Effects of Initial Crack Defect on Fatigue Crack Growth of Camshaft for Nuclear Emergency Diesel Engine

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Abstract. In this paper, the finite element analysis model of camshaft for nuclear emergency diesel engine with initial crack defect is established based on ABAQUS finite element analysis software. The effects of initial crack defect parameters on crack tip stress intensity factor are studied by a working condition discretization method. The numerical results show that the crack tip stress intensity factors of transverse crack and longitudinal crack are quite different in a load cycle of camshaft. The crack tip stress intensity factors of transverse crack fluctuate greatly, and the crack tip stress intensity factor range is much larger than that of longitudinal crack, which indicates that the fatigue fracture risk of transverse crack on the camshaft journal is higher. With the increase of initial crack depth from 1 mm to 4 mm, the crack tip stress intensity factor range increases from 410.84 MPa·mm$^{1/2}$ to 720.24 MPa·mm$^{1/2}$ by 75.3%, which indicates that the increase of initial crack depth can lead to a significant increase of the fatigue fracture risk. As the initial crack defect moves away from the cam, the maximum of the crack tip stress intensity factor initially increases and then decreases after reaching a maximum value. When the initial crack is 3 mm away from the end face of the cam, the crack tip stress intensity factor range is the largest (843.98 MPa·mm$^{1/2}$), which indicates that the fatigue fracture risk of transverse crack at this position is the highest. The research results obtained in this paper may provide some reference for the fracture assessment and reliability analysis of camshaft for nuclear emergency diesel engine.

1. Introduction
The camshaft, a key component of the nuclear emergency diesel engine, is used to control the opening and closing of the valve of the diesel engine, and it has complex structure and complicated treatment process [1, 2]. Meanwhile, it has harsh working conditions, high running speed, complicated force condition, and have to bear large torque and periodic impact load [3]. Under such complicated working conditions, fracture failure often occurs in the camshaft, resulting in heavy losses. Therefore, it is of great significance for the safe operation of the camshaft to study the fatigue crack growth mechanisms of the camshaft for nuclear emergency diesel engine.

Stress intensity factor is a physical quantity to judge whether the existing cracks are growing or not. In the analysis of fracture mechanics, stress intensity factor is the first criterion to predict fracture and the crack growth rate of components with initial crack defect [4, 5]. The stress intensity factor in crack growth not only reflects the stress singularity at the crack tip, but also reflects the relationship between...
stress and geometric defects, and it is the key parameter to characterize the stress and displacement fields at the crack tip [6]. Methods of obtaining stress intensity factors can be roughly divided into analytical method, numerical method and experimental method. Therefore, the finite element analysis model of camshaft for nuclear emergency diesel engine with initial crack defect is established based on ABAQUS software, and the effects of the direction, depth and location of the initial crack defect on the crack tip stress intensity factor are studied.

2. Finite element model
The research object of this paper is the camshaft for nuclear emergency diesel engine. The diesel engine is a six-cylinder large-scale diesel engine. Different cylinder blocks correspond to different parts of the camshaft. In view of the large model and repeatability of its structure, it will consume huge computer resources to solve the problem by establishing a complete model. Therefore, a local camshaft model is used to analyze the crack tip stress intensity factor, and the local model established in this paper and its boundary conditions are shown in Fig. 1.

![Figure 1. Local finite element analysis model of camshaft.](image1)

Stress intensity factor is a state quantity. The operation of camshaft for nuclear emergency diesel engine is an uninterrupted and continuous process. It is difficult to calculate the dynamic stress intensity factor of camshaft in the whole continuous operation period. Therefore, in this paper, the working condition discretization method is used to divide a period of camshaft operation into 24 corresponding static load conditions, and calculate the stress intensity factors of camshaft under the 24 static load conditions. The discretization of a load cycle is shown in Fig. 2.

