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FATIGUE STRESS ANALYSIS OF ORTHOTROPIC STEEL BRIDGE DECKS IN XINGHAI BAY CROSS-SEA BRIDGE

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Abstract—Fatigue properties of orthotropic steel bridge deck of Xinghai Bay Cross-sea Bridge in Dalian were analyzed. The segment model of orthotropic bridge deck was established by using the finite element software Abaqus. The intersection between diaphragm and U-rib was selected to analysis. The fatigue loading model III was adopted which was provided by “Specifications for Design of Highway Steel Bridge”. First, the transverse stress influence line and the transverse severest loading position were determined. Then, five loading regions were selected near the transverse severest position. The stress amplitude of the intersection was ascertained through loading on the longitudinal bridge for each region. Finally, the fatigue checking for the intersection was carried out. The results showed that the maximum fatigue stress amplitude of orthotropic deck in Xinghai Bay Cross-sea Bridge met the requirements of “Specifications for Design of Highway Steel Bridge”.

Key Words: Orthotropic steel deck, Stress influence line, Fatigue stress, Xinghai Bay cross-sea Bridge

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1. INTRODUCTION

The orthotropic steel bridge deck, which is composed of the bridge cover plate, perpendicular longitudinal ribs and transverse ribs, mainly resists the wheel load. According to the traditional analytical approach on three-structure system, it is divided into the main girder system, the deck slab system and the cover plate system. Orthotropic steel deck was first applied to rebuild Kurpfalz Bridge, which was about 33.3% less steel than the original structure. By virtue of its better economy, it had been widely applied to various types of bridges in the following decades^[1]. However, the research and application of orthotropic steel bridge deck were very late in China, and the Yellow River Railway Bridge in Tongguan which was built in June 1970 is the first bridge with orthotropic steel bridge^[2-5]. In recent years, different degrees of fatigue damage had been observed in bridges using orthotropic steel deck. It is because of increasing traffic load and poor construction quality. Ji Bohai used the thermal-structure directly coupling method to analyze the residual stress of the weld connecting the roof and U-rib in steel bridge deck^[6]. Chuang Cui and others used the extrapolation method recommended by International Institute of Welding (IIW) to calculate the hot-spot stress spectrum of the key vulnerable part based on hot spot stress method, thus to evaluating the fatigue life^[7]. Chunsheng Wang pointed out that there were 3 kinds of failure modes in the connection between longitudinal rib and deck: the weld toe failure of longitudinal rib, the weld toe failure of bridge deck and the failure of weld throat from weld root^[8]. Petershagen proposed general hot spot stress method for shell structure^[9]. Dong proved that the stress results of the toe position in the two-dimensional structure are insensitive to the mesh which are based on the structural mechanics principle and use the finite element method^[10]. Based on the stress extrapolation method recommended by the International Institute of Welding, Maddox reassessed several groups of fatigue tests and validates the N-S curves^[11]. Samol Ya evaluated the fatigue life of the weld connecting the roof and longitudinal rib separately under the 80% penetration ratio and fusion penetration^[12]. Through the investigation of fatigue cracking in steel deck slab, the fatigue parts of orthotropic steel bridge deck included that^[13], (1) the weld connecting the roof and U-rib, (2) the weld connecting the diaphragm and U-rib (3) the slotted part of the diaphragm^[14, 15]. In this paper, the fatigue stress amplitudes of the above positions were calculated and the fatigue intensity checking to each detail part were carried out.

2. PROJECT OVERVIEW

The main bridge of Dalian Xinghai Bay cross-sea bridge is three-span earth-anchor suspension bridge. Concrete gravity anchors are set at both sides. The stiffening girder is double-deck rigid truss structure. The main span is 460m in length, whereas the two end spans are 180m. The width between the two main cables is 25.2m. The radius crest vertical curve of the bridge is 13500m with longitudinal slope 1.5%^[16-18], as shown in Fig. 1. The bridge is a double-deck bridge due to lots of traffic. The upper deck consists of four lanes and two sidewalks, and the lower deck consists of four lanes. The upper deck lanes are for vehicles driving from east to west, and the lower deck is for vehicles driving from west to east, as shown in Fig. 2.

