Fatigue Strength and Fatigue Life Evaluation of National Cultural Relic Steel Bridges

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Abstract This paper is regard with material mechanics, fatigue and fracture properties of Lanzhou Yellow River Iron Bridge, which is an old metal bridges built about 100 years ago. An original steel angel cut off from Lanzhou Yellow River Iron Bridge was used to carry out series of tests including material properties, fracture toughness and fatigue strength of riveted joints. The results have shown that the strength of the old steel is relatively equal to A3 steel in the old code, and the ductile-brittle transition temperature is nearly -23°C，which means that the structure is unsafe in winter due to the cold climate conditions of Lanzhou city. The main regression parameters of the fatigue crack growth rate are $C=7.88\times10^{-12}$m/cycle and m=3. According to the test result, the fatigue strength of tensional plate specimens with new drilling hole is similar to the category 140 in the EUROCODE. Based on the tested result, the remaining fatigue life of Lanzhou Yellow River Iron Bridge was evaluated using S-N curve and fracture mechanics method. It can be concluded that two kinds of adverse loading situations should be restricted including people loading only on half of bridge, and truck load over 120kN.

Keywords national cultural relic steel bridges, fatigue strength, fracture toughness, fatigue crack growth rate, fatigue life

1. Introduction

Until now lots of riveted old steel bridges are still in service in many countries. In recent years, traffic load and speed on both existing railway and highway steel bridges have increased, which is much higher than those originally designed load. With the great increase of load number and magnitude, these riveted bridges may close to the end of their service life. However, the work for replacement of these old riveted bridges takes time. So capacity calculation, safety assessment and remaining fatigue life calculation are essential for these ageing bridges, which is helpful to decide whether to demolish or retrofit these bridges.

To evaluate fatigue resistance of old steel and establish fatigue categories for riveted connections, this paper conduct series of fatigue behavior tests for old riveted steel bridge for Lanzhou Yellow River Iron Bridge, which is a simple supported truss bridge over Yellow River originally built in 1909. During 100 year's service time, several repair and rehabilitation were conducted for Lanzhou Yellow River Iron Bridge, and nowadays Lanzhou Yellow River Iron Bridge is the historical cite in Lanzhou City. Material properties were studied for steel used in Lanzhou Yellow River Iron Bridge, which is fabricated more than 100 years ago. From Lanzhou Yellow River Iron Bridge, standard compact specimens are cut and fabricated for fatigue crack growth rate test, and fatigue test were also conducted for specimens with newly drilled hole. Based on the tested result, the remaining fatigue life of Lanzhou Yellow River Iron Bridge was evaluated.

2. Material Properties of Old Steel

Material property is studied initially for steel of old riveted bridge. For Lanzhou Yellow River Iron Bridge, tensile specimens and toughness specimens were cut from a demolished chord to conducted material tensile test and Charpy V notch test.

2.1. Tensile test

The tensile test was conducted according to metallic materials-Tensile testing at ambient temperature (GB228-2002) [1]. Three ratio samples with same dimensions were manufactured according to the requirements of Chinese GB2975-1998 [2]. The strains in longitudinal direction are measured by strain gages for calculating the material properties. After the test, the mechanical indexes were calculated, such as elastic modus (E), yield stress (σ_s), ultimate stress (σ_b) and elongation.

The tensile test results are listed in Table 1. It can be concluded that the strength of the old steel is roughly equal to A3 steel in the old code, but the yield-strength ratio, σ_s/σ_b, is equal to 0.629, which is slightly higher than A3 steel(0.486~0.579).

Table 1. Results of tensile test

E(GPa)	σs(MPa)	σb(MPa)	Elongation(%)	Cross section reduction(%)
194.3	275.7	438	29.1	63.77

2.2. Toughness test

According to Chinese test standard for metallic materials-Charpy notch impact test (GB/T229-1994) , Charpy V toughness tests were conducted at different temperatures ranging from -53°C to 10°C [3]. 25 Charpy V notch (CVN) standard specimens were cut from one third of steel angle leg and the notch of specimen was perpendicular to rolling direction. The dimension of CVN specimen is shown in Table 2.

