Study On Key Parameters of Fatigue Performance of Orthotropic Steel Bridge Deck

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Abstract. In order to reduce the fatigue damage of steel bridge deck, fatigue design is very important. Taking the typical orthotropic steel bridge deck often used in design as the research object, the influence mechanism of different bridge deck structural parameters on fatigue performance was studied by nominal stress method. The results show that the fatigue performance of different fatigue hot spots is different. The most unfavorable fatigue hot spots are the arc notch of the diaphragm at the stiffener position and the weld junction between the diaphragm and the roof. Through reasonable optimization of structural parameters, the fatigue performance of bridge deck can be effectively improved.

Keywords: Orthotropic steel bridge deck; fatigue performance; stress amplitude; UHPC.

1. Introduction

Compared with other bridge types, the steel bridge has the advantages of light weight, large span, high bearing capacity, simple design and construction[1], and has become the preferred structural form for bridges across rivers, roads, small radius and high piers. Orthotropic steel bridge decks are widely used around the world[2] by reducing steel consumption, increasing bending stiffness and improving local stability through longitudinal and transverse stiffeners. With the migration of time and the sharp increase of traffic volume, fatigue disease has become a problem that cannot be ignored. The fatigue disease of orthotropic steel bridge deck has the characteristics of early onset, multiple occurrence, common occurrence and recurrence, which will lead to significant economic losses and adverse social impact[3].

Cui [4] et al.introduced the hot spot stress method, and obtained the stress spectrum at the weld toe of orthotropic steel bridge deck through finite element calculation. The fatigue life of a city bridge was evaluated to meet the design life requirements, and the results were more accurate than the nominal stress method. Chen [5] et al.studied the fatigue performance of the butt weld of the longitudinal stiffener of the roof through fatigue test and ANSYS finite element calculation. The results show that the fatigue sensitive area is the arc transition zone outside the weld. Optimizing the weld shape, reducing the weld width, and increasing the thickness of the longitudinal rib plate can improve its fatigue performance.

For the design of steel structure bridges, the fatigue performance does not necessarily control the design, but it cannot be ignored. This paper takes the typical orthotropic steel bridge deck as the research object, and studies the key design parameters affecting the fatigue performance, in order to provide theoretical support for the anti-fatigue design of steel structure bridges and efficiently guide the design.

2. Finite element analysis method

2.1. Fatigue details

Two typical fatigue details are selected as the research objects according to the statistical results of fatigue damage of orthotropic steel bridge deck. The fatigue details are shown in Fig.1.

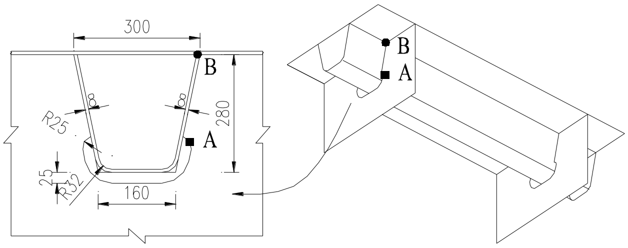

Fig. 1 Fatigue detail schematic (unit: mm)

The nominal stress method was used to study the fatigue of orthotropic steel bridge deck. For fatigue detail A, the diaphragm is selected at the stiffener notch position. The nominal stress is the stress cut at the edge of the most unfavorable section of the diaphragm opening edge. The specific

position is determined according to the calculation results of the finite element model. For the fatigue detail B, the intersection of the diaphragm and the stiffener is selected. The nominal stress is the transverse bridge stress of the roof near the connection weld of the stiffener and the diaphragm, and the stress of the stiffener perpendicular to the longitudinal connection weld. The typical stress history of fatigue details A and B is shown in Fig.2.

