Nonlinear Finite Element Analysis of the Limit State and Pressure of Dented X60 Steel Pipeline

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1. Introduction

Pipelines are the most common structures for long distance transportation of oil and gas [1], which are also called lifelines for their importance [2]. But as typical shell structures, they are vulnerable to external loads, especially for those with defects. Dent is one of the main kind of defects for pipelines. Dawson S J [3] reported that, there are 9851 dents existed in the 7022km long pipelines in Europe. A lot of literatures are available for assessment of dented pipes. Ellinas [4] proposed a relationship for dent depth with external load. Wu [5] analyzed the damage degree of oil gas pipes with type II plain. Yang [6] studied the dent shape calculation methods by interpolation model. Jiao [7] concluded the general integrity assessment procedure for dented pipes. M. Allouti [8] found that, for shallow dent, influence of dent depth on critical pressure of A37 steel pipe is negligible. Limam [9] investigated the collapse behaviour of dented tubes under combined bending and internal pressure. Zhang [10] conducted a numerical analysis for pipe's dent behaviour impacted by perilous rock. Although numbers of researches have been done, so far, no accurate limit pressure prediction model for dented X60 pipe has been propose for engineering applicability.

To fill this gap, efforts were put in this study to investigate the failure process of dented X60 steel pipe under internal pressure with a validated rigorous 3D nonlinear finite element method. Effects of common influence factors, e.g., the pipe initial pressure, ratio of diameter to wall thickness, dent depth and diameter of indenter, on failure pressure were discussed in detail. Based on the parametric analysis results and regression method, an engineering applicable limit pressure prediction model was presented. This proposed method can be referenced for the integrity assessment of X60 pipeline.

2. Numerical modelling

General finite element code package ABAQUS [11] was used in this study to establish a finite element model for limit pressure analysis of dented pipe. Due to the symmetry of the model, only one fourth of the total model was needed in the numerical model, as shown in Fig. 1. The indenter was built by 3D analytical rigid surface to reduce the calculation time, with its bottom assumed to be a sphere, for only pipe performance is concerned in this study. To apply the constrain conditions on the indenter, a reference point was defined at the center of the top surface of indenter. Eight node hexahedral solid elements with reduced integration (C3D8R) were used to simulate the pipe. Fine mesh for pipe was used in the contact area between the pipe and indenter, while coarse mesh was used for other parts both axially and circumferentially. In order to capture the accurate deformation in the pipe section, the pipe wall was discretized to three equal sized solid elements. Surface to surface contact approach implemented in ABAQUS was used to model the interaction between the indenter and pipe. Suitable boundaries were applied to conduct a reasonable numerical analysis. As shown in Fig. 1, surface A and B were applied with symmetrical boundary conditions, Surface C's motion was restrained in XY plane, and the bottom line of the pipe was constrained to eliminate the rigid motion during the analysis. Pipe length in the model was set to be four times of pipe diameter.

The pipe was subjected to four load steps during the analysis. An internal pressure was proposed fist in the inside of the pipe to simulate the service condition. Next, the indenter was displaced by imposing a vertical downward displacement to simulate the denting process. After this, the indenter was displaced again with a vertical outward displacement to release the dent. Finally, internal pressure was applied to the inner surface of pipe to investigate the pipe performance and determine the limit pressure. It should to be noticed that the model was parameterized by programing with PY code [11], which makes a series of numerical study easier to accomplish.

3. Failure criteria and experimental validation

Net section failure criteria was adopted in this study as it is commonly used in limit pressure analysis for defected pipe structures [7, 12]. According to this criteria, the pipe's failure was considered to occur once the minimum Von Mises stress in the critical pipe wall section reaches to the flow stress σ_f. The commonly used flow stress value can be assumed as:

$$\left.\begin{array}{l} \sigma_f = (\sigma_s + \sigma_b)/2, \\ \sigma_f = \sigma_b, \end{array}\right\} \qquad (1)$$

where σ_s is the yield strength of pipe steel, σ_b is the ultimate strength of pipe steel.

