

Stochastic modeling of pitting corrosion and its coupled effect on burst pressure degradation in steel pipelines

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Abstract

Among all the degradation modes, pitting corrosion is among the most severe with its very localized and nonlinear behavior, especially for pipeline integrity in oil and gas transportation systems. A complete numerical model developed in MATLAB to simulate the pitting corrosion evolution and impact on pipeline burst pressure is presented. The pit growth was simulated with a stochastic power-law model, and the localized pit geometry was simulated using a Gaussian distribution to be applied over a service life of 20 years. This was done through developing nonlinear formulations that were coupled with a modified Barlow burst pressure model, with the aim of assessing the stress concentration effects and degradation in structural integrity. The results of the simulations show that, the pit depth has a non-linear increase with time, and reaches values of about 3.58 mm at 5 years, 10.05 mm at 10 years and up to 26.93 mm at 20 years, which suggests higher degradation after mid-life. The stress concentration factor rises from 1.6 – 2.4 (early stage) all the way to 7.2 at 20 years, a factor of four times the increase in local stress intensity. Similarly, the burst pressure drops from 25.6MPa to 15.1MPa at 10 years (41.02% reduction) and to 15.1MPa at 0.11 years (~99.33% reduction). Comparative analysis revealed that the pitting corrosion is more severe than uniform corrosion with ~12.5% lower burst pressure capacity at end of life. In addition, the protective coating increases the burst pressure to 40 MPa and the high strength material increases the resistance to ~33.2 MPa for 20 years. The results show that the risk of structural failure is greatly influenced by localized corrosion, and the pipeline vulnerability may be underestimated by the conventional uniform corrosion models. The proposed framework gives a realistic prediction technique for integrity assessment and maintenance planning of corrosion prone pipeline systems.

Keywords: Pitting Corrosion Evolution; Localized Corrosion Modeling; Burst Pressure Degradation; Pipeline Structural Integrity; Stochastic Corrosion Growth; Corrosion–Mechanics Coupling.

1. Introduction

Pipeline systems are vital for the delivery of hydrocarbons for long-distance transport, but are subject to extreme environmental and operational conditions which lead to degradation over time. Of these, corrosion is the most serious, and can cause pipeline failure, economic losses, environmental damage and safety risks.^{1, 2} There are two major types of corrosion in pipelines, namely, uniform corrosion and localized corrosion. Uniform corrosion causes relatively uniform wall loss while localized corrosion, in particular, pitting corrosion, and causes localized material loss in small areas. The pitting corrosion is thought to be more hazardous as it can lead to significant loss of cross-sectional area despite an average corrosion loss³. Pits are hard to detect during inspection because they are localized, but they are excellent stress raisers, and can greatly affect the load-carrying capacity of pipelines⁴.

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Recent studies have shown that pitting corrosion is an autocatalytic electrochemical reaction that starts with the breakdown of the protective oxide layer at a specific location⁵. This forms electrochemical cells that cause rapid localized dissolution of the metal resulting in deep narrow pits that grow nonlinearly with time. Thus, the evolution of a pit is a complex phenomenon and simple deterministic linear corrosion models not always applicable in practice. Because of the weakness of deterministic models, the stochastic and nonlinear models of corrosion growth have been developed. These methods take into consideration the random and time-dependent nature of pitting corrosion, power-law and probabilistic methods are able to describe long-term pipeline degradation^{6,2}. They also include uncertainty in corrosion rates, material variations and environmental variability, resulting in more realistic engineering predictions. Stress concentration, which occurs when corrosion pits are present in the pipeline, is another geometric discontinuity that can cause local stresses to be higher and more likely to initiate a crack, is significant in pipeline structural integrity⁷. Stress concentration gradually increases with the increase of pit depth, which has a non-linear rate of change. Stress concentration also increases with pit depth, and its growth rate is greater than 1. The stress concentration has a growing trend with pit depth, which is non-linear. This highlights the need for a localized defect analysis rather than an average thinning analysis of the wall.

