Studies on Design Parameter and Fatigue Performance of a New Type of Orthotropic Steel Bridge Deck

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Abstract: The rib-to-deck and the rib-to-diaphragm details are the weak position of fatigue problem of conventional orthotropic steel bridge decks (OBDs). To improve the fatigue performance at such fatigue details, a new type of OBDs structure with semi-open longitudinal ribs was proposed. This new structure can not only realize full penetration welding between the deck and longitudinal rib, but also reduce the stiffness difference between the longitudinal rib and the diaphragm. The structural parameters of the new structure were analyzed, and the reasonable values of each structural detail of the new bridge deck were given. The lateral and longitudinal stress influence lines of different structural details in the new and conventional steel bridge deck were comparatively studied. And the results show that the stress on the deck of the rib-to-deck in this new type of OBDs is larger, but full penetration welding can effectively improve the welding quality of the rib-to-deck joint, thus ameliorate the eccentric force of the single fillet welds. The change in longitudinal ribs weakened the stress concentration at the rib-to-deck, and improved its fatigue properties.

1. Introduction
The rib-to-deck and the rib-to-diaphragm details are the weak position of fatigue problem of conventional orthotropic steel bridge decks (OBDs), the cracks are mainly generated in such fatigue details[1,2,3].

To improve the fatigue performance of conventional OBDs, many improvement measures were proposed in relative literatures. Automatic welding technology can improve the welding quality. An inside liner is used for to achieve achieving single-side welding and double-side molding[4]. Orthotropic steel decks with thickened edge U-ribs can increase welding size and improve welding quality[5]. Most of the above improvement measures were proposed from the perspective of welding technology, which can solve the fatigue problem of the rib-to-deck details and the rib-to-diaphragm details simultaneously[6,7].

To ameliorate the fatigue performance at the rib-to-deck and rib-to-diaphragm details, this paper presented a new type of OBDs, which referred to as the new steel bridge deck (shown as Fig.1). A number of connecting plates are arranged in the opening on the bottom surface of the longitudinal ribs to form a semi-open structure. The semi-open longitudinal rib can reduce the constraint of the diaphragm, which can make the deformation of the rib-to-diaphragm more coordinated. This new structure can resolve the fatigue problem of orthotropic steel decks by means of structural optimization and weld quality improvement.
As a new type of structure, the research on the OBDs with semi-open longitudinal rib is relatively lack, and the fatigue cracking parts and fatigue properties of the structure are not studied in depth. For this reason, a full-scale fatigue test with a load of 10 million cycles has been carried out (Fig. 5). Fatigue cracks did not occur during the whole loading process, which verified that the new steel deck structure had excellent fatigue resistance. The fatigue properties of the structural details in the new OBDs were studied by finite element software, and reasonable structural parameters are determined. Finally, compared with the conventional OBDs with closed longitudinal rib, the superiority of fatigue resistance of the new OBDs with semi-opened longitudinal rib was reflected.

2. Structural parameters of the new steel bridge deck

2.1 Concerned details
The new steel bridge deck was mainly designed to improve the fatigue performance of the weld joints at the rib-to-deck and the rib-to-diaphragm. However, the lining plate and the connecting plate added in the new steel bridge deck also must be studied (Figure 2).

![Diagram of new bridge deck](image1)

**Figure 1** Diagram of new bridge deck

![Diagram of each fatigue detail](image2)

**Figure 2** Diagrams of Each Fatigue Details

2.2 Research on design parameters
In Figure 2, six details included detail A (the arc opening of the diaphragm), detail B (the longitudinal rib at the rib-to-diaphragm), detail C (the deck plate at the rib-to-deck), detail D (the longitudinal rib at the rib-to-deck), detail E (the lining plate-to-deck), and detail F (the connecting plate-to-rib) were studied. Taking stress amplitude as a measure of fatigue performance, the influence of deck, longitudinal rib, and diaphragm and lining plate, the connecting plate thickness and the longitudinal rib height on the structural details fatigue properties of the new steel bridge deck were studied.

