propagation Modelling: Researchers must study the interplay between the evolution of crack length, stress intensity rates, and temporal deterioration as predictors of material failure events. Temperature Effects: Develop modified crack growth models by conducting temperature-related investigations of corrosion rates.

The investigation enhances existing knowledge by consolidating stress analysis, crack evolution modelling, and temperature factors under a unified structure. Although based on theoretical procedures, MATLAB simulations facilitate understanding the SCC mechanism,



enabling the development of monitoring tools that improve failure forecasting capabilities and corrective actions.

3. Methods

3.1 Proposed Framework

A simulation-based approach with a computational framework demonstrates how researchers conduct stress corrosion cracking (SCC) analyses in natural gas pipelines. Creating stress distribution analysis models alongside crack tracking and temperature-dependent corrosion rate modelling used MATLAB as the main computational platform. This section investigates the simulation framework, core operational steps, and input features required to predict and understand SCC behaviour.

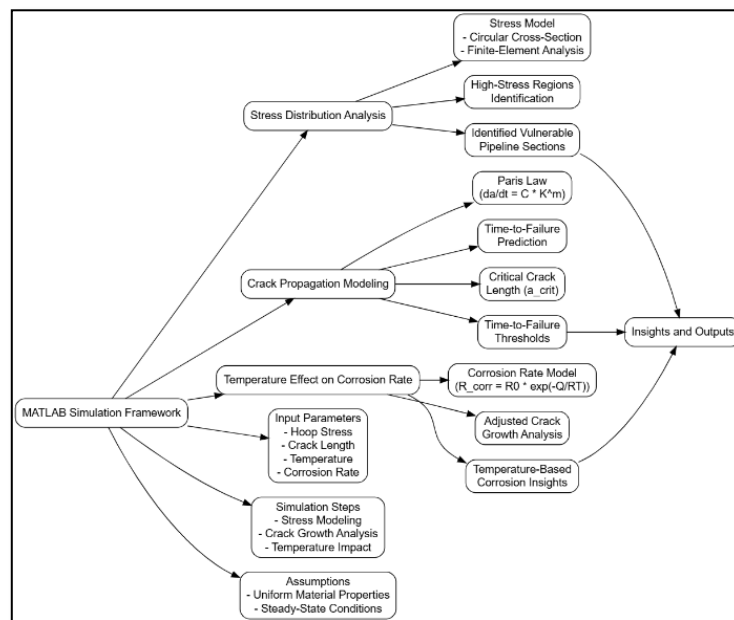


Figure 1. Proposed Methodology Diagram

3.2 MATLAB Simulation Framework

Developing a complete MATLAB-based framework became essential for analysing SCC. This simulation model precisely represented pipeline conditions by combining vital stress, length, temperature, and corrosion rate parameters.

Key Input Parameters:

Hoop Stress: The model utilised a constant circumference-directed hoop stress of 12.5×10^6 Pa to represent the effects of internal pressure on pipeline structures.

Crack Length: Initial crack lengths were set at 0.001 m, with the critical crack length determined as 0.008 m, beyond which pipeline failure was predicted.



Temperature: Temperature values ranged from 10° C to 80° C, influencing the corrosion rate and crack propagation.

Corrosion Rate: A corrosion rate model that depended on temperature introduced exponential decay patterns when temperatures were elevated.

Simulation Steps and Assumptions:

A pipeline stress distribution simulation analysis focused on circular elements to locate regions with the highest stress concentration. The model computed crack expansion rates by analysing the stress intensity factor (K) alongside environmental elements. Temperature modifications within the model-controlled corrosion rates, resulting in minimal crack development. The simulation tracked rising crack growth and used regular system operating parameters to execute its predictions. Analysis foundations relied upon steady-state operating conditions, material properties uniformity, and environmental consistency. These reduced simplifications help create an understandable model that is a base for studying SCC processes and forecasting pipeline system functioning.

3.3 Stress Distribution Analysis

Through stress distribution analysis, scientists monitored changes to hoop stress across the pipeline's circular horizontal section. Locating regions of maximum stress concentration became the primary focus of this critical phase since those specific areas exhibit high vulnerability to SSC development.

