Comparison and Analysis of Domestic and Foreign Standards for Safety Assessment for In-Service Pressure Vessels Containing Defects-A Case Study of Drum of Utility Boiler

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Abstract. Pressure vessel, a kind of special equipment with high potential explosion danger, will cause catastrophic accident once it explodes or leaks. Ensuring the safe operation of such equipment is of great significance. However, some defects inevitably occur in the process of manufacture, installation and service. Blindly shutdown or repairs will bring huge economic losses. Thus, the safety assessment for in-service pressure vessels containing defects has attracted more and more attention in the industry. The paper analysis the safety assessment for one drum of utility boiler, based on standards of API-579/ASME-2016 Fitness for Service and GB/T19624-2004 Safety Assessment for in-service pressure vessels containing defects. And based on the safety assessment for drum of utility boiler, the difference and advantages of domestic and foreign standards in the aspects of defect characterization, determination of equivalent stress and assessment methods are analyzed and compared. Meanwhile some suggestions for revising the related standards of pressure vessels with defects in China are put forward.

1. Introduction
Pressure vessel is the special equipment with potential explosion risk. Once explosion or leakage occurs, it will cause catastrophic accidents [1-2]. It is of great significance to ensure the safe operation of such equipment. The pressure vessel will inevitably produce some defects in the process of manufacture, installation and service. Blind shutdown or repairing will bring huge economic losses [3]. Therefore, more and more attention has been paid to the safety assessment of pressure vessels with defects in use. However, there are different methods and safety factors in the evaluation of pressure vessels with defects [4-6]. The paper analyses the different points and emphases of domestic and foreign standards in safety assessment of defective pressure vessels, based on the safety assessment of a defective drum.

The paper mainly analyses the comparison of two methods for evaluating pressure vessels containing planar crack, the Level 2 Assessment method of API579-2016 [7] and the Normal Assessment method of GB/T19624-2004 [8], including reference stress, partial safety factor, and so on.
And based on the fatigue leakage assessment results of drum of utility boiler containing crack, two standards are used to evaluate the fatigue fracture of the drum, and the differences between the domestic and foreign criteria in the assessment process and their effects on the assessment results were studied.

2. The Level 2 Assessment Based on API579-2016

The safety assessment of crack in the standard is based on three-level assessment, and the second-level assessment is based on failure FAD diagram. The failure assessment curve is,

\[ K_r = f(L_r) = (1 - 0.14I_c^2) \times [0.3 + 0.7e^{-0.65L_e}] \] (1)

Where \( K_r \) is the toughness ratio, \( L_r \) is the load ratio.

At present, the main criteria for evaluating failure of fracture and plastic collapse are partial safety factors. The partial safety factor is a common method to deal with uncertainties of material performance, stress level and defect size in safety assessment of pressure vessels with defects and to meet the reliability requirements of different targets. Modifying the primary stress, material fracture toughness and defect size by, \( P_m = P_m \cdot PSFs \), \( P_b = P_b \cdot PSFs \), \( K_{mat} = K_{mat}/PSF_k \) and \( 2a = 2a \cdot PSF_a \). Where \( P_m \) is the membrane stress, \( P_b \) is the bending stress, \( PSFs \) is the partial safety factor for stress, \( PSF_k \) is the partial safety for fracture toughness, and \( PSF_a \) is the partial safety factor for defect size.

Then the reference stress \( \sigma_{ref}^P \) is calculated according to the revised primary stress distribution, the revised defect size and the reference stress solution. And the load ratio or the abscissa of failure assessment diagram (FAD) can be obtained, ie,

\[ L_r^p = \frac{\sigma_{ref}^p}{\sigma_{ys}} \] (2)

According to the solution of stress intensity factor in Appendix C, the stress intensity \( K_i^P \) caused by main load is calculated. The reference stress is obtained by fitting the stress distribution of the quadratic polynomial, and the stress intensity factor is calculated by the stress distribution of the fourth-order equation. For the reference stress, fitting by the total stress as follow,

\[ P(x) = P_0 + P_1 \frac{x^4}{I} + P_2 \frac{x^3}{I} + P_3 \frac{x^2}{I} + P_4 \frac{x}{I} \] (3)

The same methods can be used to calculate the reference stress \( \sigma_{ref}^{SR} \) and stress intensity factor \( K_i^{SR} \). Thus, the longitudinal coordinates of evaluation points in FAD or toughness ratio can be obtained,

\[ K_r = \frac{K_i^P + \Phi K_i^{SR}}{K_{mat}} \] (4)

3. The Normal Assessment Based on GB/T19624-2004

The conventional assessment is to prevent cracking and plastic failure, using the \( K_r-L_r \) general failure assessment chart, same as API579-2016. In terms of partial safety factor, the deterministic safety factor is still used to evaluate, as shown in Table 1.
Table 1. The Partial Safety Factor.

