Safety assessment of Cracked K-joint Structure Based on Fracture Mechanics

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Abstract. The K-joint is the main bearing structure of lattice jib crane. During frequent operation of the crane, surface cracks often occur at its weld toe, and then continue to expand until failure. The safety of the weak structure K-joint of the crane jib can be evaluated by BS7910 failure assessment standard in order to improve its utilization. The finite element model of K-joint structure with cracks is established, and its mechanical properties is analyzed by ABAQUS software, the results show that the crack depth has a great influence on the bearing capacity of the structure compared with the crack length. It is assumed that the K-joint with the semi-elliptical surface crack under the action of the tension propagate stably under the condition that the c/a (ratio of short axis to long axis of ellipse) is about 0.3. The safety assessment of K-joint with different lengths crack is presented according to the 2A failure assessment diagram of BS7910, and the critical crack of K-joint under different loads can be obtained.

1. Introduction

Large tonnage cargo lifting machinery is widely used in engineering, and the bearing structure tends to produce fatigue damage due to fluctuating loads, which greatly influence the safety of the machinery. K-joint structure is an important bearing structure of lattice jib crane, and the cracks often occur in the weld toe, and then expand during the working process, which is a great threat to the safety of the crane. A safe and economical life assessment method for fatigue strength analysis can provide a reliable basis to determine whether it is necessary to repair or immediately stop operation or even to for scrap [1]. At present, there are two fatigue life assessment methods for welded structures: traditional fatigue analysis and fatigue analysis, the former combines with S-N curve and cumulative damage theory, many scholars [2-3] use this kind of method to assess the life of the engineering machinery. But the method is only suitable for the prediction of fatigue crack initiation life because it does not consider the initial imperfection of the structure. The latter method provides a greater reference value for the safety evaluation of crane based on fracture mechanics to consider the initial imperfection of structure. Literature [4-5] shows the use of fracture mechanics to evaluate the residual life of crane, but there is a lack of a widely used standard for the life assessment of the crane with defects.

In this paper, it is put forward the residual life assessment method and process of structure with crack by combining with fitness for purpose assessment and fatigue life assessment. Taken typical load bearing structure K-joint of 25t crawler crane as a model, the safety assessment of K-joint with different crack lengths is analyzed based on BS7910. And then, the critical crack lengths of K-joint under different stress amplitude are obtained. By the Paris formula in fracture mechanics, the residual life of the K-joint can be calculated from the initial crack to the critical crack. The proposed
assessment method and process can provide theoretical basis for the structural optimization design, crack detection and making maintenance cycle, and greatly reduce the cost of design and maintenance.

2. K-joint model with cracks
In this paper, the research object is the K-joint of 25t crawler crane in Figure.1, whose parameters are shown as table 1 and table 2. During the annual inspection, 20% main welding seam should be detected by magnetic particle inspection and their sizes and shape are inspected. K-joint is a typical bearing structure of crane, and its surface cracks tend to be initiated in the weld toe stress zone, then expand along the length direction and the depth direction. When the crack extends to the limit lengths, the structure will be suddenly unstable or even broken. According to the correlation statistics of the actual crack location and analysis of the paper [6], the crack is established to the stress concentration zone at weld toe named crown in the finite element analysis of K-joint in Figure.2. The surface crack at the toe of the K-joint structure can be simplified into a semi elliptical surface crack in Figure.3, where 3(a) is a 3D crack along the weld toe line, the length of which is \( 2a \), the depth of which is \( c \); 3(b) is the 2D projection of the 3D crack on the chord section, the length of which is \( 2a' \), the depth of which is \( c' \).

![Figure 1. Main view of the K-joint](image1)

![Figure 2. Weld toe profile](image2)

![Figure 3. (a) 3D crack surface (b) 2D crack surface](image3)

![Table 1. Material Properties.](table1)

| Property                  | Value  |
|---------------------------|--------|
| Yield strength (MPa)      | 345    |
| Tensile strength (MPa)    | 573    |
| Elongation rate (%)       | 23.45  |
| Impact energy, 20°C (J)   | 76     |
Table 2. Model Parameters.

| D  | d  | L  | l  | T  | t  | g  | $\theta_1$ | $\theta_2$ |
|----|----|----|----|----|----|----|-----------|-----------|
| (mm)| (mm)| (mm)| (mm)| (mm)| (mm)| (mm)| (°)       | (°)       |
| 76 | 38 | 600| 250| 6  | 4  | 30 | 60        | 60        |

It is necessary to use the FEM to do mechanics analysis of K-joint in order to obtain the evaluation parameters for its safety assessment. The ABAQUS is one kind of commercial finite element software, and it can well handle the crack problem. In the software, the linear elastic analysis and elastic-plastic analysis can be provided for finite element calculation. In the linear elastic analysis, the structure is considered elastic material, and the parameter stress intensity factor $K$ representing brittle fracture of structure can be obtained. In the elastic-plastic analysis, the true stress-strain data of the material needs to be input into the software, the structure is considered plastic material, and the parameter plastic collapse load $P_c$ representing plastic damage bearing capacity of structure can be obtained.