Due to the need to leave enough space to weld inside the longitudinal ribs, the size of the longitudinal ribs should be enlarged. However, as the opening of the longitudinal rib increased, the deck was bound to produce a larger vertical bending deformation under the load, and there was a larger torsional deformation at the rib-to-deck joint. This out of plane deformation was unfavorable to the fatigue performance of the structural details, so the width of the longitudinal rib opening was 400mm. The selection of the remaining parameters are shown in Table 1.

| Analysis parameters                  | Values (mm) |
|-------------------------------------|-------------|
| Deck thickness                      | 12, 14, 16, 18, 20, 22, 24 |
| Rib thickness                       | 8, 10, 12, 14, 16, 18 |
| Diaphragm and lining plate thickness| 10, 12, 14, 16, 18 |
The relevant literature shows that the bearing system of steel deck under wheel load has obvious local effect. Therefore, the model size can be reduced and the wheel load can be simulated with a single wheel.

The shell element model was established by finite element software using ABAQUS, and the parameters of each component were changed, and the six fatigue details mentioned above were studied. The model was 7000mm long and 3500mm wide, including 3 diaphragms and 4 open longitudinal ribs, with two vertical stiffeners on both sides considering the boundary conditions. The elastic modulus is $E=206\text{GPa}$ and the Poisson's ratio is 0.3. A single point loading method was adopted. The load was loaded by the fatigue load model III in the JTG D64-2015. The loading area was 710mm×310mm, and the uniform load set was 0.273N/mm². The finite element model is shown in Figure 3. The loading position was at 600mm from the middle diaphragm, which was also the loading location selected by the test.

### Table 1.

| Connection plate thickness | 8, 10, 12, 14, 16 |
|---------------------------|-------------------|
| Rib height                | 340, 360, 380, 400, 420 |

As shown in Fig. 4 (a) ~4 (E), the stress of the structural details varies with the parameters in Table 1.

#### 2.3 Determination of each parameter in steel bridge deck

As shown in Fig. 4 (a) ~4 (E), the stress of the structural details varies with the parameters in Table 1.

**Figure 3** Finite element model

**Figure 4** Curves of stress in different structural details with main parameters

From Figure 4(a), it can be seen that the stress amplitude at the rib-to-deck increased with the deck plate thickness, which was the most significant change from 121.76MPa to 21.0MPa, about 82.6% reduction. But when the deck thickness was less than 16mm, the span ratio of the steel deck without
paving was greater than 1/700, which did not meet the requirements of JTG D64-2015. Under the control of the local deflection of the new bridge deck, the lower limit of the deck plate was 16mm. With the increase of deck thickness, the economic cost of the whole bridge will also add, so the upper limit would be 20mm.

From Figure 4 (b), it can be seen that the stress of the detail D (the longitudinal rib at the rib-to-deck) had a greater downward trend in stress, and the stress was reduced from 13.8MPa to 6.84MPa, about is 50.4% decrease. However, the stress amplitude was small, so increasing the longitudinal rib thickness was very uneconomical. Therefore, the thickness of longitudinal rib was 10mm controlled by the local stability.

As can be seen from Figure4(c), the stress of the detail A (the arc opening at the diaphragm) was most significant with the increase of the diaphragm thickness and the lining plate thickness, from 58.3MPa to 29.3MPa, about 49.7% drop. The hot spot stress of detail B showed a linear decreasing trend from 12.2MPa to 9.6MPa with a drop of 21.3%. Increasing the diaphragm and lining plate thickness can reduce the stress amplitude in the lower end of the longitudinal rib at the diaphragm-to-rib and the arc opening at the diaphragms to a certain extent. Therefore, the diaphragm and lining plate thickness can be reasonably increased to reduce the stress amplitude at the opening at the diaphragm. Considering the fatigue force and economy, the diaphragm thickness was recommended to be 12mm~14mm.

From Figure 4(d), we can see that the stress of detail A (the arc opening of the diaphragm) was most significant with the increase of longitudinal rib height. When the longitudinal rib height changed between 340mm~380mm, the stress of detail A had been decreasing, with a drop of 23.7%. When the longitudinal rib height changed between 380mm~420mm, the stress of detail A began to increase. Therefore, considering the influence of the stress amplitude at the arc opening of the diaphragm, the longitudinal rib height was recommended to be 380mm.

It can be seen from Fig.4 (E) that the connecting plate thickness had little effect on the fatigue properties of the structural details. The plate thickness was controlled by local stiffness, and 10mm was recommended.

3. Model test and finite element analysis of the new steel bridge deck

3.1 Test situation
Due to the need to be applied to practical engineering, considering the economy, the minimum value of the recommended thickness was taken. In order to verify the fatigue performance of the new structure, 10 million full-scale fatigue tests were carried out, and the superiority of the new structure fatigue performance was confirmed.