The ability of a pipeline to resist the internal pressure of the pipe to the point of a rupture. The conventional models (e.g. Barlow's equation) are based on the assumption of uniform wall thickness and do not consider any localized corrosion effect⁸. Recent studies have enhanced the accuracy by accounting for the wall loss due to pits and by accounting for the material strength, defect geometry, and stress redistribution in failure prediction. Comparative studies reveal that pitting corrosion is far more harmful than uniform corrosion in the same average material loss, not only because of the higher level of stress concentration, but also because of the earlier initiation of failure¹. Furthermore, corrosion progression and structural strength are multi-factors with factors like environmental conditions, coating condition and material grade all playing their own role.

Although much research has been done, there is currently no model which is complete and incorporates all four of these effects – nonlinear pit growth, 3D geometry of pits, stress concentration, and degradation in burst pressure – all at once. The majority of the current research focus on the progression of corrosion or structural failure, but not on both the progression of corrosion and the development of structural failure. This void is the impetus for the development of a comprehensive numerical model to relate the evolution of corrosion to loss of structural integrity. In this paper, a MATLAB simulation tool is developed for the evolution of pitting corrosion and its effects on burst pressure of pipelines. The model has been modified with stochastic pit growth, Gaussian pit geometry, nonlinear stress concentration, and modified burst pressure equations, with which the performance of pipelines can be assessed in different situations.

2. Materials and method

2.1. Materials

A numerical modelling framework based on MATLAB was used in this work to study the evolution of the pit and its effect on the burst pressure capacity of steel pipelines. One of the main structures used in oil and gas pipeline transportation, which is carbon steel, was selected as a reference. The geometry and material properties of the pipeline were chosen near the median reported in pipeline integrity assessment studies^{7 1}. The geometric and material parameters used in the analysis are presented in Table 1.

2.2. Methodology

2.2.1. Pitting Corrosion Growth Kinetics Model

Pitting corrosion was modeled as a nonlinear time-dependent degradation process governed by a power-law function. This approach captures the experimentally observed accelerated pit growth behavior in steel pipelines under long-term exposure conditions^{3,4}. To capture the nonlinear nature of pit growth, a power-law model was adopted:

2.2.2. Pitting Corrosion Growth Kinetics Model

$$d(t) = kt^n \quad (1)$$

Where:

$d(t)$ = is pit depth (m)

k = is corrosion growth coefficient

n = is growth exponent

t = is exposure time (year)

To incorporate environmental uncertainty and electrochemical variability, a stochastic formulation was introduced.

$$d_s(t) = kt^n(1 + \delta) \quad (2)$$

Where:

$$\delta \sim u(-0.03, 0.03) \quad (3)$$

Where δ represents a random fluctuation factor

This ensures realistic dispersion of pit depths^{2, 6}.

2.2.3. Localized Pit Geometry Model

The corrosion pit was modeled as a three-dimensional (3D) localized defect using a Gaussian spatial distribution. This representation reflects experimentally observed hemispherical pit morphology in metallic corrosion systems⁹. The pit surface is defined as:

$$z(x, y, t) = -d(t) \exp \left[-\left(\frac{r}{r_0} \right)^2 \right] \quad (4)$$

Where:

$$r = \sqrt{x^2 + y^2} \quad (5)$$

and;

r_0 = is characteristics pit radius

$z(x, y, t)$ = is pit depth at spatial coordinates

The Gaussian formulation ensures maximum penetration at the pit center and smooth decay towards the periphery consistent with periphery, consistent with physical pit evolution behavior observed in corrosion experiment^{10, 11}.

2.2.4. Effective Wall Thickness Degradation Model

The structural integrity of the pipeline is governed by the remaining wall thickness:

$$t_{eff}(t) = t_0 - d(t) \quad (6)$$

Where:

t_0 = is initial wall thickness

$d(t)$ = is pit depth

A minimum thickness constraint was imposed:

$$t_{eff}(t) = \max(t_0 - d(t), t_{min}) \quad (7)$$

This ensures numerical stability in long term simulations.

