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Research on the Rationality of Setting the Transverse Ribs of Large Cantilever Segmental Prefabricated Box Girders

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Abstract: This article develops three transverse rib setting schemes for a 20 m wide cantilever segmental box girder of a particular engineering bridge deck, analyzes the stress rules under loads such as dead load, live load, and temperature, and studies the lateral deformation characteristics of the three schemes under symmetrical and eccentric live load arrangements on the bridge deck. Research has shown that setting transverse ribs can significantly improve the transverse stress, crack resistance, and reduce vertical deformation of the cross-section. However, its effect gradually weakens with the increase in the number of transverse ribs. Considering the convenience and simplicity of construction, installing a transverse rib structure for the large cantilever section box girder in this project is recommended.

Keywords: large cantilever segmental assembly box girder; transverse rib; lateral force; crack resistance; vertical deformation

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1. Introduction

With the rapid development of the economy and society in recent years, existing transportation needs to be improved to meet urban development requirements. In order to solve the problems caused by road congestion and low traffic efficiency, urban transportation increasingly needs to develop toward three-dimensional transportation, that is, building elevated bridges based on existing roads. In the construction of elevated urban bridges, the concept of "industrial manufacture, rapid construction" has been proposed through engineering practice in China and internationally. This means the upper and lower structures are assembled, manufactured in the factory, and transported to the site for installation [1–3] as shown in Figure 1.

Figure 1. Rapid construction of segmental precast box girder.

When using prefabricated bridges for the upper structure, to coordinate the contradiction between "high urban landscape requirements" and "small on-site construction workload", some projects have proposed large cantilever segmental assembled box girder structures suitable for medium spans. This structural form is beautiful, and the box beam segments can be factory standardized. The on-site construction workload is small, and the construction quality and efficiency are high. The box girder segment is relatively small and lightweight, making it suitable for long-distance transportation, which is strong adaptability to curved and widened bridges. This scheme can adopt a system with few or no supports, resulting in less maintenance work in the later stage. However, due to the use of a large cantilever structure, such spatial force characteristics of this bridge and lateral distribution are generally more complex.

This article designs three construction schemes for a 20 m wide cantilever segmental assembled box girder (single box and single chamber) section of a certain bridge, including no transverse ribs, one transverse rib, and two transverse ribs. The transverse force analysis of the structure under vehicle load is carried out by establishing a finite element solid model of the segmental girder. Based on the transverse force performance of the three construction schemes, feasible design, and structural optimization schemes are proposed.

2. Project Overview

A certain highway renovation and expansion project is located in a developed economic region with highly urbanized surroundings, and there are many control factors along the project, including primary water sources, basic farmland, and other environmentally sensitive points, as well as parallel and intersecting various subways, highways, and local roads of various levels. Therefore, a three-dimensional expansion method for elevated bridges needs to be adopted.

The main design parameters of this project are a bridge width of 20 m with a single-lane road with 4 lanes on the highway with a design speed of 100 km/h and a vehicle load level of Highway I.

To meet rapid construction requirements, this project adopts a large-scale prefabricated and assembled concrete beam bridge span of 48 m, a single box, and a single chamber scheme, with a bridge deck width of 20 m and a bottom width of 10.24 m. The top plate is 28 cm, the bottom plate is 27 cm, and the thickness of the side and web plates is 60 cm. The standard cantilever length is 4 m, the height of the cantilever end is 20 cm, and the height of the cantilever root is 60 cm. The cross-section of the main beam is shown in Figure 2, and the standard segment length is 3 m.

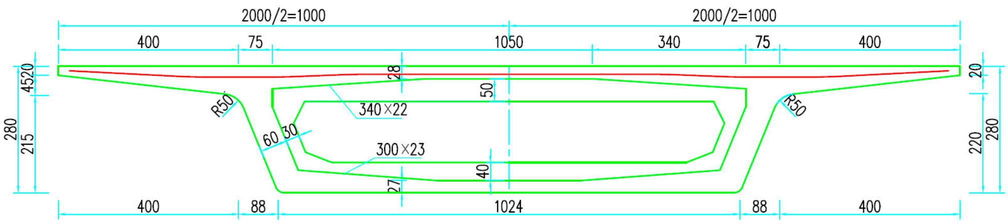

Figure 2. Cross-section of segmental prefabricated box girders (Unit: cm).

