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Study on Stress Intensity Factor of Girth Weld with Crack Defects

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Abstract: In order to study the safety performance of the girth weld with cracks in the pressure vessel in use, based on fracture mechanics, this paper adopts ABAQUS and FRANC3D joint simulation to calculate the crack tip stress intensity factor(SIF). The influence of crack location, length and depth on the stress intensity factor of crack tip is analyzed. The results show that the crack SIF at different crack locations (inner crack > buried crack > outside crack) increases with the increase of crack length and increases with the increase of crack depth.

Keywords: Girth weld, Stress Intensity Factor, Crack, Franc3d.

1. Introduction

Pressure vessels are widely used in various fields of process industry. Welding is a key process in the process of assembling components into a complete pressure vessel. Although non-destructive testing is required after welding of pressure vessels, cracks and other defects will inevitably occur in the weld after working for a period of time, which is related to the safety of equipment and personnel. Therefore, safety research on girth welds with cracks can effectively reduce safety accidents. Based on the theory of fracture mechanics, the stress intensity factor is used to characterize the safety degree of girth weld. The joint simulation of ABAQUS and FRANC3D was used to calculate the stress intensity factor (SIF) at crack tip and analyze the influence factors of stress factor.

2. Stress Intensity Factor Theory

2.1. Stress intensity factor

The stress intensity factor is a "ruler" to measure the stress, which reflects the strength of the stress at each point near the crack tip. It is an effective way to use stress intensity factor in safety assessment. The methods used to calculate stress intensity factor in engineering mainly include analytical method, numerical method and superposition method. Among them, the finite element method has become the main method of solving, and it is a kind of calculation method with a wide range of application.

The calculation of K values of different types of cracks requires the introduction of a geometric shape parameter for numerical correction. The influences of load type, direction and crack propagation direction are mainly considered. The general expressions of the three types of cracks constructed by fracture mechanics are as follows:

$$\begin{cases} K_I = Y\sigma\sqrt{\pi a} \\ K_{II} = \beta\sigma\sqrt{\pi a} \\ K_{III} = \gamma\sigma\sqrt{\pi a} \end{cases} \quad (1)$$

K_I, K_{II}, K_{III} is a stress intensity factor, Y, β, γ is a form factor.

2.2. Calculation of stress intensity factor

In this paper, ABAQUS and FRANC3D are used to jointly simulate SIF. FRANC3D is a new generation crack analysis software, and the finite element software is used to calculate fracture mechanics[1-3]. The three final stress intensity factors KI, KII and KII can be calculated under the three-dimensional crack mode.FRANC3D uses M integral to calculate SIF, and the expression of M integral energy is as follows:

$$\bar{M}^{(1,2)} = \int_\Gamma \left(\sigma_{ij}^{(1)}\frac{\partial u_i^{(2)}}{\partial x_1} + \sigma_{ij}^{(2)}\frac{\partial u_i^{(1)}}{\partial x_1}\right)\frac{\partial q}{\partial x_j}ds - \int_\Gamma \left(W^{1/2}\delta_{1j}\right)\frac{\partial q}{\partial x_j}ds \quad (2)$$

$\Gamma$is an integral loop around the crack tip.

The relationship between M-integral and stress intensity factor is as follows:

$$\bar{M}^{(1,2)} = \frac{1-\nu^2}{E}\bar{K}_I^{(1)}\bar{K}_I^{(2)} + \frac{1-\nu^2}{E}\bar{K}_{II}^{(1)}\bar{K}_{II}^{(2)} + \frac{1+\nu}{E}K_{III}^{(-1)}K_{III}^{(-2)} \quad (3)$$

3. Finite Element Numerical Simulation of Girth Weld Cracks

3.1. ABAQUS and FRANC3D Joint simulation

FRANC3D uses finite element method to calculate mechanical parameters and simulate arbitrary three-dimensional crack growth, and provides Ansys, Abaqus and Nastran interfaces. ABAQUS provides the initial finite element model and operational solver, and FRANC3D can be used for crack insertion, remeshing and stress intensity factor calculations. The simulation process is as follows:

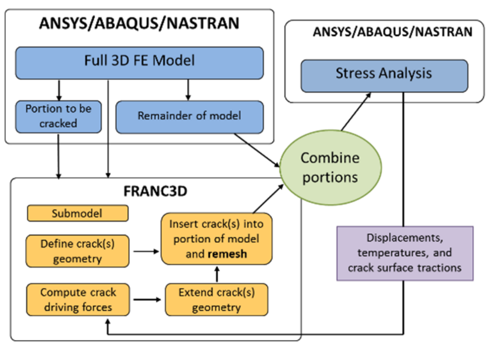

Figure 1. Flow chart of co-simulation

3.2. Establishment of finite element Model of girth weld Crack

In this study, a pressure vessel with girth weld between cylinder and cylinder was adopted, and its specific parameters are shown in Table1. ABAQUS was adopted to establish the girth weld model of pressure vessel, and material assignment, mesh division and load constraint were carried out.

