Research on Pressure bearing capacity of Defective Urban Gas Polyethylene Pipes

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Abstract: Polyethylene pipes have been widely used in the urban gas industry. However, there are few researches on the safety performance evaluation of polyethylene pipes in use at home and abroad, which makes it impossible to carry out Fitness-For-Service evaluation of defects found in the inspection, and thus cannot accurately judge the safety status of defective polyethylene pipes. In this paper, two typical polyethylene pipe materials, PE80 and PE100 are selected. Based on the tensile performance test, the constitutive model is established. Using the method of finite element simulation, the ultimate pressure bearing capacity of 9 defect models was analyzed and studied. And the relationship between defect size and pressure bearing capacity was initially determined. Provides a foundation for subsequent engineering applications.

1. Introduction
City gas pipeline as a crucial component of municipal public utilities and critical infrastructure of modern cities, is closely related to economic and social development as well as people’s wellbeing. Polyethylene (PE) pipes have the features of great corrosion resistance, long service life and relatively low cost. In the field of gas, they are one of the top choices for repair and renewal of newly laid pipelines or old pipelines.[1] Compared with steel pipes, the research and application of polyethylene pipes are relatively lagging behind. In recent years, there are more in-depth research on selection of raw materials, quality control of pipes and engineering construction of polyethylene pipes and these researches are being perfected in many years of practice. But there are fewer research findings of safety performance evaluation of polyethylene pipes.[2] The research and evaluation of carrying capacity is the focus of safety performance evaluation, especially for that of polyethylene pipes with defects, which can solve the problem of whether polyethylene pipes can still be used safely in case of defects caused by external force, thus having important social significance and engineering value.[3]

2. Research Contents

2.1. Mechanical constitutive model of the polyethylene
Polyethylene is a viscoelastic material between ideal elastic solid and viscous liquid. The mechanical property of polyethylene is much more complicated than that of steels. In addition, polyethylene also creeps at room temperature, and the yield stress has obvious strain rate effect.[4] Therefore, in order to
study the carrying capacity of PE gas pipelines with defects, we must have an in-depth understanding of their mechanical properties. This paper mainly selects two types of polyethylene, PE80 and PE100, which are most used in China currently, for research.\[5\]

2.1.1. Tensile property test of polyethylene pipes
In this test, the slatted sample was made by longitudinal cutting of polyethylene pipes, and the tensile yield stress of polyethylene pipes was measured by tensile testing machine under specified conditions.\[6\] Before the test, the sample was placed in an environment at temperatures of 23 °C ± 2 °C for conditioning for about 6.5 hours. Based on the nominal wall thickness of the pipes and the sample preparation method of cutting by the cutter, the speeds of the test are 0.01 m/s, 0.005 m/s, 1 × 10^{-3} m/s, 5 × 10^{-4} m/s, 1 × 10^{-4} m/s and 1 × 10^{-5} m/s respectively. The tensile fracture diagram of the tensile test is shown in Figure 1.

![Figure 1 Tensile fracture diagram of tensile specimen](image)

Figure 1 Tensile fracture diagram of tensile specimen

Figure 2 and 3 are stress-strain curves of the tensile test of polyethylene pipes under different strain rates. It can be seen that there is evident rate dependence of polyethylene pipes.\[7\]

![Figure 2 Engineering stress-strain curve under different strain rates of PE80](image)

![Figure 3 Engineering stress-strain curve under different strain rates of PE100](image)

After obtaining the average value of repeated tests, it is found that the yield stress and tensile strain rate of polyethylene pipes fit the logarithmic linear relationship shown in Figure 4 and 5.
The relationship between yield stress and strain rate obtained by numerical fitting is almost in line with the following equation:

\[
\sigma_y^{PE100} = 34.073 + 4.637 \times \log \dot{\varepsilon}
\]

\[
\sigma_y^{PE80} = 20.061 + 1.74 \times \log \dot{\varepsilon}
\]

Where: \( \dot{\varepsilon} \) - strain rate, \( \text{s}^{-1} \); \( \sigma_y \) - the yield stress at the strain rate \( \dot{\varepsilon} \), MPa.