Due to the sizeable transverse span of the bridge deck and the use of a single box and single chamber section, how to reasonably set up transverse stiffeners inside the box (from now on referred to as 'transverse ribs') to improve the transverse stress of the box girder is a technical challenge faced by this project. Three plans have been formulated for the above main beam cross-section.

3. Explanation of Finite Element Model and Calculation Conditions

3.1. Finite Element Model

Based on existing research from the literature [4–10], the lateral analysis of box girders generally adopts spatial solid finite element calculation, which can effectively simulate the spatial force effect of large cantilever box girders. The commercial finite element program Abaqus establishes the spatial finite element model. According to the principle of Saint-

Venant, the segment length of 24 m is taken for modeling. The finite element model is shown in Figure 3. Bearings are set on both sides to form a spatial, simple supported structure.

The concrete is simulated using the solid element C3D8R. Ordinary steel bars and prestressed steel bars are simulated using rod element T3D2. The mesh dimension is 0.1 m.

The concrete box girder, the ordinary steel bars and the prestressed steel bars are constrained by embedded constrain.

The C55 concrete uses the ordinary concrete damage plastic mode, and its constitutive model adopts the relevant provisions of the "Code for Design of Concrete Structures" (GB 50010-2010) [11]. Ordinary steel bars adopt a bilinear elastic-plastic model. The prestressed reinforcement adopts an ideal elastic-plastic model and is prestressed by the cooling method.

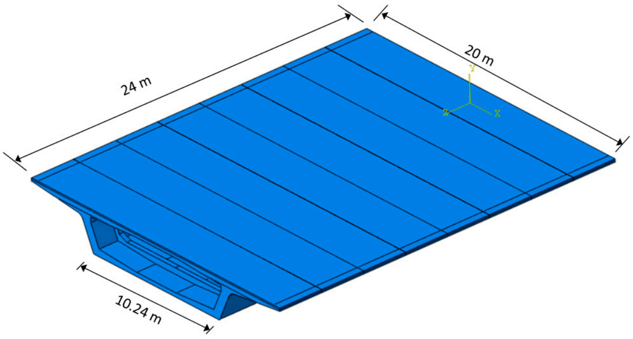

Figure 3. Segmental calculation model.

3.2. Explanation of Calculation Conditions

The structure adopts C55 concrete, with a material gravity density of 26 kN/m^3 and a steel strand gravity density of 78.5 kN/m^3.

The prestressed steel strands are post-tensioning and adopt 5-Φ_S 15.2; please refer to Table 1 for specific arrangements. The strength of prestressed steel strands is 1860 MPa, and the tensile control strength is 1395 MPa. The friction coefficient between the steel bundle and pipeline wall μ is taken as 0.55, the pipeline deviation coefficient k is taken as 0.0015. The instantaneous loss caused by frictional resistance, elastic compression, etc., is considered to be 8%, and the long-term prestress loss caused by shrinkage and creep is considered to be 12%.

Table 1. Layout plan for transverse ribs of 20 m wide segmental prefabricated and assembled concrete beams.

Number	Number of Transverse Ribs	Transverse Rib Spacing	Transverse Rib Thickness	Horizontal Prestressing Arrangement
Scheme 1	0	—	0.5 m	5-Φ_S 15.2 with a spacing of 0.5 m
Scheme 2	1	1.5 m	0.5 m	5-Φ_S 15.2 with a spacing of 0.5 m
Scheme 3	2	1 m	0.3 m	5-Φ_S 15.2 with a spacing of 0.75 m

Phase II dead load: the gravity load of ancillary facilities such as bridge deck pavement and guardrails. The bridge deck pavement is made of 10 cm asphalt concrete with a unit weight of 24 kN/m^3. The load concentration of the guardrail is considered as 22 kN/m^3 on one side.

