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Research on the Influence Characteristics of Pitting Damage on the Stress of Downhole Tubular Columns

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Abstract: Production gas well tubing is long-term exposed to harsh corrosive environments, and pitting damage has become one of the main forms of tubing failure, seriously threatening the safe production of oil and gas fields. In response to the failure problems of tubing surface multi-pitting damage and under the action of complex loads in actual working conditions, this paper adopts a method combining finite element numerical simulation and fracture mechanics theory analysis to systematically study the influence of pitting damage on the stress distribution, load-bearing characteristics and failure mechanism of downhole tubing. The research shows that the depth of a single pitting pit is significantly positively correlated with stress concentration, while the hole diameter is negatively correlated with equivalent stress when the depth remains unchanged. For multi-point overlapping damage, the smaller the axial distance between the two holes, the more significant the stress concentration, while the radial distance has a smaller impact on the equivalent stress. In addition, under various loading conditions such as tension, internal pressure and external pressure, the increase in the number of pits will significantly intensify the stress concentration phenomenon and greatly reduce the ultimate load-bearing capacity of the tubing. Theoretical analysis further reveals that pitting damage leads to tubing failure through inducing crack initiation and propagation as well as weakening the effective load-bearing cross-section, ultimately resulting in tensile fracture and collapse. The results of this study provide important theoretical basis for the corrosion protection, remaining life assessment and structural safety design of gas well tubing.

Keywords: Production gas well tubing string; Pitting damage; Stress concentration; Bearing characteristics; Numerical simulation; Failure mechanism.

1. Introduction

The production gas well pipe string, as a key pressure-bearing and transmission component in the oil and gas extraction process, is constantly exposed to a harsh environment of high temperature, high pressure, multiphase flow, and corrosive media. Its structural integrity and service life directly affect the safe production and economic operation of the oil and gas field. Among various corrosion types, pitting corrosion, due to its local nature, concealment, and high destructiveness, has become one of the main forms causing the failure of the pipe string[1-3]. Pitting corrosion not only reduces the effective bearing cross-section of the pipe string, but also causes significant stress concentration due to its geometric discontinuity, significantly reducing the fatigue strength and fracture resistance of the material, and subsequently triggering crack initiation and propagation, even causing sudden leakage or fracture accidents[4-7].

In recent years, with the advancement of unconventional gas reservoirs and the development of deep and ultra-deep wells, the pipe string is facing more complex mechanical and chemical environmental coupling effects, and the problem of pitting corrosion has become increasingly prominent[8-10]. Domestic and foreign scholars have conducted a large number of studies on the impact of pitting corrosion damage on the integrity of pipelines and pressure vessels, with most focusing on the calculation of stress concentration coefficients for single pitting pits, prediction of corrosion rates, and assessment of remaining strength[11-13]. However, in actual working conditions, the pipe string surface often has randomly distributed multiple pitting damages, and the stress superposition and interference effects among them have not been systematically studied[14-16]. Especially under the combined action of tensile, internal pressure, and external pressure loads, the mechanism of the synergistic effect of pitting clusters on the ultimate bearing capacity of the pipe string remains unclear[17-19].

Furthermore, most existing studies are based on idealized assumptions or single load conditions, lacking comprehensive analysis of the point erosion damage behavior of gas well string under combined loads (such as axial tension, internal and external pressure differences, bending, etc.) during actual operation[20]. Especially in high-pressure gas wells, the string is simultaneously subjected to high internal pressure and tensile loads, and the stress redistribution caused by point erosion may significantly accelerate the damage progression, thereby affecting the reliability of the entire well string system[21]. Therefore, conducting systematic research on the impact of point erosion damage on the stress distribution and bearing characteristics of downhole well strings has important theoretical significance and engineering application value[22].

This study focuses on the production gas well pipe string as the object. By combining numerical simulation and theoretical analysis, it systematically explores the influence of pitting damage on the stress concentration characteristics, the ultimate bearing capacity of the pipe string, and the failure modes. Firstly, the influence law of single pitting crater size parameters (diameter and depth) on the stress concentration coefficient is analyzed; then, the stress superposition effect when multiple pitting pits coexist is studied; finally, the influence of the number and distribution of pitting pits on the failure behavior of the pipe string under various loading conditions (such as tension, internal pressure, and external pressure) is investigated. From the perspectives of fracture mechanics and strength theory, the main mechanism of pipe string failure caused by pitting is analyzed, with the aim of providing theoretical basis and technical support for corrosion protection, safety assessment, and life prediction of gas well pipe strings.