![Figure 2. Discretization of camshaft load condition.](image2)

3. Results and discussion

3.1. Effects of crack direction on crack growth
In order to ensure that the crack depth is the same, the transverse crack (radial distribution along the camshaft) selected in this paper is a sector-ring crack with a depth of 5 mm. The longitudinal crack (axial distribution along the camshaft) selected in this paper is rectangular crack with a depth of 5 mm. In addition, in order to eliminate the interference of crack area factor, the initial crack area of prefabricated cracks in this paper is equal (98.8 mm²). The geometric parameters and schematic diagram of the crack are shown in Fig. 3. The stress intensity factors of two kinds of prefabricated crack models in a load cycle are calculated respectively. The variation of the stress intensity factors in a load cycle is shown in Fig. 4. From Fig. 4, it can be seen that the stress intensity factors of transverse and longitudinal cracks are quite different in a load cycle. The stress intensity factor of transverse crack fluctuates greatly, which provides a greater impetus for fatigue crack growth. However, the fluctuation of the stress intensity factor of longitudinal crack is smaller. Paris [7] considered that the stress field strength at the crack tip can be expressed by the stress intensity factor which is the real driving force of crack growth. Therefore, an estimation equation of the crack growth rate related to the stress intensity factor range is proposed [7]:
\[ \frac{da}{dN} = C(\Delta K)^m \]  

(1)

Where, \( \frac{da}{dN} \) is the crack growth rate, \( \Delta K \) is the stress intensity factor range, \( C \) and \( m \) are the material-related constant. Generally, the crack growth rate increases with the increase of the stress intensity factor range.

Figure 3. Schematic diagrams of (a) transverse and (b) longitudinal crack.

Figure 4. The results of transverse and longitudinal crack.

Figure 5. Schematic diagram of crack damage effect.

As can be seen from Fig. 5, when the stress intensity factor is positive, there is a tendency that the crack surface A and B are far away from each other, the crack opens continuously, and the crack tip is damaged and grows forward; when the stress intensity factor is negative, the crack surface A and B are close to each other and squeezed each other, and the crack tip area cannot be damaged, so the minimum stress intensity factor \( K_{\text{min}} \) is 0 when calculating the stress intensity factor range. The calculated results of stress intensity factors for transverse and longitudinal cracks are sorted out, as listed in Table 1. For transverse and longitudinal cracks with the same size, the stress intensity factor range of transverse crack...
is much larger than that of longitudinal crack (transverse crack: 687.78 MPa·mm$^{1/2}$ > longitudinal crack: 72.53 MPa·mm$^{1/2}$), implying that the crack growth rate of transverse crack is obviously larger than that of longitudinal crack. Therefore, the fatigue fracture risk of transverse crack on the camshaft journal is higher than that of longitudinal crack.

Table 1. The results of transverse and longitudinal cracks.

| Crack direction       | $K_{max}$ (MPa·mm$^{1/2}$) | $K_{min}$ (MPa·mm$^{1/2}$) | $\Delta K$ (MPa·mm$^{1/2}$) |
|-----------------------|----------------------------|-----------------------------|-----------------------------|
| Transverse crack      | 687.78                     | 0                           | 687.78                      |
| Longitudinal crack    | 72.53                      | 0                           | 72.53                       |

3.2. Effects of crack depth on crack growth

In order to investigate the effects of different depth cracks on crack growth, the stress intensity factors of transverse cracks are calculated when the crack depth ($D$) is 1 mm, 2 mm, 3 mm and 4 mm, respectively. The variation of stress intensity factors in a load cycle is shown in Fig. 6. From Fig. 6, the variation of stress intensity factor at crack tip is similar under different crack depths in a load cycle. With the increase of crack depth from 1 mm to 4 mm, the maximum stress intensity factor increases gradually from 410.84 MPa·mm$^{1/2}$ to 720.24 MPa·mm$^{1/2}$ by 75.3%. Referring to the above section, the minimum stress intensity factor $K_{min}$ is 0 when calculating the stress intensity factor range. The calculated results of stress intensity factors with different crack depth are sorted out, as listed in Table 2. As the crack depth increases from 1 mm to 4 mm, the stress intensity factor range increases from 410.84 MPa·mm$^{1/2}$ to 720.24 MPa·mm$^{1/2}$ by 75.3%. That is to say, with the increase of the crack depth, the crack growth rate of transverse crack increases gradually, and the fatigue fracture risk increases gradually. In addition, it can be obtained that the fatigue crack growth rate increases gradually during the process of surface crack growth to the internal part.

