Fatigue Stress Analysis of Key Nodes in Cable-girder Anchorage Zone of Long-span Cable-stayed Bridge

Dai Li*, Jiang Xianglin2
1Jiangxi Transportation Institute, Nanchang Jiangxi, 330200, China
2Research and Development Center on Technologies and Equipment of Long-span Bridge Construction Ministry of Transport, PRC, Nanchang Jiangxi, 330200, China
*Corresponding author's e-mail: 1194414140@qq.com

Abstract. Under the long-term effect of traffic load, the cable-girder anchorage zone of the cable-stayed bridge will be continuously subjected to fatigue stress, so the real-time stress state of this part is one of the important factors affecting the safe operation of the long-span cable-stayed bridge. In the present paper, finite element software was used to analyze the stress state of the key nodes of a typical steel anchor box of a long-span cable-stayed bridge, and based on the European, American and Chinese standards, the fatigue strength of the key nodes was evaluated according to the stress results. The evaluation results show that the fatigue strength of the cable-girder anchorage zone can meet the requirements of various codes and can continue to operate safely.

1. Introduction
With the vigorous development of transportation and the continuous development of engineering design and construction technology in recent years, the cable-stayed bridge, a structural form suitable for large-span traffic, has also been widely used in rivers, canyons and even straits[1-2]. However, under the long-term action of vehicle load, the connection area between steel box girder and anchor cable of cable-stayed bridge is prone to fatigue failure [3-5]. Therefore, many scholars at home and abroad have conducted in-depth studies on the fatigue problem of this part. For example, Yuan Rui et al. [6] took the Jinsha River super bridge as an example, and conducted a stress analysis on its cable-girder anchorage area, and consequently adopted a reasonable structural design type. Hua Bo et al. [7] analyzed the stress state of the composite anchor cable-girder anchorage structure in the concrete cable-stayed bridge, and verified the fatigue resistance of key welds through self-established model. Fatigue analysis and strength evaluation of cable-girder anchorage zone of cable-stayed bridge have become the focus of cable-stayed bridge technology research.

Based on the finite element model simulation analysis of the cable-girder anchorage zone of a long-span cable-stayed bridge, the stress cloud diagram and amplitude curve at three key nodes were calculated, and the stress distribution law of the weld joints in the cable-girder anchorage zone were discussed and analyzed in this paper. According to "European Steel Structure Design Code", "American Highway Bridge Design Code" and China's "Steel Structure Design Code", the fatigue strength evaluation of the shear stress amplitude and the tensile stress amplitude at each key node shows that the fatigue strength of the weld in the cable-girder anchorage zone can meet the requirements of the design codes.
2. Engineering Background
Taking a long-span cable-stayed bridge as the engineering entity, the cable-stayed bridge is a mixed girder structure with double towers and double cable-stayed surfaces. The span layout is 229m+818m+358m, and the height of the two concrete bridge towers are respectively 232.9m and 244.3m.

The main span and part of the side span of the cable-stayed bridge are made of steel box girder, and the middle section of part of the side span main girder is of prestressed concrete structure, and the main girder of the combined section is of steel-concrete structure. In this study, part of the anchorage area of the cable and the steel box girder is selected as the research object.

3. Establishing Finite Element Model
In order to explore the stress distribution law of cable-girder anchorage zone, the finite element model of cable-girder anchorage zone was established with the help of Ansys finite element simulation analysis platform. The steel anchor box of the cable-stayed bridge with a small height was selected as the analysis object. Its rigidity is relatively small and the cable force is relatively large. The maximum cable force is 4983.2 kN, and the cable force amplitude is also relatively large at 1680 kN, reaching 33.7% of the maximum cable force. The fatigue performance of the cable-girder anchorage zone of the cable-stayed bridge was reflected by the fatigue evaluation of the steel anchor box.

The finite element model of the steel anchor box was established by the substructure method, and its boundary conditions were applied to the substructure using the corresponding finite element calculation results. Solid45 units were used for the substructure units, with a total number of 105,834 units and 87,152 nodes. The steel grade of the steel anchor box was Q345, and the finite element model was an ideal elastoplastic analysis model.

Under the action of load, the welds of each steel plate structure in the cable-girder anchorage zone are the areas where the initial cracks of fatigue damage occur, and the stress distribution of longitudinal fillet welds is usually large at both ends and small in the middle. Therefore, in the study of fatigue performance of the cable-girder anchorage zone, it is usually focused on the end zone of the weld. In this paper, the welding ends of the two stiffened plates in the cable-girder anchorage zone were selected as key node 1 and key node 2, and the midpoint of the bottom weld of the anchor box pressure plate was selected as key node 3.

