Journal of Physics: Conference Series

**PAPER** • **OPEN ACCESS**

# Fatigue reliability analysis of bridge crane metal structure considering maintenance

To cite this article: Yanchao Zhang *et al* 2022 *J. Phys.: Conf. Ser.* **2383** 012060

# Fatigue reliability analysis of bridge crane metal structure considering maintenance

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**Abstract—**Periodic inspection and maintenance of cracks have great influence on the reliability and safety of metal structures of bridge cranes. However, the influence of maintenance factors on the fatigue reliability of in-service bridge cranes is rarely considered at present. Taking a metal structure of a certain type bridge crane as an example, this paper establishes the limit state equation according to the residual strength of the structure. Considering the reduction of section modulus by fatigue cracks, the influence of periodic inspection and maintenance is quantitatively analyzed. The fatigue reliability of metal structure of bridge crane is analyzed and calculated by using MATLAB program. The results show that the fatigue damage will lead to the continuous decrease of reliability, and the fatigue reliability of metal structure can be restored to a certain extent by considering maintenance, which delays the decrease of reliability.

## 1. Introduction

Bridge cranes have harsh working environment and great accident hazards. As the main part of bridge crane, metal structure bears almost all the loads. Once a fault occurs, it may cause significant economic damage and serious consequences. Therefore, the safety evaluation and reliability analysis of bridge cranes have more and more important practical significance.

Some scholars have studied the fatigue reliability analysis of metal structure. In view of the randomness of the parameters of fatigue life, relevant scholars used methods such as Monte Carlo method to carry out simulation estimation of fatigue reliability [1-3]. Zhang established a delay time model based on RCM for the bridge crane by using the equipment's long-term working fault record data, and calculated the optimal maintenance period[4]. Wang established the fatigue reliability analysis model of bridge crane metal structure under constant amplitude load and variable amplitude load[5]. Cao proposed a fatigue reliability evaluation method that divides the metal structure into lattice calculation for the multi-crack phenomenon of bridge cranes[6]. Wei analyzed the fatigue reliability of metal structure and gave the minimum reliable reference value of weld bead height[7]. Wang calculated the time-variant reliability by using the simulation data of fatigue crack propagation of metal structure[8].

Previous scholars have done many researches on fatigue reliability of metal structure of bridge crane. However, the effect of repair on fatigue reliability is rarely considered. In fact, the crane needs to be regularly inspected during service. Once it is found that the metal structure is seriously damaged, it needs to be repaired. And the reliability will be improved. Thus, considering the influence of maintenance factors can be more realistic. In view of the above situation, this paper established the fatigue reliability model based on the fracture mechanics theory, and gave the fatigue reliability analysis steps of metal structure based on maintenance by quantitatively analyzing the influence of maintenance factors. Finally, the 100t bridge crane was taken as an example to analyze and calculate to verify the feasibility and applicability of the method.

## 2. Variation analysis of cross section

The stress of metal structure is related to external load and modulus of section. The modulus of the section is related to the size and position of each plate in the section. This paper assumes that the position of each plate remains unchanged during the operation of the crane. The propagation of fatigue cracks will lead to the effective size of each plate decreases, so that the effective cross-sectional area decreases, and eventually lead to stress changes. Therefore, it is necessary to analyze the cross-section changes caused by fatigue crack propagation.

### *2.1. Crack length at any time*

Since it is assumed in this paper that the propagation of fatigue cracks will lead to the decrease of the effective size of the cross section, it is necessary to calculate the crack propagation length at any time when calculating the effective cross section at any time. According to the Paris formula, the rate of crack propagation is related to the range of stress intensity factors $\Delta K$ at the crack tip[9].

$$da / dN = C\left(\Delta K\right)^{m} \tag{1}$$

Where, $a$ is the length of the crack, $N$ is the number of stress cycles, $da/dN$ is a crack extension speed, $\Delta K$ is the stress intensity factor amplitude, $C$ and $m$ are the material constant.

