Fracture Behavior Analysis of Mitred Welded Joint of High Grade Steel Pipeline

Jian Chen[2,3], Haonan Zhang[1], Yue Yang[1], Yuanhong Chen[1]
Feng Wang[4], Hao Wang[1], Xiaoben Liu[1,*]

[1]China University of Petroleum-Beijing, Beijing, 102249, China
[2]PipeChina Research Institute, Langfang, Hebei, 065000, China
[3]PipeChina North Pipeline Company, Langfang, Hebei, 065000, China
[4]PipeChina Engineering Technology Innovation Company, Tianjin, 300500, China
*Corresponding author's e-mail: xiaobenliu@cup.edu.cn

Abstract. Crack is a high-risk engineering disease in civil engineering. It is necessary to master the specific types and causes and strengthen crack control. Pipeline welded joint is one of the most prone to crack position. Pipeline structures are widely used in civil engineering, especially in the field of oil and gas transportation. In the installation of long-distance oil and gas pipelines, there are often mitred joints to meet different laying requirements. A parametric numerical model of mitred joints with crack defects was established based on Python-Abaqus, the Key Hole model was used to accurately simulate the passivation behavior of crack tip during crack opening. The results show that for the inclined joint of high steel grade pipeline, under the same load, the crack surface of the outer wall of the bottom of the mitred joint is more prone to fracture failure than the cracks at other positions. The larger mitre angle and the low strength matching of the material will lead to a sharp rise in the crack driving force at the girth weld, and the mitred joint is more prone to cracking failure. Among them, the mitre angle and crack position have the most obvious influence on the crack driving force. It is an effective method to improve the bearing capacity of the inclined nozzle by limiting the angle of the inclined joint and ensuring the high matching of the strength.

Keywords: mitred welded joint; mitre angle; crack driving force; Strength matching coefficient.

1 Introduction

In recent years, the relationship between people 's production, life and civil engineering has become increasingly close. In civil engineering, what measures should be taken to make the engineering structure safer and more reliable is one of the most important research contents at present. However, at present, cracks are very easy to occur in both the construction and application stages of civil engineering. Cracks are high-risk engineering diseases. It is necessary to master the specific types and causes and strengthen crack control, which has far-reaching significance [1]. The position of the pipe girth

F. Ding et al. (eds.), *Proceedings of the 2024 International Conference on Civil Engineering Structures and Concrete Materials (CESCM 2024)*, Advances in Engineering Research 247,
https://doi.org/10.2991/978-94-6463-564-5_8

weld is one of the most prone to cracks. There are many types of pipeline structures in civil engineering, the most prominent of which is the oil and gas transportation system. With the deepening implementation of the national strategy for petroleum and natural gas energy, the construction scale of oil and gas pipelines in China continues to expand [2]. During the assembly and installation of underground pipelines, when there is a need for direction change or errors prevent direct connection, it may be necessary to adjust the position of the pipeline through mitred connections to achieve smooth connection. As a geometrically discontinuous structure, the mitred joint is prone to stress concentration under axial load.[3] Additionally, high-grade steel pipelines are prone to crack defects at the circumferential weld positions during the welding process. Under axial and bending loads and other additional loads, these crack defects can easily propagate, thereby reducing the strain capacity of the circumferential welds, leading to frequent accidents such as the cracking of mitred circumferential welds [4-6]. Studies suggest that the mitre angle control within 3 ° can ensure the structural integrity and operation safety of the pipeline, and avoid fatigue fracture due to stress concentration caused by improper docking. However, when carrying out internal inspection of pipelines, things that the mitre angle does not meet the requirements often occur [7-10]. In Reference [11], the finite element software was used to simulate the no-crack mitred joint, and the stress concentration stress was the largest at the inner angle of mitred joint. Under the condition of stress concentration, the bearing capacity of defective joints and the bearing capacity under large mitre angle need quantitative research results.The welding strength matching coefficient has a great influence on the crack driving force and ultimate tensile strain of the pipe girth weld.[12] It is of great significance to determine the critical strength matching coefficient of the pipe girth weld for the safety design of the pipeline[13]. Based on the finite element method, this paper analyzes the variation law of the bearing capacity of the girth weld of the inclined pipe with defects with the influencing factors, in order to provide reference for the safety assessment of the girth weld of the inclined pipe of the in-service pipeline.

2 Mitred Pipe and Finite Element Model

2.1 Pipe Geometry Size

The full-scale high-grade steel pipeline mitred joints are the focus of this research, where the developed finite element model is aimed at X80 line pipes with an outer diameter (D=1422 mm, wall thickness B=21.4 mm), and a mitred joint length of 2L=6 m; the geometric dimensions of the crack include the crack depth a and the length 2c. The geometric model of the mitred pipeline with a circumferential direction crack is illustrated in Fig. 1.