The geometric model and key nodes of cable-girder anchorage area are shown in Figure 1.
4. Calculation Results

Since the finite element simulation and analysis software can read the stress at the specified point in the model, but cannot obtain its nominal stress. Actually the domestic and foreign relevant fatigue strength inspection specifications and evaluations all use nominal stress as the strength index. In this paper, the stress at a distance of 1.5t from the key nodes was selected as the nominal stress of the key nodes according to the recommended standard of the International Welding Association.

4.1. Fatigue Stress at Key Node1

On the basis of the output of the calculated results, the maximum shear stress at the key node 1 occurred at the outer web side, where the maximum shear stress amplitude was 25.79Mpa and the first main stress amplitude was 30.67Mpa. The shear stress amplitude and the first main stress amplitude cloud images at key node 1 are given in figure 2 respectively.

![Weld shear stress amplitude cloud image](a) 
![Weld first main stress amplitude cloud image](b)

Figure 2. Shear stress and The first main stress amplitude at key node 1.

4.2. Fatigue Stress at Key Node2

On the basis of the output of the calculated results, the maximum shear stress at the key node 2 occurred at the outer web side, where the maximum shear stress amplitude was 25.79Mpa and the first principal stress amplitude was 30.10Mpa. The shear stress amplitude and the first principal stress amplitude cloud images at key node 2 are given in figure 3 respectively.

![Weld shear stress amplitude cloud image](a) 
![Weld first main stress amplitude cloud image](b)

Figure 3. Shear stress and The first main stress amplitude at key node 2.

4.3. Fatigue Stress at Key Node3

The dangerous positions at the key node 3 are outer web side of the weld and the pressure-bearing side of the weld, so they need to be separately conducted when extracting the results.

   1) outer web side of the weld

   On the basis of the output of the calculated results, the maximum shear stress at the key node 3 occurred at the the outer web side, where the maximum shear stress amplitude was 34.00Mpa and the
The first principal stress amplitude was 58.05 MPa. The shear stress amplitude and the first principal stress amplitude cloud images at key node 3 outer web side are given figure 4 respectively.

![Weld shear stress amplitude cloud image](image1)
![Weld first main stress amplitude cloud image](image2)

**Figure 4. Shear stress and The first main stress amplitude of the outer web at key node 3.**

2) Weld Pressure-bearing Side

On the basis of the output of the calculated results, the maximum shear stress amplitude was 23.99 MPa, and the first principal stress amplitude was 26.26 MPa. The shear stress amplitude and the first main stress amplitude cloud images at key node 3 pressure side are given in figure 5 respectively.

![Weld shear stress amplitude cloud image](image3)
![Weld first main stress amplitude cloud image](image4)

**Figure 5. Shear stress and The first main stress amplitude of the outer web at key node 3.**

5. Weld Fatigue Strength Evaluation

Footnotes should be avoided whenever possible. If required they should be used only for brief notes that do not fit conveniently into the text.

5.1. Shear stress fatigue evaluation

According to the "European Steel Structure Design Code", when the weld is subjected to shear stress, the minimum allowable fatigue amplitude corresponding to $2 \times 10^6$ cycles is 80 MPa, while the maximum shear stress amplitude at key node 1 was 25.79 MPa, at key node 2 was 28.69 MPa, the maximum shear stress amplitude at the web pressure-bearing side of key node 3 was 23.99 MPa, and the maximum shear stress amplitude at key node 3 outer web side was 34 MPa. Therefore, the maximum shear stress amplitude at these 3 key points were less than the allowable amplitude,
indicating that the shear stress fatigue strength of each key node meet the requirements of the domestic and foreign specification.

5.2. Tensile stress fatigue evaluation

(1) Check in conformity with "European Steel Structure Design Code"

Select the detailed classification 56 for the stress state of the weld outer web side at key node 1 and key node 2, and the allowable stress amplitude of its fatigue strength is 56MPa, which is greater than the first main stress amplitude (30.67 Mpa) at the weld outer web side of key node 1, which is also greater than the first main stress amplitude (30.10Mpa) at the weld the outer web side of key node 2. Select the detail classification 71 for the stress state of the weld pressure-bearing side and the outer web side at the key node 3, and the allowable fatigue strength amplitude is 71MPa, which is greater than the maximum tensile stress amplitude (26.26MPa) of the weld pressure-bearing side at the key node 3, which is also greater than the maximum tensile stress amplitude (58.05Mpa) of the weld outer web side at key node 3.

(2) Check in conformity with "American Highway Bridge Design Code"

Select the detail structure class E' for the stress state of the weld outer web side at key node 1 and key node 2, and its allowable fatigue stress amplitude can be expressed as

\[
\left(\Delta F\right)_n = A \left(\frac{N}{3}\right) 
\]

Where A is detail classification constant (E' class detail structure constant is A=1.28×1011Mpa3); N is fatigue cycle number, \((\Delta F) N\) is allowable fatigue stress amplitude corresponding to cycle number N.

