Study on Remaining Life of Pressure Vessel Containing Through Crack Based on FAD Failure Path

Zhihui Mao, Wei Long, Huaguuo Liu, Xin Xu and Van Thanh Hoang

ABSTRACT

Aiming at the safety evaluation of pressure vessels with through cracks, based on the simulation of the safe decay path of penetrating cracks, a calculation method for predicting the remaining life of buried cracks is proposed. A safe attenuation path trajectory for the simulation of through crack defects on FAD is obtained by using the fracture ratio and load ratio calculation formula for a given crack size increment, Then the digital integral method is used to solve the remaining trajectory line segment of the safe attenuation path, and the calculation model of the penetration safety margin is established. And using the weight function and the step-by-step integration method, combined with the Paris formula to solve the defect stress intensity factor and the number of fatigue cycles.1

INTRODUCTION

As a commonly used pressure equipment, pressure vessels are widely used in industrial production, people's livelihood engineering, national defense military and other fields, and pressure vessels are also special equipment with high explosion risk. The major accident rate of 10,000 pressure vessel equipment worldwide is about 0.39, Ten years ago, the major accident rate of China’s Wantai equipment was 100 times that of developed countries[1]. Most of the pressure vessel accidents are caused by crack fatigue defects. Through crack is a kind of fatigue crack of pressure vessel. Through crack has the characteristics of later occurrence and sudden appearance[2, 3], which is the kind of crack that has the greatest influence on the safety performance of pressure vessel. For penetrating cracks, although the entire

1 Zhihui Mao, Wei Long, Huaguuo Liu, Xin Xu, Van Thanh Hoang, Sichuan University, Sichuan, China
Figure 1. Safety margin characterization based on failure assessment map ray method.

crack has penetrated from the inner wall of the pressure vessel to the outer wall, the initial crack may cause the container to leak but does not cause it to collapse directly. This is a unique feature of penetrating cracks. Accurate calculation of the safety and residual life of a pressure vessel containing cracks will provide better preparation for remedial pressure vessels and prevent further accidents.

The FAD (Failure Assessment Diagram) is based on the theory of elastoplastic fracture mechanics. When determining the safety of defects, two extreme failure conditions, namely linear elastic fracture and plastic instability, are considered. There is a transitional failure state between the two. For this transition state, a linear elastic fracture criterion and a plastic instability criterion which respectively reflect degradation are introduced. Typical methods of evaluation such as the UK CEGB-R6 guidelines and the US EPRI guidelines. [4]. All along, the characterization method of defect safety margin based on elastoplastic fracture mechanics theory mostly uses the ray method based on double criterion failure assessment map, as shown in Figure 1, but this method does not reflect the true attenuation trend of crack defects.

Therefore, in order to solve the problem of safety evaluation of through cracks in pressure vessels, this paper based on the Failure assessment diagram to simulate a new safety attenuation model for through cracks. Based on this, a new method for predicting the remaining life of through cracks is proposed.

**FAD-BASED SAFE ATTENUATION PATH CHARACTERIZATION MODEL AND SAFETY MARGIN MODEL**

Many of the safety attenuation paths for pressure vessels are now mostly using the ray method based on the double criterion failure assessment diagram shown in Figure 1. For Figure 1, set the safety factor for a given load to $F_s$, and have:

$$F_s = \frac{OB}{OA}$$  \(1\)

The safety margin of defect assessment point A in figure 1 is expressed as:

$$M_s = F_s - 1$$  \(2\)
However, it is obviously impractical for the pressure vessel crack assessment point to expand according to the ray method or the parallel method. The safe to unsafe attenuation path is not a uniform straight line, but a curve with a gradually increasing rate. We refer to this path as the safe attenuation path of the defect assessment point under geometric extension, and the degree to which the defect assessment point gradually approaches the critical line along the safe attenuation path is called the safety degree \( P \). In order to obtain an accurate safety attenuation path, based on GB/T19624-2004, an evaluation point is generated on the failure assessment diagram from the relevant data of the crack defect. Using the pressure vessel safety assessment simulation platform for simulation, that is, as the loading time increases, according to the geometric relationship of the length and depth of the crack, each crack size in the crack change process is indicated in the failure assessment diagram, the safety assessment point is gradually moved from the safe zone to the non-safe zone along a curve, as shown in Figure 2.

The through crack is first regularized when simulating the safe attenuation path of the penetrating crack. The length of the crack is the measured maximum length of the surface direction, and the crack depth is the wall thickness. Figure 3 shows the regularization of through cracking, length \( 2c=l \). Figure 4 is a schematic diagram of the failure path of a through crack on an in-service pressure vessel simulated by a pressure vessel safety assessment simulation platform in the case of simulated national defense aerodynamic test fatigue. Theoretically, the simulated safety attenuation path not only estimates the remaining life of the current crack size, but also estimates the remaining life at any point on the curve.

