Fatigue Fracture Analysis and Design of Bridge Steel

Jing Yang, Tongwei He, min Xu, Cunwan Liao, Yu Yang

School of Civil Engineering and Architecture, Southwest Petroleum University, Chengdu, 610500, China

Abstract

Steel structure bridges are widely used in practical engineering, but bridge steel is susceptible to fatigue. In order to ensure safety, the fatigue phenomenon needs to be analyzed. This paper summarizes the characteristics of fatigue damage, analyzes the influencing factors of bridge steel fatigue damage, summarizes the research methods of bridge steel fatigue, and finally explores and analyzes the anti-fatigue design of steel structure bridges, providing a reference for the anti-fatigue design of bridge steel.

Keywords

Bridge steel; Fatigue fracture; Influencing factors; Anti - fatigue design.

1. Introduction

Under the dynamic load, the metal will gradually accumulate damage, crack and expand. After a finite cycle, it will eventually destroy,this phenomenon is called fatigue. Bridge steel structural members of steel bridges also have this kind of fatigue property.During the service process, the bridge carries the dynamic load of the vehicle, the changing crowd load and the wind load day after day, the steel bridge has the variable amplitude alternating stress effect on the rigid structure of each part, which will cause local permanent cumulative damage of the steel bridge, resulting in small fatigue cracks, with the continuous expansion of cyclic stress action, cracks will form, resulting in structural deterioration, thus affecting the safe use of the bridge.

Once the fatigue fracture of bridge steel occurs, it will often lead to serious accidents of bridges, causing heavy personnel and economic losses. On December 15, 1967, the Silver Bridge on the Ohio River collapsed completely in a short period of time, killing 46 people. The investigation of the debris pointed out that it was the fatigue fracture of a steel member on the bridge that caused the accident.On October 21, 1994, the Seongsu Bridge in Seoul, south Korea suddenly collapsed. Six vehicles, including a bus full of students and a car full of police, crashed into the Han River, killing 32 people and injuring 17 others. The investigation found that one of the reasons for the collapse was the fatigue of a section of metal in the middle of the bridge. With the continuous development of China's infrastructure construction, the traffic volume increases rapidly and the traffic load has become heavier. The fatigue problem of bridge steel is also more important and needs to be paid enough attention.

2. Fatigue Failure Characteristics of Bridge Steel

The fatigue fracture of bridge steel is mostly sudden and difficult to detect, and it is a brittle fracture.

2.1. The Fatigue Fracture Process Goes Through Three Main Stages

(1) The formation of fatigue microcracks. After thousands of cycles of stress, dislocation slip occurs in some crystalline grain of steel structures, forming a permanent slip band, resulting in stress deformation on the surface of the material and finally forming fatigue microcracks.

(2) fatigue micro crack growth. At this stage, the fatigue crack first grows along the plane of high shear stress, its growth rate is relatively slow and is a single slip. When the plastic

deformation at the front end of the fatigue crack becomes multiple slip or the growth of the fatigue crack is blocked by obstacles, the growth direction becomes perpendicular to the stress direction, and the growth rate is accelerated.

(3) final failure fracture. Fatigue microcracks gradually grow into macroscopic fatigue cracks. However, when the critical crack length is reached, a new small section composed of the material where no crack occurs will suddenly break down due to insufficient bearing capacity.

2.2. Fatigue Fracture Is Sudden

Fatigue fracture of bridge steel is characterized by sudden breakage after prolonged action. Fatigue occurs only after a long-term cumulative damage process under a low stress cycle where the nominal stress is below the yield limit. There is generally no noticeable macroscopic significant deformation before breaking, which will suddenly break. Moreover, under the action of alternating stress, fatigue failure may occur when the maximum stress of bridge steel members is less than the yield stress. Therefore, the yield stress or tensile strength of bridge steel cannot be used as an index of fatigue strength.