Full scale experimental results [13] were used here to determine the correct value of flow stress for limit pressure analysis of dented pipe. An API X52 steel pipe was adopted to conducted the experiment, the pipe diameter D and pipe wall thickness t are 323.8mm and 4.775mm, respectively. The yield strength σ_s and ultimate strength σ_b of the steel are 437MPa and 567.2MPa, respectively. The dent depth h was 0.12D. Burst pressure of this pipe was 16.05MPa. Parameters were all employed to conduct a comparison numerical investigation with the experiment.

a

b
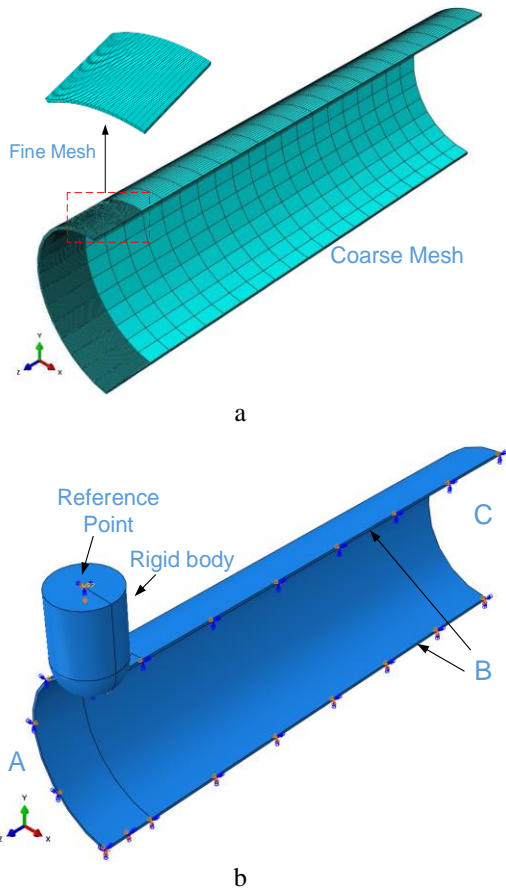
Fig. 1 3D nonlinear finite element model: a-mesh pipe, b-boundaries of the model
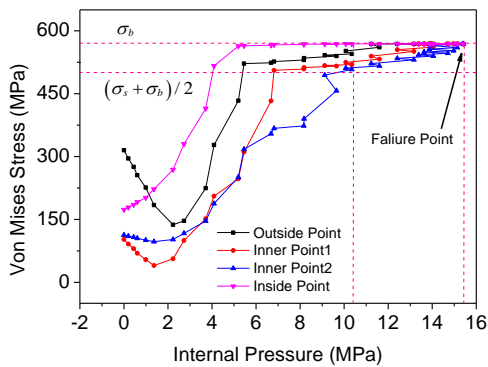

Fig. 2 Von Mises Stress trends in the critical wall section in pressure loading step

Fig. 2 shows the von Mises stress trends of the critical wall section under internal pressure load. It can be derived that stresses in the superficial points of pipe wall are larger than those of inner points. This is mainly caused by the bending strain in the dent area. And limit pressures determined by σ_b and $(\sigma_b+\sigma_b)/2$ are 15.4 MPa and 10.5 MPa. It is obvious that, taking σ_b as the flow stress is more reasonable for failure predicting of dented pipe.
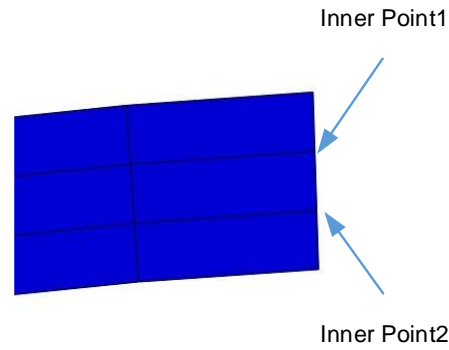

