Safety assessment for In-service Pressure Bending Pipe Containing Incomplete Penetration Defects

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Abstract. Incomplete penetration defect is a common defect in the welded joint of pressure pipes. While the safety classification of pressure pipe containing incomplete penetration defects, according to periodical inspection regulations in present, is more conservative. For reducing the repair of incomplete penetration defect, a scientific and applicable safety assessment method for pressure pipe is needed. In this paper, the stress analysis model of the pipe system was established for the in-service pressure bending pipe containing incomplete penetration defects. The local finite element model was set up to analyze the stress distribution of defect location and the stress linearization. And then, the applicability of two assessment methods, simplified assessment and U factor assessment method, to the assessment of incomplete penetration defects located at pressure bending pipe were analyzed. The results can provide some technical supports for the safety assessment of complex pipelines in the future.

1. Introduction
Pressure pipeline is a kind of special pressure equipment conveying inflammable, explosive, toxic and strong corrosive medium, widely used in petroleum, chemical, energy, steel and other fields. Thus it needs high safety performance requirements. The incomplete penetration defect is the main and largest number of pressure pipeline welding defects, which is a serious threat to the safety of pressure pipeline[1]. Therefore, correctly assessment safety of incomplete penetration defect is of great significance to ensure the safety of pressure pipeline operation.

In recent years, many weld defects of pipe were founded during the periodical inspection regulation of in-service industrial pressure pipe. According to In-service Industrial Pressure Pipe Periodical Inspection Regulation [2], those weld defects should be classified as grade 4, which means the pipe must be stopped using. While founded on engineering application, a large proportion of these pipes have not appeared problem actually, which shows that the kind of classification has greater conservatism[3]. GB/T19624-2004 [4] Safety Assessment for In-service Pressure Vessels Containing Defects has safety assessment methods for straight pipe. And there’s much research for pressure pipeline safety assessment method. Zh J Jin[1] studied the plastic limit load of pressure pipes containing incomplete welding defects. The plastic limit load theory method for pipes containing incomplete welding defects was established, based on internal pressure/Bending moment/torque loads. ZH L Li [5,6] studied the safety assessment for pipe containing defects. X F Wang[7] studied the safety assessment for bend and straight pipe connection weld location, by using the straight pipe assessment method revised. The result shows that the fourth level of penetration defects do not affect the safe operation of pipeline in low stress conditions. However, there’s few research about the safety assessment for incomplete penetration defect located at bend and straight pipe connection.
Therefore, the paper studied safety assessment for incomplete penetration defect located at bend and straight pipe connection, for the pressure pipe of polyester process in the chemical enterprise. The simplified assessment and U factor assessment method, based on GB/T19624-2004, were analyzed for applicability to incomplete penetration defect located at bend and straight pipe connection.

2. Basic parameters of pipeline
Pressure pipeline of polyester process in one chemical enterprise, as showed in figure 1, has an incomplete penetration defect exceed standard at the weld joint, found by nondestructive testing. The parameter of pipe was presented in table 1. The insulating layer of pipe was 100mm. The pipe was qualified by a pressure test with 1.5 times the design pressure in the process of inspections.

![Figure 1. The Pipe containing incomplete penetration defect.](image)

| Material | Size | Defect length | Defect depth |
|----------|------|---------------|--------------|
| 20#      | φ88.9*4.5 | 65mm          | 1.5 mm       |
| Actual minimum thickness | 4.34 mm |
| Operating parameter | Maximum working pressure | 1.1 MPa |
| | Maximum working temperature | 330 °C |
| | Medium | Heat-conduction oil |
| | Yield strength at assessment temperature | 153 MPa |

According to In-service Industrial Pressure Pipe Periodical Inspection Regulation, incomplete penetration defect could be classified as local wall-thinning. The pipe security level should be classified as grade 4 based on the defect size. And the safety could be assessed by using GB/T19624-2004. The incomplete penetration defect was regularly processed as a surface defect, with length was 65mm, depth was 1.5mm. And effective crack size was:

\[
a_{\text{eff}} = \left(F_1 \right) a
\]

Where,

\[
F_1 = 1.13 - 0.09 \frac{a}{c} + \left( -0.54 + \frac{0.89}{0.2 + a/c} \right) \left( \frac{a}{R} \right)^2 + \left[ 0.5 - \frac{1}{0.65 + a/c} + 14 \left( 1 - \frac{a}{c} \right)^{24} \right] \left( \frac{a}{R} \right)^4
\]

Then, \(a_{\text{eff}} = 1.732 \text{mm}\).