2.3. Fatigue Fracture Belongs to Brittle Fracture

There is no obvious deformation deformation before fatigue fracture, which is brittle fracture, but the fracture of fatigue fracture is different from the general brittle fracture, which can be clearly divided into two regions, dull smooth zone and bright rough zone.In the region where the fatigue crack is formed and developed, the surface of the fatigue crack is rubbed back and forth by the deformation of each cycle to obtain a surface similar to the honed polishing, which is a smooth region.In the final stage of fatigue failure, when the sample can not be subjected to the applied load and suddenly breaks, because there is no friction stage, the surface will have rough and irregular features, that is, the rough area, which is also called grain.Using an electron microscope to observe the smooth zone, you can see a series of mutually parallel fatigue fringes.

3. Research and Analysis on Influencing Factors of Bridge Steel Fatigue

The main factors affecting the fatigue of bridge steel are stress concentration, stress amplitude and stress cycle times.The formation of microscopic cracks and the stress concentration at the crack sites are prerequisites for fatigue fracture.

3.1. Effect of Stress Concentration

Fatigue is very sensitive to defects such as notches, weld defects and cracks. Stress concentration at the defect location accelerates the initiation and expansion of fatigue failure.In the welding part, due to the limitation of the welding process, it is easy to produce welding defects such as pores, incomplete fusion, slag inclusions or hot and cold cracks.These defects provide a large-scale crack source for fatigue, while stress concentration occurs, making the crack spread faster.As the crack develops gradually, the effective bearing area of the section decreases correspondingly, and the stress concentration phenomenon is also more serious, which further promotes the continued expansion of the crack.

Among the various weld defects of steel on the fatigue strength, the effect of the non-weld weld is the largest, followed by the slag, and the smallest is the void.The length of the steel slag inclusions has a great influence on the fatigue strength, but the number of inclusions is small.

The type of connection determines the geometry of the joint, so the different types of connections have different levels of stress concentration.The butt joint has a small stress concentration factor and its fatigue strength is higher than other joint forms.But there are also special cases, such as butt joints with permanent gaskets, which have much lower fatigue strength than ordinary butt joints because of the severe stress concentration at the gasket.T-joints and cross-links are widely used in welded steel structures, but due to the obvious change in cross-section of the transition section, the stress concentration of the two welds is greater than that of the butt joint, and the fatigue strength is lower than that of the butt joint.

3.2. Effect of Stress Amplitude

One of the main factors controlling fatigue is the stress amplitude.In the process of smelting, rolling, welding, hot-shaping, etc., due to the uneven thermal process, the residual tensile stress of the value close to (or equal to) the yield point will be generated in the weld zone.They are produced during the welding shrinkage process and change their actual stress state.This residual tensile stress is always involved in the cyclic stress process, superimposed or offset with the stress generated by the external load, which shifts the actual maximum or minimum stress.But no matter what form of cyclic stress spectrum, the difference between the maximum stress and the minimum stress can be used to express the stress amplitude.It can be seen that the fatigue strength of the welded structure is independent of the nominal maximum stress and is related to the stress amplitude.

The stress amplitude is usually used as the stress index of the fatigue resistance of the welded structure.By comparing the critical stress amplitude caused by fatigue failure under a certain number of cycles with the corresponding allowable stress amplitude, it can be judged whether the fatigue resistance requirement is met.For variable amplitude stress, equivalent conversion is required.

3.3. Effect of Cycle Times

Under different stress amplitudes, the number of stress cycles caused by fatigue failure of various components and connections is different. The greater the stress amplitude, the less the number of cycles,otherwise the more. When the stress amplitude is less than a certain value, fatigue failure will not occur even after an infinite number of cycles.The fatigue life of steel is the number of stress cycles experienced before fatigue failure.In order to get better fatigue strength, we can start from two aspects to improve the fatigue life.On the one hand, try to use steel with high finish and smooth transition in appearance. On the other hand, try to eliminate tensile stress and preset pressure stress.Hawker's technology perfectly combines these two aspects, while meeting the requirements of these two aspects, greatly improving the fatigue life.