$$\Delta K = K_{\max} - K_{\min} = Y\sigma\sqrt{\pi a} \tag{2}$$

Where, $Y$ is the geometric correction coefficient, $\sigma$ is the stress amplitude. Substitute the formula (2) for the calculation of the stress intensity factor amplitude into the formula (1), and after integration, the number of stress cycles experienced from the initial crack to the critical crack can be obtained, that is, the fatigue residual life of the metal structure.

$$N = \begin{cases} \dfrac{1}{C\left(Y\sigma\sqrt{\pi}\right)^{m}\left(0.5m-1\right)}\left(\dfrac{1}{a_0^{0.5m-1}} - \dfrac{1}{a_1^{0.5m-1}}\right) & m \neq 2 \\ \dfrac{1}{C\left(Y\sigma\sqrt{\pi}\right)^{2}}\ln\left(a_1/a_0\right) & m = 2 \end{cases} \tag{3}$$

Where, $a_0$ is the length of the initial crack, $a_1$ is the length of the critical crack. The critical crack length is calculated according to formula (4) [10].

$$a_1 = \frac{1}{\pi}\left(\frac{K_C}{Y\sigma_{\max}}\right)^{2} \tag{4}$$

Where, $K_C$ is the fracture toughness of the material, $\sigma_{\max}$ is the maximum stress. Assume that the average frequency of the number of stress cycles per year is $f$ , the time-dependent crack size can be obtained as follows.

$$a(t) = \left[a_0^{1-0.5m} + \left(1-0.5m\right)C\left(\sigma Y\sqrt{\pi}\right)^{m} ft\right]^{1/(1-0.5m)} \tag{5}$$

Where, $\sigma$ is the stress range, $Y$ is the geometric correction coefficient, $a_0$ is the initial crack length, $a(t)$ is the crack size at times t.

### *2.2. Variation of section height*

In this paper, it is assumed that the fatigue crack propagates on the web. Then the effective size of the web of the crane main girder will be correspondingly reduced with the increase of the crack length, which will affect the effective height of the section and lead to the change of the section size. This paper assumes that the initial height of the web and the height at time t are $h_0$ and $h(t)$ .Then the reduction of fatigue cracks to the member size can be expressed as formula (6)

$$h(t) = h_0 - a(t) \tag{6}$$

Where, $a(t)$ is the crack length at time t.

### 2.3. Variation of sectional modulus

It is assumed that the welding seam connecting the web and the lower cover plate on one side of the metal structure of the overhead crane produces fatigue cracks and propagates. According to the definition of the moment of inertia, the moment of inertia of the metal structure section of the bridge crane is equal to the sum of the moments of inertia of the upper and lower flange plates and the left and right web sections that make up the section to the centroid axis of the entire section. Then the moment of inertia $I_x(t)$ of the section at any time t is shown in formula (7)[11].

$$I_x(t) = \sum_{i=1}^{n} I_{x_i} == \sum_{i=1}^{n} \left( I_{x_{ci}} + a_i^2 b_i h_i(t) \right) \tag{7}$$

Where, $I_{x_i}$ is the inertial moment for each part, $a_i$ is the distance of the overall cross-sectional axis of the wheelbase of each part, $b_i$ is the length of the section of each part. Therefore, the amount of anti-bending section $W(t)$ can be obtained.

$$W(t) = \frac{I_x(t)}{y_{\max}} \tag{8}$$

Where, $y_{\max}$ is the distance from the farthest of the section to the neutral axis.

## 3. Fatigue Reliability model

### 3.1. Calculation of fatigue stress

According to the structural characteristics and stress analysis of metal structure of bridge crane, the normal stress of the fatigue dangerous point is calculated according to the formula (9) [12].

$$\sigma = 1.15\left( \frac{M_y}{W_x} + \frac{M_x}{W_y} \right) \tag{9}$$

Where, $\sigma$ is the normal stress of the fatigue risk point, $M_x$ and $M_y$ are the curved moment of $x$ and $y$ axis where the dangerous danger point is located, $W_x$ and $W_y$ are the anti-bending section coefficients of $x$ and $y$ axis of the dangerous point. The shear stress at the fatigue risk point of the metal structure is calculated according to formula (10) [11].