The defect safety attenuation path reflects the performance of the crack propagation trend on the failure assessment map. The distance between the starting point and the failure point of the safe attenuation path of the crack, that is, the failure dimension of the crack is defined as the safety margin \( M_s \). The reference to safety margin is to more accurately describe the remaining life and reflect the safety degree of the metal structure with crack defects. The calculation formula is:

\[
K_{P} = \frac{2c}{l}
\]

where \( K_{P} \) is the safety index, \( 2c \) is the crack length, and \( l \) is the wall thickness.
Where:

\[ M_s = \frac{S_t}{S} - 1 \]  \hspace{1cm} (3)

Where: \( S_t \) is the total length of the attenuation path in the safe area, and \( S \) is the length from the start point of the attenuation path to the evaluation point. It can be known from formula 3 that when the safety margin \( M_s \) tends to infinity, the safety of the pressure vessel is the highest at this time; when \( M_s \) is getting smaller, the safety of the pressure vessel is getting lower and lower; when \( M_s = 0 \), then in terms of through cracks, it is considered that the entire pressure vessel has collapsed.

**UNIVERSAL WEIGHT FUNCTION FOR THROUGH CRACKS**

Accurate and efficient calculation of the stress intensity factor of through cracks is the key to life assessment of pressure vessels. There are many methods for calculating the stress intensity factor. The weight function method is a method proposed by Bueckner[5] and Rice[6]. It can calculate the stress intensity factor of crack body under any load condition, especially the complex stress distribution. It is an accurate and effective method (See formula 4).

\[
K = \int_0^a \sigma(x) m(a, x) \, dx \tag{4}
\]

\[
m(a, x) = \frac{E_t}{2K} \frac{\partial U(a, x)}{\partial a} \tag{5}
\]

\[
E' = \begin{cases} E & \text{Plane stress} \\ \frac{E}{1-\mu^2} & \text{Plane strain} \end{cases} \tag{6}
\]

Where \( m(a, x) \) is a weight function; \( U \) is a crack surface opening displacement under a symmetrical load; \( E \) and \( \mu \) are the elastic modulus and Poisson's ratio of the elastomer, respectively.
Compared with other methods, the applied weight function method has the advantages of more accurate and convenient. In recent years, many research scholars have studied it and proposed different weight function determination methods. Among them, Wu, Newman[7] et al. obtained the weight function of various rectangular plate crack bodies by assuming the crack surface opening displacement, but such weight functions the form is complicated and the operation is inconvenient. The other is the universal weight function proposed by Glinka and Shen[8] by summarizing the general characteristics of the weight function. The universal weight function method directly assumes the general characteristics of the weight function, avoiding the complexity of the open displacement on the two-dimensional plane crack surface. It contains only three undetermined coefficients and is considered to be a simple, accurate and efficient method for calculating stress intensity factors. The expression is:

$$m(a, x) = \frac{2}{\sqrt{2\pi(a-x)}} \left[ 1 + P_1 \left(1 - \frac{x}{a}\right)^{1/2} + P_2 \left(1 - \frac{x}{a}\right) + P_3 \left(1 - \frac{x}{a}\right)^{3/2} \right]$$ (8)

By selecting the size of the initial point, the midpoint and the breaking point in the safe attenuation path, the stress intensity factor $K$ and the stress distribution $\sigma(x)$ are respectively obtained through finite element analysis, and are brought into the above series of formulas, and three unknown parameters can be obtained.

**CALCULATION OF REMAINING LIFE**

When the pressure vessel creates a through crack, in order to better take remedial measures, we need to accurately predict the remaining life of the pressure vessel. By integrating using the Paris formula, this is an accurate and efficient way to calculate the remaining life of a pressure vessel. According to the Paris formula, the number of fatigue load cycles of a crack is:

$$N = \int_{a_0}^{a_n} \frac{da}{C(\Delta K)^m}$$ (9)

Where $a_0, a_n$ represent the initial size of the crack and the failure size of the crack, and $N$ represents the number of cycles required for the crack to expand from the $a_0$ size to the $a_n$ size, i.e. the remaining life of the crack. In order to ensure the accuracy of the remaining life obtained, a step-by-step integration method is used for obtaining.

Applying the universal weight function method and the Paris formula to obtain the stress intensity factor $\Delta K$ and the number of cycles $N_1$ from the initial size to the next size. Repeat the above steps, and sequentially obtain the number of cycles of the next size, $N_2, N_3, N_4...N_s$ until the crack fails; Adding the number of cycles previously obtained is the final remaining life of the crack $N$:
\[ N = \sum_i^s N_i \] (10)

When using the step-by-step integration method, it is necessary to select the number of steps reasonably so that the calculation amount can be reduced while ensuring accuracy.

**CONCLUSIONS**

In this paper, a new and more accurate safety margin and residual life prediction method are proposed for the penetrating crack of pressure vessel. Prepare adequately for a more effective remedial pressure vessel. A safe attenuation path trajectory for the simulation of through crack defects on failure assessment diagram is obtained by using the fracture ratio and load ratio calculation formula for a given crack size increment. The safe attenuation path on the failure assessment diagram can more accurately and effectively reflect the expansion of the penetration crack in the pressure vessel. The crack-based safe attenuation path trajectory can theoretically give the corresponding dynamic safety margin of the crack defect at any size, reflecting the safety degree of the pressure vessel.

**ACKNOWLEDGEMENTS**

This paper is supported by the National Natural Science Foundation of China (Grant No. 51875371).

**REFERENCES**