Study on residual strength of oil and gas pipeline with corrosion defects under bending load

Chenxi Song[1,*], Jie Shu[2], Han Chen[1], Tong Shi[2], Xiatong Wu[2], Xiaoben Liu[2]

[1]Safety, Environmental Protection, and Technical Supervision Research Institute of Southwest Oil & Gasfield Branch, China National Petroleum Corporation, Chengdu, Sichuan, China.
[2]National Engineering Research Center for Pipeline Safety/MOE Key Laboratory of Petroleum Engineering/Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum-Beijing, Changping, Beijing, China.

Abstract: The significance of oil and gas pipelines in the exploration and production of oil and gas resources is well-documented. However, these pipelines are subject to a number of challenges that can compromise their integrity and operational efficiency. These challenges include structural defects, geological disasters such as earthquakes, landslides, debris flows, and land subsidence, as well as external forces such as dynamic impact forces, shear forces, extrusion forces, and uneven settlement forces. These defects can be exacerbated, thereby increasing the risk of pipeline failure. To accurately evaluate the pipeline's bearing capacity and safety, the study developed a nonlinear numerical simulation software called ABAQUS, utilising the Python programming language for analysis. Utilising this model, a systematic study of the dimensional characteristics of corrosion defects (including length, width, and depth) and the influence of pipe material (steel type) on residual strength has been conducted. The results demonstrate that an increase in the length and depth ratios of corrosion defects will result in a substantial decrease in the ultimate rupture pressure of pipelines. The integrity evaluation of oil and gas pipelines has revealed that the width of corrosion defects does not appear to have a discernible impact on residual strength. A thorough analysis of the experimental data reveals that, while the width is influenced by numerous factors, there is no statistically significant variation in the residual strength of corroded defect pipelines with different widths under standard test conditions. If the size and location of corrosion defects remain constant, upgrading the steel grade has been demonstrated to have a substantial impact on the pipeline's residual strength.

1. Introduction

It is inevitable that the oil and gas field pipeline will face the problem of outer wall corrosion as a result of its age, particularly in areas where geological disasters are frequent. In addition, the pipeline must be able to withstand various external forces. The combined effect of corrosion and external forces can significantly increase the risk of pipeline perforation, leakage and even fire accidents, which may ultimately result in pipeline failure. Consequently, it is imperative to undertake systematic and comprehensive inspection and maintenance procedures on the oil and gas field pipeline infrastructure to identify and rectify potential issues in a prompt manner, thereby ensuring the uninterrupted, reliable and secure operation of the oil and gas field [1].

A series of professional standards have been developed for the assessment of residual strength of corrosion-deficient pipes, including ASME B31G:2012, DNV RP-F101:2017, PCORRC code, API 579:2021 and SY/T 6477:2017. These standards form a scientific and unified evaluation framework, clarifying the evaluation process, calculation criteria and safety thresholds. Furthermore, they comprehensively consider the different types of corrosion defects and their specific impact on the safety of pipeline structures [2-3]. These documents are regarded as benchmarking texts within this field. The fundamental purpose of these standards is to employ a scientific and rigorous method to accurately measure the safety performance of pipelines containing corrosion defects. In particular, the ASME B31G:2012 standard has become one of the most common and indispensable evaluation bases in the field, due to its wide acceptance and the support of many practical application cases. ASME B31G [4], a recognised authoritative standard in the industry, has demonstrated its core value in practical application, but it also faces certain limitations and challenges. In response to these limitations, the China Energy Administration has introduced the SY/T 6477 standard, which, while retaining the essence of ASME B31G, pays more attention to the comprehensive consideration of defect size in the residual strength assessment, with the aim of overcoming the limitations of ASME B31G. Conversely, the DNV RP-F101 standard [5-6], developed in conjunction with Norges Verges and British Gas, has also gained significant traction within the industry. The ASME B31G standard is chiefly applied to piping systems with relatively simple internal pressure