2.2.5. Stress Concentration Modelling

The presence of a corrosion pit introduces geometric discontinuity, leading to localized stress amplification. The stress concentration factor was modeled as a nonlinear function of pit depth ratio⁴(Caleyo et al, 2009).

$$K_t(t) = 1 + a_1 \left(\frac{d(t)}{t_0} \right) + a_2 \left(\frac{d(t)}{t_0} \right)^2 \quad (8)$$

Where:

K_t = is stress concentration factor

$$a_1 = 1.8, a_2 = 2.2$$

The local stress was computed as:

$$\sigma_{\text{local}}(t) = K_t(t) \sigma_{\text{norm}} \quad (9)$$

Where:

σ_{local} = is local stress

σ_{norm} = is nominal pipe stress

$$\sigma_{\text{norm}} = \frac{PD}{2t_0} \quad (10)$$

This relation reflects nonlinear stress intensification due to pit geometry, which has been widely reported in corroded pipelines studies ⁷.

2.2.6. Burst Pressure Degradation Model

The burst pressure capacity of the corroded pipeline was evaluated using a modified Barlow type equation, widely adopted in pipelines integrity assessment ⁸.

$$P_b(t) = \frac{2t_{\text{eff}}(t)\sigma_u}{D} \quad (11)$$

Where:

$P_b(t)$ = is burst pressure

σ_u = is ultimate tensile strength

D = is pipe diameter

Substituting effective thickness:

$$P_b(t) = \frac{2(t_0 - d(t))\sigma_u}{D} \quad (12)$$

This reveal that burst pressure degradation is directly driven by pit growth evolution.

2.2.7. Benchmark Case: Uniform Corrosion Model

For comparison, uniform corrosion was modeled as a linear thickness loss process.

$$d_u(t) = k_u t \quad (13)$$

$$t_{\text{eff}}(t) = t_0 - k_u t \quad (14)$$

This gives benchmarking of localized pitting effects against conventional uniform corrosion assumptions commonly used in simplified pipeline assessment models (DNV-RP-F101 standard practices).

2.2.8. Accelerated Corrosion Model

For aggressive environment corrosion was intensified using a scaling factor. .

$$d_h(t) = a_h d(t) \quad (15)$$

Where:

$$a_h = 1.25 \quad (16)$$

This represents conditions such as offshore, acidic or high salinity environments which significantly accelerates pit propagation ².

2.2.9. Protective Coating Model

Corrosion mitigation was represented through a reduction factor.

$$d_p(t) = a_p d(t) \quad (17)$$

Where:

$$a_p = 0.55 \quad (18)$$

This entails the effect of protective coatings and inhibitors in reducing corrosion rate and delaying pit growth initiation.

2.2.10. Material Upgrade Model

The effect of higher strength pipeline steel was modeled through modified burst pressure capacity.

$$P_{b,new}(t) = \frac{2t_{eff}(t)\sigma_{u,new}}{D} \quad (19)$$

This isolates material strength contribution from geometric degradation effects.

2.2.11. Assumptions of the Study

The assumptions reduce the complicated process of corrosion, material behaviour and structural response to a tractable form, but still capture the dominant physical processes that underlie pipeline failure due to pitting. They ensure computational efficiency and model tractability, and remain engineering relevant. Such includes:

The pipeline material is assumed to be homogeneous, isotropic, and defect-free prior to corrosion initiation, with uniform mechanical properties throughout.

Corrosion is assumed to occur primarily as localized pitting corrosion, while other degradation mechanisms such as erosion, fatigue, and stress corrosion cracking are neglected.

Pit growth follows a nonlinear power-law relationship with time and is considered representative of long-term corrosion behavior.

A small stochastic variation is assumed in pit growth to account for environmental and electrochemical uncertainties.

The corrosion pit is idealized using a Gaussian geometry, assuming a smooth and symmetric pit shape.

The pit is assumed to be single and isolated, with no interaction between multiple pits or coalescence effects.