Table 2. Dimension of CVN specimens (mm)

Thickness	Width	Length
10	10	55

Toughness test was conducted at eight different temperatures, including -53 ℃, -43 ℃, -32.5℃, -26 ℃, -23 ℃, -21 ℃, 0℃ and 10 ℃. After test, the impact toughness energy (A_{kv}) was recorded and the crystallinity percentage of fracture surface was measured for each specimen, shown in Figure 1. Learn from Figure 1, A_{kv} in upper region is 146J at 10℃, A_{kv} in lower region is 7J at -53℃, and A_{kv} drops apparently from -15℃ to -28℃. At -23℃, the crystallinity percentage of fracture surface is approximately 50%. It can be concluded from the result of Charpy-V tests, the temperature of ductile-brittle of old steel used in Lanzhou Yellow River Iron Bridge is nearly -23℃. And the transition is very sharp. When the temperature drops to -23℃, steel in Lanzhou Yellow River Iron Bridge will exhibit clear brittleness instantly. Learn from test results, steel in old bridge usually exhibits both low strength and low toughness. Thus, safety of the structure should be take care especially when temperature is low, even if considering the contribution of riveted member redundancy.

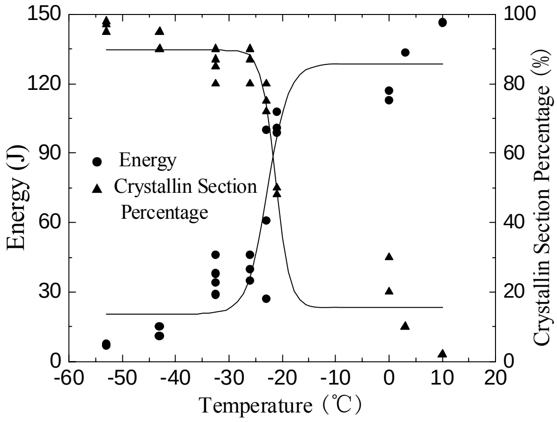

Figure 1. Toughness test result for old steel

3. Fatigue Crack Growth Rate Test of Old Steel

Fatigue crack growth rate (da/dN) tests were conducted for base steel in Lanzhou Yellow River Iron Bridge to determine its fatigue crack growth rate in region II according to requirement of ASTM E647-08 and Chinese GB/T 6398-2000 [4, 5]. da/dN tests were conducted for compact specimen [C(T)] with 11mm thick under load ratio of R=0.1, 0.5 and 0.8. The prefabricated crack for all the specimen is oriented perpendicular to the rolling direction of the steel plate (L-T). The dimension and specimen are shown in Figure 2 and Table 3.

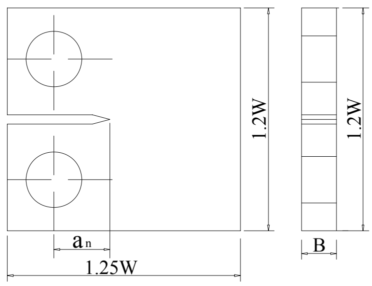

Figure 2. Compact specimen

Table 3. Specimens dimensions (mm)

B	1.25W	1.2W	a_n
11	62.5	60	12.5

After the test, the stress-intensity factor range ΔK_i under each crack length is calculated, according to Eq.1. The parameters are obtained including material constant m and C, and correlation coefficient. The da/dN test result for old steel in Lanzhou Yellow River Iron Bridge is shown in Figure 3. Learn from da/dN test result, with the increase of load ratio R, fatigue crack growth rate is increasing. Some researchers have conducted fatigue resistance behavior study for old steel. For example, the fatigue test result of Barson shows C=6.89×10^{-12} m/cycle and m=3, while Sedlacek found C=1.26×10^{-11} m/cycle and m=3 for old steel. The fatigue crack growth rate of Lanzhou Yellow River Iron Bridge is between the tested rate of Barson and Sedlacek, which serves test data for remaining fatigue life assessment of old steel bridge.

$$\Delta K = \frac{\Delta P}{B / W} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} \cdot (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \tag{1}$$

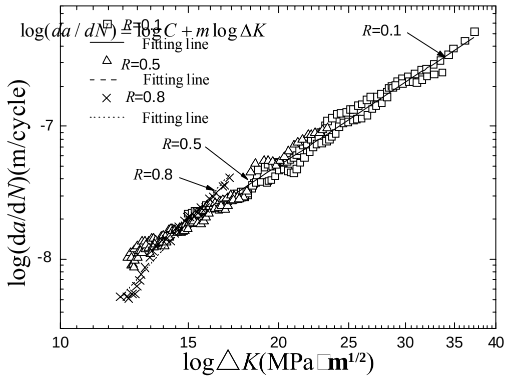

Figure 3. The da/dN~ΔK curve.

