Crack Growth Analysis of Rail Transit Steel Bridge Components Based on Damage Tolerance

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Abstract. In recent years, the accidents caused by the instability and failure of the steel structure of the bridge occur frequently. Therefore, the research on high-performance steel members is one of the key directions of the development of Engineering Technology in the 21st century. In this paper, the damage tolerance evaluation method based on the finite element calculation of crack growth is used to analyze the fatigue of the load-bearing carbon fiber suspender with cracks in the operation stage, to correctly evaluate the remaining life and the remaining safety of the component, and to effectively handle grasp the status and disease development of the bridge, so we can take timely and targeted measures to ensure the safety of the bridge.

1. Introduction
With the advantages of fast speed, large volume, high punctuality and comfortable traveling experience, many mega cities have been adopting urban rail transit as main stream mass transportation solution. To ensure the fluent operation of metro network, better safe and reliable train control system is extremely needed. Steel bridges have been widely used for its higher integration and operation efficiency. The finite element method has been used in fracture mechanics because it is not limited by the geometry and load form of the cracked body. Paris fatigue growth model is a commonly used model in fracture mechanics to study the crack growth trend of damaged components, which has a good effect on the assessment of fatigue crack growth of steel bridge welding details$^{[1][6]}$. With the peak load, the numerical ratio of the maximum stress to the minimum stress and other factors being taken into account in the fracture problem, Walker$^{[3]}$ and Forman$^{[2]}$, etc. continue to explore the fatigue crack development trend of damaged members, and Paris formula is constantly revised$^{[6]}$.

In this work, based on the basic theory of steel member yield and linear elastic fracture mechanics, we analysed the crack growth of nano steel members of rail transit bridge, so as to mastered the state and disease development of nano steel members and take timely and targeted measures to ensure the safety of bridge and operation.

2. Materials and methods
2.1. Sample information
The characteristics of carbon fiber include: light weight, thin thickness (specific gravity is 1/4 of steel, thickness is about 0.1-0.2mm, weight per unit area is about 1/100 of steel plate); high-strength and high-efficiency tensile strength (about 10 times of steel plate, its specific gravity is only 1/4 of that of steel); it has good durability and corrosion resistance (resistant to acid, alkali, salt and atmospheric environment); it has a wide application range (applicable to beams, plates, columns, bridges, tunnels, chimneys and other buildings of various industrial and civil buildings). At the same time, the strength and hardness of the material increase with the decrease of the particle size due to the decrease of the grain size. Therefore, the physical and mechanical properties of steel members are improved with the addition of nano carbon fiber.

In the process of putting the bridge into use, steel and members will inevitably appear fatigue phenomenon, when the steel members appear visible cracks, it needs special attention. The suspender of the closure section of the suspension bridge is a very important force transmission component, which connects the suspension cable and the bridge, and transfers the load of the bridge deck to the suspension cable to ensure the force balance. Because of the addition of external loads such as vehicle flow, people flow and wind force, the suspender has complex stress, so it is necessary to calculate the yield strength of the steel members in the operation stage to prevent the members from yielding due to the excessive load.

We took a suspender in the closure section as the research object. The geometric dimension and stress of the model are shown in Fig1, where $a=0.005m$, $b=0.3m$, $L=8.5m$, and the thickness is 0.5m. The upper and lower ends respectively bear 64.7Mpa tensile force, and the shear force is 0. This paper mainly uses XFEM module in ABAQUS software to calculate as shown in Fig1.In order to obtain the whole process of crack growth, the stress curve of crack tip element and the shape of plastic zone at crack tip, ABAQUS is used to carry out the numerical simulation of plane mode I crack growth. The main steps include: modeling, adding parameters, setting boundary conditions and fracture calculation.In the finite element software, the material is regarded as an ideal linear elastic body, its elastic modulus (E) is 210GPa, its Poisson's ratio (V) is 0.3, and the failure criterion based on fracture mechanics is used. The specific parameters are set according to the BIM model information in the design stage. According to the properties of the material, the maximum principal stress is 84.4MPa. The critical energy release rate of components is set as 42200N/m, and the correlation coefficient is 1. For the suspender, the rigid body displacement needs to be constrained to ensure that the suspender will not move when the upper and lower sides receive the load. For cracks, the expansion type is set as expansion finite element, and the whole suspender is selected in the expansion area, and the expansion path is not limited.

![Fig1](image1.png)

Fig1. (a) Bar sketch. (b) Finite Element Model of Bar
2.2. Stress analysis
The phenomenon that the structure loses its normal working ability due to various reasons is called failure. According to a large number of experiments, the phenomena of brittle materials and plastic materials are quite different when they reach the limit.[5]

For plastic materials, when the normal stress loaded on the cross-section reaches the yield limit \( \sigma_0 \), the yield phenomenon will occur, and the yield member will produce larger plastic deformation. When the stress loaded on the cross-section reaches the strength limit \( \sigma_\varepsilon \), the test piece will break[10]; for brittle materials, when the normal stress loaded on the cross-section reaches the strength limit \( \sigma_\varepsilon \), the test piece will directly break, and the plastic deformation like the plastic material is missing the process. The plastic deformation of the specimen before fracture is small[11][4]. In engineering application, the components in working state are absolutely not allowed to break. Similarly, large plastic deformation is also not allowed for the components, because it will change the stability of the component system, and even seriously affect the normal work. Generally, the stress in case of material failure is defined as the ultimate stress of the material, which is expressed by \( [\sigma] \). For plastic materials, plastic deformation will lead to component failure, so yield stress is taken as its ultimate stress.