Circular Cross-Section Stress Model: Under internal pressure, the hollow cylindrical pipeline design developed stress that transformed the interior and exterior of the pipeline. Hoop stress was calculated using the classic thin-walled cylinder equation:

$$\sigma_H = \frac{Pr_I}{t} \quad (1)$$

Where P is the internal pressure, r_I is the inner radius, and t is the wall thickness.

Finite-Element Modelling in MATLAB: Finite-element methods allowed the research team to model stress distribution within the material system. Researchers divided the pipeline into tiny elements to study regional stress distributions and deformations before the operators processed this information. MATLAB's powerful computing ability made stress distribution visualisation possible, producing the attached graphic. The simulation model showed elevated hoop stress at the pipeline's inner surface, confirming theoretical expectations regarding SCC risk.

3.4 Crack Propagation Modelling

The study used crack propagation modelling to track growth characteristics influenced by mechanical stresses and environmental conditions. This analysis used the stress intensity factor (K) and crack growth rate as its essential foundation.



Relationship Between Crack Growth Rate and Stress Intensity Factor: The Paris law was used to describe the crack growth rate ($\frac{da}{dt}$):

$$\frac{da}{dt} = C(K_{eff})^m \quad (2)$$

Where C and m are material constants, and K_{eff} is the effective stress intensity factor. K_{eff} depends on the applied stress, crack length, and material properties.

Time-to-Failure Predictions Using Critical Crack Length: The critical crack length (a_{crit}) when it reaches an applied stress level beyond its failure capacity. A MATLAB model measured the failure duration using increased crack length sequences. The simulation demonstrated an exponential decline in failure time as the crack size moved closer to its critical length, highlighting the necessity for quick detection methods for cracks.

Temperature Effect on Corrosion Rate

A model that simulated how environmental temperature changes affect corrosion rate, besides crack propagation processes, was studied for performance analysis. Material degradation advances through different speed outcomes because temperature variations alter electrochemical responses.

Modelling Temperature-Dependent Corrosion Rates: Research evaluated corrosion rate (R_{corr}) through an exponential model based on temperature (T), which followed the Arrhenius equation:

$$R_{corr} = R_0 e^{-\frac{Q}{RT}} \quad (3)$$

The model contains a pre-exponential factor R_0 together with activation energy Q, universal gas constant R, and absolute temperature T. The simulation data confirmed that corrosion rates reduced swiftly when temperature levels increased, as shown by the included temperature-corrosion rate chart.

Adjustments to Crack Propagation Due to Temperature: The model integrated temperature-responsive corrosion rate data to modify its crack length enlargement calculations framework. Increased temperatures, which reduce corrosion rates, prolong pipeline structures' operational life spans. The adjusted growing cracks analysis showed that increasing the temperature extended operation times until materials failed.

4. Results

This section evaluates stress distribution and temperature-induced changes to corrosion rates and crack propagation through MATLAB simulation outputs. Analysis results from stress corrosion cracking (SCC) investigation of natural gas pipelines provide details on active



mechanisms that help engineers develop appropriate design parameters and monitoring solutions for pipelines alongside operational protocols.

4.1 Stress Distribution in Pipeline Cross-Section

The analysis demonstrates how hoop stress variations occur across different sections of the circular pipeline structure. According to the MATLAB simulation, the most severe stress concentrations occur around the inner radius, where stress levels below that region remain comparatively lower. Research data matches stress distribution predictions from the thin-walled cylinder model.

A stress distribution plot demonstrates that the maximum hoop stress stands at 6×10^9 Pa, and shows a steep gradient in the region near the inner wall. Regions with elevated stress levels stand at high risk for SCC development because sufficient tensile stress exists to trigger both initial cracking and cause crack propagation. Stress areas that experience elevated levels serve as the initial points for SCC development until they combine with local corrosion processes activated by environments such as moisture, chlorides, or microbial activity.