4. Research Method of Fatigue Properties of Bridge Steel

In early engineering,traditional fatigue analysis methods based on S-N curves and Miner linear cumulative damage criteria are commonly used to evaluate the fatigue properties of bridge steels.With the further development of research level, the analysis method based on linear elastic fracture mechanics is now used to study the fatigue crack propagation law,and combined with modern non-destructive testing techniques,analyze the law of crack development and further strengthen the control of the safety of steel structure bridges.

In traditional strength theory,the initial defects of the material itself are generally ignored, and are considered to be isotropic homogeneous continuums.In practical engineering applications, under the influence of various uncertain factors,all kinds of initial defects are unavoidable in materials, and there is a gap between theoretical and theoretical assumptions, the actual strength of the component is much lower than the theoretical strength.Therefore, researchers began to study the mechanical state of cracked body, its characteristic parameters and the corresponding performance indicators of materials. Then in engineering, it is possible to theoretically calculate how much load a concrete cracked member can safely withstand, determine the tolerance of defects under load conditions,or predict the safe life of the component by calculating the rate of crack propagation,these are related research contents based on fracture mechanics.Fracture mechanics can be divided into two categories: linear elastic fracture mechanics and elastoplastic fracture mechanics,the difference is the size of the yield range near the crack tip.For the fatigue fracture of bridge steel, the yield area is small, so the linear elastic fracture mechanics is commonly used to study.

The crack propagation rate is usually used to analyze the fatigue crack growth process, is the rate of change of crack length with cycle times under the action of alternating stress,which is expressed as a function of the crack tip stress intensity factor .The empirical formula for quantitatively describing the crack propagation law is now widely used as the Paris formula:

$$da/dN = C \cdot (\Delta K) \cdot m$$

After the logarithmic change is:

$$\lg(da/dN) = \lg C + m \cdot \lg(\Delta K)$$

As can be seen in the double logarithmic coordinates, there is a linear relationship between the variables.The Paris formula is simple in form and easy to use, and is currently the most widely used.It is suitable for the crack steady expansion stage and the case where the stress is relatively small.

5. Research on Anti-Fatigue Design of Steel Structure Bridge

One of the main contents in the design of steel structure bridges is the anti-fatigue design.Anti-fatigue design is the fundamental guarantee for solving the hidden dangers caused by the fatigue of bridge steel.

5.1. Anti-Fatigue Design Method of Steel Structure Bridge

The general methods for anti-fatigue design of steel structure bridges include infinite life design, safe life design, and damage tolerance design.

Infinite life design ensures that the steel structure can be used safely for a long time under design stress, limits stress does not exceed the normal fatigue limit, ensures that the component will never break and has an infinite life.Use the constant horizontal portion of the S-N curve,for equal-amplitude cyclic stress, the working stress of the member is less than or equal to the equal-width fatigue limit,for variable amplitude cyclic stress, the maximum stress amplitude of the member is less than its equivalent equal amplitude fatigue limit.This design method usually fails to exert the potential of material bearing capacity, resulting in waste, and is not conducive to cost control.

Safe life design calculates the damage based on the lower limit of the fatigue curve and the upper limit of the fatigue load, there is no need to test the structure during the service life, also known as the limited life design.Safe life design ensures that the structure does not experience fatigue damage during a certain period of use, and allows the working stress of the component to exceed the fatigue limit. Using linear damage accumulation theory,estimating total fatigue damage,thus the safety life TS can be calculated. Finally, the design life TL is compared with the safety life TS.

Damage tolerance design monitors fatigue crack growth through one by one detection link, once the fatigue crack reaches a preset size, some components need to be repaired or replaced. The size of the preset size depends on whether the fatigue crack propagation will affect the safety performance of the structure in the remaining fatigue life. The damage tolerance design method can be used when the safe life design method cannot meet the economic requirements, or the construction details have high risk of cracking.

5.2. Problems to be Noted in Anti-Fatigue Design

Compared with other structures, the structural design of steel bridge should focus on optimizing the anti-overturning property of the bridge and ensuring the integrity of the welded steel structure.