Vehicle load: the vehicle load is used for loading, based on the 55 t vehicle load model provided in the "General Specification for Design of Highway Bridges and Culverts" (JTG

D60-2015) as the standard, considering the lateral reduction of multiple lanes and an impact coefficient of 0.3.

Temperature load:

(1) Uniform temperature: overall heating +25 °C, overall cooling −25 °C;

(2) Difference in temperatures shall be implemented in accordance with the General Specification for Design of Highway Bridges and Culverts (JTG D60-2015) [12], with a maximum temperature rise of 14 °C for the top plate and a maximum temperature drop of −7 °C. Linear interpolation shall be made according to the thickness of the bridge deck and flange.

This project is a transverse stress analysis of the box girder as shown in Figure 4. The longitudinal bridge stress analysis will be distorted because the structure was not fully simulated, and the longitudinal prestressing effect was not considered. Therefore, only the structure's transverse stress is concerned when checking bridge decks' crack resistance, and the principal stress is not taken as the standard.

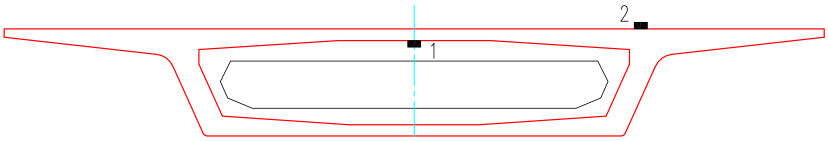

Figure 4. Schematic diagram of control section, 1 and 2 are the stress control point.

According to the influence line analysis, the vehicle load layout corresponding to the most unfavorable stress position 1 is shown in Figure 5a (eccentric load condition). The layout of the vehicle load corresponding to the most unfavorable stress position 2 is shown in Figure 5b (medium load condition).

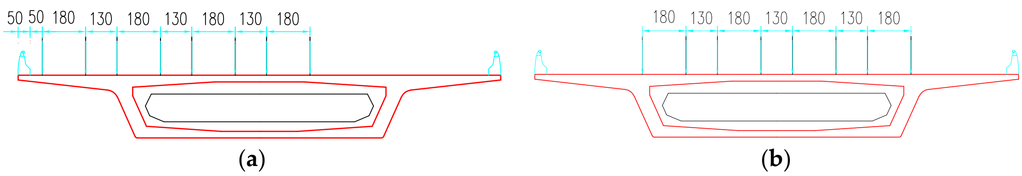

Figure 5. Load cases corresponding to the most unfavorable stress location. (**a**) Eccentric load condition (unit: cm). (**b**) Medium load condition (unit: cm).

4. Analysis of Lateral Stress Performance under the Action of Four Single Factors

The top plate of the segmental box girder serves as the compressive zone of the main beam in the longitudinal direction (the negative bending moment zone is the tensile zone), bearing a significant principal compressive stress. Due to the large transverse cantilever and wide box chamber, the top plate of the segmental box girder exhibits the force characteristics of a continuous beam in the transverse direction: there is a maximum transverse negative bending moment at the web plate and a maximum positive bending moment in the middle of the box chamber. In addition, in many current projects, the transverse tensioning and prestressing of the top plate are still being carried out. Therefore, there is a significant spatial stress effect in segmental box girders.

Based on existing research results [13–17], the transverse normal stress distribution of the box girder bridge deck is considered independent of the section's longitudinal position. Therefore, to facilitate the analysis of the stress of the segmental girder, two segments in the middle of the whole bridge span are taken as the observation targets, and the transverse normal stress distribution of the box girder roof position is focused. In order to fully show the influence of various load factors on the lateral force of the box girder, the calculation is based on self-weight, prestress, secondary dead load, difference in temperatures, and live load, respectively. The calculation results are shown in Table 2.

Table 2. Calculation results of lateral force on box girders under single factor action (unit: MPa).

