Numerical Study on Fatigue Propagation of Surface Cracks

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Abstract. Through FRANC3D software, the life curves of samples containing surface crack and through crack are analyzed respectively under the same stress ratio, whose life results are calculated when reaching each critical condition. The test results show that the sample containing surface crack whose life $N_{3D}$ is 65870, and the sample containing through crack whose life $N_{2D}$ is 6434, $N_{3D}$ is about 10.4 times of $N_{2D}$. In addition, the life test results of samples with different initial surface crack sizes under the stress ratio $R=0.1, 0.2, 0.3, 0.4, 0.5$ cyclic load are also studied. Results show that the life $N_{3D}$ and the stress ratio $R$ are obvious nonlinear relationship. Similarly, the life $N_{3D}$ and the initial crack half length $c$ also show obvious nonlinear relationship.

1 Introduction

Cracks in engineering structures usually occur under the action of fatigue loads. In addition to the cracks formed by the material itself, the crack initiation under fatigue load mostly originates from the surface with high stress level. Therefore, the fracture caused by surface cracks is the most common in engineering practice.

As surface crack is a common defect, the research on its service life is also increasing. Huimin et al. [1] studied the life prediction and life control by using the Paris formula, and used advanced non-destructive testing technology to check the crack size in the container. When the defect size is close to the critical value, maintenance or replacement should be carried out to ensure the safety. Zhang Yangyang[2] et al. used the method of theoretical derivation and numerical simulation to predict the steady state morphology of the longitudinal surface crack propagation to ensure the relationship between the crack propagation length $2c$ and the depth $a$ which provides a basis for evaluating the remaining life of the pressure vessel with surface cracks.

There are two methods to test the propagation of surface crack, which are experiment and numerical calculation. Numerical calculation has become one of the main methods to study crack propagation because of the great cost of experimental research. FANC3D is software developed by Cornell University for fracture mechanics to calculate stress intensity factors and crack propagation at the crack tip. Shen Shiming et al. [3] has verified the accuracy of the crack propagation path and the life prediction of the component.

In order to facilitate the study, the through cracks as major method often were studied. Therefore, it is necessary to study the $a$-$N$ life curve of the through crack and the surface crack under the same stress ratio in air. At the same time, this paper analyzes the effect of stress ratio and crack shape on crack propagation life, which providing data support for engineering application.

2 Experimental Method

2.1 Material Parameter

The sample material is X70, and the basic mechanical properties of the material are shown in Table 1.

| Material parameter. |
|---------------------|
| $d$/$dN$(m/cycle) | $K_{IC}$ (MPa.m$^{1/2}$) | $\Delta K_{th}$ (MPa.m$^{1/2}$) | $E$ (GPa) | $\mu$ |
| 7.65$\times 10^{-10} \times \Delta K^{1.65}$ | 221 | 10 | 200 | 0.3 |

2.2 Numerical calculation of through crack and surface crack life

2.2.1 Life Test of Through Crack

As is shown[5] in Fig. 1, for the sample model, the length of the specimen is 50mm, the width is 10mm, the thickness is 20mm. for the pre fabricated crack, the length is 5mm, the width is 10mm. The boundary condition of the specimen is to apply the uniformly distributed load 500MPa above the plate, and to apply stress ratio $R=0.1$ cyclic load. The constraint condition of the sample is adding fixed constraint under the sample. The material parameters are derived from section 2.1. The fracture criterion selected in FRANC3D is the maximum tensile stress criterion [4], which is applied in
the following sections. The \(a-N\) life curves of through cracks are calculated.

The stress intensity factor formula (1) of finite width plate is as follows, which originate from the stress intensity factor handbook \[6-8\].

\[
K = \sigma \sqrt{(\pi a) \times f(a/w)};
\]

\[
f(a/w) = 1.12 - 0.251 \times (a/w) + 10.55 \times (a/w)^3 - 21.72 \times (a/w)^3 + 30.39 \times (a/w)^4
\]

(1)

Where \(a\) is the crack length and \(w\) is the specimen width, according to the fracture toughness of materials \(K_{1c} = 221\text{MPa.m}^{1/2}\). The critical crack length 9.5mm is obtained. The crack length \(a = 9\text{ mm}\) corresponding load cycle number is defined as the specimen life \(N_{2D}\). The difference between them is 95%.

For the pre fabricated crack, the shape is semi ellipse, the semi short axis \(a= 5\text{ mm}\), the semi long axis \(c= 5\text{ mm}\), the boundary condition of the specimen is to apply the uniformly distributed load 500MPa above the plate, and to apply stress ratio \(R=0.1\) cyclic load. The constraint condition of the sample is adding fixed constraint under the sample, and the material parameters are derived from section 2.1.

The crack length \(a= 18\text{ mm}\) corresponding load cycle number is defined the specimen life \(N_{3D}\), whose length is 10% difference from the true thickness of the sample.