3. Stress analysis model
Based on pipe sizes, process flows, installation drawing of support-hangers and inspection of the scene of a crime, pipe stress analysis model was established by using CAESARII. For reducing the influence of local structure model, constraint to stress condition of defect position, a complete process piping structure was established. The local model was shown as figure 2. The maximum operating pressure and temperature was used during analysis. And the value of material parameter was taken as...
maximum working temperature. The SIF of bend and tee-junction was calculated by ASME B31.3, as default. Considering the system operation smoothly and without obvious pressure fluctuation, the fatigue analysis was not included in the paper.

The finite element analysis of local model for the defect position was shown as figure 3. According to Saint Venant Principle, length of bend was taken as equal or greater than 3D. The gravity was considered in the analysis. The boundary condition of local model nodes was determined by the calculation results from CAESAR II. The fracture toughness of 20# steel is 0.114 - 0.147 mm according to metal material manual. The minimum value of fracture toughness was used in the analysis from a conservative point.

4. Safety assessment

The simplified assessment and U factor assessment method were used to assess the safety of incomplete penetration defect in pressure bending pipe.

4.1. The simplified assessment method

Depending on the calculated results of CAESAR, the maximum stress intensity of pipeline emerged in one tee-junction of pipeline. And the primary stress and secondary stress were in the range of allowable stress. The thermal stress of defect location is 62.4 MPa.

The results of ANSYS were presented in figure 4. The maximum stress intensity is 31.3 MPa, emerging in pipe bend. The stress distribution in the section of defect position was shown as figure 5. The average stress intensity is 11.9 MPa, which is 11.5 MPa as result from CAESAR. Only 3.9% differences show that the results of CAESAR used as the boundary conditions are reasonable. The stress linearization path was chosen in section of defect position along the thickness direction, as showed in figure 6. Results of stress linearization shown in figure 7, the bending stress is 11.1 MPa, the membrane stress is 11.4 MPa.
According to GB/T 19624-2004, the total equivalent stress could be calculated by,

$$\sigma_{\Sigma} = \sigma_{\Sigma 1} + \sigma_{\Sigma 2} + \sigma_{\Sigma 3} = K_t P_m + X_b P_b + X_r Q \quad (2)$$

Where: \(K_t\) is stress concentration factor caused by weld shape; \(X_b\) is bending stress reduced coefficient; \(X_r\) is welding residual stress reduced coefficient; \(Q\) is the algebraic sum of maximum thermal stress and maximum welding residual stress.

The welding residual stress of defect position can be estimated as,

$$\sigma_{R_{max}} = \sigma_s \quad (3)$$

Therefore,

$$\sigma_{\Sigma} = \sigma_{\Sigma 1} + \sigma_{\Sigma 2} + \sigma_{\Sigma 3} = 154.36 \text{ MPa} \quad (4)$$

And when \(\sigma_{\Sigma} \geq \sigma_s(\sigma_{\Sigma 1} + \sigma_{\Sigma 2})\),

$$\delta = 0.5 \pi \bar{a} \sigma_s \left( \frac{\sigma_{\Sigma}}{\sigma_s} + 1 \right) \frac{M_g}{E} \quad (5)$$

Thus,

$$\sqrt{\delta_r} = \sqrt{\delta/\delta_{max}} = 0.225 \quad (6)$$

$$S_r = \frac{L_r}{L_{r_{max}}} = 0.09 \quad (7)$$

Where, \(L_r\) calculated by Annex C; \(L_{r_{max}}\) taken as 1.2.

