Fracture Behavior Analysis of Abnormal Girth Welded Joint of High Grade Steel Pipeline

Haonan Zhang[1], Yue Yang[1], Jian Chen[2,3], Xiatong Wu[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. In recent years, improving the safety of civil engineering structures has become an important part of structural development. In order to improve the safety of oil and gas transportation systems, it is necessary to focus on pipeline safety. The study focused on an X80 high-grade steel pipeline with a diameter of 1422mm, accurately considering the geometric features of both misalignment and variable wall-thickness in establishing a full-size pipeline finite element model. The initiation behavior of circumferential inner surface cracks under tensile loading was investigated. The computational results indicated that for circumferential welded joints with misalignment, a smaller misalignment and a higher weld strength matching coefficient contribute to reducing the crack driving force. Increasing the strength matching coefficient of the girth weld as much as possible has a good positive effect on resisting the decrease of the bearing capacity caused by the misalignment. For circumferential welded joints with unequal wall thickness, when the wall thickness of the thinner side remains unchanged, the wall thickness ratio has little effect on the bearing capacity of the girth welded joints, which can be ignored. Under the condition of small crack size, the strength matching coefficient can more effectively ensure the high strain capacity of the circumferential weld of the unequal wall thickness pipeline.

Keywords: misalignment; unequal wall-thickness; crack driving force; strain bearing capacity.

1 Introduction

In recent years, the scale of civil engineering Structures has gradually expanded, which puts forward higher requirements for the structural design and construction quality of civil engineering[1]. The safety of structure has become an inevitable and important content in the research of various civil engineering structures. The safety of pipelines is an important part of ensuring the stability of civil engineering structures, especially in the field of energy transportation such as oil and natural gas, because pipeline transportation is an efficient energy transportation method and is widely used in oil and gas

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transportation systems. The ideal condition for pipeline welding is that the connection ends of two pipes are perfectly aligned to ensure the continuity and uniformity of the weld joint structure's strength. However, due to the complex conditions of the welding process and special laying conditions, some abnormal weld joints may occur. Circumferential weld joints with misalignment and unequal wall thicknesses are two typical forms of such abnormalities. Misalignment is a common welding defect with a high frequency of occurrence. It leads to discontinuity in the weld structure, creating localized stress concentrations that severely affect the service safety of the circumferential weld [2-6]. During the pipeline laying process, different regions have varying safety levels, and to ensure transmission volumes, welding of joints with unequal wall thicknesses is required. Unequal wall thickness circumferential weld joints are an indispensable component of long-distance oil and gas pipelines [7-10]. According to statistics, among the cases of failure of unequal wall thickness circumferential weld joints, the highest proportion of failures are caused by cracking at the weld toe position on the thinner side [11-12]. The sudden change in wall thickness leading to changes in the stress state, as well as the shape mutation at the root weld toe position causing stress or even strain concentration on the thinner side, are considered the main reasons for these failures [13-16]. In previous studies, the stress concentration of no-crack abnormal girth welded joints has been widely studied, and there is a lack of quantitative research on the bearing capacity of cracked abnormal girth welded joints under stress concentration. This paper conducts modeling of two types of circumferential weld joints using finite element software, carries out failure analysis of abnormal circumferential weld joints, and provides references for further research on the microscopic mechanisms and control parameters of circumferential weld crack failures.

2 Finite Element Model

2.1 Geometric Dimensions of Full-size Pipe and Girth Welded Joints

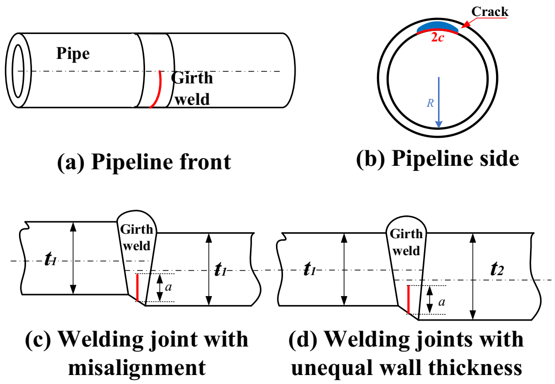

Fig. 1. Full-size pipeline and abnormal girth welded joint geometry size diagram

The geometric dimensions of the full-size pipe body and the two ring welded joints are shown in Fig. 1. The specific settings are as follows: the pipe diameter *D* is 1422 mm, the wall thickness *B* is 21.4 mm, and the weld cap height is set to 2 mm. The crack defect is a surface defect, which is located at the center line of the inner surface of the weld. The crack depth is a and the crack length is 2*c*.