2. Stress Distribution Characteristics with Pitting Damage

2.1. Stress Concentration Characteristics Caused by Pitting Corrosion

In order to verify the magnitude of the defects, the influence of hole depth and hole diameter on the plastic deformation of the production gas well pipe string during production was investigated. A three-dimensional model of the production gas well pipe string was established in SolidWorks using a Python program. By fixing a section of the pipe string and applying an axial tensile force to the other end face, with the force magnitude being 7.5×10^5N, the defects in the circular holes were determined based on the degree of plasticity. The influence of hole diameter and hole depth on plastic deformation was studied. To obtain accurate and detailed data, the finite element calculation method was adopted to investigate the size of the defects in order to determine the impact of pitting on stress concentration.

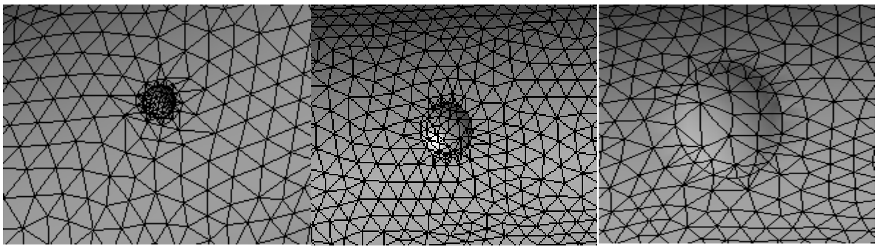

Figure 1. Schematic diagram showing the case where the hole depth remains constant while the diameter increases.

2.1.1. The influence of hole depth on stress concentration

Here, the same-sized production gas well pipe string is used for the research in this part. The material of the pipe string is selected as having a strength of 768 MPa, a Poisson's ratio of 0.3, with an inner diameter of 34.95 mm and an outer diameter of 44.45 mm. The total length of the pipe string is 500 mm. In the study of the influence of hole depth and stress concentration, the radius of the circular defect is kept at 3 mm, and the depth is increased from 0.5 mm to 5 mm in increments of 0.5 mm. The magnitude of the tension is 7.5×10^5N. The influence of the depth of the circular hole defect on stress concentration is observed.

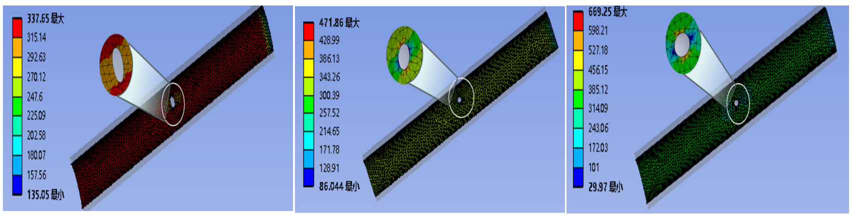

Figure 1. With the diameter of the hole remaining constant, the depth increases and the stress distribution diagram changes

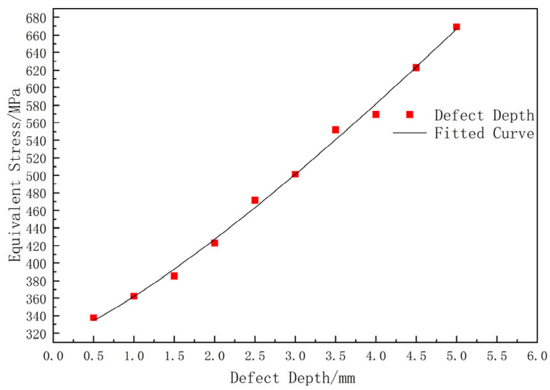

Figure 2. Stress distribution diagram of hole depth effect

The obtained data results are shown in **Figure 2**. When the diameter of the circular hole defect remains unchanged, as the depth of the circular hole continuously increases, the equivalent stress becomes larger. It can be concluded that under the condition of constant circular hole depth, the circular hole depth and diameter show a positive correlation. The deeper the circular hole is, the larger the equivalent stress is, and the more likely the pipe column is to suffer from fatigue damage.