* Corresponding author: scx1021@petrochina.com.cn

loads; its applicability is limited when complex and variable load situations are encountered. SY/T 6477 is a particularly noteworthy standard for the evaluation of residual strength in corroded and defective pipes. Its distinguishing features include consideration of internal pressure and comprehensive coverage of the effects of axial and bending loads. This provides a more extensive and nuanced perspective for evaluation purposes, facilitating a more precise understanding of the stress state of the pipeline. It is important to note that the SY/T 6477 standard does not take into account the core factor of defect width when evaluating the residual strength of pipelines. Defect width is the key to measuring the degree of corrosion, which has a significant impact on the bearing capacity and safety performance of the pipeline. If this factor is ignored, the estimates may be inaccurate. To enhance the accuracy of evaluations, it is recommended that SY/T 6477 be revised in the future to incorporate defect width, thereby ensuring a comprehensive evaluation and providing a scientific foundation for managers and engineers to make informed decisions. This clearly indicates the necessity for future research to enhance the evaluation method of pipeline residual strength [7-8].

The utilization of the finite difference method has proven to be both accurate and effective that has gained widespread adoption among scholars worldwide for its ability to explore the various factors affecting the residual strength of corroded defective pipes. The method's computational efficiency and its capacity to address complex structural problems have led to its significant recognition in the field of pipeline safety assessment. In the course of their investigation into the bursting pressure characteristics of corroded defective pipes, researchers have emphasised the significance of axial pressure and bending moment, indicating that these exert direct and substantial effects on the mechanical properties, stability and bursting pressure of pipes. Through meticulous research and analysis, the researchers have elucidated the specific mechanism of these mechanical elements on the burst pressure of the pipeline, thereby establishing a theoretical foundation for pipeline safety assessment and providing a valuable guide for the operation of practical engineering projects. This assertion has been corroborated by numerous research outcomes, as evidenced by the references. In the full-scale pipeline blasting test, Zhou [9] used systematic experimental means to thoroughly examine the impact of bending load on the blasting pressure of the pipeline. He meticulously documented the response of the pipeline under varying bending load conditions. Furthermore, he analysed the underlying physical and mechanical principles, comprehensively considering influential factors such as pipeline material characteristics, wall thickness and corrosion defects. This provided valuable experimental evidence and theoretical support for the field of pipeline engineering design and safety assessment. The findings revealed that the axial strain induced by bending load significantly weakens the residual strength of the pipeline. Specifically, an increase in bending load is accompanied by an intensification of axial strain, which reduces the pipeline's bearing capacity and bursting pressure. Shuai Yi [10] employed a validated finite element model to conduct a comprehensive analysis of how crack dimensions and positions influence the rupture pressure of corroded defective pipes subjected to simultaneous bending and axial compression. The study meticulously documented experimental results, provided an in-depth discussion of the relevant physical mechanisms and mechanical principles, and thoroughly assessed various potential influencing factors. This research offers a solid theoretical foundation and serves as a valuable resource for pipeline engineering design and safety evaluations.

In the context of pipeline integrity assessment, the prevailing focus has been on the behaviour of pipelines under internal pressure. Despite the considerable progress that has been made in the field of pipeline engineering, there remains a significant gap in the study of the influence of bending load on the residual strength of corroded defective straight pipe. In order to accurately evaluate the safety and reliability of such pipelines, it is imperative that a more robust and comprehensive theoretical framework is developed without delay. In order to construct this framework, it is necessary to effectively integrate various research methods, such as experimental verification, numerical simulation and theoretical analysis, and to fully consider various key factors, such as pipeline material, wall thickness, corrosion degree and load condition. In addressing this knowledge gap, this paper aims to contribute to the field by studying the influence of pipeline corrosion defects under bending load environments.

