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Numerical and experimental study on critical crack tip opening displacement of X80 pipeline steel

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1. Introduction

High strength pipeline is the most effective and economical option for long distance transportation of gas resources [1]. For instance, X80 steel pipelines have been widely used in the long distance gas pipelines in China [2]. The critical CTOD values of X80 steel serve as a basis in the performance evaluation for these pipelines [3]. The CTOD parameter was proposed in 1963 by Wells [4] to perform as an engineering fracture parameter for fracture beyond yielding. The CTOD criterion assumes that fracture occurs When CTOD reaches critical CTOD or exceeds it.

For buried pipeline fracture failure, valuable work has been conducted by a series of researchers. Zhang [5] studied the ductile fracture of X65 steel pipes based on extended finite element method. Han [6] studied the effect of constraint on the critical CTOD of X65 steel using a Gurson type void model. Yang [7] studied the fracture toughness of the materials in welded joint of X80 steel. Yan Di [8] developed a new specimen for high-grade pipeline steels CTOA test. Wang [9] conducted quasi-static tests to analyze the crack propagation process and fracture mechanism of X70 and X80 pipeline steels. Oh and his research group derived ductile failure histories of varieties of pipe steels by tensile and 3-point bending tests using GTN model [10-12].

In this study, both experimental and numerical study were conducted for 3-point bending tests of different thickness X80 pipeline steel specimens with initial crack. Based on experiment results, suitable numerical model using the extended finite element method was developed, which can be referenced for the performance evaluation and quality assurance for X80 steel gas pipelines.

2. Experimental study on three-point bending tests of X80 steel specimens

The Critical CTOD δ_c is effected by the thickness t of the specimen, as when t is small, the specimen is close to plane stress state. With increase of t, the specimen changes to plane strain state gradually. So X80 steel specimens with different thicknesses were considered in this study.

According to GB/T 21143-2007 [13], the maximum force P_c and the plastic component of the crack mouth opening displacement V_p. both can be derived by the measured P-V curve of tested specimen, as shown in Fig. 1. The detailed dimension parameters of the specimen are illustrated in Fig. 2. And based on Eq. (1), the critical CTOD δ_c can be easily determined.

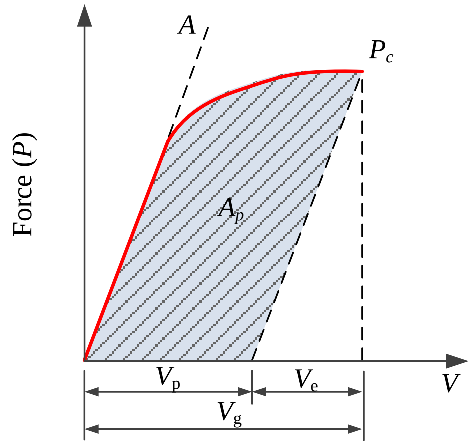


Fig. 1 P-V curve and definition of V_P

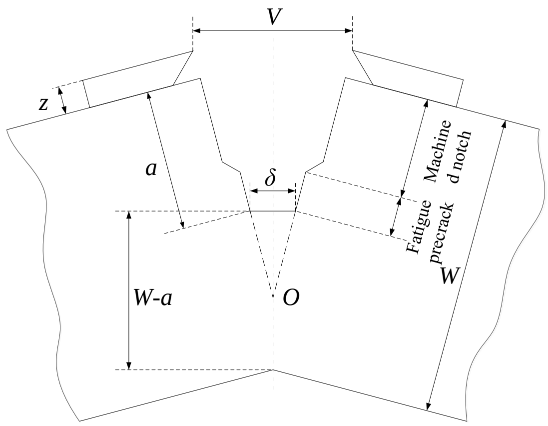


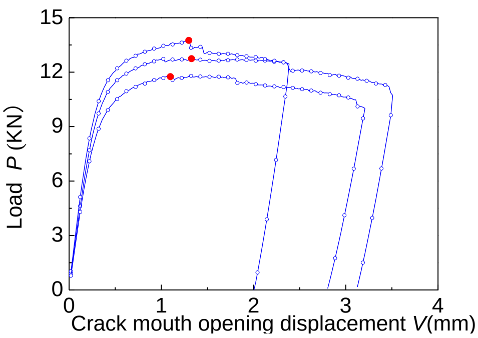
Fig. 2 Dimension of CTOD specimen

$$\delta = \left[\frac{PS}{WB^{1.5}} \times f\left(\frac{a}{W}\right)\right]^2 \left[\frac{\left(1-\mu^2\right)}{2\sigma_s E}\right] + \frac{0.4(W-a)V_p}{0.6a+0.4W+z}, \quad (1)$$