Fig. 3 Sketch of the inter point positions

4. Failure analysis of dented X60 pipe

4.1. X60 steel property model

API X60 pipe steel used in the Shanxi-Beijing Natural Gas Pipeline was considered in the numerical study. Stress strain relationship of X60 steel is illustrated in Fig. 4. Nominal stress-strain curve was obtained by tensile tests and then transformed to true stress-strain curve by the following formula:

$$\left.\begin{aligned} \varepsilon_{ture} &= ln1 + \varepsilon_{nom}, \\ \sigma_{ture} &= \sigma_{nom}1 + \varepsilon_{nom}, \end{aligned}\right\} \tag{2}$$

where σ_{nom}, ε_{nom} are nominal stress and strain, respectively; σ_{true}, ε_{true} are true stress and strain, respectively.
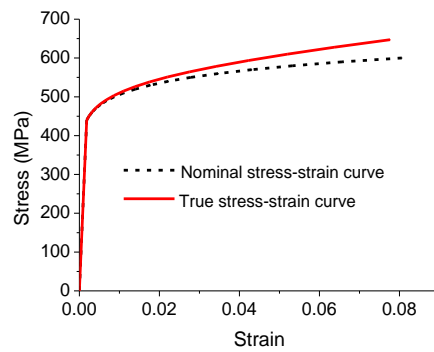

Fig. 4 Stress-strain curve for X60 steel

4.2. Critical dent depth

The main purpose of this study is to investigate the limit pressure of dented pipe. But it should be mentioned that, the failure may occur to the pipe in the denting process, if the external load is extremely large. So the critical dent depth of X60 pipe was discussed first. The diameter and wall thickness are 660 mm and 8.7mm, and the diameter of the indenter was set to be 50mm. Fig. 5 illustrates the Mises stress trends of the four points in the critical wall section in pipe. The superficial points get larger stress during the whole load process, and when the stress

of the inner point reaches σ_f. the pipe can be considered as failure. The critical dent depth for this case is 0.168D. Thus, in limit pressure analysis of dented pipe, the dent depth must be less than the critical dent depth.
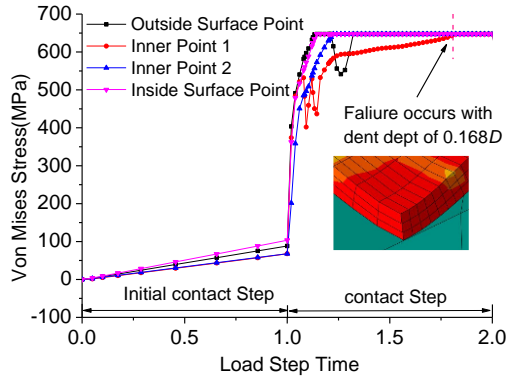

Fig. 5 Von Mises Stress trends in the critical wall section in contact step

4.3. Burst failure process of dented X60 pipe

In this section, a full burst failure process of a dented X60 steel pipe was performed. The pipe geometrical parameters were the same as above. While the diameter of indenter was changed to 80mm to maintain a larger dent depth. Fig. 6 shows the Mises stress trends in critical wall section during the load process. In the dent load step the entire section becomes highly plastic which is similar to Fig. 5, but the inner point didn't reach σ_f, and when indenter release the dent load, residual stresses retain in the section. Finally the failure to the section when the stress of the inner point reaches σ_f under pressure load.
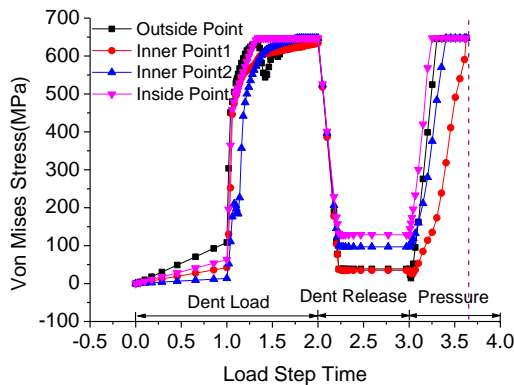

