On Account of Fracture Mechanics to Analyze Basic Theory of Steel Bridge Fatigue

Ke TAN
School of Civil and Architectual Engineering, Chongqing Jiaotong University,Chongqing,400074,CHINA

Abstract: Steel bridges are all facing the fatigue problem now, the fatigue damage of steel bridge is caused due to the initiation and evolvement of micro-cracks under the impact of varying loads. The article expounds the fatigue crack damage mechanism, develop process and reasons of steel bridge also provides the method to calculate fatigue life of steel bridge by using fracture mechanics.

Keywords: Steel Bridge; Fracture Mechanics; Fatigue Crack; Fatigue Life

1. Introduction

With constant addition of the total weight of the operated vehicle and traffic, steel bridges bear alternating cycle stress loads of train and bus dynamic load, steel bridges are facing more and more fatigue problem which often lead accident because of fatigue cracks. In 1999,Chongqing CaiHong Bridge collapsed due to the fatigue damage that leads 55 people casualties.

Fatigue crack problem of steer bridge is always a focus of attention in engineering, fatigue design and fatigue life forecast become key technologies in steel bridge design and security assessment and also give some method and model to analyze steer bridge fatigue cracks.The article stands aspect of fracture mechanics which uses Center Crack Model CCT to analyze steel bridge fatigue cracks.

2. Fatigue cracks

2.1. Fatigue Damage Mechanism

Fatigue is the main factor to cause bridge damage and influence useful life of bridge. Most of steer structure use crafts about welding and riveting now, in these areas, bridge structure produce stress easily with the cyclic load, and then there are fatigue cracks in steer structure.

In the steer bridge structure, causing fatigue cracks due to deformation are divided two kinds: one is breathing fatigue of webs, when the length radio and thickness ratio of webs exceed a certain limit, in the inner surface loads which are greater than buckling load, webs will produce wider plane displacement which becomes bigger bending stress in the edge of welded plate. In the long time, bridge will produce fatigue cracks in the cyclic load which lead steer structure lose effect early. Another one dues to without consideration about interaction between horizontal and vertical members in bridge design, this phenomenon usually produce in gap of girder webs.

2.2. Develop Process of Fatigue Cracks

Due to varying loads, steer structure of bridge produce very small cracks and then develop macro cracks constantly. At the beginning of cracks appear stress concentration which leads members are in the Three-stretched state, the specimen's section appear serious weak, when the cyclic loads reach a certain cycle times, material are damaged and the steer structure produce fatigue fracture.

As to high strength material which have higher yield strength, bigger gap sensitivity and include many hard grains in the inner member, so the section dehiscence which include grain, direct access macro cracks development stage without micro stage. In the actually engineering, fatigue cracks cause member's damage usually leave apparent fracture where can see the cradle of fatigue cracks clearly and the whole process of crack development.

2.3. External Factors of Crack Appearance

The inner causes which cause fatigue damage are steer's material nature and part tensile stress's degree of concentration. External causes are cyclic feature and times of stress cycle. So, when you calculate steer bridge's fatigue life, you need to have a research on nature, short age, structure style, load feature and connector detail's stress distribution of steer bridge material.

3. Steer Bridge's Fatigue Analysis According to Fracture Mechanics

Fracture mechanics mainly research on the material performance of cracks sophisticated around and frontier. Basing on the liner fracture mechanics and crack expand rate, which is Paris, Paris's stress intensity factor method is in line with the best of a theory in all the method and experiment result.

The basic parameter of fracture analysis is stress intensity factor K:

$$K = y(a)s\,(p\,a)^{1/2} \qquad (1)$$

σ is load stress; y(a) is the limited geometry shape correction factor which is related to a; a is crack wide of section crack hole, or half wide of run through crack hole.

When the structure details with shortage and fatigue are known, using fracture mechanics to analyze fatigue crack problem of structure details. According to many experiment dota's fitting. In the double logaritheic coordination da/dN-ΔK curve as figure 1,Paris is only useful in the subcritical expand stage, it is a semiempirical formula about fatigue crack expand rate which is widely used in engineering.

$$\frac{da}{dN} = C(\Delta K)^m \qquad (2)$$

$\frac{da}{dN}$ is crack growth rate; a is crack size; N is stress cycle times; ΔK is stress intensity factor width of crack sophistication; C, m are fatigue crack expand parameter.