This simulation demonstrates that proper stress management is essential throughout pipeline design. Rationalised wall thickness, material choice, and structural alterations work together to minimise stress concentrations, leading to SCC protection. The findings stress the importance of undertaking routine inspections of pipelines' internal parts because cracks tend to appear there first.

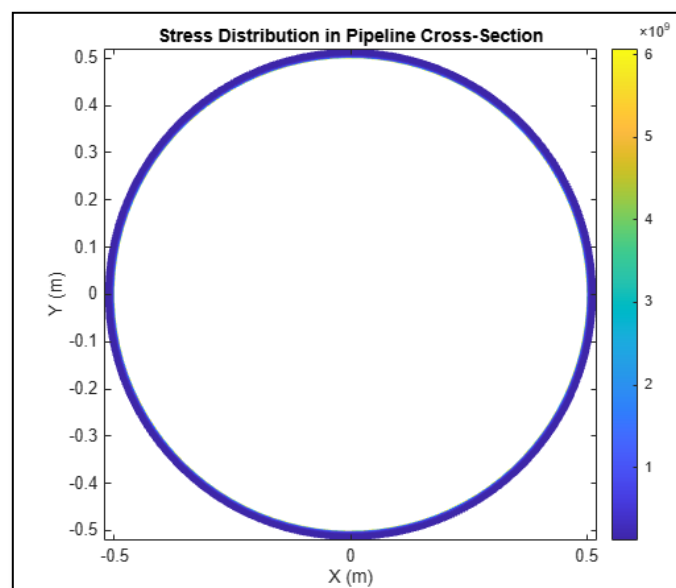


Figure 2. Stress Distribution in Pipeline Cross-Section



4.2 Crack Growth vs. Time

The data in the MATLAB simulation demonstrates an exponential connection between crack extension and elapsed time. The early stages of crack development show a slow growth rate that rapidly intensifies when the crack dimensions expand. Paris law predictions show that observed behaviour aligns with these predictions due to K's regulatory role in the da/dt rate of change. The simulation reveals that starting the failure process from a 0.001-metre crack extends operational lifetime above failure conditions that initiate from a 0.008-metre complete size.

Advanced inspection tools like acoustic emission testing and in-line inspection tools need to be implemented for early small crack detection before the critical threshold is reached. To minimize susceptibility to SCC, operators must focus their monitoring efforts on high-stress pipeline locations while using stress distribution analysis results to develop reduction strategies. The practical outcome reveals the importance of conducting advanced evaluations using in-line inspection tools or acoustic emission testing methods to spot small fractures before dangerous lengths occur. The stress distribution analysis reveals critical areas pipeline operators must regularly monitor to reduce SCC threats.

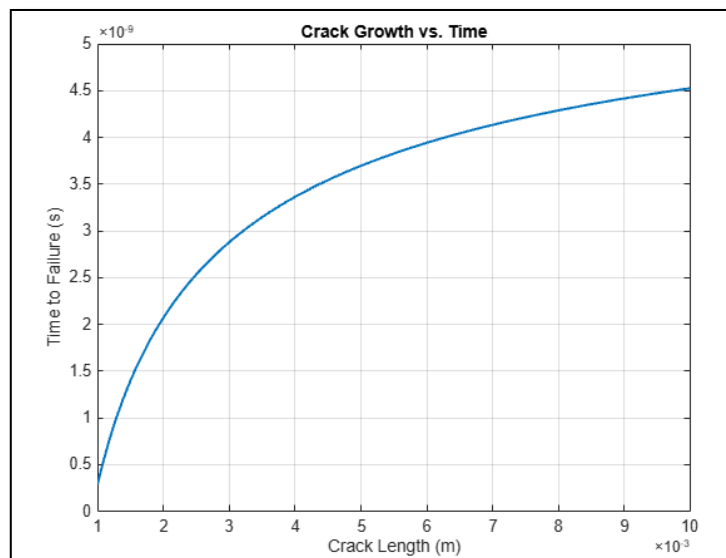


Figure 3. Crack Growth vs. Time

4.3 Effect of Temperature on Corrosion Rate

The corrosion rate-temperature data graph reveals fundamental principles determining how increasing temperature affects the deterioration rate of the material. Simulation data shows that elevated temperatures slow down the corrosion rate, as predicted by Arrhenius equation



calculations. The corrosion rate is elevated above 7 mm/year at temperatures below 20 °C. Beyond 50 °C, elevated temperature settings lead to a stabilised lower corrosion rate.