2.1.2. The influence of hole diameter on stress concentration

Here, the same material model as the hole depth is selected. The length of the pipe column is 500mm. When observing the influence of the hole diameter on stress concentration, the depth remains unchanged. A tensile force of 7.5×10^5N is selected, with a depth of 3mm. The diameter varies from 6mm to 20mm, increasing by 1mm each time.

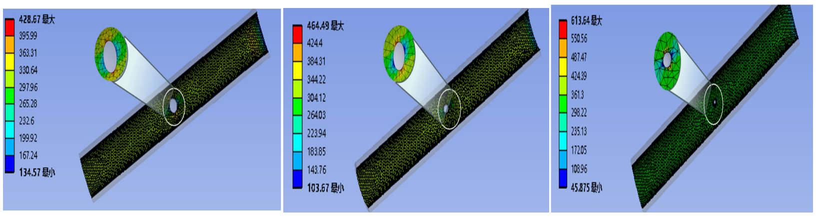

Figure 3. With the hole depth remaining constant and the diameter increasing, the stress distribution map

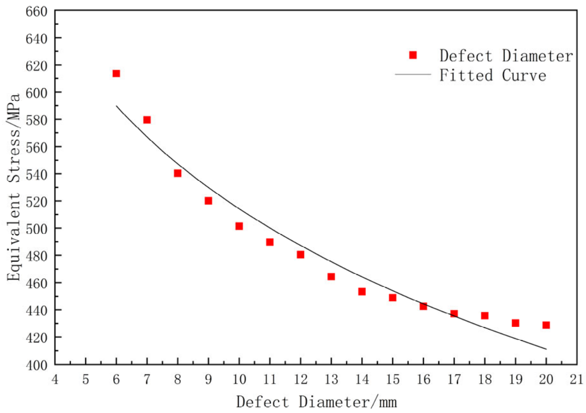

Figure 4. Stress distribution diagram for hole diameter equivalence

The obtained data results are shown in **Figure 4** as follows: When the depth remains constant, as the diameter of the circular hole keeps increasing, its equivalent stress gradually decreases. The following conclusion can be drawn: When the depth remains unchanged, the larger the diameter of the circular hole, the more negative the correlation between the equivalent stress is. The smaller the diameter of the circular hole, the more likely the pipe column is to suffer from fatigue damage.

2.2. Stress Concentration Characteristics of Multiple Overlapping Injuries

In the studies on multi-point damage and stress concentration, for this case, the axial and radial hole spacings were increased by 1mm each from 1mm to 20mm. The selected material for the production gas well pipe string was one with a strength of 768 MPa and a Poisson's ratio of 0.3. Its dimensions were an inner wall of 34.95mm, an outer wall of 44.45mm, and the entire pipe string was 500mm in length.

2.2.1. The influence of axial distance on stress concentration

When studying the influence of axial distance on stress concentration, the diameters and depths of the two holes were kept constant, while only the distance between the two holes was changed. The distance ranged from 1mm to 20mm, increasing by 1mm each time. The tensile force was 7.5×10^5N. The influence was judged based on the magnitude of the equivalent stress.

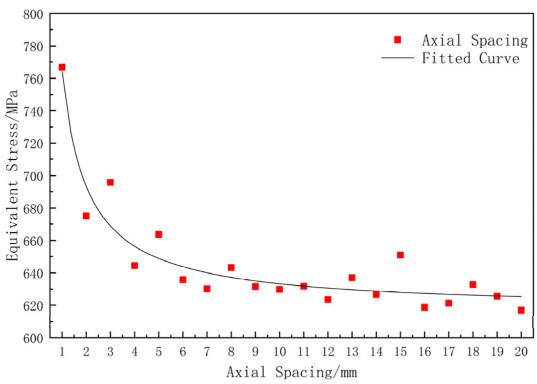

Figure 5. Axial hole spacing equivalent stress diagram

The obtained data results are shown in **Figure 5** as follows: Under the condition that the depth and diameter remain unchanged, the pulling force is 7.5×10^5N, and the radial distance between the two holes varies from 1mm to 20mm, increasing by 1mm each time. From the figure, it can be seen that the smaller the axial distance, the greater the equivalent stress, and the greater the possibility of the pipe column to deform and fail. The larger the axial distance, the smaller the equivalent stress between the two holes, and the less likely the pipe column will fail.

2.2.2. The influence of radial spacing on stress concentration

When studying the influence of radial distance on stress concentration, just like in the study of axial spacing, the diameters and depths of the two holes were kept constant, and only the spacing between the two holes was changed. The spacing ranged from 1mm to 20mm, increasing by 1mm each time.