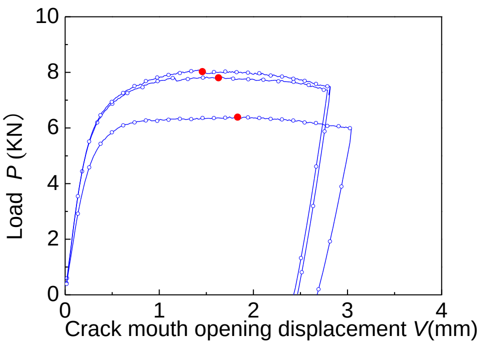
where δ is crack tip opening displacement; P is applied force; S is span between outer loading points in three point bend test; W is effective width of test specimen; V_p is plastic component of crack mouth opening displacement; E is elastic modules; σ_s is yield strength; a is original crack length; z is distance of the crack opening gauge location above the surface of the specimen; B is specimen thickness; μ is Poisson's ratio; f is a mathematical function of (a/W).

In this study, the length and width of the specimen are 120 mm and 25 mm, respectively. And two specimen thicknesses, 12.5 mm and 7 mm, are considered. The initial machined notch of the specimen is 5 mm, and the fatigue precrack is generated by the MTS 632.03C-20 High Frequency Fatigue Tester. The total original crack length should be between $0.45W$ and $0.70W$ for all specimens [13]. In the process, the loading frequency is 10 Hz, and the loading rate is 0.0167 mm/s.

Fig. 3 Three Point Bending Testing



a

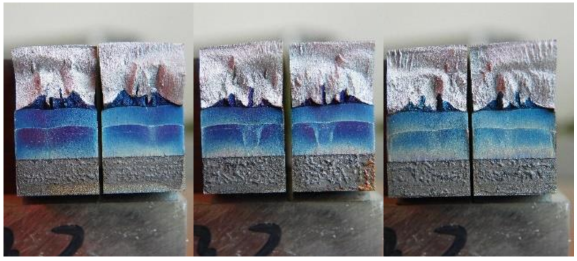


b

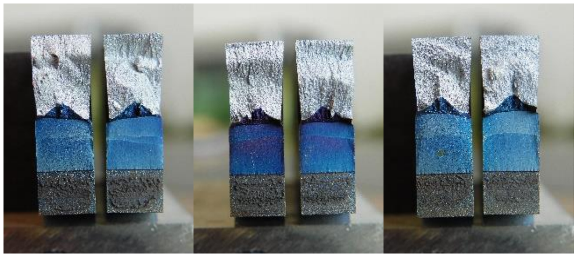
Fig. 4 The *P-V* curves for all specimens: a - B = 12.5 mm; b - B = 7 mm

The 3 point bending tests were conducted on the prepared specimens with the *P-V* curve measured by the computer, as shown in Fig. 3. Totally, six specimens were tested, and the *P-V* curves are shown in Fig. 4. The red points represents the maximum applied forces (P_c), and the Plastic crack mouth opening displacements (V_p) can also obtained from the figure, as listed in Table 1. Results show that, for the same pipe material, V_p was influenced obviously by the specimen thickness B, and if B is smaller, V_p is larger.

After the test, the specimens were technically treated to make the fracture surface turn blue, and the color of the initial crack would be a little lighter. The colored fracture surfaces are shown in Fig. 5. It can be derived that for both kinds of specimens, the crack propagation occurs first in the center area of the specimen. For specimens with thinner thickness, the propagation crack length is linearly distributed from center to edge. For specimens with thicker thickness, the crack length in the center segment is nearly the same, and linearly attenuated from center to edge.



a



b

Fig. 5 Fracture surface of the specimens: a - B = 12.5 mm; b - B = 7 mm

The original crack length of the specimen can be calculated by Eq. (2), in which the nine crack lengths can be measured as shown in Fig. 6. Eventually, by the measured parameters, the critical CTOD can be calculated, as listed in Table 1. The results show that the thicker specimens have smaller critical CTOD.

$$a_0 = \frac{1}{8}\left[\left(\frac{a_1 + a_9}{2}\right) + \sum\left(a_2 + a_3 + a_4 + a_5 + a_6 + a_7 + a_8\right)\right]. \quad (2)$$

3. Numerical simulation and results

In this study, the crack propagation of the X80 steel specimens is simulated using by ABAQUS XFEM software package. It is proven to be an effective way to study the ductile fracture mechanism of pipe steels [5]. The true stress-strain curve of the tested X80 steel was used in the model, as shown in Fig. 7. For X80 pipeline steel with the occurrence of ductile failure, the maximum principal strain criterion is used for damage initiation of the crack, and the exponential response is used for damage evolution.