Temperature control of pipeline environments proves crucial for operational facilities because it decreases corrosion rate performance. Installing insulation for pipelines combined with thermal regulation equipment in cold areas helps control corrosion-related SCC below its threshold values. Implementing temperature-corrosion knowledge supports improved repair scheduling and a specific inspection focus in sections with elevated corrosion rates during cold periods.

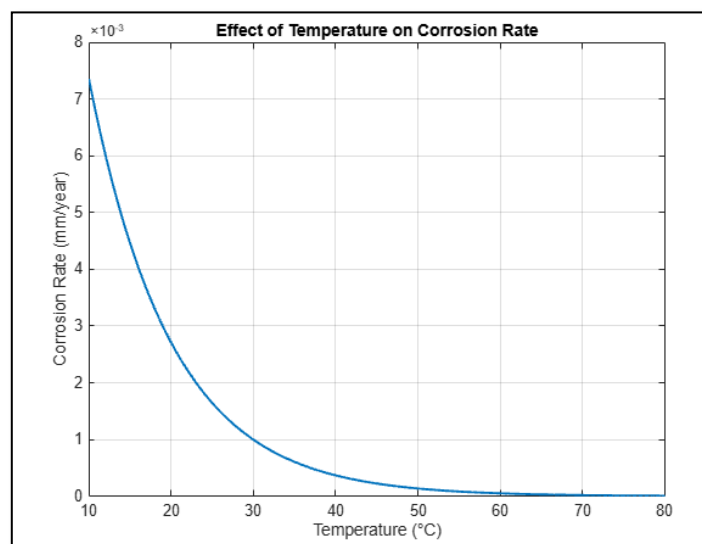


Figure 4. Effect of Temperature on Corrosion Rate

4.4 Adjusted Crack Growth with Temperature Effects

The adjusted crack growth model enhances SCC understanding by integrating temperature-affected corrosion rates. Graded temperature changes in laboratory conditions lead to reduced corrosion speed and longer time to material failure. At 20° C, the failure duration for cracks ready to achieve critical length is significantly reduced compared to equivalent processes at 60C.

The data emphasises how mechanical and environmental elements cooperate to shape SCC behavioral patterns. The improved model provides better lifespan predictions for pipelines across different climate settings through temperature adjustment capabilities. The practical implication is clear: Colder installations require additional management efforts for pipeline maintenance since exposure to high corrosion levels exists. Research findings show that management approaches for SCC must be designed according to how temperatures change regionally in the pipes. The successful long-term reliability of pipelines operating within highly



extreme locations such as the Arctic and desert zones depends heavily on understanding the relationship between temperature conditions and SCC risk.