Part		Self-Weight	Transverse Prestressing	Phase II Dead Load	Overall Temperature		Difference in Temperatures		Live Load	
					Heating	Cooling	Heating	Cooling	Eccentric Load Condition	Medium Load Condition
Scheme 1	Pos 1	0.33	−8.10	0.15	−0.16	0.21	0.93	−0.46	2.29	3.12
	Pos 2	2.01	−6.01	0.71	−0.21	0.15	−1.95	0.97	7.62	6.63
Scheme 2	Pos 1	0.13	−7.25	0.06	−0.18	0.19	0.47	−0.235	−0.47	−0.42
	Pos 2	1.21	−5.41	0.62	−0.19	0.17	−2.16	1.08	4.63	2.99
Scheme 3	Pos 1	0.02	−6.16	0.01	−0.13	0.15	0.28	−0.14	−0.49	−0.43
	Pos 2	0.75	−4.25	0.53	−0.14	0.13	−2.43	1.22	3.21	2.01

Positive stress represents tensile stress, while negative represents compressive stress.

From the above calculation results, it can be seen that:

(1) Under the action of self-weight, as the number of transverse ribs increases, the internal forces at positions 1 and 2 of the cross-section gradually decrease, which is due to the increase in the stiffness of the closed frame due to the arrangement of transverse ribs.

(2) Under the action of transverse prestress, when there is no rib plate scheme, the transverse prestress is 6–8 MPa compressive stress. When adding a rib plate, the transverse prestress is reduced to a compressive stress of 5–7 MPa. When adding two rib plates, the transverse prestress is reduced to a compressive stress of 4–6 MPa. Overall, as the number of transverse ribs increases, the prestressing effect gradually decreases.

(3) Under the action of the second phase dead load, the stress pattern is the same as under the action of self-weight. The cross-sectional stress improves with the increase in the number of transverse ribs set.

(4) Under the overall temperature effect, the setting of stiffeners does not significantly improve temperature stress.

(5) Under the effect of the difference in temperatures, as the number of transverse ribs increases, the additional tensile stress generated by the difference in temperatures gradually decreases.

(6) Under live load, the ribbed plate scheme significantly improves the stress at both critical positions. The scheme without ribs generates a maximum tensile stress of about 7.62 MPa at position 2. The scheme of adding a rib plate reduces the tensile stress at position 2 to about 4.63 MPa. The scheme of adding two rib plates reduces the tensile stress at this position to about 3.21 MPa, and its stress improvement effect is better than the scheme of one rib plate. At crucial position 1, after setting a rib plate, there is no tensile stress on the bottom surface of the top plate, and the effect of setting two rib plates is the same. However, it should be noted that considerable tensile stress will be generated at the position of the top plate transverse rib, as shown in Figure 6. One transverse rib has a maximum tensile stress of 5.86 MPa, and two transverse ribs have a maximum tensile stress of 3.21 MPa, significantly exceeding the tensile design strength of ordinary concrete. It is possible to consider partially prestressed passing through transverse ribs when designing this girder.

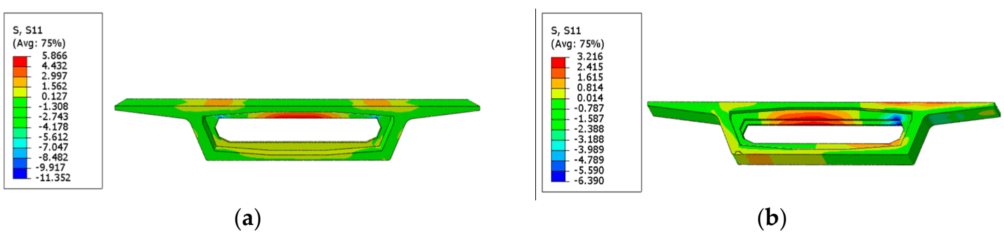

Figure 6. Calculation results of transverse ribs under vehicle load (unit: MPa). (**a**) One transverse ribbed box girder. (**b**) Two transverse ribbed box beams.