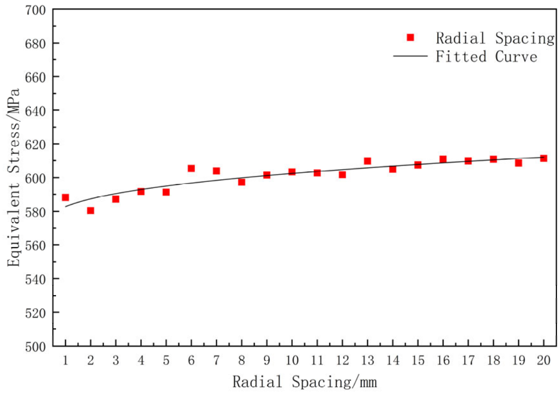

Figure 6. Radial hole spacing equivalent stress diagram

The obtained data results are shown in **Figure 6** as follows: When the depth and diameter remain unchanged, the pulling force is 7.5×10^5N, and the radial distance between the two holes varies from 1mm to 20mm, increasing by 1mm each time. From the figure, it can be seen that the radial distance has little effect on the equivalent stress, and it increases gradually with a small amplitude. The pipe column is not prone to damage or deformation.

3. Corrosion-induced Damage to the Bearing Characteristics of The Pipe Column

In the study of pitting corrosion damage, the changes in the limit of the pipe column caused by different numbers of pitting corrosion were investigated with random distribution. The length of the pipe column was 1000mm. The material of the production gas well pipe column was selected as having a strength of 768 MPa and a Poisson's ratio of 0.3, with an inner diameter of 34.95mm and an outer diameter of 44.45mm. The number of defects was set to 10,25,50,100, and 200, with a depth of 2mm and a diameter of 4mm. Each defect model was tested 10 times, and the average equivalent stress from 10 groups was used for comparison to study its impact.

3.1. Study on the Damage of Tubing Column Caused by Tensile Load

When studying the damage caused by tensile load to the pipe column, first apply tensile load to the pipe column without any defects, and observe the magnitude of the stress. Then, observe the magnitude of the stress when there are defects.

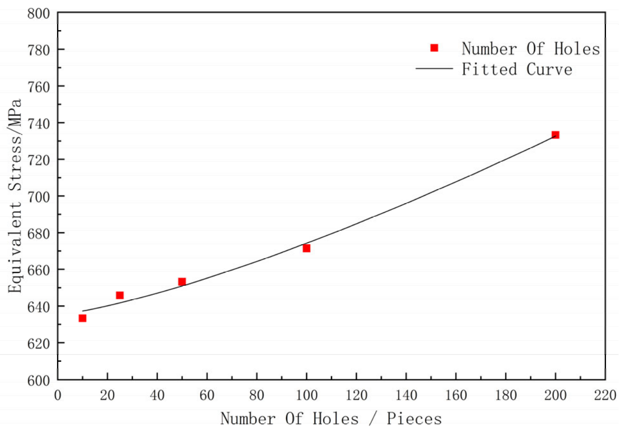

Figure 7. Stress distribution diagram for the number of holes at a tensile force of 7.5×10^5

The obtained data results are shown in **Figure 7**: When there are no defects, fix one end and apply a pressure of 7.5×10^5N to the other end. The stress at this point is 338.06 MPa. As the number of holes increases, the stress concentration phenomenon also increases. We conducted 10 sets for each type of defect, and for each defect, we obtained a range. However, the overall stress concentration phenomenon also increases with the increase in the number of defects. At 10, 25, 50, and 100 holes, the pipe column is not damaged. At 200 holes, when a pressure of 7.5×10^5 is applied, the equivalent stress of the pipe column exceeds the strength of the pipe column, and at this point, the pipe column is damaged.

3.2. Study on the Damage Caused by Internal Pressure to the Tubing String

When studying the damage caused by internal pressure to the pipe column, a node constraint was applied to one end. Typically, 10 nodes were selected for this purpose. Pressure was applied to the inner wall to obtain the ideal results.

When each type of quantity defect was tested with 10 instances, the following results were obtained. As the number of defects increased and the internal pressure increased, the stress also increased, and the stress concentration phenomenon became more obvious. When compared with the pipe column without defects, it was found that the internal pressure had little effect on the stress concentration phenomenon.

