Crack growth life estimation for No. 17 coupler knuckle in China Datong-Qinhuangdao railway freight trains

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Abstract. In order to predict the fatigue life of couplers for heavy haul railway freight trains of the Datong-Qinhuangdao Railway in China, a model for calculating the crack initiation life of coupler knuckle is established based on the stress-strain relationship of coupler knuckle material and the theory of cumulative damage. Considering the local plastic effect of coupler structure, the stress dangerous part of coupler knuckle is defined by adopting the steady state method in the local stress-strain method. Based on the longitudinal coupler load spectrum of the 20,000-ton freight train under study and considering the randomness of coupler position, the mixed coupler load spectrum is obtained for the first time. The fatigue life of coupler knuckle of a particular heavy haul railway freight train is calculated. The life of coupler knuckle calculated by the method presented in this paper is consistent with the actual repair cycle of coupler, which can effectively minimize the impact of coupler crack fault on the train operation safety.

1. Introduction

As the most important coal transportation channel in China, the Datong-Qinhuangdao railway has about 35,000 freight trains, including 17,400 freight gondola trains with 80 t axle weight (C 80). The C 80 trains have been running on the Datong-Qinhuangdao railway since 2002 as special coal transport vehicles. The hook and release device of the C 80 trains uses the domestic product class E steel interlock type turning coupler and the fixed coupler (the NO. 16 coupler and NO. 17 coupler). Compared with 13A type coupler, the strength and fatigue resistance of couplers in C 80 train are improved greatly. It plays a key role in the safe operation of C 80 vehicle. But with the acceleration of the Datong-Qinhuangdao railway and the increase of heavy load, the longitudinal force of the train will be increased in the complex working conditions, which will make the operating conditions of the hook and release system worse. The longitudinal force beyond the limit of strength acting on the coupler may cause the coupler to break or crush and derail. No. 16 and No. 17 coupler cracks gradually increased, to a certain extent has constituted a driving safety hazard. In 2006, No. 16 and No. 17 coupler knuckle cracks used in C 80 train were found to be 17% and 64.5%, respectively, during the repair. In 2007, the proportion of coupler and the knuckle crack increased to 22.3% and 65.3% respectively. All the tongue cracks occurred on the inner surface of the tongue, the lower bend Angle and the middle and inner part, and the longest crack was up to 40 mm [1]. Therefore, it is very important to estimate the fatigue crack initiation life of type 17 coupler and the knuckle of the Datong-Qinhuangdao railway. In this paper, the steady state method of local stress strain method is used to estimate the fatigue life of NO. 17 type coupler and
the knuckle under the consideration of local plasticity.

2. Life calculation of the coupler knuckle with Local stress strain method

The coupler structure is generally in the elastic range during its service. However, due to the stress concentration in some dangerous parts, it is possible to enter the elasto-plastic state. At the same time, because the fatigue life is very sensitive to the local strain, a change of one-tenth of the local strain will lead to the difference of several times of the fatigue life. Therefore, it is of great significance to accurately determine the local stress and strain. At this time, the nominal stress method can no longer meet the requirements of life estimation. Low cycle fatigue analysis of fatigue crack formation life should be carried out for these local dangerous parts under the influence of local plasticity. And this is the basic idea of local stress strain method to estimate the life of structures [2].

2.1. Determination of the fatigue dangerous part of the coupler knuckle

In this paper, the hook tongue was analyzed by finite element method to determine the fatigue dangerous part of the coupler knuckle.

As the coupler knuckle has a very irregular shape, so the local structures that do not affect the calculation results are simplified firstly. Then carried on the finite element analysis to the coupler knuckle. The isoparametric element (Solid 95) was used to construct the finite element mesh. Figure 1 is the finite element model of coupler knuckle. This FE model has 23,432 elements, and 41,301 nodes. The coupler knuckle can bear not only tensile load but also compression load in train operation. Therefore, the static strength analysis of the tongue can be divided into two working conditions of tension and compression, and the amplitude of the tensile and compressive loads are both 1000 kN.

![Figure 1. The FE model of coupler knuckle.](image1)

![Figure 2. Static strength calculation results of coupler knuckle of coupler.](image2)

The finite element analysis software ANSYS was used for finite element calculation. The results show that, the stress of the coupler knuckle is larger in the tensile condition. The larger stress appeared in the s-plane and the transition zone of the front end of the coupler knuckle. The maximum tensile resultant stress is 589.01 MPa. At compress condition, the pressure stress of this point is 396.839 MPa. The stress calculation results are shown in figure 2.