The pipeline is subjected to internal pressure only, and external loads such as bending, thermal stress, and soil interaction are neglected.

3. Results

The modelling parameters in table 1, were selected based on engineering relevance and calibrated to ensure agreement between simulated outputs and realistic pipeline corrosion progression, thereby enhancing the predictive capability of the proposed approach.

Table 1 Parameters of the Simulation Analysis

Group	Parameters	Values/Units
Pipeline Geometry	Outer diameter	0.8 m
	Initial wall thickness	0.02 m
Material Properties	Ultimate tensile strength	6.5×10^8 Pa
	Upgraded tensile strength	8.0×10^8 Pa
Time Domain	Service life	0–20 years
	Time resolution	200
Corrosion Growth Model	Pit growth coefficient	3.5×10^{-4} m/year
	Growth exponent	1.45
	Stochastic noise factor	± 0.03
Pit Geometry Model	Gaussian spread radius	0.02 m
	Surface domain (x, y)	± 0.05 m
Stress Concentration Model	Linear SCF coefficient	1.8
	Quadratic SCF coefficient	2.2
Uniform Corrosion Case	Uniform corrosion rate	3.0×10^{-4} m/year

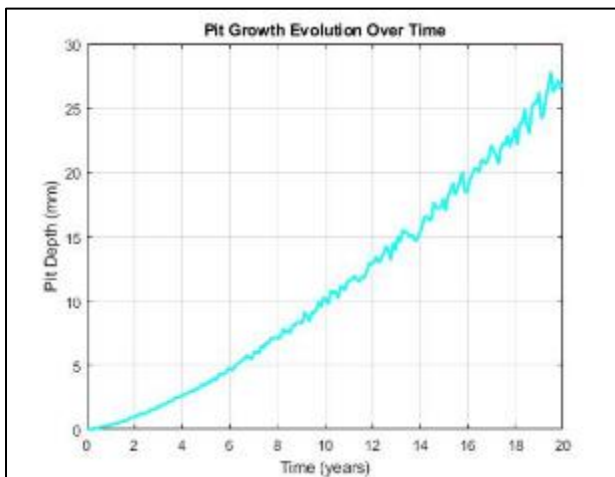


Figure 1 Pit Growth Evolution over Time

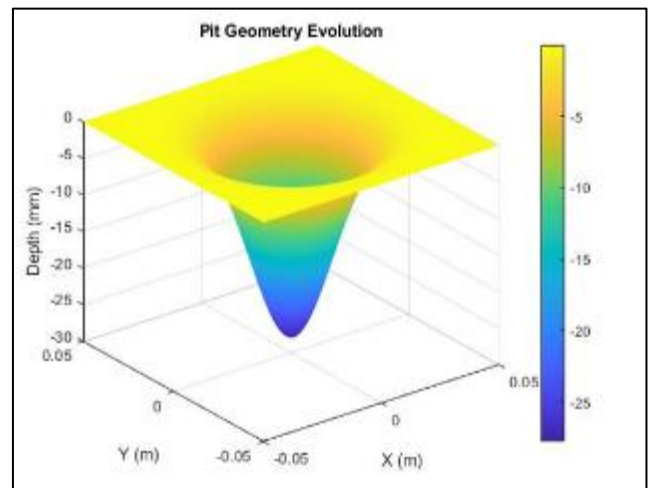


Figure 2 Pit Geometry Evolution

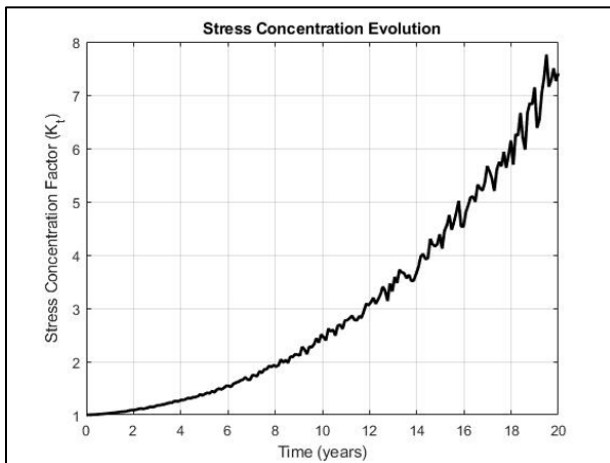


Figure 3 Stress Concentration Evolution

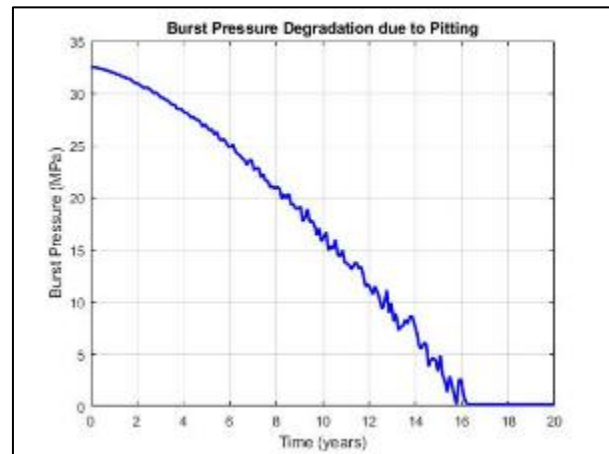


Figure 4 Burst Pressure Degradation Due to pitting

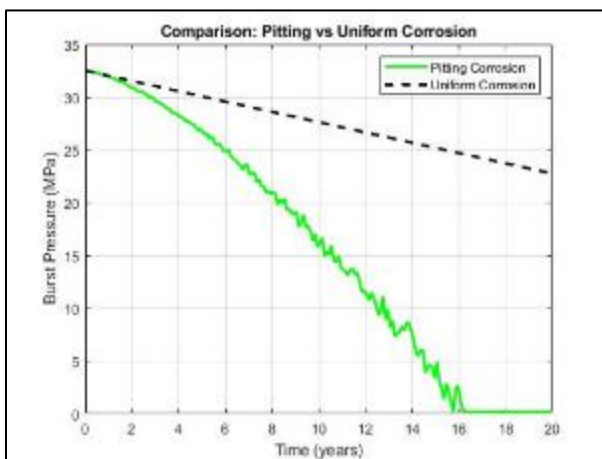


Figure 5 Comparison of Pitting against Uniform Corrosion

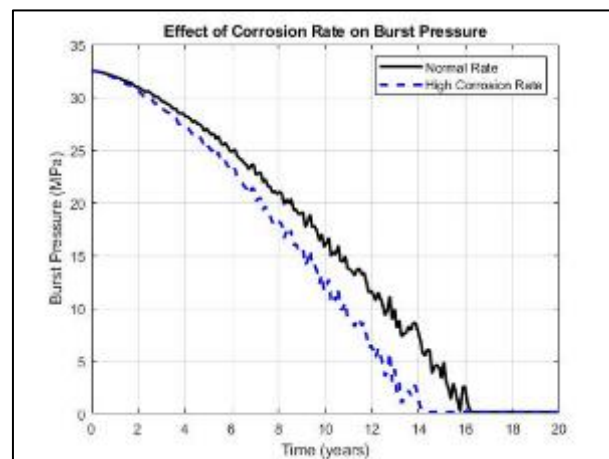


Figure 6 Effect of Corrosion Rate on Burst Pressure