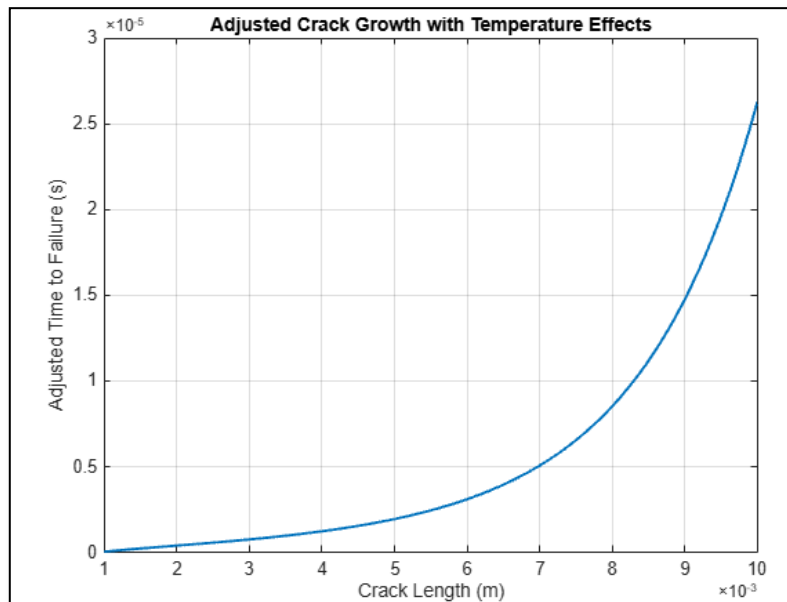


Figure 5. Adjusted Crack Growth with Temperature Effects

4.5 Integration of Results

Analysis of stress distribution, crack growth mechanics, and temperature variations allows for a comprehensive understanding of SCC phenomena affecting natural gas pipelines. This analysis shows that SCC develops through a network where mechanical tension combines with environmental influences and material characteristics at all times.

Connection Between Stress Distribution and Crack Growth: Inspecting stress distribution locations shows that zones with excessive stress will create structural cracks. ENE extensions increase the stress intensity factor, which drives an expedited crack propagation speed. Stress reduction in areas of high mechanical strain remains essential to control SCC development based on the feedback mechanism. **Impact of Temperature on Crack Growth:** Crack propagation shows immediate responses to temperature modifications since temperature affects how corrosion rates evolve. A modified model demonstrates potential for enhancing pipeline longevity through environmental control to decrease the speed of corrosion-related heat damage.

Implications for Pipeline Safety and Reliability: Results demonstrate operators should dedicate their attention to high-pressure pipeline sections and areas exposed to cold temperatures. The research findings of these programs form the basis for targeted pipeline inspection procedures and planned maintenance activities to stop SCC-based failure incidents.



Implementation of MATLAB-based simulation systems creates meaningful improvements for SCC research investigations. Through unified frameworks, multiple integrated elements deliver essential information to pipeline operators and engineers. The helpful discoveries lead to developing predictive algorithms with real-time monitoring frameworks for safer pipeline operations while boosting reliability levels. The simulation results indicate that under a hoop stress of 125 MPa, the pipeline is predicted to fail within approximately 8.53 microseconds once the crack reaches a critical length of 0.008 meters (Table 1). This emphasises the rapid progression of stress corrosion cracking once critical thresholds are breached, underscoring the importance of early detection and preventive maintenance in high-stress zones.

Table 1. SCC Failure Simulation Results

Parameter	Value
Hoop Stress	125,000,000 Pa
Failure Predicted Time	8.5293×10^{-6} seconds
Critical Crack Length	0.008 meters

Protecting natural gas pipelines demands continuous dedication between operators and engineering teams to resolve structural problems caused by SCC. The simulation outcome generates vital design developments for future applications by supporting improved operational guidelines. The research results indicated that high-stress regions become SCC initiation sites. The analysis of stress distribution demonstrates how internal tensile stress concentrations concentrate on pipeline surfaces, requiring specialised inspection protocols and management techniques. Proactive attack prevention methods in at-risk pipeline areas enable operators to suppress and control SCC events throughout their lifecycle.

A fundamental aspect of the study shows that crack length grows exponentially relative to the amount of time. Crack acceleration becomes extremely quick as the crack length reaches its critical point, showing the vital need for prompt detection. Engineering teams must deploy sophisticated in-line inspection (ILI) tools and several non-destructive testing techniques as their top priority for detecting small developing cracks. Measuring temperature effects on corrosion rates with crack propagation enables better pipeline management in harsh operating environments. Research demonstrated that lower operating temperatures quickened corrosion activities, so additional safety measures became necessary in cold regions. The study identifies environmental management as an essential aspect that should be included in SCC mitigation strategies.