In this paper, the upper orthotropic steel deck plate is selected as the research object. The bridge deck is made of Q345qE steel. The orthotropic steel plate forms the bridge deck, which is 21.26m width. The bridge deck thickness is 16 mm, and the U-rib thickness is 8 mm. The longitudinal beam height varies from 664 mm to 784 mm, and the distance between longitudinal beams is 2620 mm. The diaphragm plate height is 596 mm, and the distance between diaphragm plates is 2500 mm as shown in Fig. 3. The stringers adopt 14mm thick steel plate. The bridge deck is fitted with 55mm thick double-layer epoxy asphalt, as shown in Fig. 4

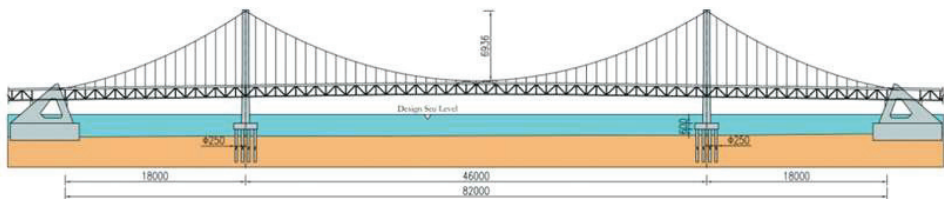


Fig. 1 The layout drawing of main bridge (m)

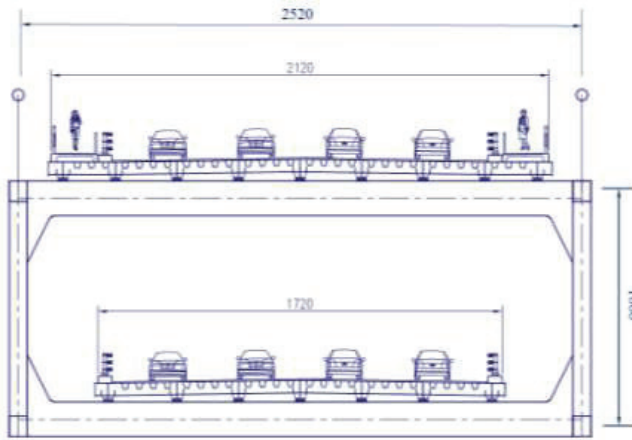


Fig. 2 Bridge cross section (cm)

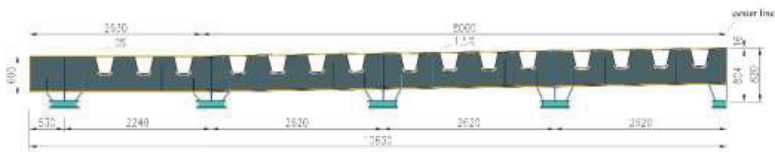
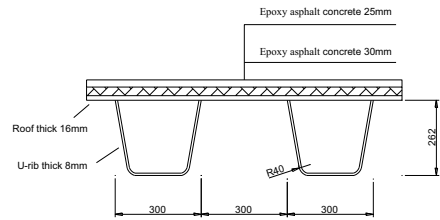


Fig. 3 Bridge deck (mm)



(a) The layout drawing of bridge deck



(b) Bridge deck detail size (mm)

Fig. 4 Orthotropic deck detail

3. FINITE ELEMENT CALCULATION

3.1. FINITE ELEMENT MODEL

The three-dimensional shell model is established using the general finite element software Abaqus. The model is 13.8m long, which includes 5 diaphragms and 15 U-ribs. The model is 10.63m wide, which is half width of the bridge deck. The elastic modulus of steel is 206Gpa and the Poisson ratio is 0.3. Global mesh size is 100mm and local refinement mesh size is 30mm, as shown in Fig.5 and Fig.6. The total number of elements is 209,877. According to the Saint-Venant's principle, the boundary conditions of the model is not significant for distant load. So symmetrical boundary condition is set at the plane of mid-span, and fixed supports and simple supports are set under longitudinal beams and diaphragms, as shown in Fig.7.

