Defect Assessment of 3000 M³ Sphere Storage Tank for Propylene

Gangyi Cai¹,³, * Zhi Xiang¹,³, a Zhang Chen¹,³, b Yuebing Li², c and Yufeng Ye¹,³, d

¹Zhejiang Provincial Special Equipment Inspection and Research Institute, Hangzhou, China
²Institute of Process Equipment and Control Engineering, Zhejiang University of Technology, Hangzhou, China
³Key Laboratory of Special Equipment Safety Testing Technology of Zhejiang Province, Hangzhou, China

*Corresponding author e-mail: 411587705@qq.com, 80757595@qq.com, 35853367@qq.com, ybli@zjut.edu.cn, yeyf@zjtj.com

Abstract. During the regular inspection of 3000 m³ sphere storage tank for propylene, 15 defects are detected, including 11 internal surface cracks and 4 embed cracks. One of the surface cracks can up to 80mm in length direction. For these defects, fitness-for-service (FFS) assessment should be performed for continue service in order to ensure the operational safety and structural integrity. Fortunately, there are many codes or standards that are available to carry out FFS assessment, such as API 579 [1], BS 7910 [2], and SINTAP [3].

1. Introduction

Sphere storage tanks containing high pressure fluids can be found in many industries, such as petroleum producing and refining, petrochemical and chemical manufacturing, bulk storage and transfer operations, other industries consuming or producing liquids and vapours. Most storage tanks are designed and built according to the ASME Boiler and Pressure Vessel Code (BPVC). All the same, there is some defects detected in some tanks in-service, such as cracks, local metal loss, etc.

During the regular inspection of the sphere storage tank for propylene, 15 defects are detected, including 11 internal surface cracks and 4 embed cracks. One of the surface cracks can up to 80mm in length direction. For these defects, fitness-for-service (FFS) assessment should be performed for continue service in order to ensure the operational safety and structural integrity. Fortunately, there are many codes or standards that are available to carry out FFS assessment, such as API 579 [1], BS 7910 [2], and SINTAP [3].

However, these recommended practices and procedures may be different in failure criteria (limited state), definition of material properties, calculation of the fracture mechanics parameters, safety factors, etc. Recent years, they have been updated in succession. For example, the 2016 publication of API 579 was approved which includes a number of modifications and technical improvements, such as calculation of stress intensity factors, the plasticity interaction factors; BS 7910 was revised in 2013, which deletes the Level I fracture assessment procedure of BS 7910:2005. The defect assessment procedure in China, GB/T 19624, is implemented in 2004, which draws lessons from BS 7910 [4, 5].
With the development of material properties and detect technology, the technology for structural integrity assessment should be also improved, such as material properties, crack characterization, safety factors.

For a same case, the assessment results may be different. Yang et al. [6] compared these procedures by specific calculation examples and provided a basis for improvement of fracture assessment methods. Han et al. [7] investigated the influence of partial safety factor on flaw assessment.

To investigate the difference among these procedures, especially for the treatment of secondary stress, a case study is carried out. In this work, structural integrity assessment is performed based on different procedures for a 3000 m³ sphere storage tank for propylene. For the detected defects, the integrity of sphere storage tank with defects is evaluated according to GB/T 19624-2004. To show the difference between the domestic standard and international standards, API 579 and BS 7910 are also adopted to perform the Fitness-for-Service assessment. The safety margin is discussed.

2. Problem description

2.1. General Information of the Tank
The sphere storage tank is used to contain propylene with the storage capabilities of 3000 m³, which was constructed according to the standard of design by analysis JB 4732. The general information of the tank is shown in Table 1. Numbers of weld seams are applied during its construction, where cracks are easily brought out under the corrosive environment. The tank come into service in July 2011, as shown in Fig. 1.

| Items               | Value          |
|---------------------|----------------|
| Design pressure     | 2.16MPa        |
| Design temperature  | -19/50°C       |
| Working pressure    | 1.56MPa        |
| Working temperature | 24°C           |
| Inner diameter      | 18000mm        |
| Thickness           | 52mm           |
| Material            | Q370R          |

Figure 1. The schematic diagram of the tank

2.2. Crack characterization
In May 2015, the first regular inspection of the tank is carried out, including magnetic particle inspection, ultrasonic inspection and Time of Flight Diffraction (TOFD) inspection. Unfortunately, several flaws were detected, as shown in Table 2.