| Failure consequence | Defect characterization size | Fracture toughness | Stress primary stress | Stress secondary stress |
|---------------------|-----------------------------|--------------------|----------------------|------------------------|
| ordinary            | 1.0                         | 1.1                | 1.2                  | 1.0                    |
| serious             | 1.1                         | 1.2                | 1.5                  | 1.0                    |

Then the fracture toughness $K_C$ can be determined according to the material performance data. The fracture toughness $\delta_c$ can be estimated as

$$K_C = \sqrt{1.5\sigma_s \delta_c E / (1 - \nu^2)}$$  \hspace{1cm} (5)

The stress intensity factor can be calculated, then the fracture ratio $K_r$ gained as,

$$K_r = \frac{G(K_P^p + K_I^p)}{K_P} + \rho$$  \hspace{1cm} (6)

Where, $G$ is the coefficient of elastic interference effect between two adjacent cracks. $K_P$ is fracture toughness of evaluation material.

The load ratio $L_r$ can be calculated in accordance with Appendix C2.2 as follows,

$$L_r = \frac{(3\zeta P_m + P_b) + \sqrt{(3\zeta P_m + P)^2 + 9[(1 - \zeta^2) + 4\zeta\gamma]P_m^2}}{3[(1 - \zeta^2) + 4\zeta\gamma]\sigma_S}$$  \hspace{1cm} (7)

Where, $\zeta = 2ac / (B(c + B))$ , $\gamma = p_1 / B$.

4. Safety Assessment for Drum Containing Crack

The basic parameters of a boiler barrel with crack are shown in Table 2. And the Yield strength at evaluation temperature of material is 185.66MPa, the elasticity modulus at evaluation temperature is 194.02GPa, the basic allowable stress is 133MPa, the coefficient of linear expansion is $13.22 \times 10^{-6} \text{mm/mm·℃}$, the Poisson's ratio $\nu$ is 0.3. And the minimum wall thickness is 100mm. According to the TOFD ultrasonic testing report, the type of defect is buried defect, which 32.6mm in length and 5.8mm in depth. For conservation, the buried crack length was taken as 33mm and the depth as 6mm.

Table 2. Basic Parameters of Drum.

| Material | Specification/mm×mm | Length/mm | Depth/mm | medium | calculating pressure/MPa | operating temperature/℃ |
|----------|---------------------|-----------|----------|--------|-------------------------|-------------------------|
| 19Mn6    | Ф1600×100           | 33        | 6        | Steam  | 11.399                  | 322                     |

Defects are regularized according to domestic and foreign standards. The regularized elliptical buried crack is $2c=33\text{mm}$ and $2a=h=6\text{mm}$. Then $a=3.0\text{mm}$, $c=16.5\text{mm}$.

The stress analysis model of the drum was established by ANSYS Workbench according to the drum drawings. The stress at the defect position of the drum under internal pressure was calculated. After linearization, the membrane stress is 96.572MPa and the bending stress is 11.44MPa.

According to the temperature curve of boiler monitoring point, conservatively, the maximum circumferential temperature difference and radial temperature difference between the inner and outer walls of the drum were respectively taken for 318K and 313K. The calculated thermal stress caused by
radial temperature gradient is \( \sigma_{nt1} = 172.55 \text{ MPa} \), and the circumferential thermal stress caused by temperature gradient is \( \sigma_{nt2} = -49.97 \text{ MPa} \).

Therefore, there are three different stress variety in the drum based on the changing of pressure and temperature, namely, the primary membrane stress caused by internal pressure, the primary bending stress and the secondary stress caused by temperature difference. For the sake of conservativeness, the safety factor of primary membrane stress was taken as 1.5, so the value of primary stress range is \( (\Delta \sigma_m)^1 = 144.858 \text{ MPa} \).

### 4.1. Fatigue Leakage Assessment

The design life of drum is 30 years, mainly starting and stopping in cold state. To be conservative, suppose that the steam drum starts and stops three times a year and can run for another 20 years. And in the estimation of fatigue extended life, the safety factor was taken as 20 times. Therefore, the number of cycles in each stress range is \( N = 1200 \).

According to API579-1/ASME FFS-1 2016, the formulas of fatigue crack growth rate and stress intensity factor at crack tip are as follows, for \( \Delta K > \Delta K_{th} (\text{mm}/\text{cycle}, \text{MPa}\sqrt{\text{mm}}) \),

\[
\frac{da}{dN} = A(\Delta K)^m = 6.62 \times 10^{-13} (\Delta K)^{3.0} \quad (8)
\]