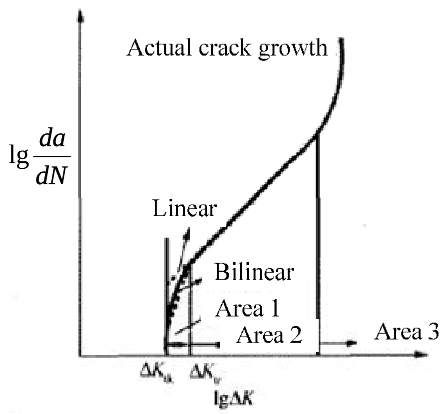

Figure 1. Fatigue crack growth rate-stress intensity factor factor amplitude curve

Stress intensity factor width is defined:

$$\Delta K = K_{\max} - K_{\min} = F(a,Y)s_{eq}\sqrt{p\,a} \qquad (3)$$

$K_{\max}$, $K_{\min}$ are stress intensity factor which is maximum or minimum; $F(a,Y)$ is the composite function which is considered member and crack shape.

Fatigue life of structure details are the time or cycle times of crack that initial cracks length a_0 expand to a_f . (3) is substituted to (2). Integration get fatigue life N:

$$N = \frac{1}{Cs_{eq}^{m}}\int_{a_0}^{a_f}\frac{da}{[F(a,Y)\sqrt{p\,a}]^m} \qquad (4)$$

a_f is fatigue crack size of anytime

3.1. Recogniting critical member

The starting point of evaluating steer bridge security is recogniting some member's damage that lead bridge in danger or collapse, these members are included: series rods, redundant member,minor member and deck.

3.2. Fracture mechanics model

Traditional design method makes great contribution to prevent fatigue damage, but it doesn't consider possible defects of actual member and reflect the law of crack expanding. Using fracture mechanics to research the expanding law of fatigue crack and building design calculation method on the basis that are the supplement and development to traditional fatigue analysis method.

There are two basic fracture mechanics modes to research steer bridge fatigue cracks: Center Crack CCT Model and Double Edge Crack DECT Model.

3.3. Calculation of critical crack

When the net section of robs yield, crack length can be calculated by the following formula:

CCT(Center Crack Model)

$$a_N = w(1 - s_{\max}/R_{el}) \qquad (5)$$

DECT(Double Edge Crack Model)

$$a_N = w\sqrt{2.25 + 4(1 - s_{\max}/R_{el})} - 1.5w \qquad (6)$$

a_N is crack length when the net section yield; σmax is the maximum of the dead load and the live load stress; Rel is yield intensity.

When tensile stress is perpendicular to the crack initiation direction, stress intensity factor is calculated by the following formula:

$$K = s\sqrt{p\,a}Y \qquad (7)$$

Y is geometry correction factor.

For the simple fracture mechanics mode ,it can be finded from stress intensity factor manual:

CCT

$$Y(\frac{a}{w}) = \frac{1.0 - 0.5\frac{a}{w} + 0.37(\frac{a}{w})^2 - 0.044(\frac{a}{w})^3}{\sqrt{1 - \frac{a}{w}}} \qquad (8)$$

DECT

$$Y(\frac{a}{w}) = \frac{1.122 - 0.561\frac{a}{w} - 0.015(\frac{a}{w})^2 + 0.091(\frac{a}{w})^3}{\sqrt{1 - \frac{a}{w}}} \qquad (9)$$

Because crack exist, robs may produce embrittlement, calculation of crack length can use correction formula that has considered elastoplastic method:

$$K = \frac{K}{K_{IC}} = \frac{1}{\sqrt{1 + \frac{L_R^2}{2}}}, K = s_{\max}Y\sqrt{p\,af} \qquad (10)$$

$$K_{IC} = 50MPa\sqrt{m}, L_R = \frac{s_n}{f_y} \qquad (11)$$

K_R is brittleness fracture parameter; K is stress intensity factor; K_{IC} is material fracture toughness; L_R is plastic fracture parameter; s_n is net section stress; f_y is material yield stress.