Select the detail structure class E' for the weld outer web side at key node 1 and key node 2, the allowable fatigue stress amplitude corresponding to \(2 \times 10^6\) cycles is 40MPa, which is greater than the first main stress amplitude of the welds at key node 1 (30.67mpa) and at key node 2 (30.10 Mpa ).

Select the detailed structure class C for the stress state of the weld pressure bearing side at key node 3, A is 14.4×1011MPa3, the allowable fatigue stress amplitude corresponding to \(2 \times 10^6\) cycles is 89.6MPa, which is larger than the maximum tensile stress amplitude of the weld pressure-bearing side at key node 3 (26.26Mpa).

Select the detail structure class D for the stress state of the weld pressure-bearing side at key node3, A is 14.4×1011MPa3, the allowable fatigue stress amplitude corresponding to \(2 \times 10^6\) cycles is 71.17MPa, which is larger than the maximum tensile stress amplitude of the weld outer web side at key node 3 (58.05Mpa).

(3) Check in conformity with China's "Steel Structure Design Code"

Select the detail classification 7 for the stress state of the weld outer web side at key node 1and key node 2, the allowable fatigue stress amplitude corresponding to \(2 \times 10^6\) cycles is 69MPa, which is larger than the maximum tensile stress amplitude of the weld at key node 1(30.67mpa) and the maximum shear stress amplitude of the weld at key node 2 (30.10mpa).

Select the detailed classification 5 for the stress state of the weld pressure-bearing side at key node 3, the allowable fatigue stress amplitude corresponding to \(2 \times 10^6\) cycles is 90MPa, which is larger than the maximum tensile stress amplitude of the weld pressure-bearing side at key node3 (26.26Mpa) and the maximum tensile stress amplitude of the weld outer web side at key node 3 (58.05Mpa).

(4) Check in conformity with China's "Highway Bridge Culvert Steel Structure and Wooden Structure Design Code"

Select the detail classification D for the stress state of the weld pressure-bearing side and the weld outer web side at key node 3, and the allowable fatigue strength stress amplitude can be expressed as

\[
\frac{145}{1-0.6\rho} \leq [\sigma] 
\]

Where \([\sigma]\) is basic allowable stress of steel, \(\rho\) is stress ratio.
\[
\rho = \frac{\sigma_{\text{min}}}{\sigma_{\text{max}}} \quad (3)
\]

Since the cable-girder anchorage zone of is subjected to the force of the diagonal cable, it is only under tension and not under pressure, so \(0 < \rho \leq 1\), when \(\rho = 0\), the fatigue strength stress amplitude is allowed to obtain a minimum value of 145MPa, which is larger than the maximum tensile stress of the weld pressure-bearing side at key node 3 and the maximum tensile stress of the weld outer web side at key node 3.

**Acknowledgments**

This work was partially supported by the Science and Technology Support Project of Jiangxi Province, China (2017H0015).

**6. Conclusion**

In this paper, the finite element analysis software Ansys was used to perform static analysis on the specified steel anchor box of a long-span cable-stayed bridge. Through finite element calculation, the stress distribution of the key weld area in the cable-girder anchorage area was presented and the fatigue strength at different key nodes was evaluated according to the relevant design codes. The results show that the fatigue strength of the cable-girder the anchorage area can meet the requirements of these codes.

**References**

[1] MAO Weiqi, HU Xiongwei. Latest Developments and Prospects for Long-Span Bridges in China.[J]Bridge Construction, 2020, 50(1): 13−19.

[2] LEI Junqing, HUANG Zuwei, CAO Shanshan, et al. Study on long-span rail-road cable-stayed bridge for cross-sea channel[J]. Science and Technology Review, 2016, 34(21): 27–33.

[3] WEI Xing, QIANG Shizhong. Fatigue performance of cable-to-girder connection of a long span high-speed railway cablestayed bridge with steel truss[J]. Journal of Vibration and Shock, 2013, 32(23): 180–185.

[4] ZENG Yongping, CHEN Kejian, YUAN Ming, et al. Design study and fatigue test of cable-to-girder anchorage structure of double tensile anchor plates and anchor box[J]. Bridge Construction, 2013, 43(6): 45–50.

[5] CAO Shanshan, LEI Junqing, HUANG Zuwei. Fatigue test study of combined cable−girder anchorage structure in cable-stayed bridge with steel truss girder[J]. Journal of Central South University (Science and Technology), 2020, 51(1): 165-175.

[6] YUAN Rui, ZHANG Min, LUO Sibi. Stress analysis and structural design of anchorage zone of cable beam of Jinshajiang super large bridge[J]. HIGHWAY, 2019, 10: 89−93.

[7] HUA Bo, ZHU Anjing, SUN Lei. Application of Cable-Girder Anchorage Structure formed of Composite Anchor Tensile Plates to Concrete Cable-Stayed Bridge[J].World Bridge, 2019, 47(2): 72–77.