4. Fatigue Test for Drilled Specimen

3 fatigue specimens were cut from a chord of Lanzhou Yellow River Iron Bridge, and holds were newly drilled in the specimen. The dimension of fatigue specimens are shown in Figure 4 and Table 4. In order to observe the fatigue crack accurately, surface clean and polishing was conducted for each specimen. Strain gauge was located on the specimen before test. During testing procedure, the loading frequency is 15 Hz.

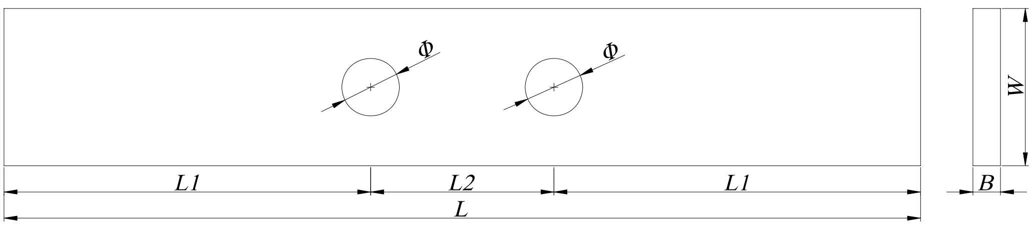

Figure 4. Dimension of fatigue specimen

Table 4. Dimension of fatigue specimen with drilled holes (mm)

Specimen	*B*	*W*	*Φ*	*L*	*L1*	*L2*
1	11	50	18	330	127	76
2	10.5	60	22	350	140	70
3	10.5	60	22	350	140	70

Fatigue test result is classified by fatigue details specified in AASHTO specification and Eurocode [6, 7]. Learning from Fig. 15 and 16, the fatigue detail of old steel with drilled hole is better than detail C in AASHTO specification and is higher than detail category 100 in Eurocode. The tested fatigue strength is greater than actual situation since two causes. Firstly, holes on specimens were newly drilled for fatigue test, avoiding fatigue crack initiate and corrosion during bridge service period over 100 years. Secondly, the surface of specimen was polished to observe and capture fatigue crack precisely, eliminating effect of surface defects.

5. Remaining Fatigue Life Evaluation

Based on the analysis of riveted steel bridge fatigue failure mechanism, the assessment model on the basis of S-N curve and fracture mechanics was applied to evaluate the remaining life of Lanzhou Yellow River Iron Bridge.

5.1. Evaluation methods

5.1.1. S-N curve and linear damage accumulation rule

Linear damage accumulation theory is based on fatigue damage D and assumes structural fatigue damage can be linearly accumulated if varying stresses spectrum was determined. The linear damage accumulation model described the sum of structure damage, D. The typical linear damage accumulation rule is Palmgren-Miner rule. It defined that D=1 indicated failure where D was the amount of damage degree in material. Sum of fatigue damage for all stress range levels is shown in Eq. 2. In Eq. 2, in which in each stress range level σ_{i}, the damage fraction D_{i} was linearly proportional to n_{i}, where n_{i} was the number of cycles at σ_{i} and D_{i} was the ratio of $n_{\mathrm{i}}/N_{\mathrm{i}}$. N_{i} is the total number of cycles that would cause failure under that stress range level. Loading sequence is not considered in Miner rules, but it has great affection when calculating fatigue life. The critical damage (D_{CR}) member is near 1 when failure occurs.

$$D = \sum_{i=1}^{n} D_i = \sum_{i=1}^{n} \frac{n_i}{N_i} \tag{2}$$

In this paper, detail category D in AASHTO is used during the evaluation, with reference to the riveted joint fatigue strength analysis of Lanzhou Yellow River Iron Bridge when it was built, and the fatigue tests results conducted nationally and internationally, as well as the fatigue test result of Lanzhou Yellow River Iron Bridge.

5.1.2. Fracture mechanics assessment mode

For riveted steel bridge, crack is usually propagating from edge of hole perpendicularly until member fracture. Two basic fracture mechanics modes are used in this paper. One is central crack tension (CCT) mode and another mode is double edge crack tension (DECT) mode.