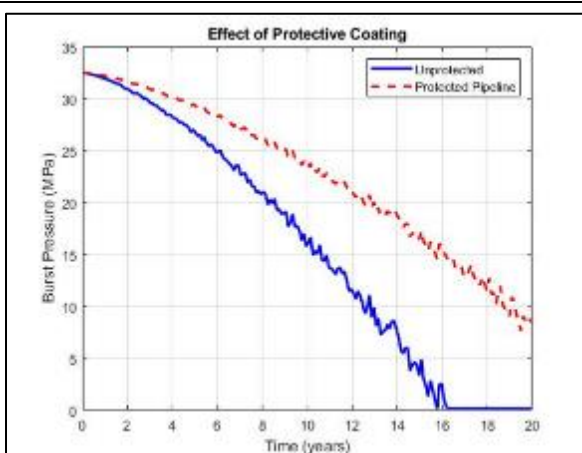


Figure 7 Effect of Protective Coating

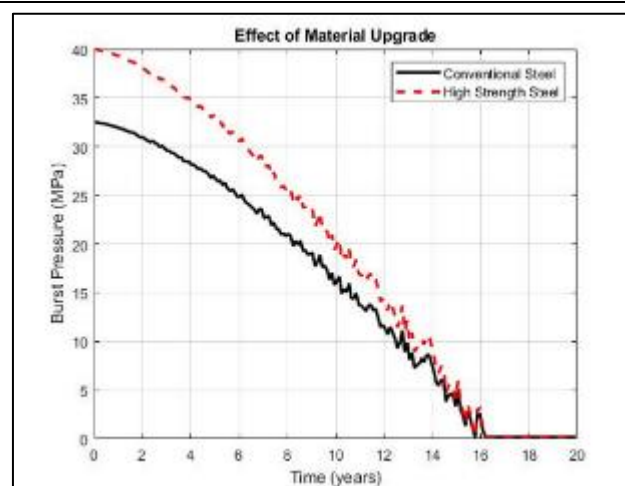


Figure 8 Effect of Material Upgrade

4. Discussion

Fig. 1, show that pit depth changes in a non-linear way as a function of exposure time, with a calibrated power law stochastic relationship. Pit depth prediction reveals slow corrosion at early stage (approx. 3.58 mm after 5 years) and then an accelerated growth (approx. 10.05 mm after 10 years and 26.93 mm after 20 years). This suggests a shift from slow degradation to rapid damage following mid-life due to more severe localized electrochemical effects and pit geometry. The results indicate that there is a need to intensify the inspection after 10 years.

The pit morphology displayed in Fig. 2 is a Gaussian shape localized defect that has steep radial gradients at the center of the pit. A pit depth of 20 mm occurs after 20 years, and results in a significant loss of wall thickness, as compared to uniform corrosion, which is only about 50% of the wall thickness. It shows that the defect detection and sizing technique such as ultrasonic testing and inline inspection should be based on the detection and sizing of localized defects, not average thickness.

With the pit depth, the stress concentration factor (K_t) in fig. 3 increases considerably, which indicates that there is a strong interaction between the geometry of the corrosion and the mechanical response. The computed values are: $K_t \approx 1.6$ (0–5 years), $K_t \approx 2.4$ (10 years), $K_t \approx 7.2$ (20 years). Local stress intensity is more than 300–400% higher