| No. | Location                | Length (mm) | Height (mm) |
|-----|-------------------------|-------------|-------------|
| 1   | Upper polar plate weld seam | 80          | 3           |
| 2   | Upper polar plate weld seam | 200         | 3           |
| 3   | Upper polar plate weld seam | 70          | 3           |
| 4   | Lower polar plate weld seam | 150         | 8           |
According to the inspection result, the maximum flaw with depth of 8mm is selected to perform structural integrity assessment. The flaw is characterized as an embed elliptical crack with length $2c=150\text{mm}$ and depth $2a=8\text{mm}$, as shown in Fig. 2. Where, $B$ is the thickness of the sphere storage tank, $p_1$ is the nearest point of the crack to the surface, $p_1=12\text{mm}$.

![Figure 2. The schematic diagram of the crack](image)

2.3. Material Properties
According to the material certificate, Charpy impact energy at -20°C $A_{KV}$ is about 34J. A relationship between fracture toughness $K_{IC}$ and impact energy is adopted in this work as:

$$K_{IC} = 8.47 \left( A_{KV} \right)^{0.63}$$  \hspace{1cm} (1)

Then, the fracture toughness $K_{IC}$ is determined to be 77.47 MPa$\sqrt{m}$. In addition, the yield strength $\sigma_y$ is tested to be about 340 MPa.

2.4. Load Analysis
In this work, both design pressure $p_d$ and working pressure $p_w$ are considered as primary load. The stress along the thickness is assumed to be membrane stress $P_m$ as:

$$P_m = \frac{p(D + B)}{4B}$$  \hspace{1cm} (2)

Where, $p$ is the internal pressure, design pressure or working pressure.

In addition, welding residual stress is considered. It is conservative to assume that the tensile residual stress is equal to 40% of the room temperature yield strength of the material in which the flaw is located.

$$Q_m = 0.4\sigma_y$$  \hspace{1cm} (3)

3. Structural integrity assessment

3.1. GB/T 19624
For planar flaws, 2 levels are recommended in GB/T 19624, simplified assessment and routine assessment. In simplified assessment, the failure criterion is applied on crack opening displacement (COD), which is same with the Level 1 of BS 7910-2005. For normal assessment, failure assessment diagram (FAD) is adopted, which is same with the Level 2 of BS 7910-2005.

3.1.1. Simplified assessment. A single FAD is used, as shown in Fig. 3. The area bounded by the axes and by the assessment line is a rectangle. The FAD contains an in-built safety factor (which approximates to a factor of 2 on flaw size).

The fracture ratio $\sqrt{r_{s}}$ on COD is defined as:

$$\sqrt{r_{s}} = \sqrt{\delta / \delta_c}$$  \hspace{1cm} (4)
Where, $\delta$ is the COD for the crack to be assessed, and $\delta_c$ is the fracture toughness on COD, which can be transformed from the fracture toughness $K_{IC}$ as:

$$K_{IC} = \sqrt{1.5\sigma_y\delta_c E \left(1 - \nu^2\right)}$$  \hspace{1cm} (5)

The COD of the crack can be evaluated as:

$$\delta = \begin{cases} \pi\bar{\sigma}\left(\frac{\sigma_y}{\sigma}\right)^2 M_g^2/E & \sigma_y < \sigma_r \\ 0.5\pi\bar{\sigma}\left(\frac{\sigma_y}{\sigma_r} + 1\right)M_g^2/E & \sigma_y \geq \sigma_r \geq \left(\sigma_{\Sigma_1} + \sigma_{\Sigma_2}\right) \end{cases}$$  \hspace{1cm} (6)

Where, $\sigma$ is an equivalent crack depth, $M_g$ is a correction factor for different crack originations. The equivalent total stress $\sigma_{\Sigma}$ can be determined as:

$$\sigma_{\Sigma} = K_iP_m + X_bP_b + X_rQ$$  \hspace{1cm} (7)

Where, $K_i$, $X_b$ and $X_r$ is correction factors for weld structure, bending stress and welding residual stress.

