NUMERICAL LIMIT LOAD ANALYSIS OF PIPELINES WITH LOCAL WALL-THINNINGS

Yinghua Liu[1], Gang Chen[2] and Bingye Xu[1]

[1]Department of Engineering Mechanics, Tsinghua University, Beijing, 100084, China

[2]Center of Boiler and Pressure Vessel Inspection & Research, Beijing, 10013, China

ABSTRACT

Local wall-thinning, which can be found frequently on the surfaces of pipelines, may not only reduce the load-carrying capacities of pipelines, but also cause serious industrial accidents. In this paper, through a large number of computational examples, the effects of axial, circumferential, small area and large area local wall-thinnings with different sizes on load-carrying capacities and failure modes of pipelines under both internal pressure and bending moment were studied. Finally, by data fitting, an engineering computational formula for plastic limit loads of pipelines with local wall-thinnings was presented.

1 INTRODUCTION

Pipelines are widely used in various fields such as the petrochemical industry, energy and electric power engineering, etc. During their operation, many defects such as local wall-thinnings can be produced by corrosion, mechanical damage or by abrading surface cracks. These defects may jeopardized the integrity (i.e. reduce load-carrying capacity) of pipelines and sometimes even lead to severe industrial accidents. The integrity assessment of pipelines with local wall-thinnings is a very important research subject with significant and extensive application background in the pipeline industry. Plastic limit analysis plays a significant role in the integrity assessment of defective pipelines. The limit load, which determines the load- carrying capacities of structures, is an important parameter in performing structural integrity assessment (Anisworth and Budden [1], Chen et al. [2]). Unfortunately, research efforts on plastic limit load analysis of pipelines with various local wall-thinnings remain few up to now.

In this paper, through more than 800 computational examples, the effects of small-area, axial, circumferential, and large area local wall-thinnings with different sizes on plastic limit loads and failure modes of pipelines were studied. By fitting for all computational data, a simple and practical computational formula for plastic limit loads of pipelines with local wall-thinnings was presented. It is shown that the formula is reliable and conservative.

2 COMPUTATIONAL MODEL

Figure 1 shows a pipe with local wall-thinning under both internal pressure and bending moment.

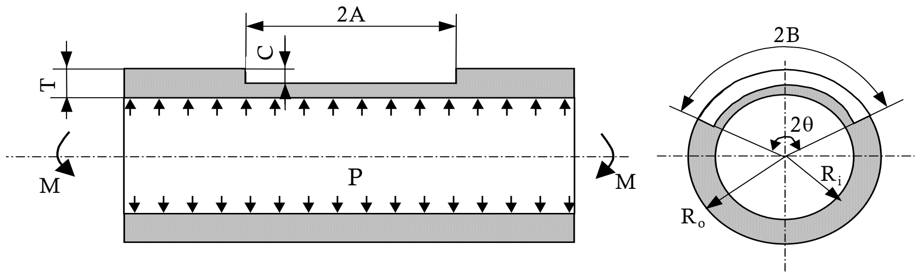


Figure 1: A pipe with local wall-thinning

where R_o is the outer radius of the pipeline, R_i the inner radius of the pipeline, T the wall thickness of the pipeline, A a half of axial length of the local wall-thinning, B a half of circumferential length of the local wall-thinning, C the depth of the local wall-thinning, θ a half of angle corresponding to the local wall-thinning, M the bending moment, and P the internal pressure.

Define the dimensionless axial length of the local wall-thinning $a = A/\sqrt{R_o T}$, the dimensionless circumferential length of the local wall-thinning $b = B/\pi R_o$, and the dimensionless depth of the local wall-thinning $c = C/T$.

M_L and P_L denote respectively the limit bending moment and limit internal pressure of pipeline under both bending moment and internal pressure. Define $m_L = \frac{M_L}{M_{L0}}$, $p_L = \frac{P_L}{P_{L0}}$, where M_{L0} is the limit bending moment of the pipeline without defect only under bending moment, $M_{L0} = 4\sigma_f \frac{R_o^{\ 3} - R_i^{\ 3}}{3}$, P_{L0} is the limit internal pressure of the pipeline without defect only under internal pressure, $P_{L0} = \frac{2}{\sqrt{3}}\sigma_f \ln\frac{R_o}{R_i}$, σ_f is the flow stress of material.

800 computational examples were completed with the finite element software of lower bound

limit analysis and the pre-process procedure developed by the authors (Liu et al. [3]), which can intelligently mesh the solid and change parameters easily. Due to the symmetry of structure, a quadrant of pipe was discretized by 3-D 20-node iso-parametric finite elements. The corresponding displacement constraints are imposed on the symmetric boundaries.