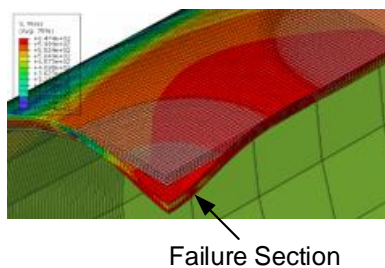Fig. 6 Von Mises Stress trends in the critical wall section in burst process

Fig. 7 Failure section under burst pressure

Fig. 7 illustrates the failure section under internal pressure. It can be derived that; failure occurs in the boundary of the dent area along the pipe axial direction. The influence factors on limit pressure for dented X60 steel pipe will be investigated in detail in the following part by this method.

5. Results and Discussion

5.1. Effects of dent depth

Dent depth reflects the damage degree of the pipe caused by the indenter [5]. In this section, influences of dent depth on pipe failure was studied. The diameter of the indenter was also set to be 120mm, and five values of dent depth h was considered as 0.04D, 0.08D, 0.12D, 0.16D, 0.2D. Fig. 8 illustrates the relationship of the limit pressure plim with dent depth. It can be obtained that, if $h<0.08D$, $p_{\lim}$ almost remain the same value 16.9MPa, which is very close to the burst pressure of the perfect pipe 17.05MPa calculated by $\sigma_u/2D$. This is consistent with previous results for another kind of steel pipeline [8]. The result also reflects that critical dent depth of 6% for pressurized pipe suggested by ASME [14, 15] is conservative from the view of pipe strength. If $h>0.12D$, $p_{\lim}$ decreases as h increases. The limit stress state of dent area when pipe failure occurs is also investigated here. If dent depth h is 0.04D, the pipe expands obviously with regard to the original pipe position and failure occurs in the center point of dent area. While, if dent depth h is 0.16D, the pipe has no obvious deformation with regard to the original pipe position and failure occurs in the side of the dent area along the axial direction.
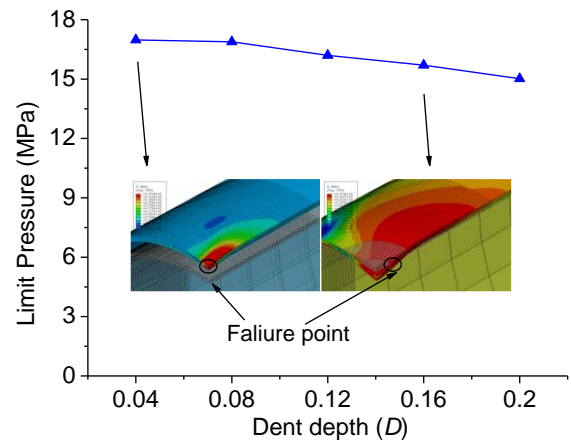

Fig. 8 Effects of dent depth on limit pressure

For all the stress is so large, which is not suitable for comparison analysis, the plastic strain PE of the inner point (failure point) in the pipe was investigated here. Fig. 9 shows the distribution of PE in dent area along the axial direction.

It can be obtained that, with the increase of dent depth, PE increases, which is consistent with the large strain induced by the indenter. What's more, when dent depth h is less than 0.08D, PE peaks in the center of dent area, so pipe failure occurs in the center, while when h is larger than 0.12D, PE peaks in the boundary of dent area, so pipe failure occurs in the side.
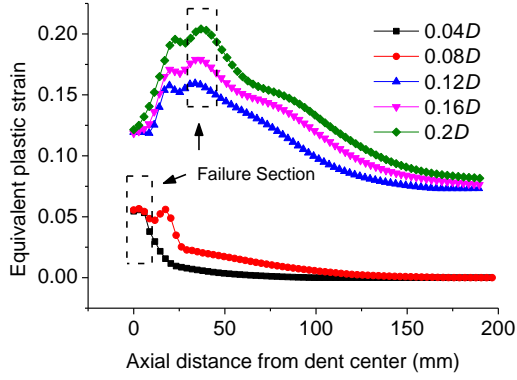
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Fig. 9 Equivalent plastic strain distribution of inner point along axial direction

5.2. Effects of indenter diameter

The indenter diameter D_{ind} directly influences the curvature of the dent area which finally affects the stress and strain in this area. In this section five diameter values were considered, i.e., 50, 80, 120, 160 and 200 mm. Fig. 10 illustrates the relationship of the limit pressure p_{lim} with indenter diameter under different dent depth conditions.