$$\tau = \frac{FS_x}{I_x \delta} \tag{10}$$

Where, $\tau$ is shear stress, $F$ is shear, $S_x$ is static moment, $I_x$ is inertia moment, $\delta$ is the thickness of the web. In the multiaxial complex stress state, fatigue cracks usually occur at the three-dimensional maximum stress, and the crack propagation direction is the vertical direction of the maximum tensile stress. Therefore, the normal stress and shear stress of the fatigue risk point should be converted into the first principal stress according to formula (11).

$$\sigma_1 = \frac{\sigma}{2} + \sqrt{\left( \frac{\sigma}{2} \right)^2 + \tau^2} \tag{11}$$

Where, $\sigma_1$ is the first principal stress, $\tau$ is shear stress, $\sigma$ is the normal stress. According to GB/T 36697-2018, the first principal stress of the fatigue danger point needs to be calculated respectively, and the point with the largest first principal stress is selected as the research object by comparison, and its first principal stress is recorded as the maximum stress $\sigma_{\max}$ [10].

### *3.2. Calculation of residual strength*

For heavy lifting machinery above 100 tons, fatigue failure is the most important and typical failure mode. The residual strength of the metal structure decreases continuously as the fatigue crack propagates. For the convenience of research, the correction factor is defined as the product of the combined configuration factor $\beta_J$ and the load redistribution factor $\beta_C$ . The combined configuration factor considers the influence of crack geometry and load conditions. The load redistribution factor reflects the effect that some internal forces are transferred to adjacent elements due to longer cracks in the structure[13]. The calculation formula of the allowable value of residual strength is shown in formula (12).

$$\frac{[\sigma]_{rs}\cdot\beta_C}{[\sigma]_n}=\begin{cases}1-(1-\eta)\left(\dfrac{a(t)}{a_y}\right)^{\mu} & \left(a(t)\le a_y\right)\\ \eta\left(\dfrac{a(t)}{a_y}\right)^{-0.5} & \left(a(t)>a_y\right)\end{cases} \tag{12}$$

Where, $\beta_C$ is the load redistribution factor, according to the reference[13], $\beta_C = 1.455$ is acceptable, $a(t)$ is the length of crack, $a_y$ is the length of transition crack, $[\sigma]_n$ is the reference stress, its calculation formula is as follows.

$$[\sigma]_n=\frac{\sigma_{ys}\cdot W_n}{W_g} \tag{13}$$

Where, $\sigma_{ys}$ is the yield strength, $W_n$ and $W_g$ are the bending modulus of the net area and gross area respectively. The transition crack length can be determined from formula (14).

$$a_y=\frac{1}{\eta^2\pi}\left(\frac{K_C}{\beta_J\cdot[\sigma]_n}\right)^2 \tag{14}$$

Where, $K_C$ is fracture toughness, $\eta$ is the damage parameter, $\beta_J$ is the combinatorial configurational factor, and according to the reference[13], $\eta = 0.558$ and $\beta_J = 0.77$ are acceptable.

### *3.3. Establishment of reliability model*

According to the characteristics of metal structure of bridge crane, the maximum stress at the dangerous point should be less than the residual strength to ensure the safe operation of the crane during service. Then the functional function of fatigue reliability analysis of metal structure of bridge crane can be shown as follows.

$$M=[\sigma]_{rs}-\sigma_{\max} \tag{15}$$

When $M > 0$ , it means that the metal structure is safe, when $M \le 0$ , it means that the metal structure fails. According to reference, both fatigue strength and stress follow normal distribution, and the first order second moment method can be used to calculate the reliability[14]. Its reliability index is shown below.

$$\beta=\frac{n-1}{\sqrt{n^2C_1^2+C_2^2}},n=\frac{[\sigma]_{rs}}{\sigma_{\max}} \tag{16}$$

Where, $n$ is safety factor, $C_1$ and $C_2$ are the coefficient of variation of $[\sigma]_{rs}$ and $\sigma_{\max}$ . When the parameters are determined, the reliability index of the metal structure can be calculated. Then the static strength failure probability of the structure can be found through the standard normal distribution table.

$$P_f=1-\Phi(\beta)=\Phi(-\beta) \tag{17}$$

Where, $P_f$ is the probability of failure, $\Phi(\cdot)$ is the standard normal cumulative distribution function.