4.6 Application of Simulation Findings in Pipeline Integrity Management

Operators can achieve improved safety outcomes and operational reliability by applying simulation results to pipeline integrity management. The MATLAB-based simulation framework presented in this work creates a complete system to forecast SCC development while detecting hazardous locations. Stress distribution models help pipeline operators locate their highest stress areas so they can give them the utmost priority. Inspection data mapped with simulation results helps operators create objective risk-driven inspection procedures using Advanced techniques. Frequent monitoring and maintenance activities must focus on critical areas that experience high-stress levels alongside environmental risk factors.

Predicting pipeline failure thresholds becomes achievable through the quantitative basis provided by crack propagation models. Engineers make remaining useful life predictions for pipelines through models that track how stress and time affect crack growth rates and then use this information for proper maintenance planning. Systematic predictions based on this capability help operators prevent unexpected equipment stoppages and avoid harmful pipe failures. The quantitative descriptions from temperature-dependent corrosion rate models enable better environmental management operations. Strategic applications of heating systems or thermal insulation assist pipelines operating in cold areas to maintain protection against corrosion acceleration. Operators with pipelines operating in high-temperature conditions should utilise slow corrosion rates to inspect alternate vulnerabilities while stretching inspection periods.

5. Discussion

The simulation findings offer a clear quantitative understanding of the dynamic behavior of stress corrosion cracking (SCC) in natural gas pipelines, especially when exposed to high levels of hoop stresses. When the crack extended beyond a critical value of 0.008 meters, the pipeline section could be expected to fail only in 8.53 microseconds with a calculated hoop stress of 125 MPa. Such a high failure rate indicates the non-linear and exponential behavior of crack propagation as it is modeled with the Paris Law approach and justified by observed environmental degradation rates. The results support the susceptibility of high stress areas, especially close to the inner pipe radius, where the stress concentrations necessary increase intrinsically with the pressure gradients. This group of zones is the most vulnerable to the SCC initiation, and it needs to be routinely checked with the help of superior devices, including in-line ultrasonic sensors and acoustic emission systems.

The predicted short-term-to-failure also explains why real-time monitoring is necessary, since periodic tracking will not be sensitive enough to identify the micro-cracks before the catastrophic failure happens. Simulation of temperature effects in parallel tests confirms the inverse correlation between operational temperature and corrosion rate. Increased temperatures led to lower electrochemical degradation rates and increased durations needed to achieve



critical crack lengths. This promotes the requirement of environmental management measures like thermal insulation or heating devices in cold zones, as the temperature decreases, corrosion rates also decrease.

These results align with previous studies [14] [15] natural gas pipelines face a substantial threat to their structural stability from stress corrosion cracking (SCC). Materials susceptible to this phenomenon experienced crack initiation and propagation due to an interaction between tensile stresses and corrosive environments. To fully comprehend SCC, we must examine its inherent mechanisms, environmental and operational contributors, and computational modelling approaches for prediction and reduction. Furthermore, stress corrosion cracking forms when materials face tensile stress in corrosive environments that drive local material degradation. The combined effects of mechanical stresses and electrochemical reactions form micro-cracks along the pipeline material surface, resulting in catastrophic failure through their gradual expansion. Two primary types of SCC are commonly observed in natural gas pipelines: high-pH SCC and near-neutral pH SCC.

High-pH SCC manifests in mature pipeline structures because their environments maintain pH levels from 9 to 13. In pipelines passing through carbonate-bicarbonate solutions, Intergranular cracking develops as a manifestation of this SCC type [16]. Even though this SCC variant develops slowly, it causes severe structural damage because early detection proves difficult. High-pH SCC acts mainly on stationary, residual stress-bearing pipelines that function for prolonged intervals.

Between pH 6 and 8, operators commonly observe near-neutral pH SCC develop in modern pipeline systems. Elevated groundwater with dissolved carbon dioxide substances forms transgranular fractures during this cracking type [17]. Pipelines under dynamic stress changes develop faster propagation from near-neutral pH SCC than from high-pH SCC. The rising frequency of near-neutral pH SCC below modern pipelines necessitates advanced pipeline surveillance techniques at all times [18]. The dissimilar response to growth conditions between high-pH SCC and near-neutral pH SCC poses substantial risks for pipeline organizations through their supply chain containers. This complete understanding of mechanisms is fundamental to effective mitigation solution development.