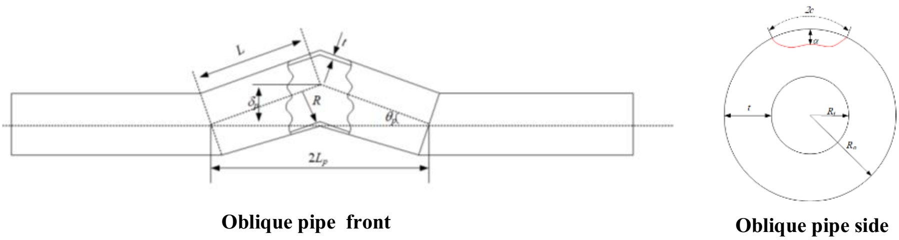

Fig. 1. Full-size mitred pipe with circumferential surface crack defects

2.2 Grid and Boundary Conditions

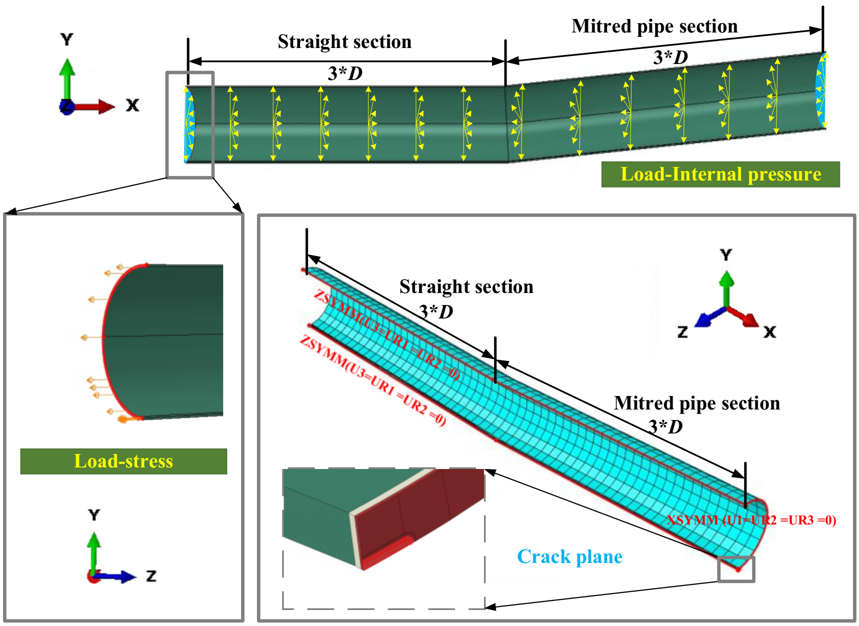

Fig. 2. Finite element model of Full-size mitred pipe with circumferential surface crack defects

A quarter-scale finite element model of the pipeline mitred joint was constructed using ABAQUS software. The load and boundary conditions of the quarter-scale model are set as shown in Fig. 2.

Symmetric boundary conditions were applied to the XY plane and the YZ plane (circumferential weld) of axial symmetry of the pipeline. An axial compressive load in the negative X-axis direction was applied to the left end face of the straight pipe, and constraints were imposed on all directions except for the translation along the Y-axis for the straight pipe section. This section employs a static crack to mimic the crack configuration at the mitre's circumferential weld. Studies suggest [14] that the canoe-shaped crack more accurately represents the crack features under real-world operating conditions compared to the semi-elliptical shape, and thus it is chosen as the crack model for investigation. The crack tip is refined into a dense, arachnid-web like mesh to ensure highly precise computation results in the vicinity of the crack tip.

2.3 Material

CSA Z662 [15] introduces a stress-strain curve format that defines the stress-strain relationship for high-grade steel pipes, as shown in equation 1-2. The constitutive curve is described using the R-O equation:

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

$$n = \frac{3.14}{1-\lambda} \tag{2}$$

In the formula: λ represents the yield-to-tensile ratio; n is the hardening exponent.

Typically, the circumferential weld region of oil and gas pipeline welded joints includes the base material, heat-affected zone, and weld metal [16-17]. To differentiate the variations in the heat-affected zone, weld zone, and base material zone, the concepts of softening rate and strength matching coefficient are introduced respectively.