2.2 Finite Element Model Mesh and Boundary Conditions

The finite element model was constructed based on the nonlinear finite element software ABAQUS are shown in Fig. 2.

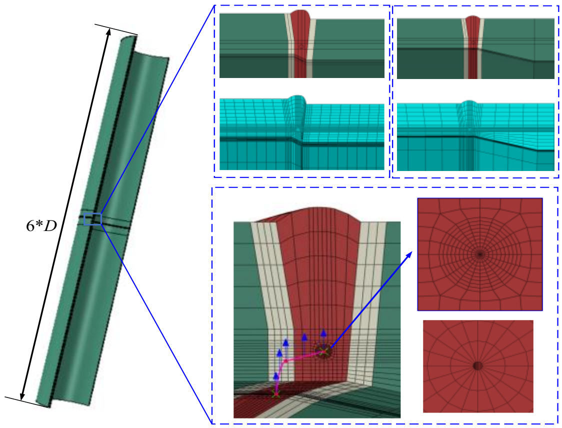

Fig. 2. Full-size pipeline and crack finite element model

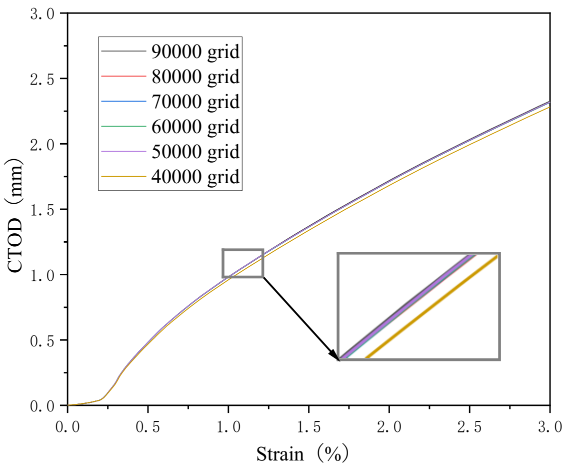

Fig. 3. Grid-independence test

The total length of the full-scale pipe model was set to six times the diameter of the pipe. Considering the geometric symmetry of the model, a 1/2 model was established to simplify the calculation process. Studies have shown that the ' Key Hole ' modeling method can well simulate the crack passivation process, so in the weld area, the center line position adopts the ' Key Hole ' modeling method [17]. The center of the "Key Hole" is a hole with a radius of 0.02mm. A spider web type of local encryption method was used to refine the grids near the crack, thus ensuring that the model could more accurately reflect the mechanical behavior near the crack. A grid-independence test is carried out. The results are shown in Fig. 3. In this paper, 70000 grids are selected to ensure both accuracy and computational efficiency.

2.3 Verify the Finite Element Model

To verify the accuracy of the finite element model, it is necessary to carry out experiments corresponding to the finite element model. Our team has successfully conducted a full-scale tensile test on the welded joints of the curvature wide plate of the X80 pipeline with a diameter of 1422 mm in the China-Russia Eastern Route Project. In [18], the static crack method was used to establish the finite element model of the wide plate test, and the CMOD-strain curve obtained by the experiment was compared with the curve obtained by the finite element method, as shown in Fig. 4. The comparison results show that the relative error is only 0.95 %, which fully proves the accuracy of the finite element model. The modeling method introduced in this paper is consistent with the method used by Yue et al. The finite element model of staggered edge and variable wall thickness established by this method can be used for numerical simulation analysis of crack fracture.

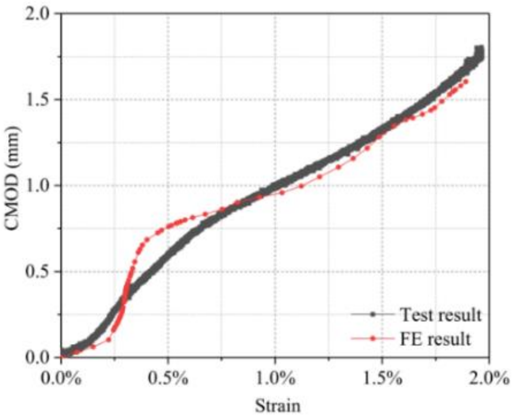

Fig. 4. Comparison of CMOD-strain curves between tension test and finite element method[18]

2.4 Constitutive Relationship of Pipe Girth Weld Material

In this paper, the X80 pipeline is used as a benchmark for research, and the tensile strength is set to 625 MPa. The stress-strain relationship of high-grade pipe materials is often described by the Ramberg-Osgood equation, as shown in formula 1.[19] The hardening coefficient of base metal is expressed by formula 2.