3.4. Life calculation of crack expanding

For the constant amplitude load and the situation that cracks are in the simple stress field, crack expanding can be calculated by Paris:

$$\frac{da}{dN} = C(\Delta K)^m$$

As the growth rate of crack is very slow in bridge structure, crack growth formula can use Paris that has corrected by Kesnil and Lukas

$$\frac{da}{dN} = \begin{cases} 0 & \Delta K_{eff} \le \Delta K_{eff,th} \\ C(\Delta K_{eff}^m - \Delta K_{eff,th}^m) & \Delta K_{eff} > \Delta K_{eff,th} \end{cases} \qquad (12)$$

Fatigue calculation method above only apply to the situation that is low stress, high cycle, low expanding rate and long life, if just consider Δσ in Paris, it will get a very partial safe result. In reality, there is a threshold number which is related to stress ratio R($R = K_{\max} / K_{\min}$) threshold ΔK_{th} . When $\Delta K < \Delta K_{th}$,Cracks can not expand, using crack growth rate as followed:

$$\frac{da}{dN} = \begin{cases} 0 & \Delta K \le \Delta K_{th} \\ C(\Delta K^m - \Delta K_{th}^m) & \Delta K > \Delta K_{th} \end{cases} \qquad (13)$$

$$\Delta K = \Delta s \sqrt{p a} Y$$

For the simple fracture mechanics model, if it can be finded from stress intensity factor manual:

CCT

$$Y(\frac{a}{w}) = \frac{1.0 - 0.5\frac{a}{w} + 0.37(\frac{a}{w})^2 - 0.044(\frac{a}{w})^3}{\sqrt{1 - \frac{a}{w}}} \qquad (14)$$

Threshold ΔK_{th} is:

$$\Delta K_{th}(R) = \begin{cases} 5.38 - 6.77R & R \le 0.5 \\ 2.0 & R > 0.5 \end{cases} \qquad (15)$$

Cracks are expanded from initial cracks a_0 to critical cracks a_{cr} ,crack expanding life of robs can be calculated by the following formula:

$$N = \int_{a_0}^{a_{cr}} \frac{da}{\left(\frac{da}{dN}\right)} \qquad (16)$$

A lot of experiment research show, stress amplitude components are under the luffing random load can be replaced by a equivalent constant stress amplitude like luffing stress amplitude that load on the components. Under the equivalent stress amplitude, fatigue life of components equal to the fatigue life of luffing stress amplitude. The article applies this method and fracture mechanics to fatigue life research.

Under the luffing fatigue load, fatigue cycle between different margin can affect each other. If the influence should be considered, the calculation of fatigue crack expanding is very complicated. Linear accumulation damage rule of Miner is commonly used, it ignores the influence between different margin fatigue cycle and calculates independently crack expanding amount of different margin cycle, the total expanding amount can be known by linear superposition rule.

Equivalent stress amplitude calculation formula:

$$\Delta s_e = \sqrt[3]{\frac{\sum n_i \Delta s_i^3}{\sum n_i}} \qquad (17)$$

Δs_e is equivalent stress amplitude; Δs_i is some stress amplitude; n_i is the corresponding cyclic times.

After equivalent stress amplitude is known, crack growth rate is:

$$\frac{da}{dN} = C(\Delta K_e)^m = C(Y \Delta s_e \sqrt{p a})^m \qquad (18)$$

By taking crack growth rate formula into formula(18) and integrating, it can get crack expanding life calculation formula:

$$N = \frac{1}{C(Y \Delta s_e \sqrt{p})^m (0.5m - 1)} (a_0^{1-0.5m} - a_{cr}^{1-0.5m}) \qquad (19)$$

4. Conclusion

1) The biggest feature of fracture mechanics is that judge whether initial crack size can be expanded in the given stress situation and determine fatigue life by cracks and shortage of steel bridge details.

2) Process of calculating steel bridge fatigue life by fracture mechanics: firstly, determining critical components and calculating maximum allowable crack size. Secondly, calculating crack growth time from initial crack assumed value to fracture and checking whether exceed normal detection interval. Finally, estimating surplus life of bridge.

3) There are many factors that affect fatigue crack, but the most important are material performance, local tensile stress, stress cycle feature and times.

4) Fatigue fracture process of steer is very complicated, we need to do further research in the future.

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