2.4 Finite Element Model

The accuracy of the finite element model can be verified by the finite element model inversion mitred pipe test. Jiang et al. [18] inverted the blasting test of small diameter inclined elbow, and compared the test results with the equivalent plastic strain of the finite element model, as shown in Fig. 3. The experimental results show that there is a good correlation between the results of the finite element model and the experimental data when the internal pressure is less than 9.2 MPa, and the maximum relative error is 12.3 %.

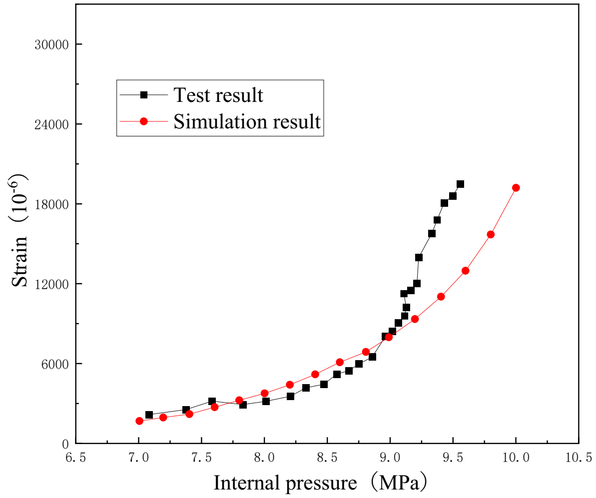

Fig. 3. Comparison of numerical inversion results with full-scale experiment data [18]

Because the model in this study is static crack model, it cannot accurately simulate the burst leakage phenomenon of the inclined elbow under high pressure. However, from the model results before the burst of the inclined pipe, the calculation results of the finite element model do not show significant deviation from the full-scale experimental data, and the simulation results are reliable. The model in this paper is the same as Jiang et al. [18], which can be simulated in the following.

3 Numerical Simulation

3.1 Crack Location

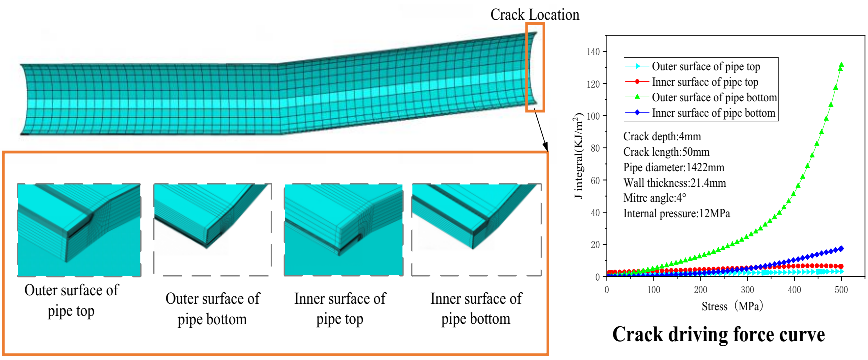

Fig. 4. The crack driving force of mitred joints with different crack positions

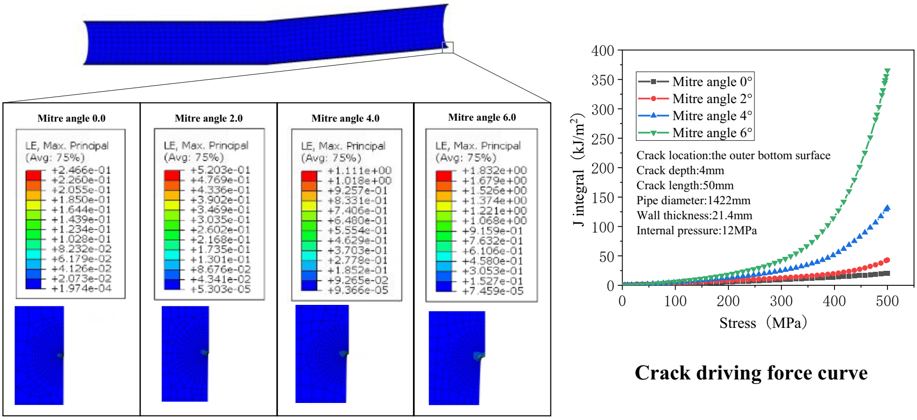

Fig. 5. The crack driving force of mitred joints with different crack angle

To elucidate the magnitude and variation of the crack driving force under loading when a crack defect is present at different locations in high-grade steel pipeline mitred welded joints, numerical modeling analysis of the mitred welded joints was conducted is shown in Fig. 4. The comparative results indicate that when a crack defect is present on the outer bottom surface of the mitred joint, opposite the symmetrical plane of the pipe body, the variation in the J-integral value is the most significant, whereas the other three locations exhibit relatively smaller changes. Under the same loading conditions, the crack plane on the outer bottom surface of the mitred joint is under tension, whereas the crack planes at the other locations are under compression. Tensile loading is relatively more dangerous and prone to fracture failure, thus meriting particular attention. Subsequent full-scale analyses of the fracture behavior of the slanted pipeline only considered cracks located on the outer bottom surface of the mitred joint.