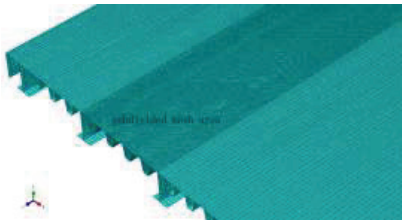


Fig.5 Global mesh



Fig.6 Refinement mesh

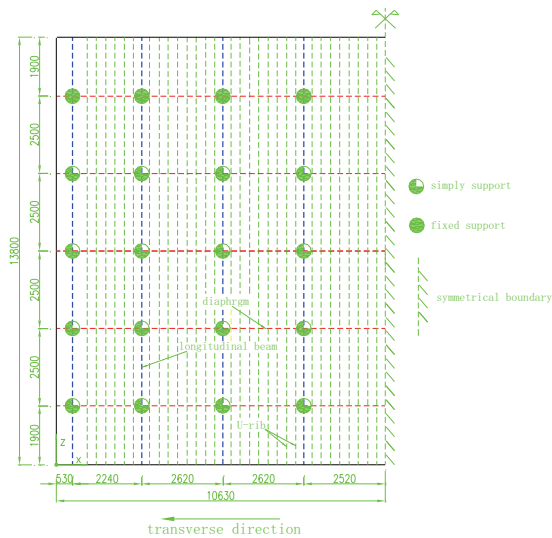


Fig.7 Plane Boundary conditions (mm)

3.2. CALCULATION LOAD

According to “Specifications for Design of Highway Steel Bridge” (JTG D64-2015)^[19], the fatigue checking of bridge deck system is based on fatigue load calculation model III. There are four axles on the vehicle, and each axle weight is 120kN. The distance between the axles are 1.2m and 6m. The distance between wheels is 2m. The wheel contact area is 600mm×200mm. The axle load and distribution is shown in Fig. 8. The influence range of vehicle local load is rather limited which base on research results of Lewei Tong and others^[20, 21]. The simplified load model is that a single wheel loads on the local subdivided area of the finite element model. The pavement layer is 55mm thick and the axle load expands by 45°, so the final load area is 710mm×310mm. The single wheel weighs is 60kN, thus the wheel pressure is 0.2726Mpa.