In summary, it can be seen that after the prefabrication of the box girder is completed (prestressed tensioning has been completed), the primary control load condition for key positions 1 and 2 of the box girder is live load, which generates more than 80% of the internal force. The setting of transverse prestressing also plays a crucial role in improving the transverse crack resistance performance of the top of the box girder, and attention should be paid to the reasonable and adequate arrangement of transverse prestressing in design.

5. Analysis of Lateral Crack Resistance Performance

When analyzing the transverse stress of box beams, considering the economic benefits of setting up transverse prestressed steel tendons as shown in Figure 7, the transverse prestressed effect can be designed as a Class A prestressed structure, and its crack resistance calculation should comply with the requirements of the "Design Specification for Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts" (JTG 3362-2018) [18], so that the stress under frequently combined actions should not exceed 0.7 ftk (ftk is the standard value of concrete tensile strength). In this project, the box girder is made of C55 concrete, with tensile stress not exceeding 1.848 MPa.

The crack resistance calculation results of the three most unfavorable combination conditions under the combined action of "self-weight + lateral prestressing + second stage dead load + temperature load + live load" are shown in Figure 8. In this calculation, the top plate steel tendon is considered to pass through the transverse ribs.

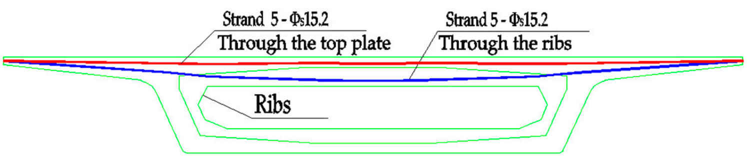

Figure 7. Schematic diagram of strand passing through transverse ribs.

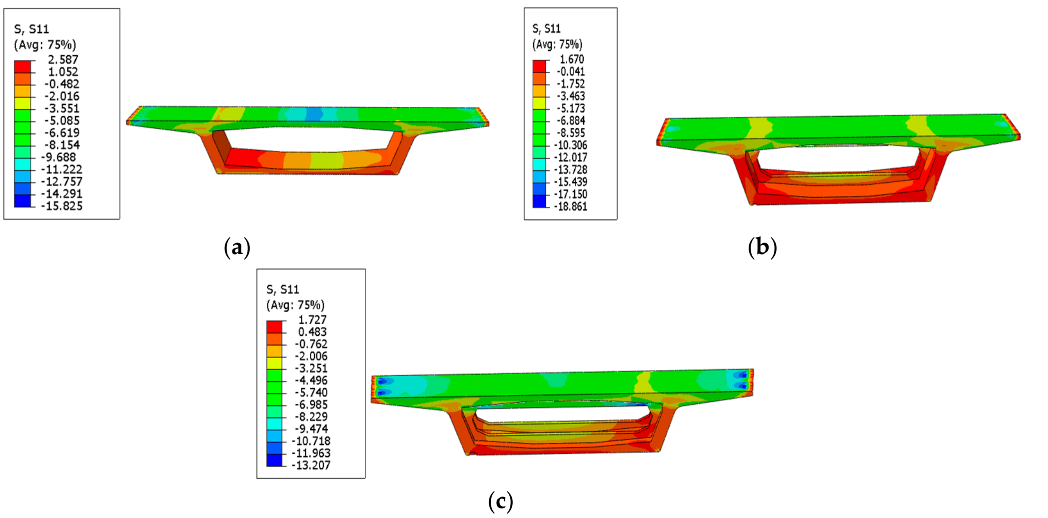

Figure 8. Calculation results of crack resistance performance of box beam cross-section (Unit: MPa). (**a**) Box girder without transverse ribs. (**b**) One transverse ribbed box beam. (**c**) Two transverse ribbed box beams.

The above calculation results show that when using the non-transverse rib scheme, there will be a tensile stress of about 2.58 MPa at the bottom plate position of the box beam. Although the tensile stress value is small, it does not meet the crack resistance requirements. Using one transverse rib and two transverse ribs can effectively decrease the stress on the top and bottom plates, but the strengthening effect of one transverse rib and two transverse ribs is similar.