2.2. Determination of cyclic stress-strain and parameters of E grade steel

It can be seen from figure 3 that the stress-strain hysteretic loop of grade E steel is symmetrical in tension and pressure. In the tensile stress state, the double \( \Delta \varepsilon = \Delta \varepsilon \) curve data was fitted by the least square method. The parameters \( K' \) and \( n' \) [3] in the double \( \Delta \varepsilon = \Delta \varepsilon \) relation of grade E steel can be obtained. The fitting result is \( K' = 1043.4 \text{MPa} \) and \( n' = 0.2551 \). The relationship between the fitting curve and
the actual experimental data of grade E steel which has been obtained through laboratory tests [4] has been shown in figure 4.

Figure 3. Stress-strain hysteresis loop of grade E steel.

Figure 4. Measured data of grade E steel and fitted stress-strain curve.

2.3. Determination of strain-life relationships and parameters

$\Delta \varepsilon - N$ curve is used to describe the relationship between strain and life. The Manson-Coffin formula was proposed for the symmetric strain cycle, while actual fatigue loads have mostly asymmetric strain cycles. In this paper, the linear correction method of Morrow elastic stress [5] was adopted, as follows:

$$E_a = \frac{\sigma_f - \sigma_m}{E} (2N)^b + \varepsilon^f (2N)^c$$  \hspace{1cm} (1)

In this equation, the local mean stress $\sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2}$ and the equivalent strain $E_a = \frac{\varepsilon_{\text{max}} - \varepsilon_{\text{min}}}{2}$.

As for the parameters $\sigma_f$, $\varepsilon_f$, b and c in the above equation, the empirical formula for estimation proposed by Manson is adopted for calculation:

$$b = -[0.083 + 0.166 \times \log(\frac{\sigma_f}{\sigma_b}) ]$$ \hspace{1cm} (2)

$$c=-0.52+0.25 \times \log \left( \varepsilon_f \right) - \frac{1}{3} \left[ 1-81.8 \times \left( \frac{\sigma_b}{E} \right) \left( \frac{\sigma_f}{\sigma_b} \right)^{0.179} \right]$$ \hspace{1cm} (3)

$$\sigma_f = \frac{9}{4} \times \sigma_b \times \left( \frac{\sigma_f}{\sigma_b} \right)^{0.9} \text{ and } \varepsilon_f = 0.5 \times \varepsilon_f^{0.6}$$ \hspace{1cm} (4)

In equations (2-4), $\sigma_b$ is the material tensile strength and $\varepsilon_f$ is the material ductile fracture strain.

Using data $\sigma_b$ as shown in table 1, provided by the plant depot [6]. Assume that $\sigma_f / \sigma_b = 0.9$, the value of parameters can be obtained.
Table 1. Mechanical properties of grade E steel of coupler knuckle.

| Performance index | $\sigma_b$ (MPa) | $\sigma_s$ (MPa) | $\delta$ (%) | $\psi$ (%) |
|-------------------|------------------|------------------|--------------|------------|
| Experimental value| 850              | 755              | 18           | 44         |
| AAR-M-2O1-84      | $\geq$830        | $\geq$690        | $\geq$14     | $\geq$30   |

2.4. Determination of strain-life relationships and parameters

Fatigue design requires the definition of casting defect morphological characteristics. In conventional stress-life design method, introduces fatigue notch coefficient $K_f$ to give a vague description of casting defects. And damage tolerance design based on fracture mechanics requires that defects of various shapes be equivalent to crack-like defects and quantified.

Moderate defects were most common, where $K_f = 1.5 \sim 2.0$. The largest defects are infrequent, where $K_f = 2.0 \sim 3.0$. Minor defects are unusual, where $K_f = 1.25$ (maximum) [7]. Considering the serious actual defects of the coupler, the fatigue strength reduction coefficients $K_f = 1.5, 1.6, 1.7, ..., 2.9, 3.0$ are used for calculation.