Table 1. Parameters of research objects

Material	σ_s	E	v	Apparent radius R	t	P
16MnR	360MPa	210GPa	0.3	600mm	12mm	2.6MPa

Because the girth weld is an axisymmetric model, a 1/4 model of girth weld is established in this study, and symmetric loads and displacement constraints are applied to its symmetric cracks, that is, symmetric constraints are set on the lower end crack and the front end crack. Meanwhile, loads are applied to the side cracks of the girth weld, as shown in Figure 2. 2.6MPa pressure is applied to the surface crack, and 56MPa uniform tensile force is applied to the axial crack.

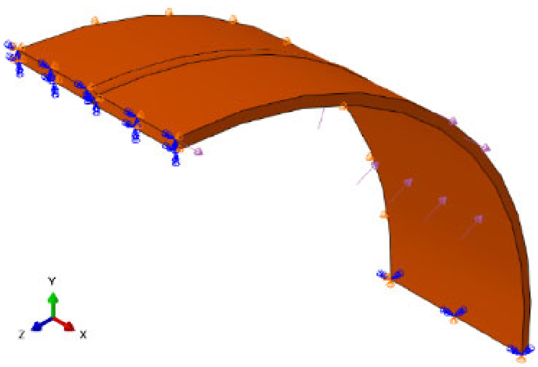

Figure 2. Load and constraint application(left)

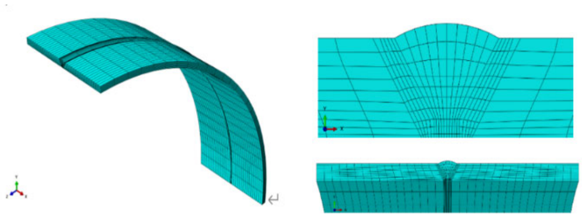

Figure 3. Finite element model of pressure vessel girth weld(right)

In order to facilitate the calculation of the model, the hexagonal mesh was used to grid the model as shown in Figure 3.

3.3. Model Crack implantation

The above ABAQUs-based pressure vessel girth weld model was saved in inp. file and imported into FRANC3D for crack insertion, mesh redivision and stress-intensity factor calculation. Since the cracks are too small compared to the model, FRANC3D can cut the original model in order to reduce the calculation amount, as shown in Figure 4, cut the sub-model, implant cracks in the sub-model and calculate. Multiple styles of cracks can be inserted into FRANC3D. This paper takes elliptical cracks as an example for analysis, as shown in Figure 5.

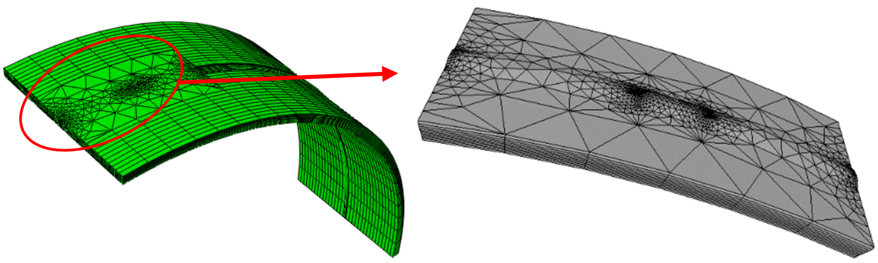

Figure 4. Submodel cut in mesh

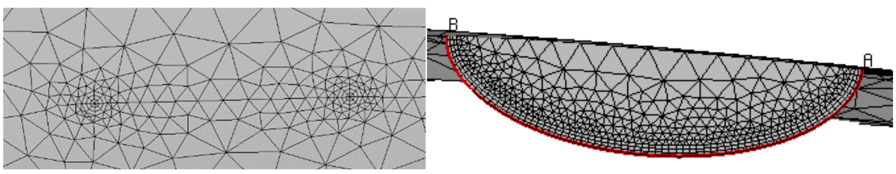

Figure 5. Crack tip singular element and front mesh

4. Analysis of Fracture Stress Field and Stress Intensity Factor of Girth Weld Defects

According to the equivalent simplification of common defects in the weld, it is regarded as a crack of a certain size. In this study, in order to provide a sufficient range of evaluation results for practical projects, the cases of multiple crack sizes with different depth to width ratios a/c and a/t were considered, and the cases of buried cracks with 2a/t were considered, as shown in Table 2.