### *3.4. Steps of reliability analysis considering periodic maintenance*

The detection accuracy of cracks is generally related to the detection method and the actual size of the cracks on the structure. Each detection technique theoretically has a crack detection threshold. If the crack length of the structure at the inspection time is greater than or equal to the crack detection threshold, the crack will be detected and maintained[15]. The detection process can be described by the following formula.

$$a(t) \ge a_c \tag{18}$$

Where, $a_c$ is crack detection threshold, $a(t)$ is the size of a crack during detection. The metal structure of bridge crane can be inspected and maintained quarterly or annually[16]. This paper assumes that the periodic inspection interval is 1 year, and once a crack is found to reach the detection threshold during the inspection, it is maintained to restore it to its initial size. However, the repair methods commonly used at present, such as crack tip stop holes, welded steel and bolt or riveting repair methods on the crack surface will cause secondary damage to the structure[17]. Therefore, on the other hand, it is assumed that each repair work will bring certain damage to the metal structure and reduce its residual strength. Its analysis steps considering periodic inspection and maintenance are shown in Figure 1.

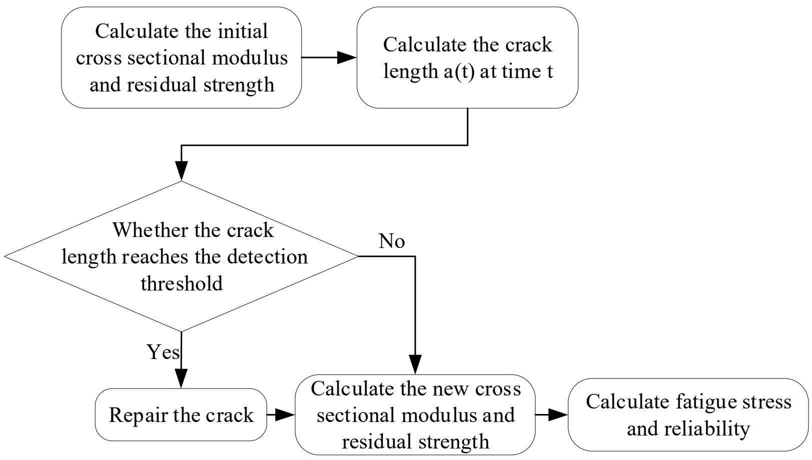


Fig.1 Reliability analysis steps considering periodic inspection and maintenance work

## 4. Case analysis

Take a certain type of 100t×20m bridge crane as an example. The height of the main girder web is 2150mm. The thickness of the upper and lower flange plates are both 20mm. The length of the upper and lower flange plates are both 2040mm. The thickness of the web is 10mm. The fatigue reliability of the sample is analyzed and calculated, and the fatigue reliability parameters before and after maintenance are analyzed and compared.

It is assumed that the fatigue crack growth rate parameter $C$ is $1.06\times10^{-13}$, and $m$ is 3, the geometric correction coefficient $Y$ of crack is 1.12, and the fracture toughness is 3529.1 $\sqrt{mm}$ [18]. It is assumed that the initial crack length is 1mm, the maximum stress is 147.64MPa, and the equivalent stress amplitude is 80Mpa[19]. It is assumed that the periodic inspection interval of the crane is 1 year and the crack detection threshold is 2.5mm, and the average frequency of the number of stress cycles is 44800.

Then according to formula (4) and formula (3), it can be obtained that the critical crack length is 145.07mm, and the fatigue life is 39.14 years. The variation curve of between propagation time and crack length is shown in Figure 2.