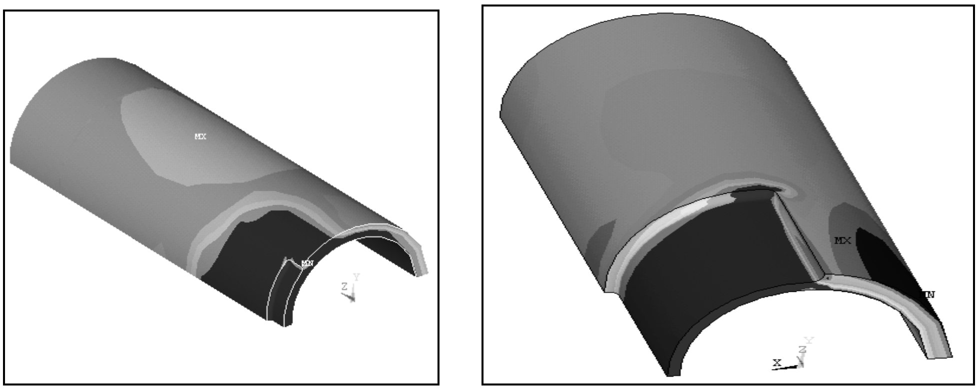
3 FAILURE MODES

The failure mode of pipeline with local wall-thinning under both bending moment and internal pressure depends on the ratio of m_L and p_L .

1) If $m_L / p_L \leq 0.5$

①As shown in Figure 2(a) , if axial length of the local wall-thinning is relatively small (including small area and circumferential local wall-thinnings), the local wall-thinning affects the limit loads slightly. The pipe collapses globally.

②As shown in Figure 2(b) , if axial length of the local wall-thinning is relatively large (including axial and large area local wall-thinnings), the limit load decreases greatly due to the local plastic hinge in a very small area near the local wall-thinning. The pipe will leak locally.



(a) circumferential wall-thinning (b) large area wall-thinning

Figure 2: Failure modes for $m_L / p_L \leq 0.5$

2) If $m_L / p_L \geq 2$

① For small area and axial local wall-thinnings, the whole pipe yields except a very small zone under the limit load. That is, there is no local plastic hinge. The pipe collapses globally.

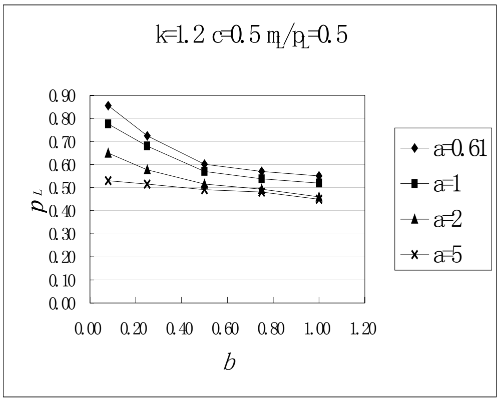
② For circumferential and large area local wall-thinnings, the whole section where the local wall-thinning locates yields under the limit load, though the whole pipe doesn't yield. The limit load decreases greatly due to the local wall-thinning.

3) If $0.5 < m_L / p_L < 2$

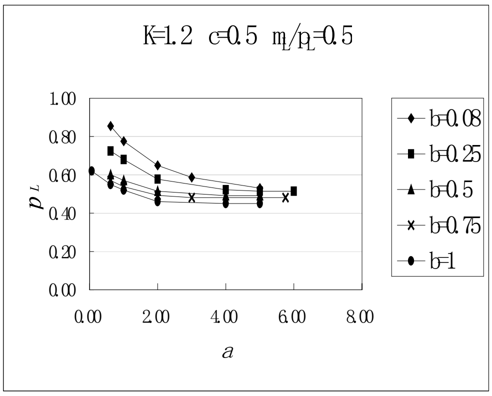
The failure mode is complex and difficult to classify. When the internal pressure is predominant compared with the bending moment, the failure mode of pipeline is similar to that under a single internal pressure. The axial length of local wall-thinning has great effects on the limit load in this case. When the bending moment is predominant compared with the internal pressure, the failure mode of pipeline is similar to that under a single bending moment. The circumferential length of local wall-thinning has great effects on the limit load in this case.