Table 2. Crack variable parameters

Crack location	a/c	a/t(2a/t)
Outside crack	0.125、0.25	0.2
Inner crack		0.4
Buried crack	0.5、1	0.6

4.1. Analysis of stress field of annulus Weld

When there are no defects in the welded joint of the annulus weld of the pressure vessel, the load cut-off at the weld is complete and continuous, the residual height of the weld and the transition arc of the weld toe take reasonable values, the stress of the joint is relatively uniform, and the stress concentration coefficient is generally small as shown in FIG. 6.When there is a crack in the girth weld, the stress at the crack tip is concentrated and the stress changes are complicated. Fig.7shows the stress change in the area near the crack, and Fig. 7 shows the horizontal stress changes of the upper and lower crack tips along the X-axis (axial direction). It can be seen that the stress distribution of the axial horizontal line where the crack tip is located suddenly increases at the crack tip, and the further away from the crack tip the stress value decreases.

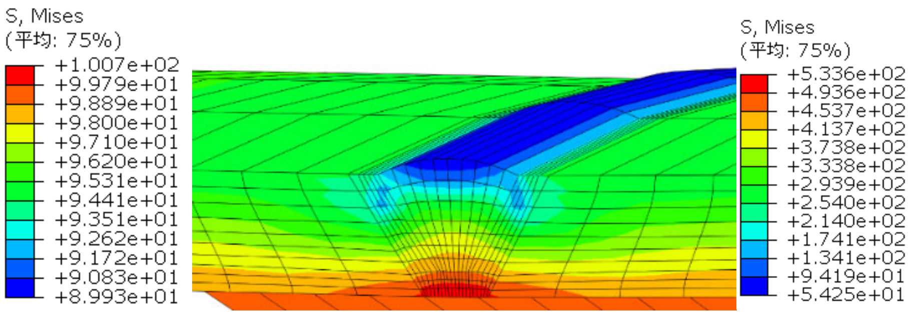

Figure 6. Stress nephogram of non-defective weld(left)

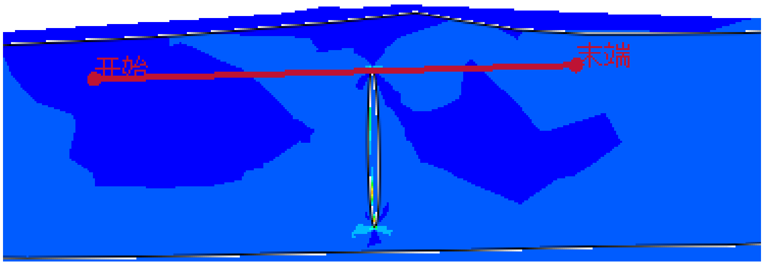

Figure 7. Stress nephogram of defects with cracks(right)

4.2. Influence of Different factors on the stress intensity factor

The stress intensity factor KI is a physical quantity reflecting the strength of the elastic stress field at the crack tip, which is closely related to the crack size, the geometric characteristics of the component and the load. The greater the KI value, the greater the stress at the tip. According to the calculated results of the stress field of the weld, the stress intensity factor KI value was extracted with the crack location, crack size a/t ((2a/t) and a/c, and the influence of these factors on it was studied.

(1) Effect of crack location on KI

In this study, the weld crack defects of pressure vessels are equivalent to surface crack, surface crack and buried crack. For buried cracks, the cracks are located on the surface of the weld and have two crack tips, upper and lower. The simulation results show that under the same depth ratio, the stress intensity factor decreases gradually from surface crack, buried crack and surface crack. Under the same surface pressure and axial load, it can be seen from Figure 8 that the stress of surface crack is higher than that of buried crack than that of surface crack.