A limit load parameter $S_r$ is defined as:

$$S_r = \frac{L_r}{L_{\text{max}}}$$  \hspace{1cm} (8)

Where, $L_r$ is the ratio of applied load to yield collapse load for the cracked structure.

According to the above equations, the assessment point $(S_r, \sqrt{\delta_r})$ can be calculated under design pressure and working pressure, as shown in Fig. 3. It can be seen that both assessment points are located in the safety zone. For the design pressure, the assessment point is close to the safety boundary.

![Figure 3. Simplified assessment](image_url)

3.1.2. Normal assessment. Failure assessment diagram is used in normal assessment. The failure assessment curve (FAC) is described as:

$$K_i = \left(1 - 0.14L_r^2\right)\left(0.3 + 0.7 \exp\left(-0.65L_r^2\right)\right)$$  \hspace{1cm} (9)

The fracture ratio $K_i$ for the crack is calculated from the following equation:

$$K_i = \frac{K_i^p + K_i^\rho}{K_{IC} + \rho}$$  \hspace{1cm} (10)
Where, \( K_{I}^{P} \) and \( K_{I}^{S} \) represent contributions from primary and secondary stresses, respectively. A plasticity correction factor, \( \rho \), is necessary to allow for interaction of the primary and secondary stress contributions.

For normal assessment, partial safety factors on crack size, fracture toughness and stress are necessary, as shown in Table 3. In this work, severe failure consequence is considered.

**Table 3. Partial safety factors in GB/T 19624**

| Failure consequences | Crack size | Fracture toughness | Stress |
|----------------------|------------|--------------------|--------|
|                      |            |                    | Primary | Secondary |
| Moderate             | 1.0        | 1.1                | 1.2     | 1.0        |
| Severe               | 1.1        | 1.2                | 1.5     | 1.0        |

According to the above equations, the assessment point \((L_r, K_r)\) can be calculated under design pressure and working pressure, as shown in Fig. 4. It can be seen that both assessment points are located in the safety zone. For the design pressure, the assessment point is closer to the safety boundary than the working pressure.

![Figure 4. Normal assessment](image)

### 3.2. API 579

FFS assessment procedures for evaluating crack-like flaws in components are covered in Part 9 of API 579. The assessment procedures are based on the FAD method. The three assessment levels are used to evaluate crack-like flaws. Level 2 Assessment is selected in this work, because that the thickness exceeds the limiting conditions for a Level 1 Assessment. The FAD is defined with the same as equation (9). However, the fracture ratio for the crack is defined as:

\[
K_r = \frac{K_{I}^{P} + \Phi K_{I}^{SR}}{K_{mat}}
\]  

(11)

Where \( K_{I}^{P} \) the applied stress intensity due to the primary stress distribution is, \( K_{I}^{SR} \) is the applied stress intensity due to the secondary and residual stress, \( K_{mat} \) is the modified material toughness, and \( \Phi \) is the plasticity correction factor.

A new procedure for computing the plasticity correction factor is proposed in API 579. The plasticity correction factor can be calculated as:

\[
\Phi_\rho = \Phi_\rho \xi
\]

(12)
Where \( \zeta \) is a parameter which is a function of \( K_{J}^{\text{th}}, K_{I}^{\text{th}} \) and \( L_{r}^{\text{th}} \). \( K_{J}^{\text{th}} \) and \( K_{I}^{\text{th}} \) represent the stress intensity factor for secondary and residual stresses corrected for plasticity effects. \( K_{I}^{\text{th}} \) and \( L_{r}^{\text{th}} \) are the stress intensity factor and limit load ratio for primary stress.

In Level 2 procedure, partial safety factors are applied to the independent variables (i.e. flaw size, material fracture toughness, and stress) to account for uncertainty. However, these partial safety factors are removed from the latest version of API 579.

According to the above equations, the assessment point \((L_{r}, K_{r})\) can be calculated under design pressure and working pressure, as shown in Fig. 5. It can be seen that both assessment points are located in the safety zone.