2.1.2. Establishment of constitutive model of the polyethylene

In order to show that the strain rate effect of polyethylene has nothing to do with strain history, this paper selects the stress-strain model proposed by Suleiman\[8\]:

\[
\sigma = \frac{\varepsilon}{a + b \varepsilon}
\]

Where: \( a, b \) - parameters related to strain rate, \( \text{MPa}^{-1} \); \( \sigma \) - stress, MPa; \( \varepsilon \) - strain, dimensionless.

Through tensile tests under different strain rates, the above formula is used to fit the curves under different rates as shown in Figure 6 and 7, and the parameters obtained \( a \) and \( b \) have logarithmic correlation with the strain rate\[9\]:

\[
a = a_1 \ln(\dot{\varepsilon}) + a_2
\]

\[
b = b_1 \ln(\dot{\varepsilon}) + b_2
\]

Where: \( a_1, a_2, b_1, b_2 \) can be obtained by fitting the curves of Figure 8 and 9, as shown in Table 1.
Parameters of the constitutive model of PE80 and PE100 are shown in Table 1.

| Parameters | Pipe material | a1         | a2         | b1         | b2         |
|------------|---------------|------------|------------|------------|------------|
| PE80       | -1.35×10^{-4} | -2.09×10^{-4} | -2.69×10^{-3} | 2.57×10^{-2} |
| PE100      | -7.51×10^{-5} | -3.11×10^{-5} | -2.37×10^{-3} | 2.03×10^{-2} |

2.2. Finite element analysis of ultimate carrying capacity of polyethylene pipe with defects

2.2.1. Introduction of the model for polyethylene pipes with local thinning defects

This paper mainly takes local thinning defects as the research object, and the design of the defect model chiefly considers the size of local thinning defects. For ease of analysis, dimensionless parameters of local thinning defects are adopted, which are respectively the relative depth (\(a/t\)), relative circumferential length (\(\theta/\pi\)) and relative axial length of local thinning defects (\(L/\sqrt{Rt}\)). With the orthogonal method, three factors are considered here (\(a/t\), \(\theta/\pi\), \(L/\sqrt{Rt}\)), 3 values are selected for each factor, and 9 defect models are designed for each material, as shown in Table 2.
Among them: \(d\) - depth of defect; \(\theta\) - circumferential angle of defect; \(L\) - axial length of defect; \(R\) - mean radius of the pipe; \(t\) - nominal wall thickness), the schematic diagram of the defect model is shown in Figure 10.

![Figure 10 Model of partial thinning defect of PE pipe](image)

Table 2 Defect model design table

| Serial number | Defect size | \(a / t\) | \(\theta / \pi\) | \(L / \sqrt{Rt}\) |
|---------------|-------------|-----------|----------------|-----------------|
| 1             | 0.1         | 1/12      | 0.5            |                 |
| 2             | 0.1         | 1/3       | 1.5            |                 |
| 3             | 0.1         | 2/3       | 2.5            |                 |
| 4             | 0.4         | 1/12      | 1.5            |                 |
| 5             | 0.4         | 1/3       | 2.5            |                 |
| 6             | 0.4         | 2/3       | 0.5            |                 |
| 7             | 0.7         | 1/12      | 2.5            |                 |
| 8             | 0.7         | 1/3       | 0.5            |                 |
| 9             | 0.7         | 2/3       | 1.5            |                 |

2.2.2. FEM analysis results of ultimate carrying capacity of pipes with different defects

(1) Analysis software and model establishment

The finite element analysis software ABAQUS is used for simulation analysis. The pipe diameter is \(\Phi 160\) mm and the nominal wall thickness is 9.1 mm. Firstly, a three-dimensional model of polyethylene pipes is established. Because the polyethylene pipes are symmetrical along the axis, and in order to simplify the calculation, only a quarter of the model needs to be established by cutting the polyethylene pipes, as shown in Figure 11.