The ultimate stress of a material in tension or compression is the stress it is subjected to when it fails, which is represented by \( [\sigma] \). For steel, the yield stress is taken as the ultimate stress. Considering the difference between the mechanical model and the actual situation, it is necessary to set up an appropriate strength safety reserve factor. Therefore, for members of different materials, it is necessary to specify different maximum allowable working stress, which is called allowable stress, expressed by \( [\sigma] \).

\[
[\sigma] = \frac{\sigma_u}{n_s} \quad (1)
\]

Where \( n_s \) is the safety factor, usually 1.25-2.5.

According to the strength conditions, the maximum load that the component can bear is:

\[
F_{N_{\text{max}}} \leq [\sigma] A \quad (2)
\]

Where A is the component area.

Bending normal stress: When the ratio of span to height \( (L/h) \) is more than 5, the pure bending stress formula can be applied and can meet the accuracy required by engineering problems.

\[
\sigma_{\text{max}} = \frac{M_{\text{max}}}{W} \quad (3)
\]

Where \( M_{\text{max}} \) is the maximum bending moment of the member, \( W \) is the bending section coefficient of the member, \( W = \frac{I_z}{y_{\text{max}}} \), where \( I_z \) is the moment of inertia of the cross section facing the neutral axis, \( y_{\text{max}} \) is the longest distance between the cross section and the neutral axis.

Bending shear stress: In general, the maximum shear stress of the beam occurs on the neutral axis of the section where the maximum shear stress is located.

\[
\tau_{\text{max}} = \frac{F_{S_{\text{max}}}S_{Z_{\text{max}}}}{I_zb} \quad (4)
\]

Where \( S_{Z_{\text{max}}} \) is the clear distance between the section below the neutral axis and the neutral axis, \( \frac{S_{Z_{\text{max}}}}{I_z} \) can be found in the section steel table.

3. Results and discussion
In order to ensure the accuracy of the fitting of the analytical solution of the stress intensity factor, the coordinate origin of the stress field and the displacement field at the crack tip area of type I is taken as the crack tip, and the X axis is in the crack surface and perpendicular to the crack front. The upper and lower force of the component is f, and the crack length is a.
Stress field formula of components at crack tip is:

\[ f_x = \frac{K_f}{\sqrt{2\pi a}} \cos \theta \left[ 1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right] \]  
(5)

Displacement field formula:

\[ u = \frac{K_f}{4\mu} \sqrt{\frac{a}{2\pi}} \left[ (2k-1) \cos \frac{\theta}{2} - \cos \frac{3\theta}{2} \right] \]  
(6)

\[ k = \frac{3 - \nu}{1 + \nu} \]  
(7)

\[ \mu = \frac{E}{2(1+\nu)} \]  
(8)

Where \( K_f \) is the stress intensity factor under the current stress state, \( \mu \) is the shear modulus, \( K \) is the coefficient related to Poisson's ratio, and \( E \) is the young's modulus.

We can get: \( K \) is 2.077, shear modulus is 80769.23 MPa, and stress intensity factor is 6.42.

By means of dividing \( \theta \) from 0° to 360° into 100 parts, and calculating the stress value and displacement value corresponding to different angles, the change of stress and displacement is shown in the Fig3.

The maximum stress at the crack tip is 51.9 MPa, which is basically consistent with the maximum stress at the finite element crack. The maximum displacement of crack tip is \( 6.2 \times 10^{-3} \) m, which is the...
same as the finite element calculation. According to the verification of the maximum value of stress field and displacement field, the fitting of stress intensity factor meets the requirements.

4. Conclusions
According to the calculation in section 3, it can be seen that the component will not break in normal use. However, the analysis data source of above is based on the current operation situation. We can not effectively predict the future traffic and weather conditions, so the calculation results of fatigue life prediction can only be used for reference, and the crack propagation direction is more based on the reference significance. The cracking direction simulated by the finite element software is shown in Fig2.(b).

According to the trend of crack growth, the maintenance personnel can effectively reinforce the broken part to ensure the safety of the steel component in use. We should pay more attention to the same type of suspenders produced by the manufacturer to determine whether the fatigue phenomenon of suspenders is a case or an example. At the same time, on the one hand, the quality of the suspender shall be tested, on the other hand, the transportation, storage, splicing and installation of the suspender shall be paid attention to, and the root cause of the problem shall be found to ensure that the remedy is right. At the same time, the fault and maintenance structure of the suspender are input into the system, which is focused on in the process of bridge operation.

However, there are still some problems to be further studied and optimized in the process of practical application and popularization of this paper: for the fatigue analysis of steel members, the fracture mechanics currently used only simplifies the members into elastic or plastic bodies, and there is a gap between the research on the influencing factors and trends of crack growth and the actual engineering, so more influencing factors need to be included in the analysis results more valuable.

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