The limit pressure p_{lim} increases with the increase of indenter diameter D_{Ind}, for larger bending strain will be induced by a smaller indenter. It indicates that, the dented pipe with same dent depth is more dangerous if the dent area is smaller. And the pipeline operators must pay more attention to the sharp dents with large depth and very small areas.
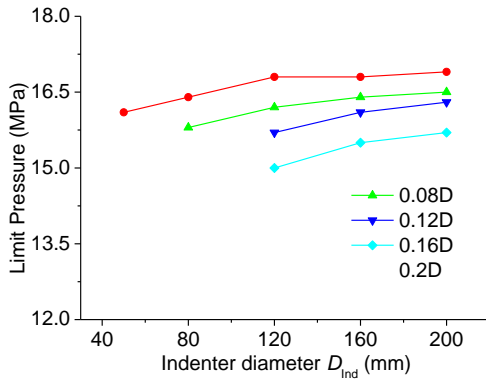

Fig. 10 Effects of indenter diameter on pipe limit pressure

5.3. Effects of initial internal pressure

The initial internal pressure will change the initial stress state of the pipe. Four internal pressures were taken into consideration, i.e., 3, 5, 6, 4, 8 MPa. Fig. 11 shows the relationship between the limit pressure p_{lim} and internal pressure with different dent depths. Results show that, if dent depth $h<0.04$, p_{lim} almost remain the same value with the increase of internal pressure p, while if dent depth $h>0.08$, the limit pressure p_{lim} decreases with the increase of internal pressure p.
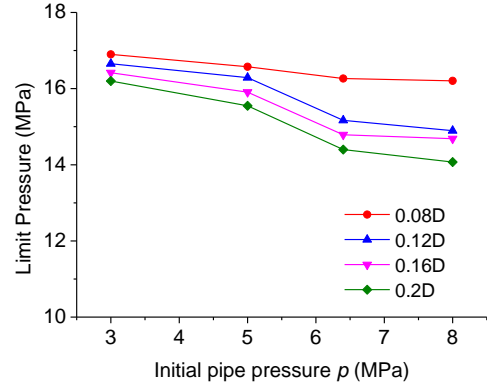

Fig. 11 Effects of pipe initial pressure on pipe limit pressure

5.4. Effects of ratio of diameter to wall thickness

Ratio of diameter to wall thickness D/t affects the pipe stiffness and stress state in working conditions. In this section, four wall thicknesses were considered, i.e., 7.14, 8, 8.7 and 10.3 mm. The corresponding values of D/t are 92.4, 82.5, 75.8 and 64. Relationship between limit pressure p_{lim} and D/t is shown in Fig. 12. It is easy to obtain that, with the increase of D/t, p_{lim} decreases, for thinner wall thickness leads to a larger hoop stress which makes failure occur easier.

6. Prediction of the limit pressure

Based on a series of FE analyses, the functional relationship for limit pressure of dented X60 steel pipe and the main influence factors can be derived. For 3D nonlinear finite element model is quite time consuming and needs some professionals to calculate, a simple limit pressure prediction model was proposed. Power functions are assumed to describe relationships. And the equation is as follows:

$$p_{lim} = a_1 \times (D/t)^{a_2} \times \left[-(h/D)^{a_3} + a_4 \right] \times$$
$$(D_{Ind}/D)^{a_5} (p/\sigma_u)^{a_6} + a_7 \quad , \quad (3)$$

where $a_1 \sim a_7$ are regression coefficients.