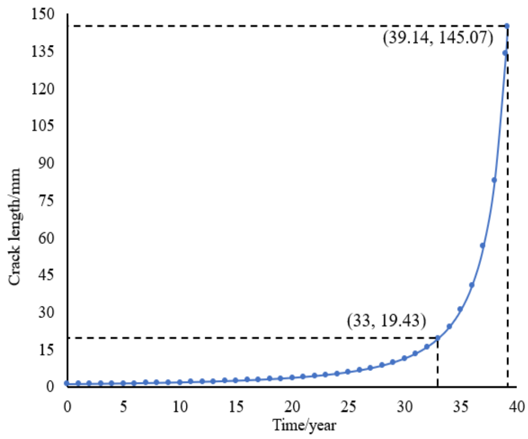


Fig.2 Relationship between propagation time and crack length

It can be seen from Fig.2 that the crack growth rate is relatively slow in the early period of crane service. When the crane is in the 33rd year and the crack length is about 19.43mm, the crack growth rate increases rapidly. Reaching the critical crack length of 145.07mm in the 39.14th year, the fatigue failure occurs. The crack length is closely related to the fatigue reliability, and the relationship is shown in Fig.3.

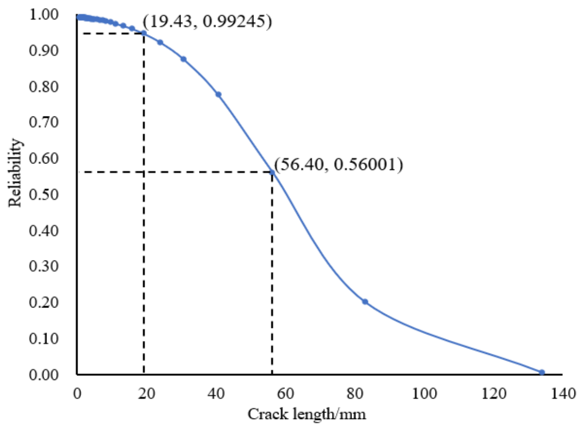


Fig.3 Relationship between crack length and reliability

It can be seen from the Fig.3 that the fatigue reliability decreases with the increase of the crack length. Especially when the crack length reaches 19.43mm in the 33rd year, the fatigue reliability decline rate increases rapidly, and the reliability at this time is 0.99245. In the 37th year, when the crack length is 56.40mm, the reliability is reduced to 0.56001. It decreased by 43.44%. Therefore, if the metal structure of bridge crane can take the corresponding preventive and maintenance measures in time before the rapid crack expansion, it can appropriately reduce the crack growth rate, and can effectively improve the fatigue reliability of the structure, so as to prolong the service life. Since the crack propagation length reaches the crack detection threshold before it can be repaired at the 16th year, before that, the reliability change considering the maintenance is the same as when the maintenance is not considered. Table 1 lists the reliability comparison results of the main years after the 16th year. $R_0$ represents the reliability without considering maintenance. $R_1$ represents the reliability considering maintenance.

Tab.1 Variation and comparison of fatigue reliability

| Time/ Year | $R_0$ | $R_1$ | Reliability improvement rate | Time/ Year | $R_0$ | $R_1$ | Reliability improvement rate |
|---|---|---|---|---|---|---|---|
| 16 | 0.98832 | 0.98883 | 0.05% | 27 | 0.98088 | 0.98483 | 0.40% |
| 17 | 0.98807 | 0.98862 | 0.06% | 28 | 0.97884 | 0.98349 | 0.48% |
| 18 | 0.98778 | 0.98839 | 0.06% | 29 | 0.97609 | 0.98213 | 0.62% |
| 19 | 0.98744 | 0.98815 | 0.07% | 30 | 0.97226 | 0.98161 | 0.96% |
| 20 | 0.98706 | 0.98788 | 0.08% | 31 | 0.96668 | 0.97904 | 1.28% |
| 21 | 0.98660 | 0.98760 | 0.10% | 32 | 0.95815 | 0.97762 | 2.04% |
| 22 | 0.98606 | 0.98727 | 0.12% | 33 | 0.94425 | 0.97282 | 3.03% |
| 23 | 0.98541 | 0.98689 | 0.15% | 34 | 0.91978 | 0.97117 | 5.59% |
| 24 | 0.98462 | 0.98646 | 0.19% | 35 | 0.87270 | 0.96681 | 10.79% |
| 25 | 0.98365 | 0.98679 | 0.32% | 36 | 0.77375 | 0.96027 | 24.19% |
| 26 | 0.98244 | 0.98592 | 0.35% | 37 | 0.56001 | 0.95071 | 69.77% |