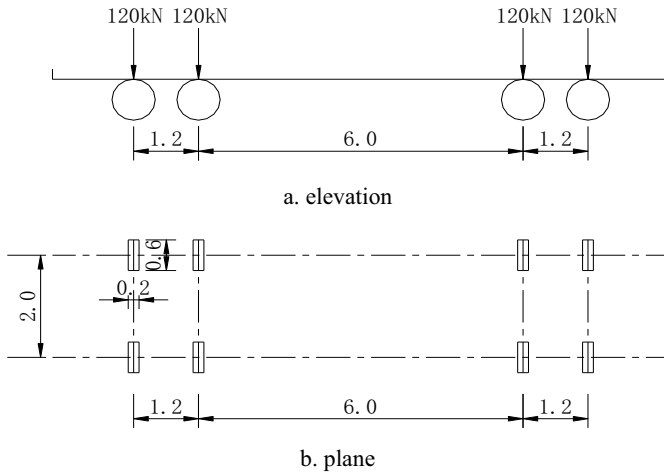
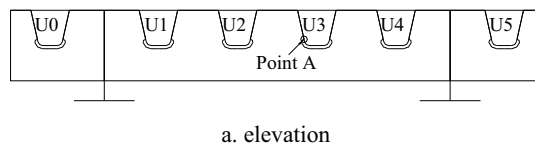
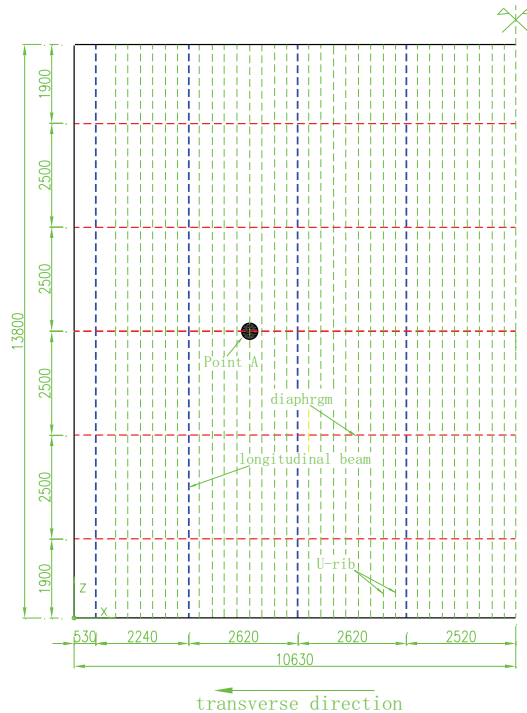


Fig. 8 Fatigue load calculation model III (m)

3.3. SELECTION OF THE LOCATION OF CONSTRUCTION DETAILS

There are many key fatigue points for orthotropic steel deck that need to inspect. Since space is limited, only point A is selected. Point A is located at the intersection between the third diaphragm and the U3. It is on the left side of the U3 in the local subdivided area, as shown in Fig. 9.





b. plane

Fig. 9 Fatigue point A location

3.4. LOADING CONDITION

The fatigue details of orthotropic plates are not sensitive to lane load, but only sensitive to wheel load. The effective influence surface of fatigue details has a narrow range and a wide range of changes, thus the fatigue details are very sensitive to the transverse position of wheel load too. When the fatigue stress of orthotropic steel bridge deck is calculated by the above vehicle load model according to specifications, the probability of the transverse position of the wheel on the lane should be taken into account according to the Fig. 10^[14]. There are five loading regions and each loading region is 0.1m wide in transverse direction. The probabilities of loading region for wheel loading are 0.5, 0.18, 0.07. The loading region 1 should be located at the transverse severest loading position. According to “Specifications for Design of Highway Steel Bridge”, the influence surface should be gotten. However, it is difficult to calculate.

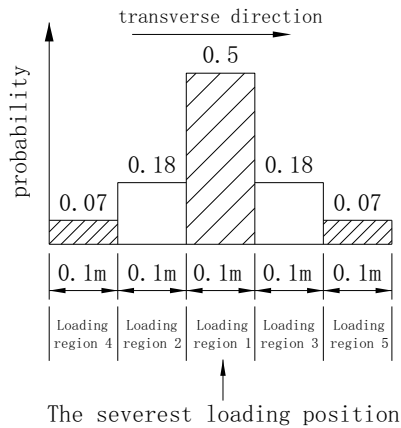
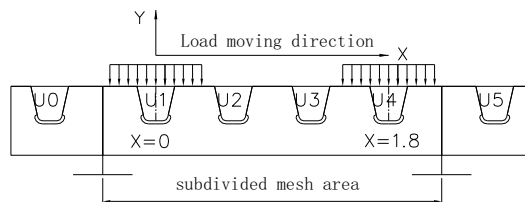
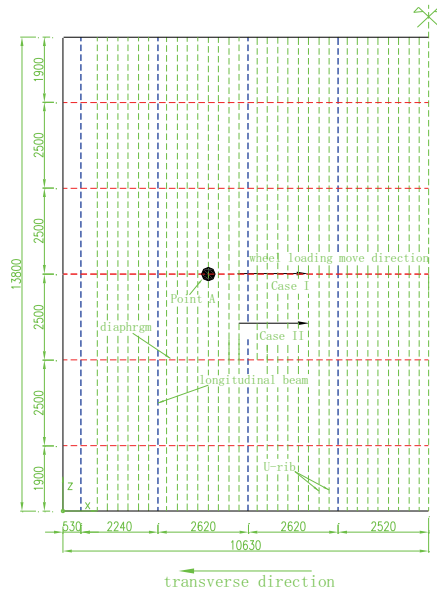