2.5. Selection of fatigue cumulative damage calculation method

Linear fatigue damage accumulation theory holds that the fatigue damage of materials at various stress levels is independent and can be linearly superimposed. The stresses are independence and non-interaction to each other. When the accumulated damage reaches the critical value, the fatigue failure occurs. The most representative theory of this kind is the Palmgren-Miner damage accumulation rule (the Miner theory, for short).

As a linear theory, the Miner theory does not consider the effect of loading sequence. However, a large number of experimental results show that the loading sequence has a great impact on the fatigue life of structural parts. Because most of the fatigue damage loads caused by engineering practice are random loads, the magnitude and sequence of loads are both random. Moreover, for random loads, the critical damage value of the test structure is approximately equal to 1. Therefore, the Miner theory will not bring much error in life calculation in this experiment.

3. Fatigue crack growth life estimation of coupler knuckle

3.1. Find the intersection of double $\Delta\sigma - \Delta\varepsilon$ curve and the Neuber hyperbola

The selected coefficients $K_f$ and the material parameters $K'$ and $n'$ of grade E steel are substituted into equation $\varepsilon_a = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K}\right)^\frac{1}{n}$, then simultaneous equations $\Delta\sigma \cdot \Delta\varepsilon = \frac{K_f^2 \Delta S^2}{E} = C$. The corresponding local stress and strain value of the hook tongue at each $K_f$ value can be calculated with the provided load spectrum. The load spectrum of coupler in Datong-Qinhuangdao railway freight trains have been given in the paper [8] and the length of every load spectrum of the coupler is 625 km. Considering the non-linearity of the formula and the non-integral form of the power exponent, when finding the intersection point, first discretize the double $\Delta\sigma - \Delta\varepsilon$ curve, it means that select a large number of specific points on the curve and replace the curve by a polyline formed by connecting these points successively. Meanwhile, the Neuber constant $C_f$ of the selected point can be calculated by the formula. On the other hand, the Neuber constant $C_f$ at each level can be obtained from the nominal stress spectrum obtained from the experimental data processing by using the formula.
\[ C = \Delta \sigma \cdot \Delta \varepsilon = \frac{K_f^2 \cdot \Delta S^2}{E} \]  

(5)

By comparison, we can get the \( i \) value, which satisfies the condition of \( C_i < C < C_{i+1} \). Then, the intersection can be figured out as follows:

\[ \Delta \varepsilon = \frac{-q + \sqrt{q^2 + 4pC}}{2p}, \Delta \sigma = \frac{C}{\Delta \varepsilon} \]  

(6)

Here \( p = \frac{\Delta \sigma_{i+1} - \Delta \sigma_i}{\Delta \varepsilon_{i+1} - \Delta \varepsilon_i} \) and \( q = \Delta \sigma_i - p \cdot \Delta \varepsilon_i \).

According to formula (6), the value of the stress and strain in the absolute coordinate system can be obtained, and the above expression can be rewritten as follows:

\[ \sigma_j = \sigma_{j+1} + \text{sign}(\Delta i_j) \cdot \Delta \sigma_j, \varepsilon_j = \varepsilon_{j+1} + \text{sign}(\Delta i_j) \cdot \Delta \varepsilon_j \]  

(7)

3.2. Fatigue life estimation

In the Morrow formula, substitute the elastic modulus \( E = 174000 \) MPa into the formula as follows:

\[ \varepsilon_a = \frac{(1929.6 - \sigma_m \cdot (2N)^{0.0754} + 0.1787 \cdot (2N)^{0.1321}}{E} \]  

(8)

The fatigue life of each peak valley point can be obtained, because of the complexity of the formula, considering the scope for different \( \varepsilon_a \), by the formula can be seen in figure 5 above the right end two parts, the contribution to the life value difference is very large, so in the calculation of different \( \varepsilon_a \) values by subsection calculation methods, avoid the right end of two coupling cause inconvenience to the solving process.

![Figure 5. \( \Delta \varepsilon - N \) curve.](image)

After the fatigue life of each level is calculated, the damage caused by each level can be calculated according to the cycle number of each level, and then the life of the structure can be estimated by damage accumulation according to the Miner rule. Matlab programming is used to solve the problem as the same.
Table 2. Life calculation of couplers when $K_f$=1.9.

| No. of Couplers | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Years Heavy     | 14.4| 2.7 | 0.9 | 3.7 | 5.9 | 20.3| 3   | 6.2 | 9.2 | 4.8 |
| Empty           | 3057| 468 | 2492| 704 | 1743| 295 | 1325| 682 | 733 | 955 |

The calculated life is measured in spectral blocks, one of which represents the operating mileage represented by the nominal stress spectrum. Here, each spectral block is measured for 625 km of train operation. At the same time, since trains of Datong-Qinhuangdao railway, run every two days, the heavy and empty trains account for half of each other, that is, the trains run every two days in the heavy state, so the Datong-Qinhuangdao railway trains run every year in the heavy state, the specific conversion results are shown in table 2.