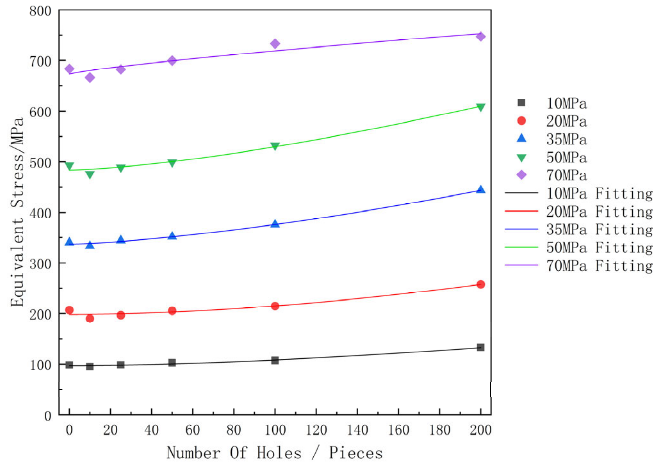

Figure 8. Stress distribution diagrams under different inner pressure conditions within the holes

The obtained data results are shown in **Figure 8** as follows: When 10 sets were conducted for each type of hole defect quantity, the average values of these 10 sets were taken and compared with those of the holes-free condition. Under the condition that other factors remain unchanged, as the number of holes increases, the equivalent stress also increases. From the obtained data, it can be understood that at 10 holes and 25 holes, the equivalent stress generated is smaller than that without holes. At 50 holes, 100 holes, and 200 holes with defects, the equivalent stress is larger than that without holes. At 100 holes and 200 holes, an internal pressure of 70 MPa may cause damage to the pipe column. At this time, the probability of the pipe column being damaged is relatively small.

3.3. Study on the Damage Caused by External Pressure to the Tubing String

When studying the damage caused by external pressure to the pipe column, we imposed node constraints on one end. Here, we typically selected 10 nodes and applied pressure to the outer wall to obtain the desired results.

When each type of quantity defect was tested with 10 instances, the following results were obtained. As the number of defects increased and the external pressure increased, the stiffness increased approximately, and the stress concentration phenomenon became more obvious. When compared with the pipe column without defects, it was found that the external pressure had little effect on the stress concentration phenomenon.

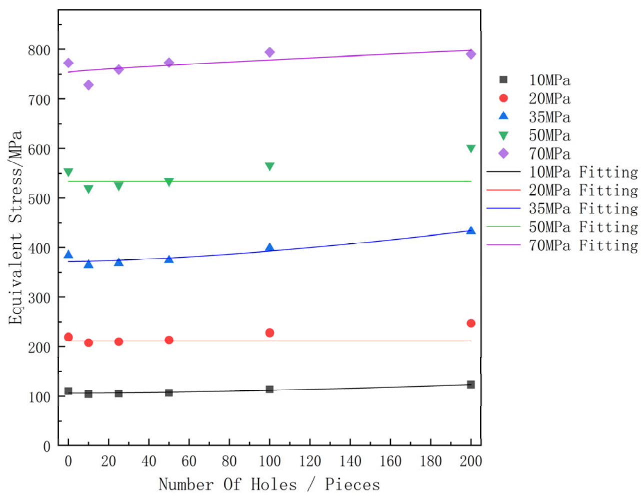

Figure 9. Stress distribution diagrams under different external pressure conditions within the hole

The obtained data results are shown in **Figure 9**: When 10 sets were conducted for each type of hole defect quantity, the average values of these 10 sets were taken and compared with those of the holes-free condition. Under the condition that other factors remain unchanged, as the number of holes increases, the equivalent stress also increases. From the obtained data, it can be understood that at 10 holes, 25 holes, and 50 holes, the equivalent stress generated is smaller than that of the holes-free condition. At 100 holes and 200 holes with defects, the equivalent stress is larger than that of the holes-free condition. At 50 holes, 100 holes, and 200 holes, an external pressure of 70 MPa may cause damage to the pipe column. The probability of pipe column damage is high.

4. Analysis of Factors Causing Failure of Tubing Column Due to Pitting Corrosion

The failure impact of pitting corrosion on the tubing string mainly manifests in two key aspects: Firstly, the stress concentration area formed at the bottom of the pitting corrosion pit is prone to induce crack initiation and propagation; Secondly, pitting corrosion leads to a reduction in the effective bearing cross-section of the tubing string, thereby lowering its tensile strength and resistance to crushing. This chapter will conduct an in-depth theoretical analysis of the failure mechanism of the tubing string caused by pitting corrosion based on fracture mechanics and strength theory.