Taken two spans in the longitudinal direction and four open longitudinal ribs spacing in the horizontal direction, the test model was 7000mm long and 3500mm wide. The diaphragm spacing was 3200mm, and the longitudinal rib width opening was 400mm. The connecting plate was 560mm long, 280mm wide, and 430mm longitudinally spaced. The thickness of deck, longitudinal rib, diaphragm and lining plate and connecting plate was 16, 10, 12, 12, 10mm respectively, the longitudinal rib height was 380mm. Consolidating at the diaphragm bottom as the boundary condition. Consistent with the actual project, the Q345D steel was adopted in the test model. The experimental model was shown in Figure 5.
Figure 5 Loading Devices of Test Model

Adopted the fatigue load model III specified in JTG D64-2015. Considering the pavement diffusion effect, the loading area was 710mm×310mm. Took two-wheeled load as loading mode, and selected the place 600mm away from the middle diaphragm as loading position.

The minimum load of this fatigue test was \( P_{\text{min}} = 30\text{kN} \), the maximum load was \( P_{\text{max}} = 300\text{kN} \), and the load amplitude was \( \Delta P = 270\text{kN} \). The number of loading cycles was 10 million times, and the loading frequency was 6Hz. During the loading process, the static load test of 0~300kN was carried out in stages by stages, with 50kN at each level.

3.2 Finite element verification of the new steel bridge deck

Using shell element to simulate, the size, thickness and structural details of each plate were consistent with the experimental model, and the modeling details were consistent with figure 3. In order to verify the reliability of the finite element model, the finite element model adopted the loading mode and boundary condition consistent with the test model. The fatigue details of each component shown in Fig. 2 were emphatically focused during the test. Limited by the length of article, only three fatigue details of RD (rib-to-deck), RF (rib-to-diaphragm) and H (arc opening of the diaphragm) were compared with the measured values, thus verifying the accuracy of the finite element calculation. The calculated values and measured values of the DB, RF and H were shown in Figure 6.

![Figure 6 The measured and calculated value of the stress amplitude](image)

As can be seen from Fig. 6, the calculated values and measured values of RD, RF and H showed a linear change. The calculated values of DB and RF were slightly larger than the measured values, while the calculated values of H were smaller than the measured values. The main reason was that during the test loading process, due to the error of the loading equipment, there was a slight horizontal force along the bridge, and the force in vertical direction was smaller than that in finite element loading, so the measured values of DB and RF were smaller. The horizontal partition made the diaphragm produced large out of plane deformation, and the external deformation had a great influence on the opening of the diaphragm, so the measured value of H was larger than that of the calculated value.

In general, the measured value in the static load of the experimental model was in good agreement
with the theoretical value of the finite element, and the variation law was more consistent. It showed that the finite element model can better reflect the actual stress state of the model and could be applied to the fatigue analysis of structural fatigue.

4. Comparison and analysis of the new and conventional steel bridge deck

4.1 Calculation condition

The difference between the new and conventional steel bridge decks was that the bottom at the longitudinal rib of the new steel bridge deck was open, the longitudinal rib height was different and the new steel bridge deck was added with the lining plate and the connecting plate (the two longitudinal rib forms of the steel bridge deck were shown in Figure7.

(a) Conventional rib (b) New type rib with connection plate (c) New type rib (no connection plate)

Fig.7 A diagram of the longitudinal rib in two kinds of steel bridge decks

The stress levels and lateral and longitudinal stress influence lines of the two kinds of steel bridge deck will be different. Considering the different transverse and longitudinal conditions, the single wheel load in fatigue load model III specified in JTG D64-2015 was loaded. Due to the obvious local effect of the loading system of the steel deck under wheel load, the wheel load was simulated by a single wheel. Considering the diffusion effect, the wheel load area was 710mm×310mm and the size was 60kN, so the surface load of 0.273kN/mm² was applied to every working condition.

The load was moved at a distance 600mm from the diaphragm and moved 100mm along the transverse, and a total of 30 working conditions. According to the lateral influence line, the most unfavorable position of the two kinds of steel bridge deck was found. In the most unfavorable position, the load moved along the longitudinal bridge, moving 200mm every time, and a total of 31 working conditions, and the longitudinal influence lines of the two kinds of bridge deck were obtained.

The lateral and longitudinal influence lines of the two kinds of bridge decks were compared, and the stress level and stress distribution of three details of the details A (rib-to-deck), the detail B (rib-to-diaphragm) and the detail C (the arc opening at the diaphragm) were emphatically analyzed.