Table 1

Experiment results

Specimen Number	Specimen thickness *B*, mm	Specimen width *W*, mm	Original crack length *a*, mm	The maximum applied force P_c, N	Plastic crack mouth opening displacement V_p, mm	Critical CTOD, mm	Average Critical CTOD, mm
1	12.53	25.00	15.45	12752.58	0.95	0.19	
2	12.53	24.99	15.36	12404.98	0.72	0.15	0.18
3	12.55	25.03	15.35	13713.15	0.99	0.20	
4	7.03	24.99	14.29	7835.46	1.22	0.28	
5	7.02	24.99	14.27	8087.34	1.25	0.28	0.28
6	7.02	24.97	15.42	6402.06	1.45	0.26	

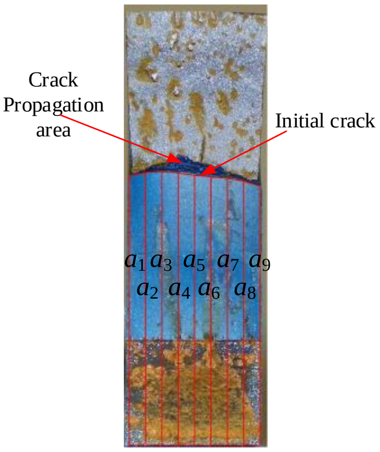


Fig. 6 Measurement of the original crack length in the crack surface

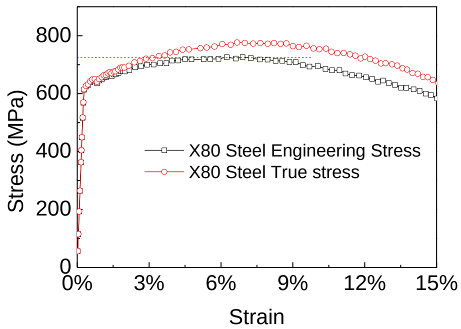


Fig. 7 Stress-Strain curve of X80 pipeline steel

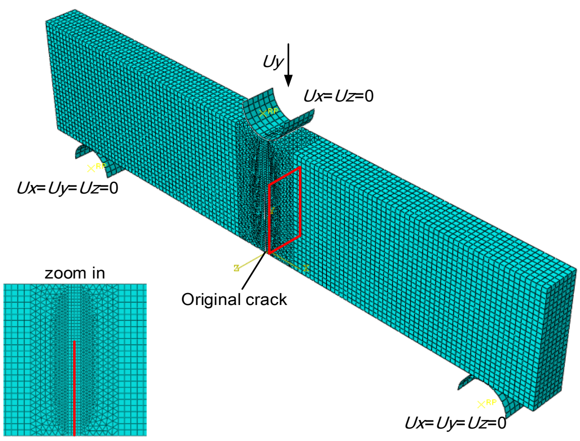


Fig. 8 Finite element model for the 3 point bending test

The finite element model associated with boundary conditions was illustrated in Fig. 8. The initial crack is insert in specimen, and in order to ensure the calculation accuracy, a fine mesh was employed in the crack area with 8-node linear brick elements (C3D8R). The transmission area was meshed by 4-node linear element C3D4 and a coarser mesh was employed in the boundary area with C3D8R elements [14]. The supports are defined as rigid bodies.

3.1. Crack propagation simulation for thin specimen

By comparing numerical results with experimental results, suitable values for the maximum principle strain in damage initiation criterion ε_{maxps} and energy release rate G_C were determined. Fig. 9 shows the effect of ε_{maxps} on the *P*-*V* Curve. Results shows that, for the specimen with thickness of 7mm, when the parameters are set as $\varepsilon_{maxps} = 0.13$ and $G_C = 200$ N/mm, the XFEM results are closest to the experimental data. The critical CTOD calculated is 0.27mm, which is almost the same with the experimental result listed in Table 1.

The crack propagation history during the bending test is also illustrated in Fig. 10. In Stage 1, Damage occurs in the crack tip when the principal strain reaches its critical value, and the load reaches its peak value. In Stage 2, cohesive crack occurs in the crack tip. In Stage 3, crack propagation appears.

3.2. Crack propagation simulation for thick specimen

Crack propagation simulation for the thick specimen was also conducted using XFEM. For the specimen with thickness of 12.5mm, when the parameters are set as $\varepsilon_{maxps} = 0.08$ and $G_C = 200$ N/mm, the XFEM results are closest to the experimental data, as illustrated in Fig. 11. The critical CTOD calculated is 0.18 mm, which is the same with the experimental result listed in Table 1. The crack propagation was also derived in Fig. 12, which is similar with the thin specimen.