2.3 Calculation of Fatigue Propagation Process with Different Initial Crack Sizes

As is shown in Fig. 2, the sample model and material parameters are the same as section 2.22. the semi short axis \(a= 5\text{ mm}\) is fixed, the semi long axis \(c\) changes successively. The life curves of the initial crack \(a \times 2c(5\text{mm} \times 4\text{mm}, 5\text{mm} \times 6\text{mm}, 5\text{mm} \times 8\text{mm}, 5\text{mm} \times 10\text{mm}, 5\text{mm} \times 12\text{mm}, 5\text{mm} \times 14\text{mm}, 5\text{mm} \times 16\text{mm}, 5\text{mm} \times 18\text{mm})\) are calculated under stress ratio \(R=0.1, 0.2, 0.3, 0.4, 0.5\) cyclic load respectively.

3 Experimental Results

3.1 Experimental Results of Through Crack and Surface Crack

Experimental results of through crack and surface crack under stress ratio \(R=0.1\) cyclic load is shown in Fig. 3. The initial crack depth of plane through crack is 5mm, the initial crack depth of three dimensional surface cracks is 5mm, and the initial crack half length is 5mm.

3.2 Life of Different Three Dimensional Initial Surface Cracks

Experimental results of the initial crack \(a \times 2c(5\text{mm} \times 4\text{mm}, 5\text{mm} \times 6\text{mm}, 5\text{mm} \times 8\text{mm}, 5\text{mm} \times 10\text{mm}, 5\text{mm} \times 12\text{mm}, 5\text{mm} \times 14\text{mm}, 5\text{mm} \times 16\text{mm}, 5\text{mm} \times 18\text{mm})\) under stress ratio \(R=0.1, 0.2, 0.3, 0.4, 0.5\) cyclic load respectively is shown in Fig. (4-11).
Figure 4. Life curve of surface crack $a=5$ mm, $c=2$ mm.

Figure 5. Life curve of surface crack $a=5$ mm, $c=3$ mm.

Figure 6. Life curve of surface crack $a=5$ mm, $c=4$ mm.

Figure 7. Life curve of surface crack $a=5$ mm, $c=5$ mm.

Figure 8. Life curve of surface crack $a=5$ mm, $c=6$ mm.

Figure 9. Life curve of surface crack $a=5$ mm, $c=7$ mm.
4 Discussions

4.1 Comparative Results of Through Crack and Surface Crack

For specimens with through cracks, the initial crack length is $a=5$ mm and the stress ratio $R=0.1$ cyclic load is applied. The life $N_{2D}$ of the sample is 6434 indicating the predicted working life of specimens with through cracks. Similarly, for specimens containing surface cracks, the initial crack length is $a=5$ mm, $c=5$ mm, and the stress ratio $R=0.1$ cyclic load is applied. The life $N_{3D}$ of the sample is 65870 indicating the predicted working life of specimens with surface cracks. The difference between the two results is 10.4 times.

4.2 The Relationship among the Life $N_{3D}$ and Stress Ratio $R$ and the Initial Crack Half Length $c$

In section 2.3, the crack length $a=18$ mm corresponding load cycle number is defined as the sample life $N_{1D}$. The 3D graph representation of the relationship among the life $N_{3D}$, the stress ratio $R$ and initial half crack length $c$ is shown in Fig. 12.

According to the Fig. 12, with the stress ratio $R$ increases, the life $N_{3D}$ increases; on the contrary, with the initial crack half length $c$ increases, the life $N_{3D}$ decreases. The reason for this phenomenon is that when the maximum load 500MPa is fixed, the greater the stress ratio $R$, the smaller the stress intensity factor ranges $\Delta K$, which leads to the larger crack propagation life. The reason for the alternative phenomenon is when the maximum load 500MPa is fixed, the greater the initial crack half length $c$, the larger the stress intensity factor $\Delta K$, which leads to the smaller crack propagation life.

Conclusion

1. The through crack sample and the surface crack sample are tested under the cyclic loading of the stress ratio of 0.1 based on FRANC3D software. The sample containing surface crack whose life $N_{3D}$ is 65870, however the sample containing through crack whose life $N_{2D}$ is 6434. In the theoretical study, we should take the surface crack as the research object more close to the real life of the material.

2. In the sample containing surface crack, the life of the initial crack $a \times 2c$ (5mm×4mm, 5mm×6mm, 5mm×8mm, 5mm×10mm, 5mm×12mm, 5mm×14mm,5mm×16mm, 5mm×18mm) under the stress ratio $R=0.1,0.2,0.3,0.4,0.5$ cyclic load is tested respectively, We observe and discover that the functional relation among the life $N_{3D}$, the stress ratio $R$ and the initial crack half length $c$ is curved surface. With the stress ratio $R$ increases, the life $N_{3D}$ increases; on the contrary, with the initial crack half length $c$ increases, the life $N_{3D}$ decreases.

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