Initial crack is assumed as $2a_{\mathrm{i}}=D+2\times$detected value, in which D is diameter of riveted hole. With propagation of fatigue crack, the net section may be yield under loading and fracture failure may be occurred. The critical crack length (a_{cr}) can be calculated by Eq. (3) and Eq. (4). In Eq. (3) and (4), W is the width of member, R_{el} is yield strength and $\sigma_{\max}$ is maximum sum of dead stress and live stress.

CCT：
$$a_N = W(1-\sigma_{\max}/R_{el}) \tag{3}$$

DECT:
$$a_N = W\sqrt{2.25+4(1-\sigma_{\max}/R_{el})} - 1.5W \tag{4}$$

If stress intensity factor at crack tip (K_{I}) is greater than fracture toughness of steel (K_{IC}), fracture may be occurred. In this case, critical crack length (a_{cr}) is calculated by Eq. (5), in which Y is geometrical amend factor.

$$a_{cr} = \left(K_{IC} \middle/ Y\sigma_{\max} \right)^2 \Big/ \pi \tag{5}$$

The calculated critical crack length by Eq. (5) should be less than the max length that member can observe (a_{max}). For steel angle, crack length should be no more than angle width. So, critical length is finally determined by Eq. (6).

$$a_f = \min(a_N, a_{cr}, a_{\max}) \tag{6}$$

A safety evaluation result will be obtained if is just considering $\triangle\sigma$ in Paris equation. However, threshold value relative to load ratio R ($R=\sigma_{min}/\sigma_{max}$) should be considered, shown in Eq. (7). When crack propagating from a_i to a_f, the remaining fatigue life is calculated by Eq. (8).

$$\frac{da}{dN} = \begin{cases} 0 & \Delta K \le \Delta K_{th} \\ C\left(\Delta K^m - \Delta K_{th}^m\right) & \Delta K > \Delta K_{th} \end{cases} \tag{7}$$

$$N = \int_{a_{\mathrm{i}}}^{a_{\mathrm{f}}} \frac{\mathrm{d}a}{C\left(\Delta K^m - \Delta K_{\mathrm{th}}^m\right)} \tag{8}$$

5.2. Evaluation results

Remaining fatigue life of Lanzhou Yellow River Iron Bridge is evaluated by the following steps. Firstly, finite element mode of Lanzhou Yellow River Iron Bridge is established and influence lines for main truss members and cross beam are acquired. Secondly, traffic load survey is conducted to determine fatigue load using in fatigue life evaluation. Thirdly, stress spectrums are acquired using flow counting method when applying fatigue load on influence lines of members considering traffic load impact factor. Fourthly, considering corrosion effect and fatigue propagation rules for riveted detail, fatigue life for Lanzhou Yellow River Iron Bridge is assessed.

By the method of S-N curve, the remaining fatigue life evaluation of main truss and deck plate in Lanzhou Yellow River Iron Bridge are all more than 100 years, except inclined truss member L3 loaded by people load. When fracture mechanics method is used, only hanger member L2 in main truss structure has remaining fatigue life more than 100 years under varieties of fatigue loads. In other members, inclined member L3 has the shortest remaining fatigue life (17 years) under people load. Learn from calculation result, all members in main truss structure have infinite remaining fatigue life under fatigue load of small cars, while they have shortest remaining fatigue life under people load and truck load. As a result, to ensure the safety of bridge structure, two kinds of adverse loading situations should be restricted including people loading only on half of bridge, and truck load over 120kN.

6. Conclusions

This paper focused on study of the actual fatigue remaining life, service safety, maintenance intervals and the ultimate bearing capacity of old historical steel bridges to preserve their high cultural value. It can be concluded that: (1) the strength of the old steel is relatively equal to A3 steel in the old code, and the ductile-brittle transition temperature is nearly -23 ℃, which means that the structure is unsafe in winter considering the cold climate of Lanzhou city; (2) The main regression parameters of the fatigue crack growth rate are $C=7.88\times10^{-12}$ and m=3 for base steel; (3)through fatigue test for specimen with drilled holes, the fatigue property of Zhongshan Steel

Bridge is superior to detail C in AASHTO and detail D in BS5400 and higher than detail 100 in Eurocode; (4) according to the fatigue remaining life evaluation of main truss and deck plate in Lanzhou Yellow River Iron Bridge by the S-N curve and fracture mechanics method, two kinds of adverse loading situations should be restricted including people loading only on half of bridge, and truck load over 120kN.

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