![Figure 11 Defect model of internal pressure analysis](image)

(2) Mesh generation

The hyperelastic material option is selected to define the polyethylene, the hybrid element (C3D8H)
is selected as the element type, and the hexahedral sweep mesh is used as the mesh control parameter. The local mesh refinement is carried out on the defect parts. Finally, the number of meshes in each model is maintained at about 20,000-50,000, as shown in Figure 12.

(3) Boundary conditions and loading

Fixed constraints are applied to the left end surface, and symmetrical constraints are applied to the middle symmetrical plane and the right end surface of the pipeline respectively. In this analysis, only the impact of internal pressure is considered, and pressure $P$ is applied to the inner-wall surface of the pipeline. Since the ultimate load of the PE pipe is unknown, the pressure uniformly rises from 0.1 MPa in the loading process. Taking the No.3 defect model of PE80 material as an example, the strain nephogram and internal pressure-strain relation diagram are as shown in Figure 13 and 14.
(4) Analysis Results

The results of finite element analysis are shown in Table 3. According to the comparative analysis of the data in the table, the impact of three factors including the relative depth ($a/t$), relative circumferential length of defect ($\theta/\pi$) and relative axial length of the defect ($L/\sqrt{Rt}$) on the limit internal pressure is ranked as follows: the relative depth has the greatest impact on the limit internal pressure, and when the relative depth changes, the limit internal pressure has the most significant changes; the relative axial length has the second largest impact; and the relative circumferential angle has the least impact on the limit internal pressure.[12]

![Figure 14 The internal pressure-strain relationship of PE80-3 defect model](image)

### Table 3 Limit internal pressure finite element analysis results of different defect models

| Serial number | Defect size | PE100 limit internal pressure | PE80 limit internal pressure |
|---------------|-------------|-------------------------------|------------------------------|
|               | $a/t$ | $\theta/\pi$ | $L/\sqrt{Rt}$ | $P_L$/MPa | $P_L$/MPa |
| 1             | 0.1   | 1/12      | 0.5           | 2.732     | 1.501     |
| 2             | 0.1   | 1/3       | 1.5           | 2.516     | 1.495     |
| 3             | 0.1   | 2/3       | 2.5           | 2.458     | 1.428     |
| 4             | 0.4   | 1/12      | 1.5           | 1.787     | 1.143     |
| 5             | 0.4   | 1/3       | 2.5           | 1.517     | 1.005     |
| 6             | 0.4   | 2/3       | 0.5           | 1.946     | 1.277     |
| 7             | 0.7   | 1/12      | 2.5           | 1.068     | 0.601     |
| 8             | 0.7   | 1/3       | 0.5           | 1.738     | 0.915     |
| 9             | 0.7   | 2/3       | 1.5           | 1.152     | 0.785     |

### 3. Conclusions

(1) The mechanical property parameters of polyethylene PE80 and PE100 are measured through the tensile test of the materials. The test shows that the rate dependence of the two materials is evident. On the basis of tensile test and analysis, the mechanical constitutive models of the two materials are established, and the basic parameters of the constitutive models of polyethylene PE80 and PE100 are obtained.

(2) The finite element analysis software is used to design different local thinning defect models, and study and analyze the ultimate carrying capacity of polyethylene PE80 and PE100 with defects simply under internal pressure. The analysis results show that the defect depth has the greatest impact on the limit internal pressure, the axial length has the second largest impact, and the circumferential length has the least impact on the limit internal pressure. Therefore, in practical engineering application, we should attach special attention to the defect depth found in the test of polyethylene pipes.[13]
(3) The load condition which only bears internal pressure is the ideal condition. In the actual operation conditions of polyethylene pipes, most of them are the combination condition of internal pressure and blending. In the following research work, the impact of combination conditions on the still-in-service capacity of polyethylene pipes with defects will be studied to better guide engineering application.

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