6. Lateral Deformation Analysis

Due to its characteristics of a large cantilever and large box chamber, as well as the presence of longitudinal and transverse coupling effects, the large cantilever box girder has obvious deformation spatial effects. The transverse bending caused by transverse force and the shear deformation caused by longitudinal force jointly constitutes its transverse deformation. The deformation characteristics can be reflected through the deformation curve of the roof. According to the analysis in Section 4, it can be concluded that live load is the controlling condition for lateral force, so the focus is on analyzing the lateral deformation under the action of live load.

Referring to the method of reference [13–17,19–21], Figures 9 and 10 show the transverse distribution of section deflection under vehicle load (eccentric load) and vehicle load (medium load).

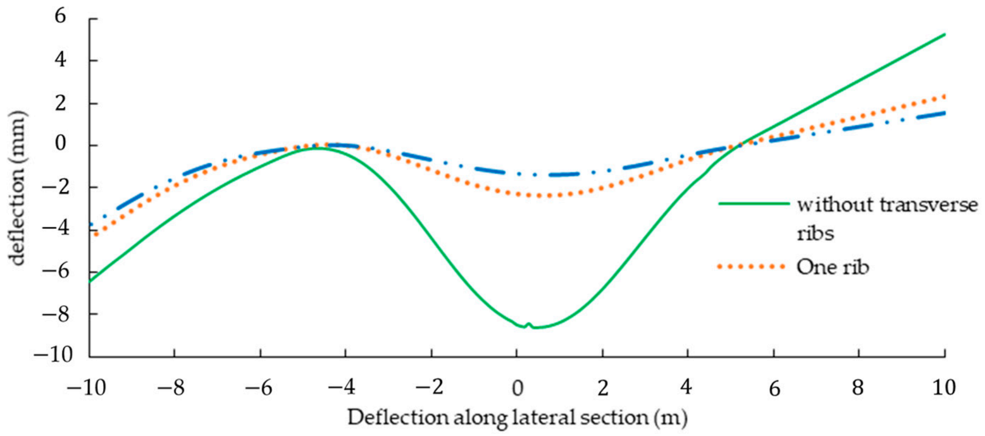

Figure 9. Calculation results of lateral deformation under vehicle load (eccentric load).

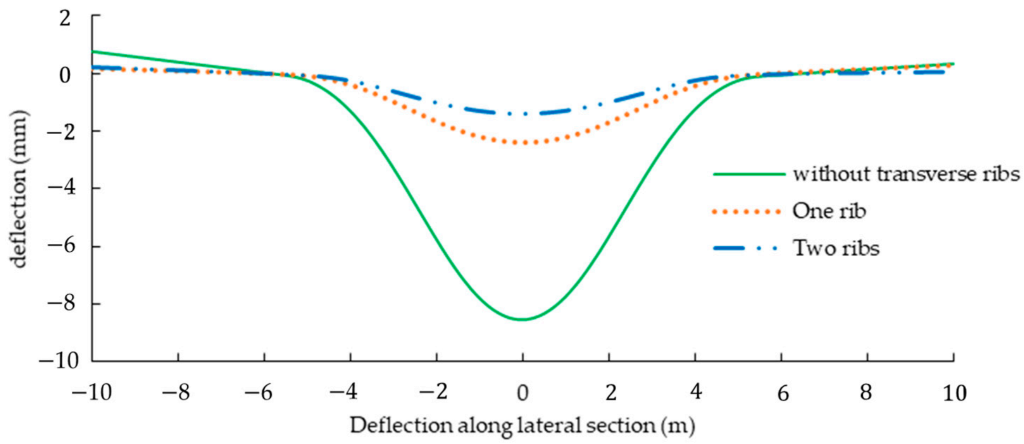

Figure 10. Calculation results of lateral deformation under vehicle load (medium load).