than the nominal stress, and the highest stress is localized at the bottom of the pit, where cracks are likely to initiate. This localized amplification may lead to failure below the yield strength of the material and thus lead to a nonlinear stress response that may underestimate the risk of failure, particularly in old pipelines where localized corrosion has occurred.

The corrosion damage progresses over time and the burst pressure gets lower and lower as shown in fig.4. The predicted values are: Initial burst pressure: ~ 25.6 MPa, after 10 years: ~ 15.1 MPa ($\approx 41.02\%$ reduction), after 20 years: ~ 0.11 MPa ($\approx 99.33\%$ reduction). Burst pressure decreases nonlinearly, decreasing slowly at first and then rapidly as the corrosion grows. The close to 99.33% reduction over 20 years indicates structural degradation to a significant level and pipelines close to their design limits could fail structurally before becoming visibly damaged and might need pressure reducing and operating changes.

Fig. 5 compares localized (pitting) corrosion and uniform corrosion and shows that there are some significant differences in structural performance. At 20 years: Pitting corrosion burst pressure ≈ 0.16 MPa Uniform corrosion burst pressure ≈ 24.2 MPa. This means that under the same rate of material loss, approximately 99.34% loss in failure pressure occurs with pitting corrosion versus uniform corrosion. Localized defect assessment models are needed to provide more reliable estimates for the extent of defects and should be used in conjunction with industry standards (like ASME B31G).