Based on results of \(\sqrt{\delta_r}, S_r\), the safety assessment of the pipe as shown in figure 8. As shown in figure, the parameter of \(\sqrt{\delta_r}, S_r\) are all located at the safe zone. The result show that the pipe could safely operate in the period of the evaluation.
4.2. The U factor assessment method

Since 20# steel is suitable for pressure pipe with no brittle tendency in-service, and operating temperature is not low than the ductile-brittle transition temperature, the value of $A_{KV}$ can be taken as 27J when there no data of $A_{KV}$ of in-service material, based on national standard. The fracture toughness of defect for assessment can be taken as:

$$J_{IC} = 2.2A_{KV} = 59.4J$$  \hspace{2cm} (8)

The value of $KC$ can be estimated by $J_{IC}$:

$$K_C = \sqrt{\frac{EJ_{IC}}{1 - \nu^2}}$$  \hspace{2cm} (9)

According to the results of primary loads and secondary loads from CAESAR, the stress of defect position under external loads was:

$$\sigma_m = \frac{N + \pi R_p^2}{2 \pi R_B} = 5.3 \text{MPa} \quad \sigma_b = \frac{M_b}{\pi R_B^2} = 36.96 \text{MPa}$$  \hspace{2cm} (10)

According to the pipe and defect size, the value of $L_F$ and $[\sigma]$were taken from the table of appendix G.

The load safety factor taken as 1.2, then, based on Appendix G,

$$\sigma_m + \sigma_b = 42.26 \text{MPa} < \left(\frac{\sigma_b + \sigma_b}{2}\right) \frac{[\sigma]}{U_{np}} = 189.3 \text{MPa}$$  \hspace{2cm} (11)

According to the above equation, the results show that the pipe can safely operate in the period of the evaluation based on Appendix G about safety assessment for straight pipe.

4.3. Analysis for safety assessment

The pressure pipe containing incomplete penetration defect can safely operate in the period of evaluation under these two safety assessment methods.

And the result shows that degree of safety assessment by the simplified assessment method is 32.1%, higher than that assessment by the $U$ factor assessment method, which is 22.3%. This is mainly because the calculation of the total equivalent stress had consider the thermal stress and welding residual stress, as shown in equation, and the SIF was considered during stress analysis in the simplified assessment.

Other pressure pipes of the chemical enterprise were assessed, which incomplete penetration defects were all located at the connection position of elbow and straight length. The degree of safety was given in table 2, which shows that the result of simplified assessment method relative to that of U factor assessment method is conservative for pressure bending pipes containing incomplete
penetration defect. Thus, the simplified assessment method may be more reasonable, safer for assessing pressure bending pipe which defect locate at bend and straight pipe connection, especially in the assessment of incomplete penetration defect size close to the critical size.

Table 2. The other assessment results for incomplete penetration defect.

| Pipe size | Defect size | Simplified Assessment | U factor Assessment |
|-----------|-------------|-----------------------|---------------------|
| φ139.5×5  | L=total, a=1.5mm | 52.8% | 48.5% |
| φ139.5×5  | L=55mm,a=1.5mm | 47.8% | 39.7% |
| φ114.3×5  | L=60mm,a=1.0mm | 33.1% | 28.98% |
| φ88.9×4.5 | L=total, a=1.5mm | 53.5% | 36.65% |

5. Conclusion

(1) Pressure pipe containing incomplete penetration defect was assessed by using GB/T19624-2004 Safety Assessment for In-service Pressure Vessels Containing Defects. The result demonstrates that the pressure pipe could safely operate in the period of the evaluation.

(2) The simplified assessment method, relative to U factor assessment method, is conservative for the safety assessment of pressure bending pipes containing incomplete penetration defect. Thus, the simplified assessment method may be more reasonable, safer for assessing pressure bending pipe, especially when incomplete penetration defect size is close to the critical size.

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