2. Numerical model

2.1 Material property

The present study is predicated on the engineering stress-strain constitutive relation of CSA Z662, which is the prevailing model of pipeline tensile mechanical properties. The objective is to construct a curve-fitting framework that will accurately simulate the stress-strain response of pipeline materials under tensile loads. Formula (1) provides a mathematical expression of this relationship, thus providing a scientific basis for strength assessment, safety design and failure prediction:

$$\varepsilon = \frac{\sigma}{E} + \left(0.005 - \frac{\sigma_y}{E}\right)\left(\frac{\sigma}{\sigma_y}\right)^n \tag{1}$$

The ε symbol is used to denote engineering strain, while the σ symbol is employed to represent engineering stress, which is measured in megapascals (MPa). The yield strength of the pipe is expressed in sigma y, also measured in MPa. The elastic modulus E is set to a constant value of 210 gigapascals (GPa), and N is used to represent the hardening index of the material. For a comprehensive numerical list of these parameters for L245 and X52 steels under specific conditions (condition number 14.14), refer to Appendix C of GB 50470:2017 Code for Seismic Design of Oil and Gas Transmission Pipeline Engineering. In the analysis stage, the yield

strength (σy) values are preset for L245 steel and X52 steel, which are 245MPa and 360MPa respectively, and their tensile strength (σt) values are also set to 415MPa and 460MPa. Following a detailed discussion of the stress-strain constitutive relation, the engineering stress-strain relation curve, which describes the mechanical properties of materials, is obtained successfully. In order to more accurately characterise the behaviour characteristics of materials during plastic deformation, it is recognised that the engineering stress-strain curve, based on the original size, should be transformed into the actual stress-strain curve, which reflects the size change during the actual deformation. This conversion process is critical for improving understanding of the plastic properties of materials and for optimising related engineering applications.

$$\sigma_{true} = \sigma_{eng}\left(1+\varepsilon_{eng}\right) \tag{2}$$

$$\varepsilon_{true} = \ln\left(1+\varepsilon_{eng}\right) \tag{3}$$

In the given formula system, σ_{eng} is used to denote the engineering stress of the pipeline material, which is calculated based on the initial cross-sectional area and used to represent the stress per unit area. ε_{eng} is employed to denote the engineering strain of the pipe material and measure the relative change in length based on the initial length definition. σ_{true} is used to denote the true stress of the pipe, which is calculated by considering the actual cross-sectional area after deformation and accurately reflects the stress characteristics in the plastic deformation stage. Finally, ε_{true} is the true strain of the tube and accurately describes the length change based on the actual length definition after deformation.

2.2 Finite element model building

In the process of constructing the pipeline corrosion damage analysis model, a three-dimensional eight-node linear simplified integral element (C3D8R) was selected to shape the pipeline solid model containing corrosion characteristics. The model accurately describes the geometry and material properties of the pipeline, including the diameter of the pipeline, the wall thickness, the specific distribution and shape of corrosion damage, and the mechanical parameters of the material. This high-precision model provides a solid and accurate foundation for the subsequent finite element analysis, thereby ensuring the reliability of the analysis results. Furthermore, it offers a robust framework for in-depth research on the specific role of corrosion damage on the performance and safety of pipeline structures.

The present study has sought to explore the blasting characteristics of corroded defective pipes. To this end, extensive and in-depth simulation research has been conducted, with the specific aim of exploring the action mechanism of corroded defects on the mechanical characteristics and structural safety of pipelines. The simulation has taken the size, shape and distribution characteristics of corrosion defects into full account, thus enabling the accurate measurement of their effects on the blasting pressure, deformation mode and fracture process of the pipeline. In order to simplify the calculation process and improve efficiency, a simplified model of a 1/2 pipe containing corrosion defects was established according to the symmetry characteristics of the pipe (see Figure 1). The model accurately reflects the location information, morphological details, specific dimensions, and important geometric parameters (including diameter, wall thickness, and the relative position between the defects and the pipeline axis) of the corrosion defects in the pipeline. This provides a solid and reliable platform for subsequent research and promotes deeper discussion on the mechanism of corrosion defects affecting pipeline performance. The outer diameter of the pipe is specified as D, and the overall length is set to five times the outer diameter, that is, 5D. In order to construct a symmetrical model of the tube, the model length is set to half the full length, specifically 2.5D. With regard to corrosion defects, the core characteristics have been documented in detail, covering defect L_c, W_c and D_c. In the setting of model constraints, in order to ensure the symmetry of the model, we specially apply symmetric boundary conditions to the left end face of the model, which plays an important role in the modelling process, and a rigid body constraint is set at the position of the pipe segment 0.25D from the right end face, with the coupling realised with the reference point RP-1.