From the above figures, it can be seen that when the box beam is not equipped with transverse ribs, the maximum deflection under medium load reaches 8 mm, located in the middle of the box chamber, with a maximum deflection difference of about 8.5 mm. The maximum deflection under eccentric load reaches 8 mm, located in the middle of the box chamber, with a maximum deflection difference of approximately 12 mm.

When a transverse rib is installed on the box girder, the maximum deflection under medium load reaches 2.4 mm, located in the middle of the box chamber, with a maximum deflection difference of about 2.6 mm. The maximum deflection under eccentric load reaches 4 mm, located on the outer side of the cantilever, with a maximum deflection difference of approximately 6 mm.

When two transverse ribs are installed on the box girder, the maximum deflection under medium load reaches 1.4 mm, located in the middle of the box chamber, with a maximum deflection difference of approximately 1.6 mm. The maximum deflection under eccentric load reaches 3.8 mm, located on the outer side of the cantilever, with a maximum deflection difference of approximately 4.9 mm.

To ensure smooth driving, referring to Article 8.2.5 of the "Design Specification for Highway Steel Structure Bridges" (JTGD64-2015) [22], the maximum lateral deflection of the box room should not exceed 1/700 of the calculated span so that the deflection at mid-span should not exceed 14.6 mm, and the cantilever end should not exceed 5.7 mm. Scheme 1 (without transverse ribs) does not meet the requirements, while both Scheme 2 and Scheme 3 can meet the requirements.

7. Main Conclusions and Suggestions

(1) Under self-weight and phase II dead load, the arrangement of stiffeners can appropriately decrease the stress of the large cantilever segment box beam, but the improvement is insignificant.

(2) When the number of transverse ribs is large, it will harm the effect of applying transverse prestress to the large cantilever section box girder. Each additional transverse rib reduces the transverse prestressing effect by about 20%.

(3) The vehicle load mainly controls the lateral stress of the large cantilever segmental box girder. The calculation results show that the ribbed plate scheme significantly improves the structural stress under vehicle load. Under three working conditions, the ribbed plate scheme can effectively reduce the tensile stress at the stress control point compared to the non-ribbed plate scheme, but two ribbed plates have no advantage compared to one rib plate. It is even possible to have adverse effects on the stress at the root position of the roof cantilever.

(4) Under the influence of temperature, the stress of the large cantilever section box girder with ribbed plates is improved compared to the large cantilever section box girder without ribbed plates. However, whether it is arranged with single- or double-ribbed plates, the impact on the transverse force of the section is relatively small. Therefore, temperature factors can be temporarily ignored when formulating the preliminary design plan.

(5) Installing rib plates inside the large cantilever segmental box girder effectively decreases the stress on the top and bottom plates. However, due to the redistribution of internal forces, the stress on the rib plates is relatively high. Designers should emphasize strengthening the crack resistance calculation and reinforcing the transverse ribs.

(6) After setting prestress in the transverse direction of the large cantilever segmental box girder. However, it can effectively control the cracking of the bridge deck. It cannot guarantee the crack resistance requirements of the entire section. Among the three schemes in this project, Scheme One (without transverse ribs) cannot meet the requirements for crack resistance of prestressed concrete Class A components. After setting the transverse ribs, the crack resistance of the entire transverse section can be significantly improved.

(7) Under the action of live load, the most unfavorable loading condition for lateral deformation of large cantilever section box beams is the eccentric load condition, and setting transverse ribs can effectively decrease lateral deformation. When more than one transverse rib is installed, the effect of improving vertical deformation in the middle of the span is significant, but the effect of controlling and improving the outermost deformation of the cantilever under eccentric load is limited.

Overall, for the web and bottom plates, the installation of transverse stiffeners can decrease their stress, reduce the maximum tensile stress in the transverse direction of the concrete bridge, and reduce the deformation of the transverse span and cantilever. However, the effect gradually weakens with the increase in transverse ribs. Considering the convenience and simplicity of construction, it is recommended to use a transverse rib structure for the large cantilever section box girder.

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