Fig. 10 The probability of transverse position of wheel loading

This paper presents a method to calculate the stress amplitude of the detail by calculating the influence line. First, the transverse stress influence line and transverse severest loading position of each detail are gotten by using the self-programmed Abaqus subroutine DLOAD. Next, the stress amplitude of each detail is achieved by loading on five selected regions near transverse severest loading position with DLOAD. At last, the fatigue strength checking is carried out for each detail part. The wheel load moves from U1 rib to the U4 rib. The distance between U1 rib and U4 rib is 1.8m, as shown in Fig. 11. In order to obtain the transverse severest loading position, the wheel load respectively moves along the third diaphragm and the middle of the second and third diaphragms, which are replaced by Case I and Case II below.





b. plane

Fig. 11 Transverse loading

4. RESULT AND DISCUSSION

4.1. THE TRANSVERSE STRESS INFLUENCE LINE OF POINT A

Same thing as above, the stress influence line of the point A is obtained as shown in Fig. 12. When loading on diaphragm, the peak value of transverse normal stress is 4.27MPa at 1.1m. Moreover, the peak value of longitudinal normal stress is 4.5MPa at 0.65m. When loading on the middle of diaphragms, the peak transverse normal stress is 12.85MPa at 0.85m. In addition, the peak longitudinal normal stress is 12.85MPa at 0.85m. The longitudinal normal stress of U-rib is concerned for this kind of detail. Therefore, the transverse severest position appears at 0.65m.

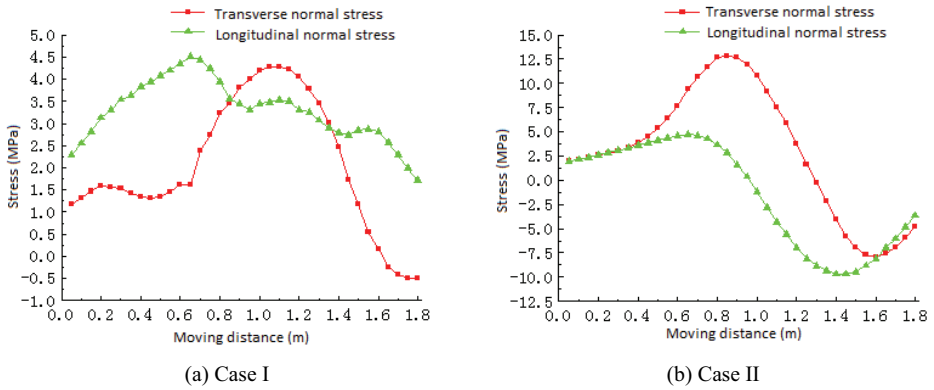


Fig. 12 The transverse normal stress influence line of point A

4.2 THE LONGITUDINAL STRESS INFLUENCE LINE OF POINT A

The transverse severest loading position of point A is shown in Fig. 13, which corresponds to the loading region 1. The loading region 2 and region 3 of point A are that the region 1 offsets transversely 0.1m to both sides. The loading region 4 and region 5 are that the region 1 offsets transversely 0.2m to both sides. The longitudinal movement of a single wheel load is realized by using the self-programmed Abaqus subroutine DLOAD too. Therefore, the longitudinal influence line is obtained.