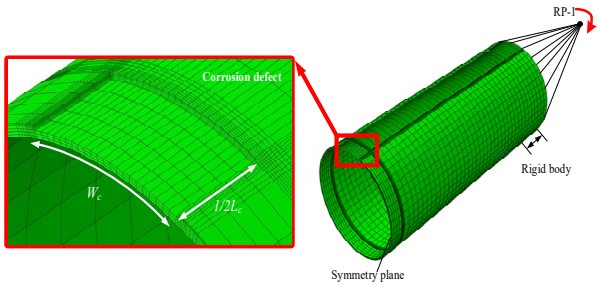

Figure 1. A finite element model designed to evaluate the remaining strength of pipelines with corrosion-induced flaws

2.3 Modeling condition statistics

For L245 and X52 pipes, the residual strength was simulated under conditions of corrosion defects and bending load, with pipe parameters (**Table 1**) and corrosion defect size (**Table 2**) recorded in detail. The blasting failure of the model was verified by applying 0.125% bending strain. The present study focuses on the analysis of the effect of corrosion defect size on the residual strength of pipelines. To this end, a series of normalized parameter systems have been adopted, covering such important factors as the normalization of defect L_r, W_r, and d_r, and the specific formulas were $L_r=L_c/\mathrm{sqrt}(Dt)$, $W_r=W_c/\mathrm{sqrt}(Dt)$, and $d_r=d_c/t$, which provided great convenience for subsequent research.

Table 1. Table of pipe geometry, material and load parameters

Steel grade	Pipe diameter, mm	Pipe thickness, mm	Bending strain,%
L245 X52 X70	323.9	7.0	0.125

Table 2. Pipe corrosion defect size parameter table

Length ratio of corrosion, L_r	Width ratio of corrosion, W_r	Depth ratio of corrosion, d_r
1, 3, 5	2, 4, 6	0.3, 0.5, 0.7

3. Residual strength analysis

In this study, the failure of pipeline blasting was evaluated according to the DNV standard, with the criterion being that the equivalent Mises stress in the thickness direction of the corroded section ligament would fail. Based on this principle, the relevant results are shown in **Table 3**.

Table 3. Results of finite element analysis on the residual strength of pipelines with corrosion defects

Diameter*thickness of pipe/mm	Bending strain, %	Steel grade	Length ratio of corrosion, L_r	Width ratio of corrosion, W_r	Depth ratio of corrosion, d_r	Residual strength of pipe, MPa
323.9*7	0.125	L245	1	2	0.3	14.25
		X52	1	2	0.3	20.50
			3			18.25
			5			17.00
			1	2	0.3	20.50
				4		20.50
				6		20.50
			1	2	0.3	20.50
					0.5	19.00
					0.7	15.75
		X70	1	2	0.3	25.00

4. Results and analysis

4.1 The effect of corrosion depth

The present study investigates the effect of defect depth ratio on the residual strength of X52 steel grade and D323.9×7mm corroded pipeline. To this end, experiments were conducted to analyse the variation of pipeline residual strength under different defect depth ratios. In order to ensure the accuracy of the results, the influence of other variables was also taken into account. The analysis results of the influencing factors are documented in detail in **Table 4**, which clearly demonstrates the close relationship between defect depth and pipeline performance. Furthermore, as demonstrated in **Figure 2**, an increase in the defect depth ratio is associated with a decrease in the ultimate rupture pressure of the pipeline. This underscores the pivotal relationship between the defect depth ratio and the ultimate rupture pressure of the pipeline, emphasising its significance in pipeline safety evaluation. An augmentation in the defect depth ratio signifies a reduction in pipe wall thickness, a weakening of the bearing capacity, and an escalation in the risk of rupture.