4.1. Crack initiation and propagation caused by pitting corrosion

Due to the abrupt change in the geometric shape at the bottom of the pitting, significant stress concentration is induced, becoming the main source for crack initiation. The stress concentration coefficient is K_t an important parameter for evaluating this effect, defined as the ratio of the local maximum stress to the nominal stress:

$$K_t = \frac{\sigma_{\max}}{\sigma_{nom}} \tag{1}$$

For the approximately hemispherical pitting defects, the stress concentration factor can be further estimated using empirical formulas, which are related to the depth of the pit (d), the diameter of the pit (ϕ), and the wall thickness of the pipe column (t).

$$K_t \approx 1 + 2.1\left(\frac{d}{\phi}\right)^{0.5}\left(\frac{t}{t-d}\right)^{0.2} \tag{2}$$

When the local stress at the bottom of the pitting corrosion pit (σ_{max}) reaches or exceeds the fatigue strength limit of the material, microcracks are highly likely to initiate under cyclic loading. Once the crack forms, its propagation behavior is dominated by fracture mechanics. The stress intensity factor at the crack tip (K_I) is a key parameter for determining whether the crack will undergo unstable propagation:

$$K_I = Y_\sigma \sqrt{\pi \mathrm{a}} \tag{3}$$

In the formula:

Y -Geometric correction factors related to the shape of the crack, the geometry of the component, and the loading method;

σ -Nominal stress in the far field;

a -The current depth of the crack.

When the stress intensity factor K_I reaches the plane strain fracture toughness K_{IC} of the material, that is, when $K_I \geqslant K_{IC}$, crack will undergo rapid instability expansion, leading to a brittle fracture of the pipe column.

During the actual operation of oil and gas well tubing strings, the loads they bear are mostly cyclic loads (such as pressure fluctuations, vibrations, tc.). Therefore, fatigue crack propagation is a more common failure mode. The classic Paris formula for describing the rate of fatigue crack propagation is as follows:

$$\frac{\mathrm{d}_\alpha}{d_N} = C\left(\Delta K\right)^m \tag{4}$$

Among them:

d_α/d_N represents the crack growth amount under each stress cycle;

ΔKrepresents the amplitude of the stress intensity factor;

Cand m are constants related to the material and environment.

The existence of pitting corrosion holes significantly increases the ΔK value at the crack initiation position, thereby greatly accelerating the expansion rate of fatigue cracks and significantly shortening the fatigue life of the pipe column.

4.2. The problems of tensile fracture and crushing caused by pitting corrosion

Pitting not only causes cracks but also directly weakens the bearing section of the pipe column, resulting in a decrease in its overall bearing capacity under static loads.

4.2.1. Tensile Strength Degradation Model

Corrosion pits cause the effective cross-sectional area of the pipe column to decrease, thereby reducing its tensile strength. The remaining tensile strength of the pipe column (σ_{ult}) can be approximately expressed as:

$$\sigma_{ult} = \sigma_u\left(1 - \frac{A_P}{A_0}\right) \tag{5}$$

Among them:

σ_u represents the ultimate tensile strength of the material;

A_P is the total area of the total section loss caused by all pitting corrosion;

A_0 is the original section area of the pipe column.

For randomly distributed multiple pits, considering the stress superposition and interference effects between the pits, the above model needs to be modified by introducing an intensity attenuation coefficient η typically ($\eta \leq 1$):

$$\sigma_{ult} = \eta\sigma_u \left(1 - \frac{A_P}{A_0}\right) \tag{6}$$

The value of η is related to the density of pitting corrosion pits, the uniformity of their distribution, and the stress state of the pipe column. It can be determined through numerical simulation or experiments.

4.2.2. Strength Decay Model for Resistance to Collapse

Corrosion erosion causes the local wall thickness of the pipe column to decrease, which will seriously weaken its ability to resist external pressure and collapse. According to the theory of elasticity, the elastic collapse pressure ($P_{cpllapse}$) of an ideal thick-walled circular pipe under uniform external pressure can be approximately calculated using the following formula:

$$P_{cpllapse} = \frac{2E}{1-\nu^2}\left(\frac{t}{D}\right)^3 \tag{7}$$

In the formula:

E represents the elastic modulus of the material;

ν represents the Poisson's ratio of the material;

t represents the original wall thickness of the pipe column;

D represents the outer diameter of the pipe column.