The stability problem of steel structure bridges is the main problem in the process of construction design.Compared with other bridge structures such as wooden bridges, stone bridges, and concrete bridges, steel bridge materials are lighter in weight, stronger in strength and have higher use value, but because of this, its anti-overturn stability is often insufficient. In bridge design, especially for bridges with multiple lanes and small radius, as the radius of the continuous steel beam is relatively small, the span of the bridge is larger, It may result a large difference in the force of the inner and outer supports of the beam, so that the force of the beam is not uniform, which has a very adverse impact on the stability of the bridge, and even causes the overturning of the bridge. Therefore, in the anti-fatigue design of the bridge steel structure, the designer should design the eccentric force of the beam through reasonable and detailed calculation, ensures that the force points on the beam is evenly distributed in maximum extent, and avoids uneven force on the beam, so that the anti-overturning performance of the beam has an effective promotion.

Generally speaking,connections between steel members are bolted - through bolt, riveted - through rivet, and welded - through metal dissolution,different joint forms have great difference in stress, and the different stress action at the joint position will directly lead to the change of the mechanical performance of the bridge steel structure. In engineering construction, the quality problems caused by the uneven quality of the joints of the steel components often occur, and the fatigue is also very sensitive to the defects existing in the joints.Current technical means cannot completely eliminate welding stress,which will cause joint deformation and weaken the strength of the joint,it is difficult to meet the requirements of the integrity of the bridge steel structure. The defects of the joint may even cause cracks, which are prone to fatigue damage.Therefore, in the overall design of bridges, in order to ensure stability and even integrity, it is necessary to consider the design of welded joints. During the welding process, the constructor shall use the test of weldability to detect the joint, and pay attention to the relevant requirements of the welding test,control non-destructive testing and other related indicators to obtain their static and fatigue levels.According to the actual project conditions, choose the most suitable form to avoid joint deformation.In addition, important details of the welded joints of bridge steel structures should be designed in detail,eliminate the uneven force of the joint,effectively avoid the stress concentration phenomenon of the welded joint during service and the uneven local stress distribution at the joints of bridge steel structures,reduce the occurrence of fatigue.

References

[1] Yang Baocen. Research on the Realization and Application of Structural Dynamic Monitoring System for Long-span Bridges Under Construction [D]. Wuhan University,2010.

[2] Soon-Bok Lee. Fatigue failure of welded vertical members of a steel truss bridge[J]. Engineering Failure Analysis,1996,3(2).

[3] M. Gao,B.A. Sun,C.C. Yuan,J. Ma,W.H. Wang. Hidden order in the fracture surface morphology of metallic glasses[J]. Acta Materialia,2012,60(20).

[4] Li Yongdong, ed. Theory and applied fracture mechanics [M]. Beijing: Ordnance Industry Press. 2005.

[5] Qi Zhengneng, ed., Applied Fracture Mechanics [M]. Beijing: Beijing University of Aeronautics and Astronautics Press. 2012.

[6] Yan Wang,Yi Sun,Peng Lv,Hao Wang. Detection of line weld defects based on multiple thresholds and support vector machine[J]. NDT and E International,2008,41(7).

[7] E.M. Anawa,A.G. Olabi. Control of welding residual stress for dissimilar laser welded materials[J]. Journal of Materials Processing Tech.,2008,204(1).

[8] Duan Lan,Structural Behavior and Design Methology Study for High Performance Steel Bridge,Chang'an University,2012.

[9] Jiang Peng, Design of Anti-fatigue Design of Bridge Steel Structure, Building technology development, 44(12)(2017)115-116.

[10] Li Xin, Integral Joint Fatigue Analysis of Long-span Railway Steel Truss Bridges Based on Coupling Vibration of Vehicle-Bridge Systems, Southwest Jiaotong University, 2013.

[11] CHEN Wei- zhen, D.Kosteas, Study on Fatigue Design Methods for Steel Bridges, Bridge construction, (02)(2000)1-3.