4.2 Stress analysis of the deck at the rib-to-deck

Selecting the mid span structure as the research object, the lateral and longitudinal stress lines of the deck at the rib-to-deck were shown in Figure 8.

(a) Lateral (b) Longitudinal

Fig.8 Lateral and longitudinal influence lines of the deck at the rib-to-deck details
The results showed that: (1) The longitudinal ribs of the conventional and new steel deck plates were different, so the most unfavorable position of structural details in lateral position was different. The conventional longitudinal ribs reached the maximum value in working condition 15, and the new longitudinal ribs reached the maximum value in working condition 16. However, the location of the centerline of both wheels was directly above the web at the longitudinal rib, which indicated that the mechanical characteristics of the conventional and new steel deck were similar. (2) With the change of load longitudinal position, the stress deceleration rate of the new steel bridge deck was smaller than that of the conventional steel deck. This is because the new steel bridge deck welded the connecting plate at the bottom of the longitudinal ribs, and the local stiffness of the place with connection plate was larger. (3) The main reason was that the longitudinal ribs opening of the new steel bridge deck was larger, and the lateral rigidity was smaller. Under the action of wheel load, the deck would produce more vertical bending, and the connection between the deck and longitudinal rib would inevitably produce greater torsional deformation. However, the full penetration welding was used to connect the deck and longitudinal ribs of the new steel deck to improve the weld eccentric force. Fatigue cracks did not occur during the 10 million loading process. The results showed that the full penetration weld of the new steel bridge deck greatly improved the fatigue performance of this structural detail, and improved the fatigue performance of this structural detail from two aspects of welding technology and structural optimization.

4.3 Stress analysis of the rib at the rib-to-deck
The structural details of the middle diaphragms were chosen as the object of study. The lateral and longitudinal stress lines were shown in Figure 9.

4.4 Stress analysis of the arc opening at the diaphragm
The lateral and longitudinal stress lines at the arc opening of the diaphragm were shown in Figure 10.
The results showed that: (1) The stress amplitude at the opening of the diaphragm of the new and conventional steel deck were equivalent. (2) The lateral and longitudinal influence lines of new and conventional steel deck had similar change rules. The most unfavorable lateral loading position was directly above the web at the longitudinal rib. The most unfavorable position in the longitudinal direction was not at the top of the diaphragm, but at the distance 200mm from the diaphragm, which was the cause of the lateral deformation and the stress concentration at the opening of the diaphragm.

5. Conclusions

(1) Through the analysis of the influence of the connecting plate thickness, the deck and the longitudinal rib thickness, the diaphragm and the lining plate thickness and the longitudinal rib height on the structural details stress amplitude, the reasonable values of the structural details of the new type bridge deck were given: the deck thickness is 16mm~20mm, the longitudinal rib thickness is 10mm, the diaphragm and the lining plate thickness are 12~14mm, the connecting plate thickness is 10mm, and the rib height is 380mm.

(2) The static measured values of the full scale model test were compared with the finite element simulation values. Both of them were in good agreement and the law was consistent, which showed that the finite element simulation results could better reflect the actual force performance of the model.

(3) The new steel bridge deck was compared with the conventional steel bridge deck. Although the stress of the deck at the rib-to-deck was larger due to the smaller lateral stiffness, the full penetration welding was adopted at the connection between the deck and longitudinal ribs, which reduced the weld eccentricity and upgraded the welding grade of this structural detail. The fatigue properties were improved from two aspects: welding technology and structural optimization.

(4) The longitudinal rib of the new type steel bridge deck reduced the restraint degree of the longitudinal rib to the diaphragm, so that the deformation of the longitudinal rib and the diaphragm was more coordinated, thus effectively reduced the stress concentration degree. The stress amplitude of the longitudinal rib of the new steel bridge deck was close to 50% smaller than that of the conventional steel bridge deck. It showed that the fatigue performance of the new type steel bridge deck was improved from the angle of structural optimization.

(5) The stress characteristics of the new and conventional steel deck were similar. The most unfavorable lateral loading positions were directly above the web at longitudinal rib of both, and the most harmful position of the deck was at the loading location. The most detrimental position at the rib-to-diaphragm was at 600mm from the diaphragm, and the most adverse position of the load at the arc opening of the diaphragm was at 200mm from the diaphragm.

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