Above of coupler in heavy loaded and empty state was calculated, and the life of a contrast table 2 of the calculation results can be seen that the life of the unloaded state coupling is far greater than the life of the full loaded state, and does not accord with the actual times of coupler cracks appear, so life for the coupler is calculated, the life of the unloaded state can be ignored.

As can be seen from table 2, the service life of the coupler is different when the coupler is in different positions of the train. In the actual running process of the train, the hook position of the train will change randomly once every time the train passes through marshalling, which is a random variable. Therefore, the life of each coupler calculated in table 2 cannot represent the general life of coupler of the Datong-Qinhuangdao railway.

Assuming that the hook position is equal likely to occur in each position in the train, a mixed load spectrum in the common sense was obtained by adding up all load spectrum of couplings, and then calculating its life to represent the life of the coupler in the Datong-Qinhuangdao railway freight trains. At this time, the mileage represented by the mixed load spectrum is 625 km×20=12500 km. Considering the serious actual defects of the coupler, the fatigue strength reduction coefficients $K_f=1.5, 1.6, 1.7....2.9, 3.0$ are used for calculation. The specific conversion results are shown in table 3:

Table 3. Life calculation of couplers with mixed load spectrum.

| $K_f$ | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 2   | 2.1 | 2.2 | 2.3 | 2.4 | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3   |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Life (year) | 6.3 | 5.6 | 4.1 | 3.7 | 2.6 | 1.7 | 1.5 | 1.3 | 1.3 | 1.2 | 1.0 | 1.0 | 0.8 | 0.8 | 0.7 |   |

At the Hudong vehicle depot, in the temporary maintenance of C 80 freight trains, five coupler knuckle crack faults were found in succession. Three of them are cracks occurred in operation after maintenance, and the operation time is less than one and a half years. From the situation that more than 60% cracks have appeared in the first repair (comprehensive inspection and repair) period after the new construction and loading of No. 16 and No. 17 coupler knuckles, it can be seen that most of them will produce cracks within 4 years after loading (two repair periods) [1]. The service life of the tongue calculated from the mixed load spectrum of the coupler calculated from table 3 is changed from 6.3 to 0.7 years when $K_f$ is 1.5-3.0, which is basically consistent with the maintenance results of the tongue of the depot.
As can be seen from the relationship between the service life of the coupler knuckle and $K_f$ in figure 6: The life of the coupler knuckle is greatly affected by the fatigue notch coefficient $K_f$. When $K_f$ is in the most common medium defect case, that is, $K_f = 1.5 \sim 2.0$, with the increase of $K_f$, the life of the coupler knuckle is reduced rapidly. When $K_f$ is in the condition of rare maximum defect, $K_f = 2.0 \sim 3.0$, with the increase of $K_f$, the life of the coupler knuckle decreases slowly.

4. Conclusion
- By using the local stress strain method, the fatigue crack life is calculated considering the local plasticity.
- It can be seen from the life calculation results of 20 couplers that the life of the coupler in the unloaded state is longer than that of the full loaded state, and the contribution to the formation of coupler crack is too small to be considered.
- Considering each train after a marshalling, the coupler of train will occur randomly changes, so will all the coupling load spectrum addition to get the Datong–Qinhuangdao railway common sense hook tongue of the mixed load spectrum calculation to the life of a representative, this method is used to calculate the coupler knuckle correspond with actual coupler repair cycle life.
- The life of the coupler knuckle is greatly affected by the fatigue notch coefficient $K_f$. When $K_f$ is in the most common medium defect case, that is, $K_f = 1.5 \sim 2.0$, with the increase in $K_f$, the life of the coupler knuckle is reduced rapidly. When $K_f$ is in the condition of rare maximum defect, $K_f = 2.0 \sim 3.0$, with the increase of $K_f$, the life of the coupler knuckle decreases slowly.

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