Table 4. Assessment of Elements Affecting the Residual Strength of Pipelines in Relation to the Defect Depth Ratio

Steel grade	Diameter, mm	Thickness, mm	Length ratio, L_r	Width ratio, W_r	Depth ratio, d_r
X52	323.9	7	1	2	0.3 0.5 0.7

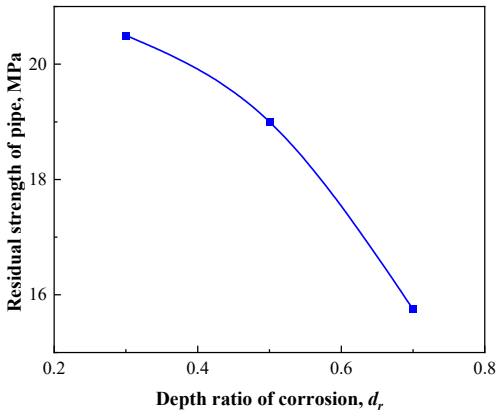

Figure 2. Impact of Defect Depth Ratio on the Residual Strength of Pipelines

4.2 The effect of corrosion length

The present study comprehensively evaluated the influence of defect length ratio on the residual strength of X52 steel corroded pipelines with a diameter of 323.9 mm and a wall thickness of 7 mm. A series of carefully planned experiments were conducted to this end, with the results of these experiments summarised in **Table 5**. The findings of this study provide a solid foundation for further exploration into the mechanism by which defect length ratio influences the residual strength of pipelines. As demonstrated in **Figure 3**, there is a clear trend of decreasing ultimate rupture pressure with increasing pipeline defect length ratio. This negative correlation once again demonstrates the significant influence of the defect length ratio on the mechanical properties of pipelines and highlights its key role in pipeline safety evaluation. An increase in the defect length ratio leads to an extension of the damage range of the pipeline, weakening its structural integrity and reducing its bearing capacity.

Table 5. Analysis of factors affecting residual strength of pipeline by defect length ratio

Steel grade	Diameter, mm	Thickness, mm	Length ratio, L_r	Width ratio, W_r	Depth ratio, d_r
X52	323.9	7	1.0 3.0 5.0	2	0.3

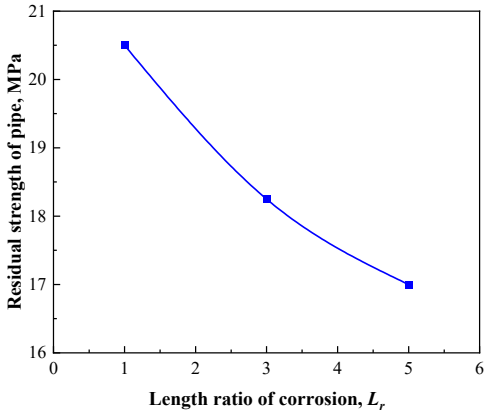

Figure 3. Influence of defect length ratio on residual strength of pipeline

4.3 The effect of corrosion width

This paper sets out to explore the impact of defect width ratio on the residual strength of X52 steel corroded pipelines with a diameter of 323.9 mm and a wall thickness of 7 mm. To this end, a series of meticulously designed experiments have been conducted to analyse the variation in residual strength of pipelines with different defect width ratios. A comprehensive analysis of the influencing factors was conducted, and the results were systematically summarised in Table 6. As demonstrated in **Figure 4**, despite an augmentation in the defect width ratio during the experiment, the ultimate rupture pressure of the pipeline exhibited relative stability.