As can be seen from Table 1, fatigue reliability is restored when periodic inspection and maintenance are taken into account. However, before the 33rd year of service, the recovery effect is not very obvious, and the reliability of the them is not much different. The reliability improvement effect is most obvious in the later stage of service. In the 37th year, the reliability without maintenance is only 0.56001. After considering maintenance, the reliability is 0.95071, increasing by 69.76%.

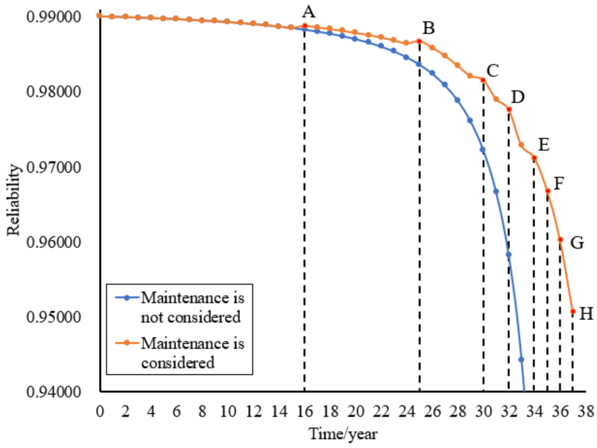


Fig.4 Comparison curve of fatigue reliability variation

Figure 4 is a schematic diagram showing the comparison of the fatigue reliability of metal structures considering maintenance and without considering maintenance factors. Points A to H in the figure indicate that the structure is maintained at that time. On the whole, the change trends of fatigue reliability when maintenance is considered and maintenance is not considered are roughly the same. They all change slowly at first and then decrease rapidly. From a local point of view, each maintenance work can improve the reliability to a certain extent, and delay the downward trend of reliability. However, in the later stages of service, this delaying effect is fading, and the downward trend of reliability is getting closer and closer to the trend without maintenance. From the perspective of maintenance intervals, the first maintenance time is 16 years, the second is 9 years, the third is 5 years, and the maintenance is required every 1 year after the 30th year. Starting from the 34th year, the crane needs to be serviced once a year. It can be seen that with the increase of service time, the maintenance interval decreases, while the number of maintenance increases.

Although maintenance work can delay the decline of reliability and prolong the life of the crane within a certain range, with the increase of maintenance times, especially in the later period of service, the effect of maintenance work on delaying the decline of reliability is getting smaller and smaller. And the increase of maintenance times means the stagnation of production and the increase of maintenance costs. Whether it needs to be maintained again needs to be considered from the perspective of production efficiency, safety and economy. If necessary, the crane should be scrapped at an appropriate time.

## 5. Conclusion

In this paper, the influence of periodic inspection and maintenance work on fatigue damage of bridge crane is considered quantitatively, and the fatigue reliability of a bridge crane is analyzed with an example. The following conclusions are drawn:

(1) In the early and middle service period of bridge crane, due to the slow crack propagation, whether the maintenance work is considered has little difference on the fatigue reliability. In the later period of service, periodic inspection and maintenance work can significantly improve the fatigue reliability of metal structures, and can delay the decreasing trend of reliability.

(2) With the increase of service time of bridge crane, the maintenance interval will decrease and the number of maintenance will increase. In the later period of service, whether to continue the maintenance work needs to be measured in terms of production efficiency, economy and safety.

(3) In this paper, it is assumed that the crack detection threshold is 2.5mm, and once the crack is detected, it will be maintained. If the crack detection threshold is smaller, that is, the crane is maintained within the smaller damage allowable range, the fatigue reliability recovery effect is better. However, this also means an increase in maintenance costs, which can be further studied and discussed in the follow-up.

## Acknowledgments

This work was financially supported by the Program of Science and Technology Planning of Administration of Market Supervision and Management of Jiangsu Province (KJ204108).

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