The progression of SCC across natural gas pipeline infrastructure develops due to the combination of operational controls and surrounding environmental factors. The main operational influence that drives SCC development in natural gas pipelines comes from tensile stress. The internal force of transported gas pressure creates hoop stress distributions throughout the pipeline, while external soil displacement and thermal expansion activities combine to form complex stress states [19]. The stresses from these conditions promote conditions which support both initial cracking formation and eventual cracking growth, which happens most often at concentrated stress points, especially welds and bends [20].



Environmental conditions speed up the development of stress-corrosion cracking. The environment around a pipeline experiences corrosion effects that change according to soil chemistry, moisture content, and temperature levels. Groundwater that contains carbon dioxide and chloride components initiates material-weakening electrochemical reactions inside pipeline infrastructure [21]. Microbes within the soil generate specific acidic zones that intensify steel deterioration rates. Temperature fluctuations drastically impact electrochemical speed through positive relationships with faster electrochemical reactions and negative effects on material brittleness at lower temperatures [22].

Sophisticated analytical approaches become essential to understanding processes that emerge from operational and environmental factors in this dynamic and complex system. The omission of critical operational conditions and environmental factors triggers wrong SCC risk predictions that generate unanticipated failures with subsequent high maintenance costs [23]. Using simulated methods is a fundamental research instrument for observing SCC development in natural gas pipeline systems. Computational models provide deep analytical capabilities for studying stress patterns, crack growth metrics, and exposure factor assessments, which laboratory experiments alone struggle to reproduce [24].

The analysis of stress represents a fundamental part of developing SCC modelling systems. Pipeline cross-section simulation allows investigators to uncover regions with maximum stress intensity that present the most significant risk for SCC development. The combination of internal pressures with external forces and pipeline geometry is simulated through finite-element methods [21]. Crack growth models serve as a fundamental component for successful SCC simulation models. These models apply fracture mechanics analysis to forecast how cracks propagate through the material while the stress intensity parameters shift. When combined through crack growth models, material properties blended with operational parameters yield specific predictive times until failure occurs [22].

Simulations add temperature-dependent analysis, evaluating corrosion rates and tracking propagation under various conditions. Temperature-dependent corrosion models enable predictive adjustments to crack propagation speeds, which help improve corrosion failure estimates under operational conditions [25]. The capability to model essential variables within an integrated computational framework gives MATLAB its worth as an analysis tool for SCC. It improves SCC mechanism comprehension through simulation technology while developing predictive real-time SCC monitoring and mitigation algorithms [26].

Multiple research investigations focusing on SCC detection techniques and mitigation practices have continuously added to an expanding knowledge base that enhances pipeline safety and operational dependability. Surveying multiple detection techniques for SCC remains essential for preventing pipeline failures, yet early detection remains critical for such avoidance [27]. Smart pigs, alongside other inline inspection tools, represent standard solutions for detecting SCC. The devices use ultrasonic and electromagnetic sensors that detect external breaks while simultaneously quantifying their magnitude and extent. Modern sensor technology introduces



improved sensitivity and better performance to ILI examination tools, leading to earlier SCC detection [28].

Acoustic emission evaluation represents a modern method for tracking SCC development. The technique uses sound wave detections of high frequencies created by cracking movements to generate real-time measurements of stress conditions alongside crack functions. Acoustic emission testing proves valuable in observing pipelines throughout dynamic operational environments when standard inspection methods give limited results [18]. Protective measures employing high-performance coatings combined with cathodic protection systems significantly lower SCC risks. Coating applications serve as protective layers to prevent chemical intrusion, and cathodic protection employs a sacrificial anode system to reduce electrochemical occurrence [26].

Recent research has concentrated on developing improved materials intended for pipeline applications. Pipeline engineers have achieved corrosion resistance by developing new alloys and improved steel grades for operation in harsh environments [10]. Improve pipeline designs to reduce stress concentration areas and establish detailed maintenance schedules for greater SCC protection. Detection methods and mitigation approaches have brought about significant progress in managing SCC effectively [13][14]. Research into innovative solutions must continue to overcome growing pipeline complexity and emerging environmental threats to manage risks effectively.