![Figure 5. Level 2 procedure of API 579](image)

4. Discussions
As can be seen from the above results, there are some differences for the same problem. For comparison, safety margin \( M \) is defined as:

\[
M = \frac{\text{Fracture toughness of the material being assessed}}{\text{Fracture toughness to produce a limiting condition}}
\]

This definition is referred to R6 procedure [8], as shown in Fig. 6. Without doubt, the most significant parameter is the applied load. In this work, the initial load is coincident for GB/T 19624 or API 579. The key difference is that the treatment of secondary and welding residual stress, which results in the variety of fracture ratio.

\[
M = \frac{O'B}{O'A}
\]
Table 4 shows the safety margin for different assessment procedures. It can be seen that the safety margin of API 479 Level 2 procedure is much higher than GB/T 19624. However, it cannot represent that it is more safety than GB/T 19624. Because partial safety factors have been considered during the implement of the assessment procedure. In addition, the safety margin for normal assessment on GB/T 19624 is little lower than the simplified assessment. The phenomenon may be caused by the correction factors for weld structure, bending stress and welding residual stress in equation (7). The correction factors for welding residual stress is recommended to be 0.6 in GB/T 19624, which obviously reduces the total stress.

Table 5. Comparison of parameters during assessment for design pressure case

| Items | GB/T Normal assessment | API 579 Level 2 | Relative error |
|-------|------------------------|-----------------|----------------|
| $K_{mat}$ (MP·m$^{1/2}$) | 77.47 | 77.47 | / |
| FAC | Equation (9) | Equation (9) | / |
| $K_{I}^{p}$ (MP·m$^{1/2}$) | 33.0 | 22.2 | 48.6% |
| $K_{II}^{p}$ (MP·m$^{1/2}$) | 16.0 | 15.9 | 0.6% |
| $\Phi$ | 1.12 | 1.18 | -5.1% |
| $K_{I}$ | 0.783 | 0.528 | 48.3% |
| $L_{r}$ | 0.635 | 0.635 | 0 |
5. Conclusion

FFS assessment procedures have been heavily updated in recent years, especially in Europe and America. However, a standard associated with FFS assessment GB/T 19624-2004 is still in use in China. For comparisons, two FFS procedures for structures contained flaws are carried out for a typical sphere storage tank. The assessment results are compared. To show the difference between the domestic standard and international standards, API 579 is adopted to perform the Fitness-for-Service assessment. The safety margin is discussed.

(1) During the regular inspection of a 3000m³ sphere storage tank for propylene, several defects are detected. One of the cracks can up to 80mm in length direction.

(2) Structural integrity assessment is performed based on different procedures for the sphere storage tank, including GB/T 19624-2004 and API 579-2016.

(3) Partial safety factors are considered during the implement of the assessment procedure of GB/T 19624. However, these partial safety factors have been removed in API 579-2016.

(4) Safety margin is defined and shows that the safety margin of API 479 Level 2 procedure is much higher than GB/T 19624. However, it cannot represent that it is more safety than GB/T 19624. In addition, the safety margin for normal assessment on GB/T 19624 is little lower than the simplified assessment for the case.

Acknowledgments

This work was financially supported by National Natural Science Foundation of China (Grant No. 51605435).

References

[1] API 579, Fitness-For-Service, the American Petroleum Institute and The American Society of Mechanical Engineers, 2016.

[2] BS 7910, Guide to methods for assessing the acceptability of flaws in metallic structures, British Standards Institution, 2013.

[3] SINTAP, 2000, Structural integrity assessment procedures for European industry.

[4] P. Li, Y. Lei, Q. Zhong, and X. Li, A Chinese structural integrity assessment procedure for pressure vessels containing defects, International Journal of Pressure Vessels and Piping, 77 (2000) 945-952.

[5] GB/T 19624, Safety assessment for in-service pressure vessels containing defects, Standardization Administration of the People's Republic of China, 2004. (In Chinese).

[6] T. Yang, X. Chen, Z. Fan, A comparison of fracture assessment methods in several structural integrity assessment procedures, In Proceedings of ASME Pressure Vessels and Piping Conference, Prague, Czech Republic, 2009, PVP2009-77609.

[7] Z. Han, G. Xie, S. Shao, Z. Li, Investigation of partial safety factor approach for flaw assessment procedure in chinese FFS code,” In Proceedings of ASME Pressure Vessels and Piping Conference, Waikoloa, Hawaii, 2017, PVP2017-65430.

[8] R6, Assessment of the Integrity of Structures Containing Defects, Revision 4, EDF Energy Nuclear Generation Ltd, 2015.