Based on the numerical results for limit pressure, all the coefficients can be calculated by the nonlinear fit tool provided by program package MATLAB, then the prediction equation can be derived Eq. (4).

$$p_{lim} = 2.93 \left(\frac{D}{t} \right)^{0.73} \left[-\left(\frac{h}{D} \right)^{0.021} + 0.61 \right]$$
$$\left(\frac{D_{Ind}}{D} \right)^{-0.0255} \left(\frac{p}{\sigma_u} \right)^{0.0169} + 38.97 \quad , \quad (4)$$

where $64<D/t<92$, $h>0.08D$, $50mm<D_{Ind}<120mm$,

$p<8MPa$, $\sigma_u=647MPa$

Fig. 13 shows that the predicted results by Eq. (4) are in good agreement with the numerical simulation results.
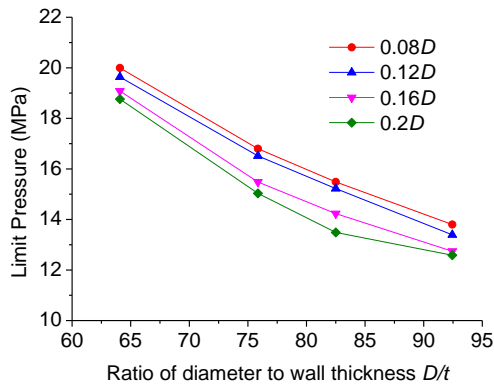
Fig. 12 Effects of Ratio of pipe diameter to wall thickness on pipe limit pressure
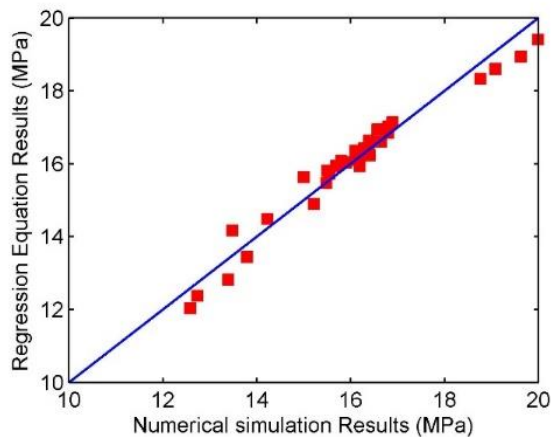

Fig. 13 Comparison of the predicting results with numerical simulation results

7. Conclusions

Limit pressure of dented X60 steel pipeline was investigated numerically in this study. A rigorous 3D finite element model was established by software package ABAQUS and validated by previous full scale results. Effects of the dent depth, dent size, initial pressure and ratio of diameter to wall thickness were discussed in detail. Some conclusion can be drawn as below:

1. Although large equivalent stress and plastic strain occurs in the dent area of pipe, numerical results show that, for X60 steel pipe, if dent depth is less than 0.08D, influence of dent on pipe limit pressure is negligible. If dent depth is larger than 0.08D, limit pressure decreases as dent depth increases.

2. With the same dent depth, limit pressure increases with the decrease of indenter diameter, for larger bending strain induced, and limit pressure decreases with the increase of initial internal pressure and ratio of diameter to wall thickness, for larger initial stress induced.

3. A limit pressure prediction equation was proposed by regression analysis. Comparison results show the predicted results are in good agreement with 3D nonlinear finite element results.

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NONLINEAR FINITE ELEMENT ANALYSIS OF THE LIMIT STATE AND PRESSURE OF DENTED X60 STEEL PIPELINE

S u m m a r y

As a main defect in pipeline, dents have brought great challenge to the integrity of oil and gas pipelines. Numerical study was presented in this paper to investigate the stress and strain state of dented X60 pipe. Suitable failure criteria is adopted and validated by full scale experimental results. And the failure process of dented X60 pipe is elucidated in detail. Based on the established model, effects of dent depth, indenter diameter, initial internal pressure, ratio of diameter to ratio thickness on limit pressure of dented pipe was discussed. Finally, a regression based prediction equation for dented X60 pipe was proposed. Results show this equation predicts accurate results with much less effort and time with regard of 3D finite element models.