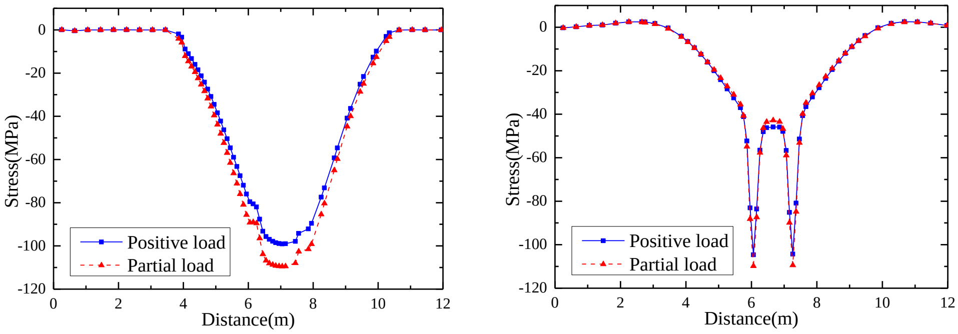

Fig. 2 Stress history of fatigue details A and B

The stress history at the arc notch of fatigue detail A is approximately a single-peak curve. The stress history curve of fatigue detail B at the intersection of diaphragm, U-rib and roof is a double-peak curve. The stress history of the two fatigue details is at its distal end. The stress is 0, and the peak interval is about 4-10 m from the beam end. The stress concentration phenomenon is significant, and the eccentric load is more unfavorable than the positive load, and the stress level under the eccentric load is higher. The fatigue details A and C have large stress amplitudes, so they are the key details of the design. If the stress amplitudes of the two fatigue details cannot be effectively reduced, it can be predicted that the bridge deck will crack prematurely.

2.2. Finite element model

The finite element solid model is established by ABAQUS program. The UHPC bridge deck is simulated by C3D8 R solid element, which is an 8-node hexahedral element. The roof, U rib and diaphragm are simulated by S4 R shell element. Because the fatigue calculation is carried out in the elastic range, the stress level is low and the interface bonding performance is good, the additional UHPC layer is directly coupled with the steel roof. The steel is Q345qD, and the material performance parameters are set according to the specification.

In order to reduce the amount of calculation, the model only establishes a half-bridge structure and imposes corresponding symmetry constraints on the symmetry plane. The bottom area of the diaphragm constrains the degrees of freedom in all directions. This method can maximise ensure the stiffness simulation of three diaphragms in the middle area of the model. The fatigue load is calculated according to the calculation model III of the 'Code for Design of Highway Steel Structure Bridges'.Two load conditions are considered. Condition 1 is positive load, that is, riding U-rib loading, and condition 2 is partial load, that is, offset U-rib top loading, as shown in Figure 3. The research shows that compared with the normal load, the stress amplitude caused by the fatigue details at the intersection of the diaphragm and the stiffener is larger under the eccentric load, but the stress amplitude of the fatigue details between the two diaphragms and the mid-span position is similar.

Fig. 3 Schematic diagram of positive and partial loading methods

The finite element model is established by selecting the orthotropic steel bridge deck section which contains the roof, U rib and diaphragm. The symmetrical half-bridge structure selected in the model contains 5 cross diaphragms, 12.1 m long and 13.8 m wide. Because the cross slope is simulated, the height varies with the diaphragm. The model is shown in Figure 4. The fatigue detail area at the intersection of U-rib and diaphragm is meshed, the unit size is 5mm, and the unit size is 10-40mm in other areas.

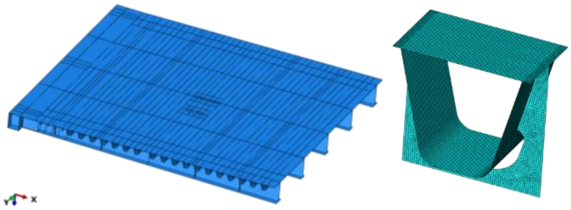

Fig. 4 Finite element model of bridge deck segment

3. Fatigue performance analysis

3.1. Stiffener parameters research

In order to study the influence mechanism of U-shaped stiffener structural parameters on fatigue performance, three typical types of U-shaped stiffeners mainly used in Chinese, Japanese and European codes are selected as the research objects, which are 300mm × 260mm small section stiffener + panel thickness 16mm, 300mm × 280mm medium section stiffener + panel thickness 16mm, 400mm × 300mm large section stiffener + panel thickness 18mm, respectively.Among them, medium section stiffener is the most widely used in China, and the nominal stress method is used to calculate and analyze the stress amplitude at two fatigue details. The stress contours of the three stiffeners are shown in Fig.5. The stress amplitudes at the two fatigue details under the two load conditions corresponding to the three stiffeners are shown in Table 1.