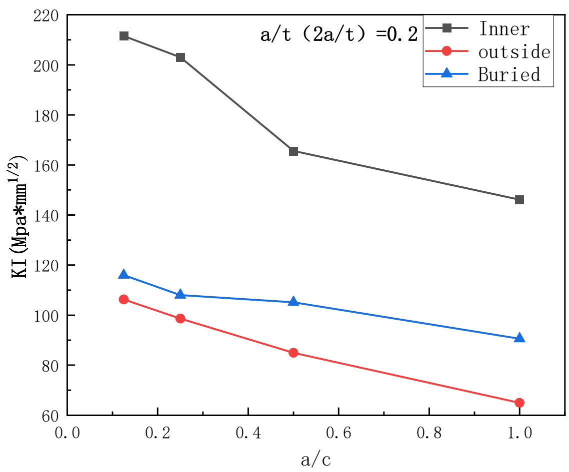

Figure 8. KI in relation to crack location a/t (2a/t)=0.2

(2) Influence of crack depth on KI

Figure(a),(b),(c)respectively show the relationship between crack depth and KI value of surface crack, buried crack and surface crack. It is sufficient to see that no matter where the crack is located, the greater the stress concentration degree of the crack front, the greater the KI value will be as the crack depth increases.

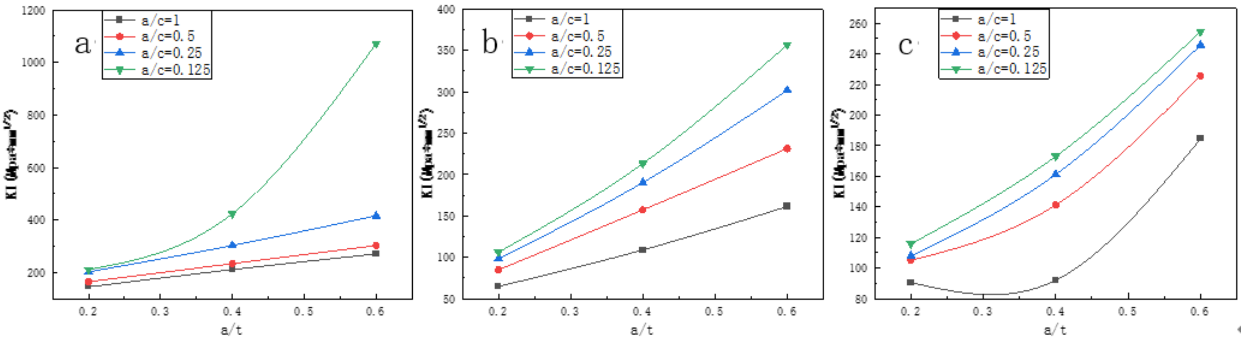

Figure 9. Relationship between KI and crack depth
(a) External crack(b) Buried crack (c) Inner crack

(3) The influence of crack length on KI

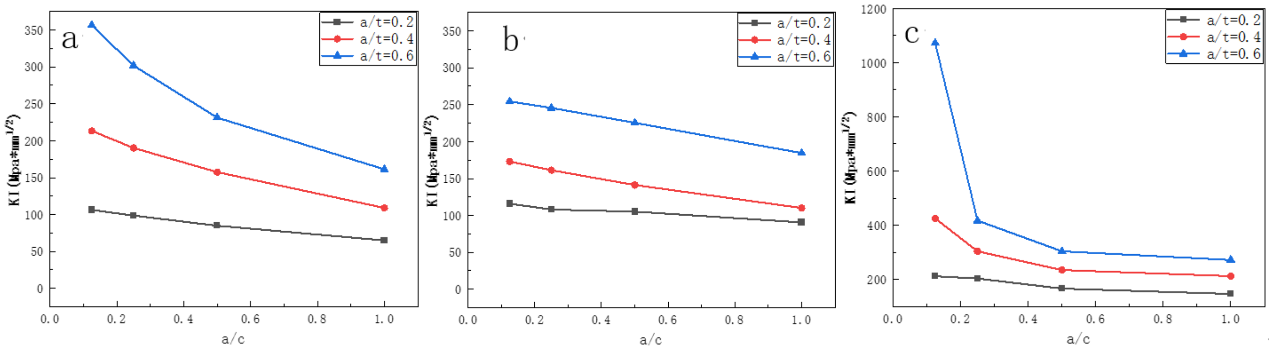

Figure 10. KI relationship with crack length
(a) External crack(b) Buried crack (c) Inner crack

Figure(a),(b),(c) respectively show the relationship between crack length and KI value of external crack, buried crack and surface crack. It can be seen that when crack depth a is constant, SIF also decreases with the increase of a/c, that is, the length of external crack, surface crack/buried crack decreases.

5. Conclusions

In this paper, the crack tip stress intensity factor (SIF) was calculated through the joint simulation of ABAQUS and FRANC3D to explore the change of SIF at different locations, lengths and depths of cracks. The results show that when the crack length and crack depth are constant, the SIF size is (surface crack>buried crack>surface crack).The SIF value is positively correlated with the length and depth of the crack.

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