3.2 Mitre Angle

The mitre angle is the key parameter affecting the crack driving force of the mitred pipe. The mitre angle is set to 0°,2°,4°,6°, and the influence of the same load on the crack driving force of the full-size mitred joint is shown in Fig. 5. It can be seen that the larger the mitre angle, the crack driving force at the girth weld will increase, making the mitred joint more prone to cracking failure. The increase of the mitre angle aggravates the structural inhomogeneity of the welded joint, so it is more likely to fail and fracture. Under the same angle increment, the increase of the angle after the mitre angle > 2 ° has a more significant effect on the crack driving force. Therefore, in the design stage of the mitred pipe, the mitre angle is limited to 2 ° as far as possible. In the pipeline maintenance stage, it is required to do regular maintenance or thickening enhancement for the mitred joint with a large mitre angle.

3.3 Strength Matching Coefficient

A notable feature of material discontinuity is the mismatch in strength between the weld region and the parent material region, which severely affects the bearing capacity of full-size pipeline circumferential welds. Based on finite element model, a full-size mitred pipeline was simulated to analyze the influence of internal pressure and axial load on the J-integral, a measure of the crack driving force as depicted in the Fig. 6. The greater the strength matching coefficient, the smaller the J-integral value under the same loading conditions. The fracture toughness is set to 100 KJ/m2, and the change of the stress bearing capacity of the full-scale pipeline girth weld with the strength matching coefficient is shown in Fig. 7. The calculation results of Fig. 6 and Fig. 7 can provide suggestions for pipeline design and maintenance. In the pipeline design stage, the critical strength matching coefficient of the mitred joint can be determined. In the operation and maintenance stage of the pipeline, the critical stress bearing capacity of the mitred joint can be determined.

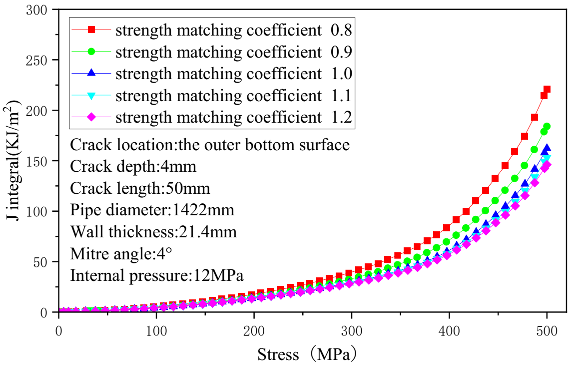

Fig. 6. The crack driving force of mitred joints with different strength matching coefficient

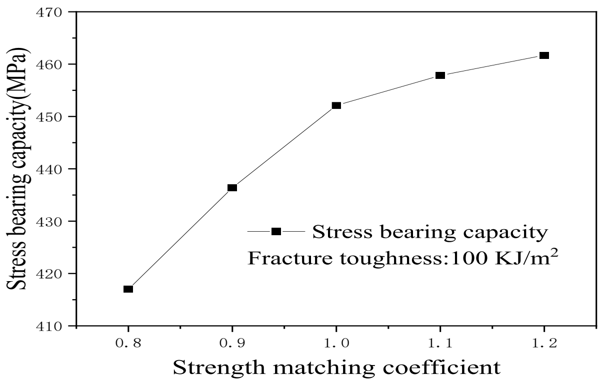

Fig. 7. Fracture toughness is 100 KJ/m^2, stress bearing capacity under different strength matching coefficients

4 Conclusions

1. A full-scale finite element model of a mitred pipeline with a crack defect was established. Numerical inversion of the experimental results related to the mitred pipeline was carried out, with a maximum relative error of 12.3%, verifying the accuracy of the finite element model.

2. Research on the crack driving force for different crack locations at welded joints was conducted. It was found that when the crack appears on the lower outer surface of the mitred joint, its J-integral value is the largest, identifying this location as more critical compared to the other three positions.

3. The influence of mitre angle and strength matching coefficient on the crack driving force was analyzed. The results show that under the same loading conditions, the greater the mitre angle, the higher the numerical value of the crack driving force; the greater the strength matching coefficient, the lower the numerical value of the crack driving force. These patterns are significant for understanding and predicting the fracture behavior of mitred pipelines under actual working conditions, and are crucial for the design and safety assessment of such structures.