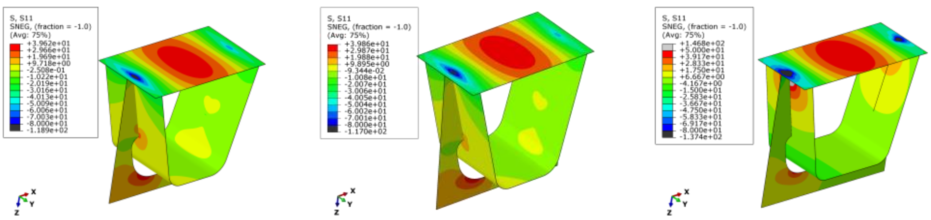

Fig. 5 Stress cloud diagram of three stiffeners

Table 1. Fatigue stress amplitude of different stiffeners (unit: MPa)

Fatigue detail name	Loading type	Small	Medium	Large
A	Partial load	100.5	99.2	69.9
	Positive load	92.7	90.8	61.9
B	Partial load	66.8	64.3	101.3
	Positive load	65.6	63.0	111.3

It can be seen from Fig.5 and Table 1 that the calculation results reveal the influence of U-rib size and loading position on fatigue details. The stress amplitude of each detail of small and medium-sized stiffeners is very close, so the fatigue performance is not much different, and the medium-sized stiffener is slightly better. For fatigue detail A, the fatigue benefit of increasing the stiffener section is obvious; for fatigue detail B, increasing the stiffener section will increase the fatigue stress amplitude; regardless of the fatigue details A or B, the eccentric load is more unfavorable than the positive load. Therefore, it is the first choice to simply reduce the stress amplitude of the steel beam panel.

3.2. Study on opening parameters of diaphragm

The opening of diaphragm directly affects the fatigue performance of U rib and diaphragm weld and arc notch. According to statistics, the number of fatigue cracks at the intersection of longitudinal ribs and diaphragms accounts for more than one-third of all cracks in the bridge deck system[6], so the fatigue performance at this place greatly affects the overall fatigue life of the bridge. In order to study the influence mechanism of the opening shape of the diaphragm on the fatigue performance, three typical arc incision shapes at home and abroad are selected as the research objects. Type I is the European Highway Specification pass, type II is the American Highway Specification pass, and type III is the European Railway Specification pass. The stress amplitude at two fatigue details is calculated and analyzed. The stress amplitude at different fatigue details under different load conditions is shown in table 2.

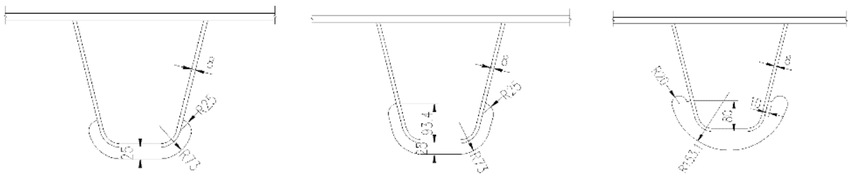

Fig. 6 Three kinds of incision structure diagram (unit: mm)

Table 2. Fatigue stress amplitude of different notch (unit: MPa)

Fatigue detail name	Loading type	Type I	Type Ⅱ	Type Ⅲ
A	Partial load	103.5	99.2	112.9
	Positive load	92.2	90.8	104.7
B	Partial load	62.7	64.3	67.5
	Positive load	61.2	63.0	66.8

From Table 2, it can be seen that type I and type II have similar stress distribution, type II has two stress peaks, and type III stress is more concentrated on both sides of the arc incision. For fatigue detail A, the three types of passes have little effect on its fatigue performance. The smallest stress amplitude is type II, and the largest stress amplitude is type III. The maximum stress difference is 13.7 MPa, and the stress drop is about 13.8%. Fatigue detail B, the influence difference is very slight, it can be considered that the fatigue performance of this detail is the same under the three kinds of passes. Therefore, type II notch has the best fatigue performance.