According to above-mentioned crack location, the crack tip is established at the corresponding position in the software. The precision of finite element calculation is determined by the mesh generation around the crack tip. In this paper, the high order singular element that degenerate hexahedral element is used to simulate the displacement singularity at the crack tip, hexahedral element to simulate 1/4 node prism element outside near the crack tip, and the four pyramid element and tetrahedral element can be used to simulate the crack tip and crack tip away from the transition region, and hexahedral element to simulate area away from the crack tip. In the linear elastic analysis, the strain singularity should be $1/r^{1/2}$ at the crack tip ($r$ is the distance from the crack tip to near location). In the elastic-plastic analysis, the plastic zone is formed at the crack tip, the strain singularity should be $1/r$. The crack tip singularity can be well simulated by the corresponding degradation treatment of the crack tip element, and the evaluation parameters such as stress intensity factor $K$ can be obtained accurately.

The finite element model of K-joint with crack is established according to above-mentioned geometric parameters as shown in Figure.4. In the process of the crawler crane loading and unloading, the tension acting on the auxiliary member plays a decisive role to cause the crack propagation. Therefore, in the finite element model, the loading and boundary condition are showed in Figure.4(a), where $P_a$ is the tension acting on one auxiliary member and the six degrees of freedom are all restricted in end face of two chords and another auxiliary member.
3. BS7910 standard

BS7910 standard [7] is a quantitative evaluation of the ability to satisfy the design function on the basis of ensuring the safety of the defective structure. It is based on the evaluation method of fracture mechanics, and plays a complementary role to the traditional quality control standards. It has brought significant economic benefits in the field of pressure vessels and oil pipelines. The failure assessment diagram (FAD) in Figure 5 considers both failure modes of plastic failure and brittle fracture, and the transverse axis parameter $L_r$ reflects the plastic damage performance of structure, the vertical axis parameter $K_r$ represents the brittle fracture performance of structure. With the increase of the load or crack length, the loading curve is close to the failure assessment curve (FAC), and the point of intersection between the two curves is called the critical point. The load or crack size before this critical point is considered to be safe, after which the load or crack size is considered to be not acceptable.

The BS7910 standard contains three levels of evaluation, with the increase in the level of assessment, assessment accuracy will increase, but the data will be increased. The three evaluation levels are as follows:

- The first level is a simple evaluation method, divided into 1A and 1B two kinds of assessment methods. In 1A level, the horizontal axis and vertical axis are limit fixed point in FAD. In 1B level, it is based on the empirical formula calculation of failure assessment. The first level
evaluation criterion is simple and conservative, and it can be used as a primary criterion when there are only limited material data or applied stress.

- The second level is the most widely evaluation method, divided into 2A and 2B two kinds of assessment methods. Each method has its own failure curve equations and cut-off lines. The 2A level does not need the material stress-strain data, the 2B level needs the true stress and strain data of the material to construct the failure curve, and the second level evaluation criterion can be taken into account for the structure of the medium and low toughness.

- The third level evaluation is suitable for ductile materials, and considers the use of this method if the material is high strain hardening index or the need for analysis of the crack stable tearing fracture. It divided into 3A, 3B, 3C three kinds of assessment methods, 3A and 3B is the promotion of 2A and 2B, 3C is an assessment level for the structure with specific materials and specific geometry. The third level evaluation criterion is suitable for high toughness and high strength structure with cracks.

Although the BS7910 provides a higher level of safety assessment, the higher the accuracy of the assessment, but more complex assessment process and more structural parameters are required in a higher level of assessment. The K-joint structure is regarded as research object in this paper, according to its structure and material properties, it is recommended to use more economical and conservative 2A level failure assessment in engineering practice. The failure curve of 2A level is represented by an equation:

$$K_e = \left(1 - 0.14L_c\right)\left[0.3 + 0.7\exp(-0.65L_c)\right]$$

(1)

Where $L_c = P_a / P_{pl}$, $P_a$ is applied load, $P_{pl}$ is plastic collapse load; in linear elastic analysis, $K_e = K_i / K_{mat}$, $K_i$ is stress intensity factor, $K_{mat}$ is fracture toughness of steel, according to the formula provided by BS7910, the value of $K_{mat}$ is 3037.7 MPa-mm$^{1/2}$.