Acknowledgments

This research has been co-financed by National Key R&D Program of China (Grant No. 2022YFC3070100), the Science and Technology Research Project of Pipechina (Grant No. CLZB202301), Young Elite Scientists Sponsorship Program by Beijing Association for Science and Technology (Grant No. BYESS2023261), National Natural Science Foundation of China (Grant No. 52304013), Science Foundation of China University of Petroleum, Beijing (No.2462023BJRC005).

References

1. ZHANG, Y L. Crack treatment measures in civil engineering construction [J]. Development guide to building materials, 2023,21(4):72-74. DOI:10.3969/j. issn.1672-1675.2023.04.022.
2. ZHANG, B., QIAN, C W., WANG, Y M., et al. Development and application of high grade pipeline steel[J]. Petroleum Engineering Construction,2012,38(1):1-4.
3. ZHU, X K., LEIS, B N., FEIER, I I. Stress Analysis of Miter Joint in Pipeline Under Internal Pressure or In-Plane Bending Loading[C]//Pressure Vessels and Piping Division / k - pvp Conference. 2010, 49255: 1011-1019.
4. ZHAO, XW., LUO, J H., LU, M X., et al. Pouting stress analysis method of spiral welded pipe weld [J]. Transactions of The China Welding Institution, 2004.25 (1): 25-28.
5. NEILSON, R., WOOD, J., HAMILTON, R., et al. A comparison of plastic collapse and limit loads for single mitred pipe bends under in - plane bending[J]. International Journal of Pressure Vessels and Piping, 2010,87 (10): 550-558.
6. WEI, G C., WANG, L J., WANG, M Y., et al. GB/T 50369-2014: Code for construction and acceptance of oil and gas long-distance transmission pipeline engineering [S]. Chinese Planning Publishing House, 2014.

7. MIN, S H., JEON, J Y., LEE, K H., et al. Limit and plastic collapse loads for un- reinforced mitred bends under pressure and bending[J]. International Journal of Pressure Vessels and Piping, 2011, 88 (7): 482-494.
8. ZHU, K F., ZHANG, W W., ZHANG, Z Y., et al. GB/T 50253-2014: Code for design of oil transportation pipeline engineering [S]. Chinese Planning Publishing House, 2014.
9. YANG, L J., GENG, H., GAO, S W., et al. Magnetic flux leakage internal detection technology of the long distance oil pipeline [J]. Chinese Journal of Scientific Instrument, 2016, 37(08):1736-1746.
10. FENG, Q S. Three-axis high-definition magnetic flux leakage internal detection technology for in-service pipelines [J]. Oil & Gas Storage and Transportation, 2009,28(10):72-75.
11. WU, G., JIA, H D., XU, C Y., et al. Study on Safety Assessment of Miter Girth Welds of the Long-distance Pipeline [J]. Petroleum Tubular Goods & Instruments,2019,5(3):16-19.
12. ZHANG, Z Y. Key factors for safety improvement design of girth weld in high-grade large diameter natural gas pipelines [J]. Oil &Gas Storage and Transportation,2020,39(7):740-748.
13. ZHANG, D., LIU, X., YANG. Y., et al. Minimum strength matching coefficient analysis of x80 pipeline welded joints under different strain demand: a numerical study[C]. Ninth International Conference on THIN-WALLED STRUCTURES(ICTWS2023).2023.
14. WANG, Y Y., LIU, M., SONG, Y. Second Generation Models for Strain-Based Design[R]. US DOT Contract No. DTPH56-06-T000014, final report, 2011.
15. Standards Council of Canada. CSA Z662-2007 Oil and gas pipeline systems. Canada Standard Association[S]. CSA Group, 2007.
16. LIU, M., WANG, Y Y., ZHANG, F., etal. Realistic strain capacity models for pipeline construction and maintenance: CRES US DOT Contract No. DTPH 56-06-T000016 final report[R]. Dublin: Center for Reliable Energy Systems, 2013: A1-10.
17. YANG, Y., ZHANG, H., CHEN, P C., etal. Strain capacity analysis of the mismatched welding joint with misalignments of D 1422 mm X80 steel pipelines: an experimental and numerical investigation[J]. Journal of Pipeline Science and Engineering, 2021, 1(2): 212-224.
18. JIANG, J X., ZHANG, H., ZHANG, D., et al. Fracture response of mitred X70 pipeline with crack defect in butt weld: Experimental and numerical investigation[J] Thin-Walled Structures,2022.