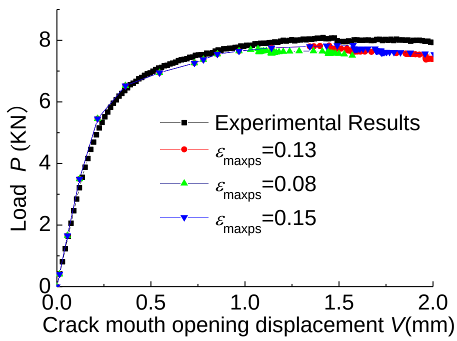


Fig. 9 Effect of ε_{maxps} on *P*-*V* Curve for thin specimen

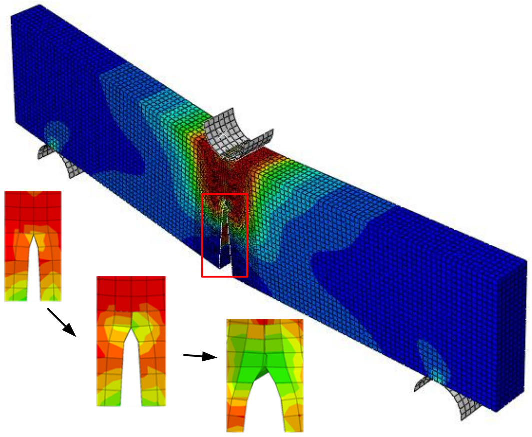


Fig. 10 The crack propagation history for thin specimen

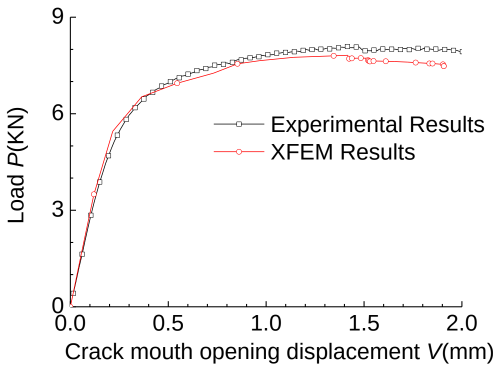


Fig. 11 Comparison of the numerical and experimental results for thick specimen

It can be obtained that, although the simulated results is quite accurate comparing with the experimental results. But the maximum principle strain criterion ε_{maxps} is different for the specimens with different thicknesses. So when conducting a numerical analysis for CTOD calculating, the failure criterion must be validated by suitable experimental results.

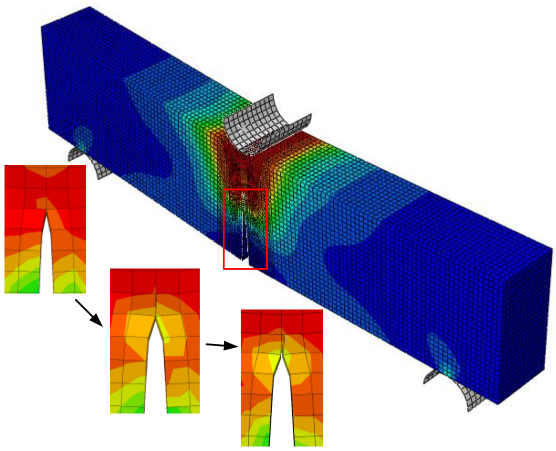


Fig. 12 The crack propagation history for thick specimen

4. Conclusions

In this study, the critical CTOD for X80 pipeline steel was studied. 3-point bending tests were conducted for two specimens with different thickness. Based on the experimental results, reasonable numerical models based on the extended finite element method was established. Results show that, the critical CTOD δ_{crit} decreases with the increase of specimen thickness *B*; the maximum principle strain criterion for damage initiation ε_{maxps} is suitable for the ductile crack simulation of X80 pipeline steel, but ε_{maxps} decreases with the increase of specimen thickness. This study can be referenced for the performance evaluation and quality assurance for X80 steel pipelines.

Acknowledgements

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NUMERICAL AND EXPERIMENTAL STUDY ON CRITICAL TIP OPENING DISPLACEMENT OF X80 STEEL PIPELINE STEEL

S u m m a r y

High strength pipelines is widely used for the long distance transportation of oil and gas resources. Fracture toughness is a significant material property for these high strength pipeline steels. In this study, the critical crack tip opening displacement (CTOD) of X80 pipeline steel was studied both experimentally and numerically. 3 point bending tests were conducted for 6 specimens with 2 thicknesses. Numerical model using the extended finite element method was also established, with maximum principle strain criterion used for damage initiation. Results show that, the critical CTOD decreases with the increase of specimen thickness. And to give reasonable simulation results in the numerical model, larger maximum principle strain criterion should be used for thin specimens. This study can be referenced for the performance evaluation and quality assurance for X80 steel gas pipelines.

Keywords: X80 pipeline steel, critical crack tip opening displacement, three point bending test, XFEM.

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