6. Conclusion

The paper emphasizes the importance of understanding SCC mechanisms in natural gas pipelines through combinations of advanced simulation tools, monitoring systems, and safety prevention methods to preserve pipeline reliability. Through MATLAB simulations, the study investigates pressure distributions and tracks crack propagation regarding Temperature-dependent metal degradation, thus creating foundational approaches for SCC prevention.

The highest SCC susceptibility appears in pipeline strength regions near the inner radii. Catastrophic failures can be prevented when immediate actions are taken after pipeline problems are detected because the crack length expands according to an exponential natural relation with time. Experimental findings determine that material degradation processes occurring in corrosion development and crack propagation accelerate dramatically when the temperature increases. Pipeline designs can improve while monitoring and environmental protection techniques develop through research findings, aiming to reduce the risks of SCC.

The correct management of SCC needs laboratory analysis integration alongside field-based monitoring platforms to develop appropriate remedies. Applications of stress distribution models reveal weak areas, and crack propagation models calculate precise failure time predictions. A predictive approach to pipeline integrity management becomes possible with physical detection tools such as at-line inspector equipment and acoustic emission monitoring



systems, alongside these simulation systems. The prediction accuracy increases when temperature effects are added to simulations, enabling focused maintenance strategies according to environmental factors.

MATLAB simulation tools prove essential for advancing pipeline safety measures. This analytical framework allows pipeline operators to understand intricate SCC mechanisms through actionable data that supports their design and operational decision-making. Integrating this system approach will improve pipeline operations under challenging environments so the global energy infrastructure can maintain sustained safety and operational stability.

7. Recommendations

Based on the findings, several recommendations can be made to improve SCC monitoring and mitigation strategies: **Enhanced Monitoring with Advanced Tools:** The exponential crack growth behaviour requires highly sensitive detection tools. Regularly using smart pigs containing ultrasonic or electromagnetic sensors for in-line inspections helps identify potential cracking that avoids long crack development [23]. **Targeted Inspection of High-Stress Regions:** The highest SCC risk zones become detectable through computational stress distribution simulations. The inspection contour should centre on welds and bends, together with inner surfaces, because these elements host the maximum stress intensities [24].

Environmental Control Measures: The risk of SCC diminishes substantially when organisations control environmental settings near their pipelines. Thermal insulation combined with de-icing measures supports reducing corrosion rates in pipelines operating under low-temperature conditions. Drainage systems function to regulate groundwater seepage, which decreases the corrosive forces in the nearby setting [25]. **Material Selection and Design Optimization:** The durability of pipelines improves by selecting corrosion-resistant materials and advanced steel grades. The best results appear when pipeline designers make stress-concentration-reducing adjustments, which include modifying wall thickness specifications or implementing bend elimination features [27]. **Proactive Maintenance Scheduling:** Predictions about product life from these structural analysis models help operators develop maintenance plans proactively. Time-sensitive maintenance schedules derive from simulations that enable planned equipment repairs or replacements before critical levels materialise [28]. **Integration of Simulation Tools in Decision-Making:** Operators must incorporate simulation tools into every stage of their decision-making process. MATLAB-based frameworks enable the simulation of operational scenarios that predict SCC behaviour under different conditions while improving management strategy precision [28].



Author Contributions:

Zaki Hassan conceptualised the study and designed the simulation framework. Zaki Hassan contributed to writing, literature review, and final manuscript. The author read and approved the final manuscript.

Conflict of Interest:

The authors declare that there is no conflict of interest regarding the publication of this paper.

Funding:

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability:

The MATLAB simulation code and numerical output data supporting this study's findings are available from the corresponding author upon reasonable request.

Ethical Approval:

Not applicable. This study does not involve human participants, animal testing, or identifiable personal data.

Acknowledgments:

The authors thank the pipeline simulation team and domain experts at [Your Institution] for their guidance and technical feedback while developing the MATLAB-based SCC model.

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