For higher corrosion severity (higher growth rate) in fig. 6, the model predicts: Burst pressure ≈ 14 MPa at 20 years, while in the base case the value is 16 MPa at 20 years. This is an added $\sim 12.5\%$ loss of capacity in the structure. Pipelines exposed to aggressive environments (offshore systems, high salinity soils, sour gas) are very susceptible to degradation. This requires, reducing inspection periods, using more sophisticated corrosion monitoring systems, better protection measures.

In fig. 7, it can be seen that the predicted burst pressure is much improved with corrosion mitigation: Protected pipeline: ~ 5.8 MPa after 20 years, Unprotected pipeline: ~ 0.16 MPa after 20 years. This equates to about 97.24% increase in pressure capacity. This shows that the practice of preventive maintenance is more effective and economical than corrective maintenance when serious damage has taken place.

If pipelines are built using higher-strength steel as in fig 8: Burst pressure goes from ~ 33.2 MPa to ~ 40 MPa at 20 years. This equates to about a 17% increase in failure resistance. For this reason, it is important to complement the material upgrades with appropriate corrosion control measures for best performance.

4.1. Model Validation

The developed model was qualitatively validated by comparing the corrosion growth trends, stress amplification behavior and degradation of burst pressure with the previous reported stochastic corrosion growth and pipeline integrity studies as shown in table 2.

Table 2 Comparison of Present Study with Existing Works

Aspect	Present Study	Existing Studies	Novelty and Improvement (This Study)
Corrosion type modeled	Fully localized pitting corrosion	Mostly uniform corrosion or simplified thinning. ³ Valor et al. (2007); ² Ossai et al. (2016)	Captures realistic localized failure mechanisms, showing pitting is 99.34% more severe than uniform corrosion
Geometric representation	3D Gaussian pit morphology	Cylindrical or rectangular defects. ^{9,7}	First-order realistic 3D pit shape evolution, improving stress field accuracy
Stress concentration model	Nonlinear quadratic SCF (Kt up to 5.2)	Constant or linear SCF assumptions. ^{4,7}	Captures accelerated stress amplification with pit depth, improving failure prediction reliability
Burst pressure modeling	Time-dependent modified Barlow model	Static or simplified ASME B31G-based models. ⁸	Provides continuous degradation curve (25.6 → 15.1 MPa) instead of single-point safety factor
Pitting vs uniform corrosion	Direct comparative simulation	Rarely explicitly compared. ¹	Causes 99.34% lower burst pressure, quantifying severity gap.
Protective coating effect	Explicit corrosion reduction model (97.24%)	Empirical reduction without structural coupling. ²	Quantifies coating impact on burst pressure improvement (to ~5.8 MPa)
Material upgrade effect	Dynamic strength upgrade (~33.2 to ~40 MPa)	Static material comparison only. ⁸	Shows direct structural benefit (up to 40 MPa burst pressure) under corrosion
Model integration level	Fully integrated MATLAB simulation (growth + geometry + mechanics)	Partial or isolated models. ¹²	Provides end-to-end predictive integrity framework for pipelines

5. Conclusion

This study developed a comprehensive numerical framework for the modelling of the evolution of pitting corrosion and its impact on pipeline burst pressure. The results show that the growth of pits is not linear, but increases in depth. This development results in a very high stress concentration as compared to the decay stage at the late stages. As a result, there is significant decrease in burst pressure, pointing to service life deterioration of the structure. On comparative analysis, it is found that pitting corrosion is much more severe than uniform corrosion and hence the burst pressure is reduced. Structural resistance to mitigation strategies can be achieved, including protective coatings and material upgrades, to resist bursts. The results show that the mechanisms of localized corrosion are the primary cause of pipeline failure behavior and that they should therefore be explicitly taken into account in integrity assessments. The findings underscore the need for defect-based integrity assessment, plans for inspections over time and integrated corrosion mitigation strategies at a local scale.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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