4. Mechanical analysis of K-joint structure with cracks

4.1. Fracture strength analysis

The surface crack of K-joint structure often occur near the top of the chord, and the crack can extend along the direction of length and depth at the same time when the structure is subjected to fluctuating load. In the ABAQUS software, the surface load of 100MPa, 150MPa and 200MPa are applied in K-joint respectively in linear elastic analysis. At present, the finite element software can’t solve the stress intensity factor of the dynamic crack. In this paper, the crack propagation process is simulated by
extending the 0.5mm solution in the direction of crack length and depth. The variation of the stress intensity factor of the initial crack at \( c = 3 \) mm and \( 2a = 20 \) mm in the length direction and depth direction is showed in Figure.6. It can be seen that under the same load, the stress intensity factor will increase with the crack growth, and the influence of the stress intensity factor on the crack depth direction is larger than the length direction.

4.2. Bearing capacity analysis
In practice, the plastic deformation often occurs near the crack region of K-joint, and the plastic damage will accumulate with the increase of load amplitude. It is necessary to conduct elastic-plastic analysis to obtain the plastic bearing capacity of the K-joint structure for safety assessment. When the load on the component or structure made of ideal elastic-plastic material reaches a certain value, even if the load is not increased, the plastic deformation on them will continue to increase, this state is called the collapse state, and the corresponding load is called the plastic collapse load. The plastic collapse load can express the bearing capacity of structural plastic damage. The load-strain curves of the welded joint of K-joint at different loads were fitted with the help of ABAQUS software of the K-joint elastic-plastic finite element analysis, and the plastic collapse load is obtained by using two elastic slope criterion(\( \tan \alpha = 2 \tan \theta \)) [6] in Figure.7. According to the above method, the plastic collapse load of K-joint structure without crack can be obtained for 313MPa.

![Load-strain curve](image)

**Figure 7.** Method to acquire plastic collapse load

![Load-strain curve](image)

**Figure 8.** Plastic collapse load in crack propagation
The semi-elliptical crack expansion in 0.3 short axis ratio \( \frac{c}{a} = 0.3 \) of plastic collapse load change of K-joint is showed in Figure 8. The horizontal axis represents the crack length is \( 2a \), the vertical axis represents the K-joint’s plastic collapse load under different crack length. With the expansion of the crack, the structural defects are more obvious, and the plastic bearing capacity of K-joint structure decrease more obviously. When the crack length is extended to 40mm, the surface crack penetrates the chord wall, the plastic collapse load of the K-joint decline significantly, namely the K-joint structure plastic bearing capacity decrease rapidly. As a result, the penetration crack has a great influence on the bearing capacity of the structure.

5. Critical crack prediction of K-joint with cracks

When a crane works a period of time, surface crack can initiate on the surface of K-joint, as the load cycle, the crack can be extended to the crack depth and the length direction at the same time. When the crack penetrates the wall thickness, the crack can continue to expand steadily along the length direction, and the crack can be considered penetrating crack. When the crack length is extended to a critical value, the structure will accelerate the expansion, and soon failure or even fracture. It is assumed that the K-joint with the semi-elliptical surface crack under the action of the tension will propagate stably under the condition that the \( c/a \) is about 0.3.

In this paper, the failure of K-joint with different cracks is evaluated by 2A level provided by BS7910, and the critical crack length of K-joint under different loads can be obtained [8]. In this paper, the safety of K-joint under different loads is evaluated through increasing crack length under short axis ratio of 0.3 in the propagation path. At \( a \) is 20mm, the crack penetrates the chord, and then the extended crack can be simplified as a penetrating crack. The stress intensity factor of the K-joints in the corresponding load is obtained by using the linear elastic analysis of finite element software ABAQUS, and the safety assessment point of K-joint with different crack is obtained in FAD using the above formula. The K-joint with growing crack safety assessment diagram is shown in Figure 9. The intersection point of the crack propagation path curve and FAC is the critical crack assessment point of the K-joint under the load. The crack size corresponding to this point is named critical crack. With the increase of the applied load, the evaluation point will be closer to the failure assessment curve. When the crack penetrates the chord, the safety of the structure will decrease obviously. The critical crack length \( 2a_c \) of the K-joint structure under different loads is showed in Table 3.
6. Conclusions
The stress intensity factor of crack front line node can be computed by using the finite element software ABAQUS mechanical analysis of K-joint with cracks, and the plastic collapse load of K-joint with cracks can be obtained with two elastic slope criterion. With cracks extension, the mechanical strength of the K-joint structure decreases. The result shows that the crack depth has a great influence on the bearing capacity of the K-joint structure by comparing the mechanical properties of the crack propagation along depth and length direction and should avoid crack propagation along depth direction in practical engineering. The critical crack length of K-joint with cracks under different loads can be obtained based on the 2A level evaluation provided by BS7910 and it can provide a theoretical basis for the safe use of K-joint structure.

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Table 3 Critical crack size under different loads

| $P_a$ (MPa) | 100  | 150  | 200  |
|-------------|------|------|------|
| $2a_c$ (mm) | 54.8 | 43.4 | 36.7 |

![Figure 9](image-url) (a) Safety assessment under 100MPa (b) Safety assessment under 150MPa (c) Safety assessment under 200MPa
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