When pitting corrosion exists, the effective wall thickness at the most dangerous section (t_{eff}) can be regarded as the original wall thickness minus the maximum pitting corrosion depth in that area (d_p).

$$t_{eff} = t - d_p \tag{8}$$

Then the anti-collapse strength of the corroded pipe column will decrease accordingly to:

$$P_{cpllapse,pitted} = \frac{2E}{1-\nu^2}\left(\frac{t_{eff}}{D}\right)^3 \tag{9}$$

This model indicates that the anti-collapse strength is highly sensitive to the wall thickness (proportional to the cube of the wall thickness), so even if the local pitting depth is not significant, it may still lead to a significant reduction in the anti-collapse capacity of the pipe column.

4.3. Comprehensive Analysis

The failure impact of pitting corrosion on the pipe column is a complex result of the combined effect of stress concentration and section weakening, which are mutually coupled. Under the combined action of various loads such as tension, internal pressure, and external pressure, the number, depth, diameter, and distribution pattern of pitting corrosion pits all have significant effects on the ultimate load-bearing capacity and failure mode of the pipe column. The numerical simulation results in the third chapter of this paper, including the changes in stress concentration for single pits and multiple pits, as well as the decrease in ultimate load-bearing capacity under different loads, are basically consistent with the laws revealed by the theoretical model in this chapter. Together, they indicate that pitting corrosion damage significantly reduces the structural integrity and service safety of the pipe column.

5. Conclusion

In the influence of pitting corrosion on stress concentration, the depth of the hole has a greater impact on stress concentration. With other conditions remaining unchanged, the deeper the hole, the greater the equivalent stress, and the more likely the pipe column is to suffer fatigue damage. The diameter of the hole has a less obvious impact on stress concentration. Under the condition that other conditions remain unchanged, the smaller the hole diameter, the more likely the pipe column is to suffer damage.

In the influence of the distance between two holes on stress concentration, the axial distance has a greater impact on the stress concentration of the pipe column. The smaller the axial distance between the two holes, the greater the equivalent stress, and the more likely the pipe column is to suffer damage. The radial distance between the two holes has a smaller impact on the pipe column. The larger the radial distance, the greater the equivalent stress.

In the bearing characteristics of the pipe column damaged by pitting corrosion, the more the number of pitting corrosion, the greater the equivalent stress, and the more likely the pipe column is to suffer damage. Under the condition that other conditions remain unchanged, apply internal pressure to the pipe column. At 10 holes and 25 holes, the generated equivalent stress is smaller than that without holes. At 50 holes, 100 holes, and 200 holes, the equivalent stress is greater than that without holes. At 100 holes and 200 holes, a 70 MPa internal pressure may cause damage to the pipe column. Under the condition that other conditions remain unchanged, apply external pressure to the pipe column. At 10 holes, 25 holes, and 50 holes, the generated equivalent stress is smaller than that without holes. At 100 holes and 200 holes, the equivalent stress is greater than that without holes. At 50 holes, 100 holes, and 200 holes, a 70 MPa external pressure may cause damage to the pipe column.

References

[1] Gao Zhan, Liu Chuansen. Analysis of the causes of pitting corrosion of P110S tubing in non-solid phase well control fluid [J]. Steel Pipe, 2024, 53(04): 22-27. DOI: 10.19938/j.steelpipe.1001-2311.2024.4.22.27.

[2] Li Zhenbo. Research on the material selection and corrosion behavior of the tubing string in a certain oilfield in the Middle East [D]. Southwest Petroleum University,2024.DOI: 10.27420/d.cnki.gxsyc.2024.000462.

[3] Wang Shushen. Research on corrosion and stress corrosion performance of CO2-driven N80 injection-production tubing string [D]. Xi'an Petroleum University, 2024. DOI: 10.27400/d.cnki.gxasc.2024.000145.

[4] Pan Yujie, Ma Jianjie, Zheng Xin. Analysis of the failure status and countermeasures of the tubing string in the block with enhanced recovery by injecting CO^2 [J]. Applied Chemical Industry, 2023, 52(S1): 231-233. DOI:10.16581/j.cnki.issn1671-3206.2023.s1.056.