4 NUMERICAL ANALYSIS OF LIMIT LOADS

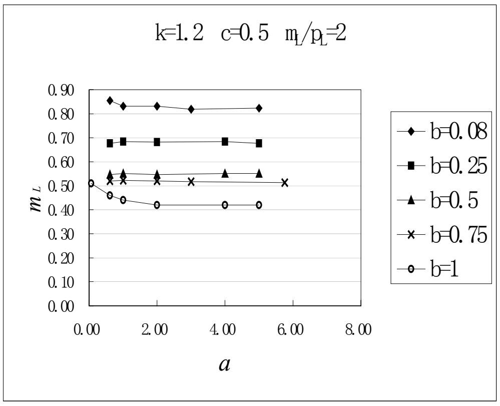
Figure 3 shows the effects of *a* and *b* on limit loads



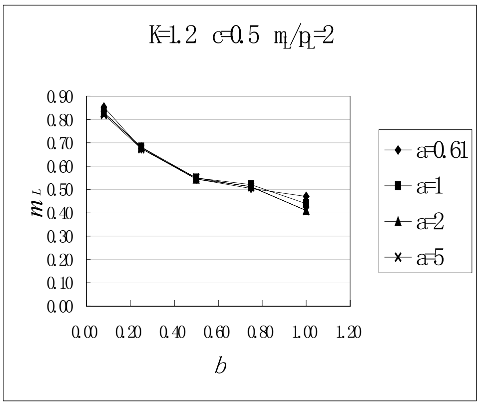
(a)



(b)



(c)



(d)

Figure 3: Limit loads versus the sizes of local wall-thinning under different m_L / p_L

1) As shown in Figures 3(a) and 3(b), if $m_L / p_L \leq 0.5$, the main factor affecting limit loads is *a*, and *b* can be ignored when *a* is large enough.

2) As shown in Figures 3(c) and 3(d), if $m_L / p_L \geq 2$, the main factor affecting limit loads is *b*. As *b* increases, the limit loads decrease quickly until a critical value is reached. From then on, the limit loads decrease very slowly and there is an inflexion in the curve.

5 FIT FORMULAE FOR LIMIT LOAD

Formula (1) was fitted from all computational results.

$$\left(\frac{m_L}{m_{Ls}}\right)^2 + \left(\frac{p_L}{p_{Ls}}\right)^2 = 1 \quad (1)$$

where m_{Ls} is the dimensionless limit bending moment of the pipeline with local wall-thinning only under bending moment, which is calculated as follows (Miller [4]):

$$m_{Ls} = \begin{cases} \cos\left(\frac{c\pi b}{2}\right) - \frac{c\sin(\pi b)}{2} & c < \frac{1-b}{b} \\ (1-c)\sin\left[\frac{\pi(1-bc)}{2(1-c)}\right] + \frac{c\sin(\pi b)}{2} & c > \frac{1-b}{b} \end{cases} \quad (2)$$

p_{Ls} is the dimensionless limit internal pressure of the pipeline with local wall-thinning only under internal pressure, which is fitted from the computational results as follows:

$$p_{Ls} = \begin{cases} 0.95 - 0.85A_e & a/b \leq 7.0 \\ 0.95 - 1.04A_e & 7.0 < a/b \leq 25.0 \\ 0.95 - 1.47A_e & a/b > 25.0 \end{cases} \quad (3)$$

where

$$A_e = c\sqrt[3]{a_e bc} \quad (3\text{-a})$$

$$a_e = \min\{3.0, a\} \quad (3\text{-b})$$

Formula (1) was verified according to 800 finite element computational results under the combined action of internal pressure and bending moment. The precision of formula (1) is satisfactory because the mean standard error is only 0.05. Through the comparison of computational results with the fit curve, it is shown that formula (1) is reliable and conservative, and can be used practically in engineering.

6 CONCLUSIONS

According to 800 computational examples, the effects of small area, axial, circumferential, and large area local wall-thinnings with different sizes on plastic limit loads and failure modes of pipelines under both internal pressure and bending moment were investigated. The following conclusions can be drawn:

1) If the internal pressure is high and bending moment is small, for small area and circumferential local wall-thinnings, the limit load decreases slightly, and the failure mode is a typical global one; for axial and large area local wall-thinnings, the limit load decreases greatly due to the local plastic hinge, and the failure mode is a typical local one.

2) If the internal pressure is low and bending moment is large, for small area and axial local wall-thinnings, the limit load decreases slightly, and the failure mode is a global one; for circumferential and large area local wall-thinnings, the limit load decreases slightly, and the whole section where the defect locates yields under the limit load though the whole pipe doesn't yield.

3) By fitting for all calculated data, a simple and practical computational formula for plastic limit loads of pipelines with local wall-thinnings was presented. It is shown that the formula is reliable and conservative, and can be used practically in engineering.

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