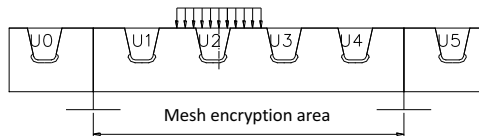


Fig. 13 The transverse severest loading position of point A

Similarly taking the position of the point A as the origin of coordinate, the longitudinal normal stress influence line of each loading region is shown in Fig. 14. The main influence range of wheel load on the point A is $\pm 2.5\text{m}$, which is the distance between adjacent diaphragms. The longitudinal stress influence line of this detail varies greatly with the loading region. The peak positions are that at $\pm 1.5\text{m}$ for the loading region 1, at $\pm 1.0\text{m}$ for the loading region 2, at $\pm 1.5\text{m}$ for the loading region 3, at $\pm 0.75\text{m}$ for the loading region 4 and at $\pm 1.75\text{m}$ for the loading region 5.

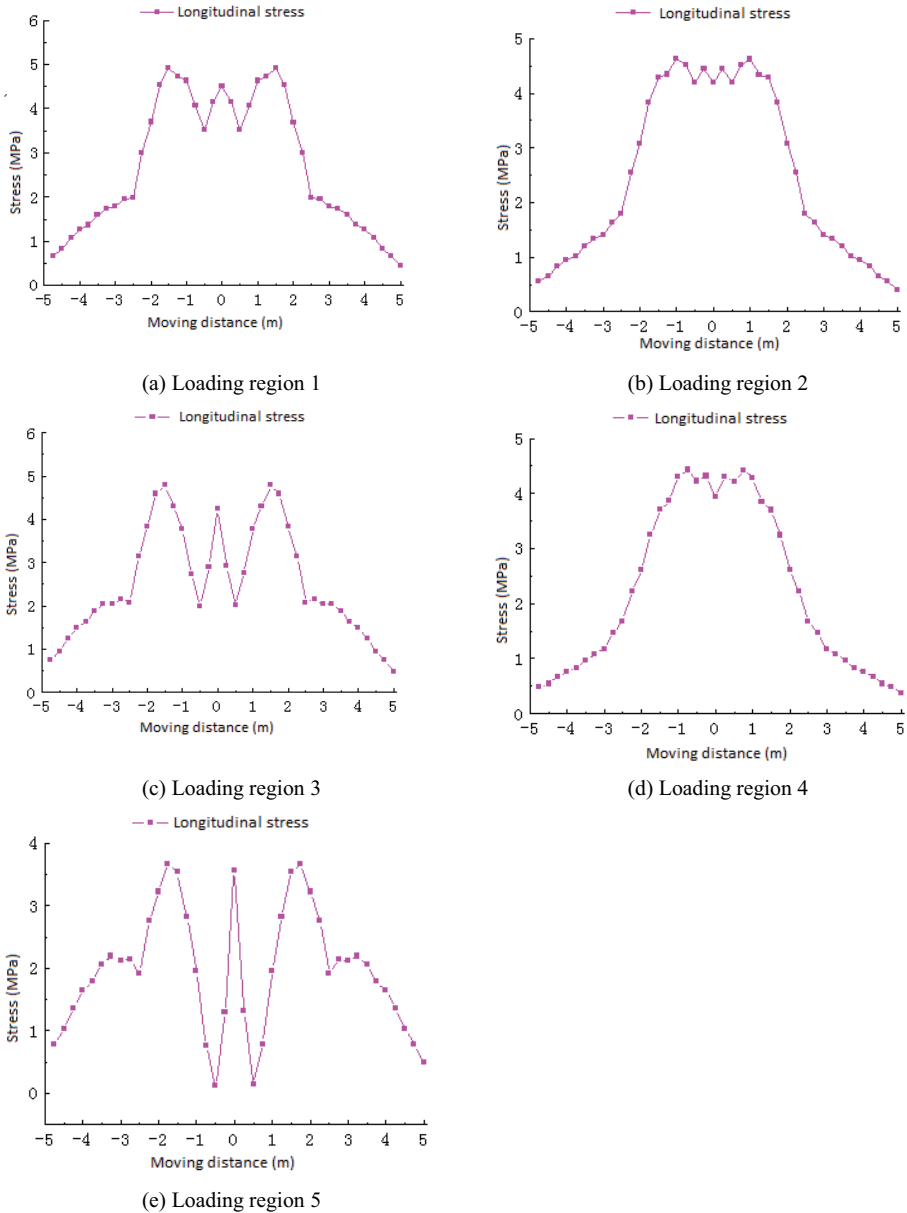


Fig. 14 The longitudinal normal stress influence line of point A for each loading region

5. FATIGUE CHECKING OF POINT A

According to “Specifications for Design of Highway Steel Bridge” (JTG D64-2015), the fatigue checking should be carried out by using the following formula,

$$(5.1) \quad \gamma_{Ff} \Delta\sigma_{E2} \leq \frac{k_s \Delta\sigma_c}{\gamma_{Mf}}$$

$$(5.2) \quad \Delta\sigma_{E2} = (1 + \Delta\phi) \gamma \sqrt[3]{0.5\omega_1^3 + 0.18\omega_2^3 + 0.18\omega_3^3 + 0.07\omega_4^3 + 0.07\omega_5^3}$$

$$(5.3) \quad \omega_i = \sigma_{p\max,i} - \sigma_{p\min,i} \quad (i = 1, 2, 3, 4, 5)$$

$$(5.4) \quad \gamma = \gamma_1 \cdot \gamma_2 \cdot \gamma_3 \cdot \gamma_4, \text{ and } \gamma \leq \gamma_{\max}$$