3.3. Study on diaphragm parameters

In order to study the influence mechanism of diaphragm spacing on fatigue detail performance, a fatigue model of three different spacing diaphragms is established. The remaining parameters remain unchanged. The diaphragm spacing is 2 meters, 2.5 meters and 3.5 meters respectively. With the increase of diaphragm spacing, the stiffness of the second system of the bridge deck gradually increases, and the deflection of the bridge deck under the action of heavy vehicles becomes smaller and smaller. The stress amplitudes at two fatigue details under two load conditions corresponding to three different diaphragm spacing models are shown in Table 3.

Table 3. Fatigue stress amplitude of different diaphragm spacing (unit: MPa)

Fatigue detail name	Loading type	2m	2.5m	3.5m
A	Partial load	93.9	99.2	124.5
	Positive load	47.7	90.8	114.7
B	Partial load	62.5	64.3	70.2
	Positive load	61.4	63.0	68.8

It can be seen from Table 3 that the influence of diaphragm spacing on fatigue details is nonlinear, and the densification of diaphragm is beneficial to fatigue performance. For fatigue detail A, when the diaphragm spacing is refined from 3.5m to 2m, the maximum stress amplitude decreases from 124.5MPa to 93.9MPa. When the diaphragm spacing is refined from 3.5m to 2.5m, the fatigue benefit efficiency is higher than that from 2.5m to 2m. For fatigue detail B, the maximum stress amplitude of the encrypted diaphragm is not significantly reduced. Considering fatigue, stiffness and cost factors, the diaphragm spacing is recommended to be 2.5m to 3m.

3.4. Study on parameters of UHPC-steel composite bridge deck

The UHPC layer is closely combined with the steel roof through welding studs to form the UHPC-steel composite bridge deck, which can effectively improve the local stiffness of the bridge deck, so it can greatly improve the stress amplitude of the fatigue details of the bridge deck system and improve the fatigue life of the steel bridge deck. In order to study the fatigue performance of UHPC-steel composite bridge deck, a model with a longitudinal beam, a diaphragm spacing of 2.5 m, a medium-sized section stiffener and a type II notch was established. A 50 mm-thick UHPC layer was added, and the thickness of the steel roof was controlled as the second variable. The remaining parameters remain unchanged from the reference model. The grid size of UHPC layer is 25mm, which is connected with the roof by direct coupling, ignoring the interface slip. The stress amplitudes at the two fatigue details under the two load conditions corresponding to the three panel models are shown in Table 4.

Table 4. Fatigue stress amplitude of different panels (unit: MPa)

Fatigue detail name	Loading type	No UHPC	50mm UHPC+12mm roof	50mm UHPC+16mm roof
A	Partial load	99.2	63.3	60.6
	Positive load	90.8	57.3	55.1
B	Partial load	64.3	14.8	15.8
	Positive load	63.0	11.6	12.3

It can be seen from Table 4 that UHPC-steel composite panel can greatly reduce the stress amplitude of fatigue details A and B, so that fatigue no longer controls the design of bridge deck. Increasing the thickness of the roof has a slight improvement on the stress amplitude of the two fatigue details; setting UHPC layer can essentially improve the fatigue problem of steel bridge deck, that is, improve the local stiffness of steel bridge deck and reduce stress concentration. Therefore, UHPC-steel composite bridge deck is recommended.

4. Summary

(1) Whether the fatigue details A or B partial load is more unfavorable than the positive load;

(2) There is little difference in the fatigue performance of the details of the small and medium-sized stiffeners, and the medium-sized is slightly better. Large stiffeners can improve the stiffness of the bridge deck and increase the fatigue stress amplitude at the fatigue detail B;

(3) In the form of diaphragm incision, type I and type II have similar stress distribution, type III has the largest stress amplitude, and the fatigue performance of the three hole types is basically the same;

(4) The influence of diaphragm spacing on fatigue details is nonlinear, and it is recommended to use 2.5m to 3m;

(5) Increasing the thickness of the roof has little effect on the improvement of the stress amplitude. The UHPC layer can essentially solve the fatigue problem of the steel bridge deck.

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