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

$$n = \frac{3.14}{1-\lambda} \quad (2)$$

where, ε is the strain, σ is the stress (MPa), E is the elastic modulus (MPa), σ_y is the material yield strength (MPa), n is the material hardening coefficient, and λ is the yield ratio of the pipe.

3 Numerical Analysis

3.1 Welded Joint with Misalignment

3.1.1 Influence of Strength Matching Factor and Misalignment.

When the circumferential weld joint contains a misalignment, additional bending stress is generated at the local position of the misalignment. To explore the comprehensive impact of strength matching coefficients and misalignment amounts on the crack driving force of circumferential weld joints, the misalignment amount was set to 1.5mm,3.0mm, and the weld strength matching coefficients were 0.8, 0.9, 1.0, 1.1, and 1.2, as shown in Fig. 5, Fig. 6. The results show that under the same misalignment condition, the lower the strength matching coefficient at the same strain condition, the greater the crack driving force. A decrease in the strength matching coefficient leads to a steeper curve in the relationship between crack driving force and strain. Under the same matching conditions, an increase in the misalignment amount significantly raises the crack driving force of the pipeline circumferential weld. A smaller misalignment amount and a higher weld strength matching coefficient help reduce the crack driving force and improve the crack resistance of the joint. By setting the fracture toughness to 0.254mm, it is possible to obtain the influence pattern of the weld strength matching coefficient on the strain capacity of the circumferential weld under different levels of fracture toughness. When the misalignment amount is equal to 0.0mm and the matching coefficient ranges from 0.8 to 1.2, the increase in the strain capacity of the circumferential weld is 1.17%. When the misalignment amount is equal to 1.5mm and the matching coefficient ranges from 0.8 to 1.2, the increase in the strain capacity of the circumferential weld is 0.87%. However, when the misalignment amount is equal to 3.0mm and the matching coefficient ranges from 0.8 to 1.2, the increase in strain capacity is only 0.58%. The larger the misalignment amount, the smaller the increase in strain capacity as the weld strength matching coefficient increases.

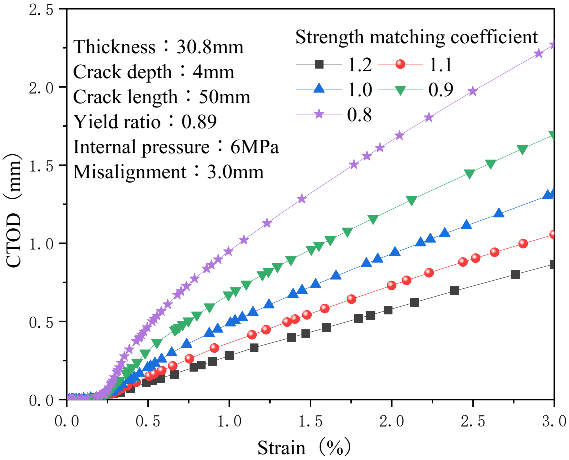

Fig. 5. The effect of the strength matching coefficient on the crack driving force when the misalignment is 3.0 mm.

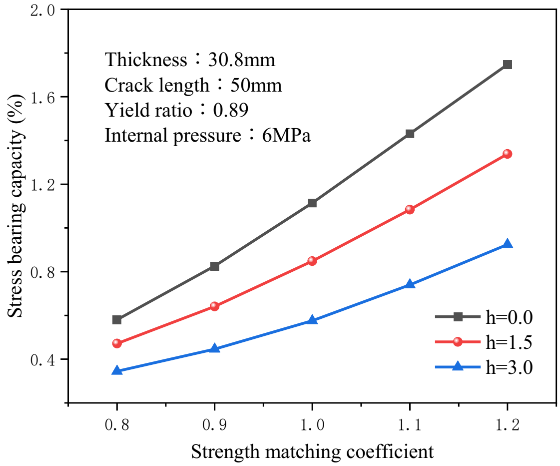

Fig. 6. Under different misalignments, the strain capacity changes with the strength-matching coefficient.

3.2 Welded Joint with Unequal Wall Thicknesses

3.2.1 Thickness Ratio.

To investigate the effect of the thickness ratio on the strain bearing capacity of circumferential weld joints, the thin side wall thickness was set to 21.4mm, and the thickness ratios were set to 1.2, 1.3, 1.4, 1.5, and 1.6, the results of the strain bearing capacity of the circumferential weld joints under crack size conditions are shown in Fig. 7, and the results of the strain bearing capacity of the circumferential weld joints under different crack size conditions are shown in Fig. 8.