Where, γ_{Ff} is the fatigue loading partial coefficient, which is 1.0. γ_{Mf} is the fatigue resistance partial coefficient, which is 1.15. k_s is the dimensional effect reduction coefficient, which is 1.0 in this paper. $\Delta\sigma_{E2}$ is the equivalent constant stress amplitude, which is obtained by 2.0×10^6 times constant amplitude fatigue cycle conversion. $\Delta\sigma_c$ is the fatigue detail category, which is the fatigue stress intensity corresponding to 2.0×10^6 times constant amplitude fatigue cycle. $\Delta\phi$ is the amplification coefficient, which is 0. γ is the damage equivalent coefficient. γ_1 is the damage effect coefficient, which is 2.55. γ_2 is the traffic flow coefficient, which is 0.66. γ_3 is the designed life influence coefficient, which is 1.0. γ_4 is the multilane effect coefficient, which is 1.0, γ_{\max} is 2.5.

The stress amplitudes of point A is calculated in Table 1, and the equivalent constant stress amplitude meets the requirement.

Table 1. Stress amplitude of Point A (MPa)

Fatigue detail	Stress amplitude					$\Delta\sigma_{E2}$	$\Delta\sigma_c$	Checking result
	ω_1	ω_2	ω_3	ω_4	ω_5			
Point A	4.92	4.62	4.79	4.43	3.67	7.98	70	Satisfied

6. CONCLUSION

In this paper, the fatigue stress analysis of orthotropic steel bridge deck in Xinghai Bay Cross-sea Bridge is carried out based on the finite element method, and the fatigue performance of the bridge deck is checked. Conclusions are as follows.

- 1) The stress of point A is obtained by calculating the influence line, which avoids calculating the influence surface. In addition, the fatigue intensity checking of point A is carried out.
- 2) The maximum fatigue stress amplitude of point A at orthotropic bridge deck in Xinghai Bay Cross-sea Bridge is 7.98MPa, which meets the requirements of “Specifications for Design of Highway Steel Bridge”.

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Table 1. Stress amplitude of Point A (MPa)