Table 2. The results under different crack depth.

| $D$ (mm) | 1      | 2      | 3      | 4      |
|---------|--------|--------|--------|--------|
| $K_{max}$ (MPa·mm$^{1/2}$) | 410.84 | 571.62 | 670.17 | 720.24 |
| $K_{min}$ (MPa·mm$^{1/2}$) | 0      | 0      | 0      | 0      |
| $\Delta K$ (MPa·mm$^{1/2}$) | 410.84 | 571.62 | 670.17 | 720.24 |

3.3. Effects of crack location on crack growth

The uneven distribution of stress field strength in different regions of camshaft results in the difference of crack risk in different positions of camshaft journal. In order to investigate the crack growth rules at
different positions on the camshaft journal, cracks are prefabricated at the distance of 1 mm to 17 mm from the camshaft journal to the cam end face (as shown in Fig. 7) for transverse crack. The stress intensity factors of cracks at different axial positions in a load cycle are calculated, and the maximum value is shown in Fig. 8. From Fig. 8, it can be seen that the maximum of the crack tip stress intensity factor initially increases and then decreases after reaching a maximum value as the crack moves away from the cam in a load cycle. The maximum of the crack tip stress intensity factor is 843.98 MPa·mm$^{-1/2}$ when the crack is 3 mm away from the end face of the cam. Similarly, the minimum of the crack tip stress intensity factor $K_{\text{min}}$ is 0 when calculating the stress intensity factor range. The calculated results of stress intensity factors for cracks at different locations are sorted out, as listed in Table 3. For transverse cracks, the stress intensity factor range initially increases and then decreases after reaching a maximum as the crack moves away from the cam. That is to say, with the crack moving away from the cam, the crack growth rate of transverse crack initially increases and then decreases after reaching a maximum, and the fatigue fracture risk initially increases and then decreases after reaching a maximum. When the crack is 3 mm away from the end face of the cam, the stress intensity factor range is the largest (843.98 MPa·mm$^{-1/2}$), which shows that the transverse crack growth rate in this position is the largest and the fatigue fracture risk is the highest.

![Figure 7. Schematic diagram of crack location.](image)

![Figure 8. The results of cracks at different axial positions.](image)

**Table 3. The results of cracks at different axial positions.**

| $D$ (mm) | 1   | 3   | 5   | 7   | 9   | 11  | 13  | 15  | 17  |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $K_{\text{max}}$ (MPa·mm$^{-1/2}$) | 687.78 | 843.98 | 669.30 | 657.42 | 552.64 | 505.06 | 487.53 | 482.72 | 474.63 |
| $K_{\text{min}}$ (MPa·mm$^{-1/2}$) | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| $\Delta K$ (MPa·mm$^{-1/2}$) | 687.78 | 843.98 | 669.30 | 657.42 | 552.64 | 505.06 | 487.53 | 482.72 | 474.63 |
4. Conclusion
In this paper, a finite element analysis model of camshaft for nuclear emergency diesel engine with initial crack defect is established based on ABAQUS finite element analysis software. The effects of initial crack defect parameters on crack tip stress intensity factor are studied. The following conclusions can be drawn:

(1) The stress intensity factors of transverse and longitudinal cracks are quite different in a load cycle. The stress intensity factors of transverse crack fluctuate greatly, and the stress intensity factor range is much larger than that of longitudinal crack, indicating that the fatigue fracture risk of transverse crack on the camshaft Journal is higher than that of longitudinal crack.

(2) With the increase of crack depth from 1 mm to 4 mm, the stress intensity factor range increases from 410.84 MPa·mm$^{1/2}$ to 720.24 MPa·mm$^{1/2}$ by 75.3%, indicating that the increase of initial crack depth can lead to a significant increase of the fatigue fracture risk.

(3) As the initial crack defect moves away from the cam, the maximum of the crack tip stress intensity factor initially increases and then decreases after reaching a maximum value. When the initial crack is 3 mm away from the end face of the cam, the crack tip stress intensity factor range is the largest (843.98 MPa·mm$^{1/2}$), indicating that the fatigue fracture risk of transverse crack at this position is the highest.

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