Table 6. Analysis of factors affecting residual strength of pipeline by defect width ratio

Steel grade	Diameter, mm	Thickness, mm	Length ratio, L_r	Width ratio, W_r	Depth ratio, d_r
X52	323.9	7	1	2.0 4.0 6.0	0.3

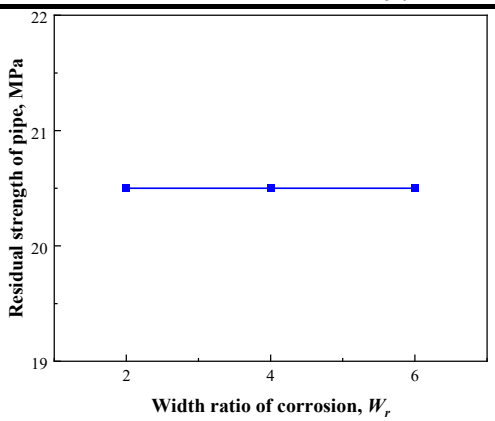

Figure 4. Influence of defect width ratio on residual strength of pipeline

4.4 The effect of steel grade

The present study investigates the impact of high-strength low-alloy steel, stainless steel and weathering steel on the residual strength of corroded D323.9 mm × 7 mm pipe. Utilising rigorous corrosion conditions as a framework, the findings reveal a substantial influence of these steels on the residual strength of pipelines. The analysis delves into the underlying factors influencing pipe steel grade, providing a detailed discussion of the key data and observation results, as outlined in **Table 7**. As demonstrated in **Figure 5**, with an increase in pipeline steel grade, the ultimate burst pressure of the pipeline exhibits a steady upward trend.

Table 7. Analysis of working condition table of influencing factors of pipeline steel grade on residual strength of pipeline

Steel grade	Diameter, mm	Thickness, mm	Length ratio, L_r	Width ratio, W_r	Depth ratio, d_r
L245 X52 X70	323.9	7	1	2	0.3

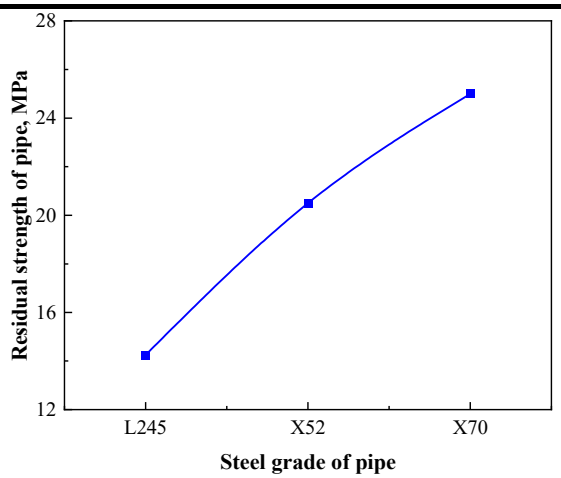

Figure 5. Influence of steel grade on residual strength of pipeline

5. Conclusion

The utilisation of ABAQUS software facilitated the successful construction of a finite element model for pipelines afflicted with corrosion defects. The model comprehensively encompassed the geometric characteristics, material properties and defect characteristics of pipelines, thereby ensuring the veracity of the simulation. Through detailed analysis of the data, the effects of defect size variables (such as depth, length and shape) and steel material characteristics on the ultimate rupture pressure of pipelines were extensively discussed.

The findings of the research indicate a negative correlation between the ultimate rupture pressure of the pipeline and the ratio of diameter to wall thickness, the increase of defect length and the deepening of defect depth. This underscores the imperative for meticulous regulation of these pivotal parameters during the design, fabrication and subsequent maintenance of the pipeline. That is to say, an increase in these factors results in a

corresponding decrease in ultimate rupture pressure. Conversely, when the defect size and location remain constant, the pipeline's residual strength is shown to exhibit a substantial enhancement with an improvement in steel grade.

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