[5] Lu Wei. Analysis of corrosion failure of deep well tubing string in a certain oilfield [D]. Southwest Petroleum University, 2023. DOI: 10.27420/d.cnki.gxsyc.2023.001766.

[6] Yang Mingfei, Dong Yueqi, Cheng Huarei, et al. Mechanical performance test and application analysis of random pitting corrosion circular steel pipe string [J]. Journal of Anhui University of Architecture and Technology, 2022, 30(04): 20-26.

[7] Huang Xianhui. Analysis of corrosion failure of deep gas well tubing string and feasibility study on anti-corrosion measures [J]. Petroleum Industry Technical Supervision, 2021, 37(11): 1-4.

[8] Zhang Naiyan. Risk analysis and prediction of tubing string failure in high-temperature, high-pressure, and high-sulfur gas wells [D]. Southwest Petroleum University, 2021. DOI: 10.27420/d.cnki.gxsyc.2021.000538.

[9] Li Yanjun, Zhang Chao, Ding Jian, et al. Applicability evaluation of tubing string corrosion in high-temperature, high-pressure, and CO2-containing gas wells in the South China Sea [J]. Equipment and Environmental Engineering, 2021, 18(01): 15-22.

[10] Wang Jizhe. Research on corrosion mechanism and protection measures of tubing string in the Suiliuguoxiu block [D]. Xi'an Petroleum University, 2020. DOI: 10.27400/d.cnki.gxasc.2020.000176.

[11] Ding Yinchuan. Study on Corrosion Characteristics of Thermal Recovery Well Tubing String in Chloride Ion and Acidic Gas Environments [D]. Xi'an Petroleum University,2020.DOI: 10.27400/d.cnki.gxasc.2020.000140.

[12] Zhang Qiang. Coupling Vibration Mechanism and Dynamic Behavior of Oil Tubing String in High-Pressure and High-Production Gas Wells [D]. Southwest Petroleum University, 2019. DOI: 10.27420/d.cnki.gxsyc.2019.001243.

[13] Chang Zeliang, Li Danping, Zhao Mifeng, et al. Analysis of Corrosion and Cracking Causes of a Gas Well Super 13Cr Completion Tubing String [J]. Welding Pipe, 2018, 41(07): 14-20. DOI: 10.19291/j.cnki.1001-3938.2018.07.003.

[14] Lu Xiaofang. Corrosion Risk Analysis and Safety Design of Injection and Production Tubing String in Underground Gas Storage [D]. China University of Petroleum (East China),2018.DOI: 10.27644/d.cnki.gsydu.2018.001818.

[15] Wu Na. Corrosion Laws and Screening Evaluation of Selective Corrosion Inhibitors for Pressure Fracturing Tubing String in Daqing Oilfield [D]. Northeast Petroleum University.

[16] Li Yan, Xie Junfeng, Chang Zeliang, et al. Corrosion Causes of Acidizing Tubing String in a Well in Tarim Oilfield [J]. Corrosion and Protection, 2016, 37(10): 861-864.

[17] Fan Heng, Luo Jiannan, Li Pengyu, et al. Analysis of the Influence of Simplified Corrosion Morphology on the Remaining Strength of Completion Tubing String [J]. Petroleum Machinery, 2016, 44(08): 65-70. DOI:10.16082/j.cnki.issn.1001-4578.2016.08.015.

[18] Chen Jianbo. Study on Corrosion Mechanism of Oil Well Tubing String Joint Gaps by One-Dimensional Array Electrode Method [D]. Southwest Petroleum University, 2016.

[19] Kou Jierong, Dong Ren, Liu Hongtao, et al. Causes of Corrosion Failure of Super 13Cr Completion Tubing String [J]. Corrosion and Protection, 2015, 36 (09): 898-902.

[20] Zhong Zhiying, Luo Tianyu, Wu Guodong, et al. Experimental Study on Corrosion of Tubing String in Gas Wells of Huotibei Gas Storage in Xinjiang Oilfield [J]. Xinjiang Oil and Gas, 2012, 8 (03): 82-86+8.

[21] Lu Shubin. Research on Corrosion Mechanism and Coating Protection of Oil Well Tubing String [D]. Southwest Petroleum University, 2011.

[22] Li Jifeng. Research on Anti-CO^2 Corrosion Technology of Oil Well Tubing String [D]. Daqing Petroleum University, 2006.