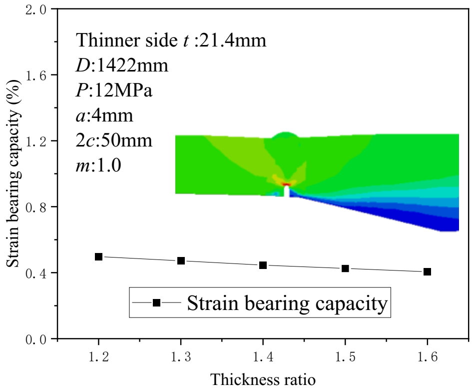

Fig. 7. Under the same Crack size, the strain capacity changes with the thickness ratio

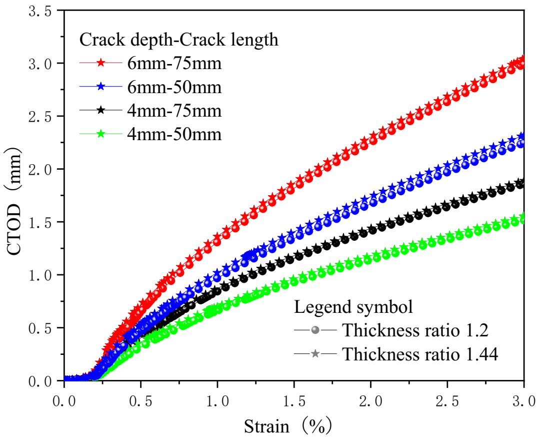

Fig. 8. Under different Crack sizes, the strain capacity changes with the thickness ratio

The results show that, with the same thin side wall thickness, the impact of the thickness ratio on strain bearing capacity is very small, within 0.1% numerically. The cloud chart indicates that the primary area of load action is on the thinner side, and the strain bearing capacity of the unequal wall thickness pipeline circumferential weld joint mainly depends on the wall thickness of the thinner side pipe. Under different defect size conditions, the carrying capacities of the joints under two different thickness ratio conditions are essentially the same, leading to a consistent conclusion.

3.2.2 Strength Matching Coefficient.

The strength matching of the weld is a key factor affecting the strain capacity of circumferential welds. With the thinner side wall thickness set to 21.4mm and the thickness ratio at 1.2, the strain bearing capacity of circumferential weld joints with crack depths of 2mm, 4mm, and 6mm were compared under five different strength matching coefficients (0.8, 0.9, 1.0, 1.1, 1.2), assuming a fracture toughness of 0.254mm as shown in Fig.9. The results indicate that an increase in the strength matching coefficient is beneficial for enhancing the carrying capacity, with a more pronounced effect on strain bearing capacity improvement under small crack size conditions. As much as possible to improve the strength matching coefficient of the girth weld, so that the girth weld has a higher bearing capacity, to ensure the safety of the girth weld to the greatest extent.

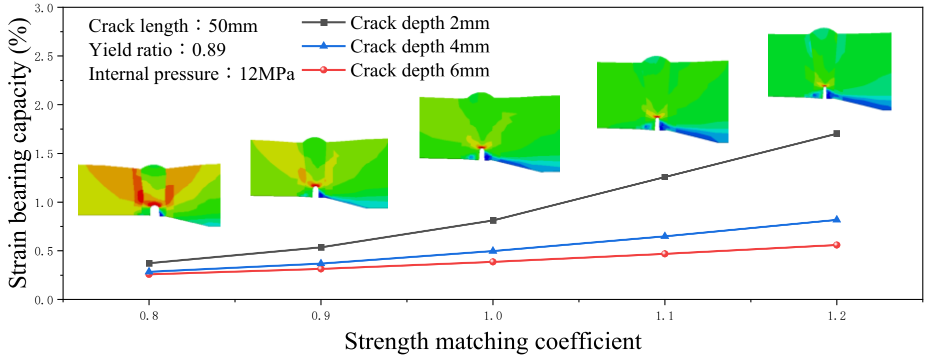

Fig. 9. Under different Crack depth, the strain capacity changes with the strength matching coefficient.

4 Conclusions

The following conclusions were reached:

(1) For circumferential weld joints with misalignment, a smaller misalignment amount and a higher weld strength matching coefficient help reduce the crack driving force and improve the joint's resistance to cracking. The larger the misalignment, the smaller the increase in strain capacity caused by an increase in the weld strength matching coefficient.

(2) Regarding circumferential weld joints of pipelines with unequal wall thicknesses, the thinner side wall thickness is the key factor determining the joint's carrying capacity. When the thinner side wall thickness is the same, the size of the thickness ratio has a minor effect on the strain bearing capacity of the circumferential weld joint. Under small crack size conditions, the improvement in strain bearing capacity due to the strength matching coefficient is more pronounced.

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