The cyclic number of stress range could be divided into five sections. Then the approximate average values \( a_j \) and \( c_j \) of crack size in each stress range can be safely calculated by using the following formula step by step until the final fatigue growth sizes \( a_f \) and \( c_f \) are calculated as follow,

\[
a_j = a_{j-1} + A \sum_{i=1}^{d} n_i [(\Delta K_{a})_i]^{m} / u \quad j = 1, 2, \Lambda, u \quad (9)
\]

\[
a_f = a_u + 0.5A \sum_{i=1}^{d} n_i [(\Delta K_{a})_i]^{m} / u \quad (10)
\]

\[
c_j = c_{j-1} + A \sum_{i=1}^{d} n_i [0.9(\Delta K_{c})_i]^{m} / u \quad j = 1, 2, \Lambda, u \quad (11)
\]

\[
c_f = c_u + 0.5A \sum_{i=1}^{d} n_i [0.9(\Delta K_{c})_i]^{m} / u \quad (12)
\]

Among them, the variation amplitude of stress intensity factor was calculated according to appendix D of GB/T19624-2004,

\[
(\Delta K_{a})_i = \sqrt{u}((\Delta \sigma_m)_i f_{a}^A + \Delta \sigma_b f_{b}^A) \quad (13)
\]

\[
(\Delta K_{c})_i = \sqrt{u}((\Delta \sigma_m)_i f_{a}^B + \Delta \sigma_b f_{b}^B) \quad (14)
\]

Then we have obtained \( a_f = 3.13 \text{mm}, c_f = 16.6 \text{mm} \).
Based on the assessment methods for fatigue leakage, there are,

\[
\frac{p_1 + a_0 - a_f}{a_f} = 3.97 > 0.8 \tag{15}
\]

and

\[
\frac{p_1 + a_0 + a_f}{B} = 0.187 < 0.7 \tag{16}
\]

Thus the drum would not leak.

4.2. Fatigue Fracture Assessment

4.2.1. Safety assessment based on API579-2016. According to the stress calculation results from ANSYS WORKBENCH, the stress distribution was fitted by the quadric polynomial, as shown in the Figure 1.

![Quadric polynomial distribution fitting of stress.](image)

**Figure 1.** Quadric polynomial distribution fitting of stress.

Then, gained, P0= 87.85, P1= 5.919, P2= 27.77, P3= -7.478, P4= -8.209. Based on standard, the equivalent membrane stress and bending stress can be obtained as,

\[
P_m = P_0 + \frac{P_1}{2} + \frac{P_2}{3} + \frac{P_3}{4} + \frac{P_4}{5} = 96.55 \text{MPa} \tag{17}
\]

\[
P_b = -\frac{P_1}{2} - \frac{P_2}{2} - \frac{9P_3}{20} - \frac{6P_4}{15} = -10.2 \text{MPa} \tag{18}
\]

Then we have,

\[
\sigma_{ref} = \frac{P_b + 3P_m \alpha + (P_b + 3P_m \alpha)^2 + 9P_m^2 (1-\alpha)^2 + \frac{4d\alpha}{t}}{3(1-\alpha)^2 + \frac{4d\alpha}{t}} = 152.42 \text{MPa} \tag{19}
\]
Where, \( d = d_i - a, \alpha = (2a/t)/(1+t/a) \).

And then we have \( L_r^p = 0.82 \). Thus \( K_I^P = 279.89 \text{N/mm}^{3/2}, K_{I_{SR}} = 512.439 \text{N/mm}^{3/2} \) and \( K_r = 0.44 \).

4.2.2. Normal assessment based on GB/T19624-2004. The value of partial safety factor was taken according to "serious" failure consequence. Then the crack size of was equal to 3.44mm, and c to 18.26mm. The primary membrane stress was 144.858Mpa, and primary bending stress was 17.16MPa. Thus we have, \( K_I^P = 500.6 \text{N/mm}^{3/2}, K_{I_{SR}} = 556.0 \text{N/mm}^{3/2} \). Then according to the formula, \( K_r = 0.536 \), \( L_r = 0.827 \). The location in the general failure assessment diagram is shown in Figure 2. The results show that the drum will not cause fatigue fracture.

![Figure 2. The assessment results of drum.](image)

As shown in Figure 2, the assessment result based on GB/T19624-2004 is more conservative than that of API579-2016. The main reason for this conservative phenomenon is the value of parameter of \( K_r \), since the values of \( L_r \) calculated by two methods were very close. This is because first equations of the reference stress from two methods are same and secondly there is little difference between the equivalent membrane stress and bending stress using in that equation, determined by Quadrinomial method and that of simulated linearization results.

While the values of \( K_r \) are difference, and the results from GB/T19624-2004 is 21.8% higher than that of API579-2016. That is because of the stress intensity factor was calculated based on the Fourth Order Equation of stress distribution and the partial safety factor during the method of API579-2016.

5. Conclusion
In this paper, the two assessment methods for pressure vessels containing crack in domestic and foreign standards were studied. The fatigue leakage assessment and fatigue fracture assessment of a drum were analyzed.

The results shows that the evaluation failure curves in domestic and foreign standards are same in the process of secondary evaluation. However, the calculation of reference stress and the selection of partial safety factor are different. And the assessment result of GB19624-2004 are more conservative than API579-2016.

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