Research on the Key Technology of Hybrid Beam Cable-stayed Bridge with Limit Side Mid-span Ratio

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Abstract: Taking the main span of 716 meters mixed girder cable-stayed bridge (side mid-span ratio 0.251) as an example, the key technologies such as fully floating and semi-floating structure system, the position of steel-concrete combined section, and the use of thick slab concrete and iron sand concrete for side span weight are studied. The results show that: (1) As for the main girder, the bending moment at the column of the full-wave scheme is only 36.4% of that of the semi-wave scheme, and the bending moment of the stiffened girder in other areas is the same as that of the semi-wave scheme. In terms of main beam stiffness, there is little difference between full-floating scheme and semi-floating scheme. (2) In the completed bridge state, the longitudinal bending moment of the joint section located at the middle span is far greater than that of the side-span scheme, and the dead load bending moment distribution of the main girder is not ideal. Under the operation condition, the longitudinal bending moment of the main girder of the two schemes is roughly the same under live load. In terms of supporting reaction force, the joint section is located at the middle span, and the supporting reaction force of the auxiliary pier near the bridge tower is far greater than that of the side-span scheme. (3) The thick slab concrete design can not only ensure that the bridge and the construction state of the side span of the fulcrum are not negative reaction and under pressure, but also has no pressure to fix measures, simplify the construction process, convenient later inspection and maintenance.

1. INTRODUCTION

Hybrid girder cable-stayed bridge, that is, the main girder in the side span of a part or all of the concrete beam, the rest of the beam section using steel beam or composite beam cable-stayed bridge\cite{1}. The midspan ratio of mixed girder cable-stayed Bridges is generally 0.3 ~ 0.45. The span layout of a mixed-beam cable-stayed bridge is 3×60+716+3×60=1076m, and the side mid-span ratio is 0.251. The overall layout of the bridge is shown in Figure 1. The mid-span ratio of this bridge is close to the limit mid-span ratio (except anchor cable-stayed bridge). Therefore, it is necessary to study the structural system, the position of joint section, the pressure weight of side span and other key technologies.
2. STRUCTURAL SYSTEM RESEARCH

According to the combination mode of tower, cable and beam, cable-stayed bridge can be composed of four different structural systems, namely, floating system (full floating), supporting system (semi-floating), consolidation system of tower and beam, and rigid structure system[2-5]. The four forms are all mature schemes and have been widely used in the world. The tower beam consolidation system and rigid frame system are mostly used in cable-stayed Bridges with the main span below 400m. The main span of this bridge is 716m. Therefore, two schemes of full floating and half floating are considered, and the corresponding full bridge finite element model is established for analysis and calculation and comparison, so as to select a more suitable structural system scheme.

2.1 Stress comparison of main girder

The bending moment pairs of main girder under dead load plus live load are shown in the figure below:

As can be seen from the above figure, the maximum longitudinal bending moment at the tower of the all-floating scheme is 46848kN·m under dead load plus live load conditions, and the maximum longitudinal bending moment at the tower of the semi-floating scheme is 128735kN·m. The bending moment at the tower of the all-floating scheme is only 36.4% of that of the semi-floating scheme. In other areas, the bending moment of both stiffeners is equivalent.
2.2 Main girder stiffness comparison
Vertical displacement of main girder under live load is shown in the figure below:

![Fig. 3 Vertical displacement of main girder under live load (unit: cm)](image)

The live load displacement of the side span near the tower area in the all-floating scheme is slightly greater than that in the semi-floating scheme, but the difference is not significant. Vertical stiffness of the two schemes meet the requirements of the code.

2.3 Analysis of construction scheme
In order to avoid the problem of high support construction risk caused by using cast-in-place concrete box girder in cable tower area, the construction scheme of two sides of cable tower area is adjusted to hoisting steel box girder stored on low support. The bridge adopts single-column cable tower. If the support is set at the cable tower, the large cantilever beam is needed, which will not only affect the appearance of the bridge, but also cause unreasonable stress on the beam. The full floating system can avoid the problems of the large cantilever beam setting affecting the appearance of the bridge and the unreasonable stress on the beam, and also facilitate the hoisting of the steel box girder.

Based on the above factors, the stress comparison of the main girder shows that the force and displacement of the whole floating system and the semi-floating system all meet the requirements of the code. Considering from the construction scheme, the bridge adopts the full floating system, which can not only avoid the problems of beautiful appearance and unreasonable stress caused by the installation of large cantilever beams, but also facilitate the hoisting of steel box girders. It can be seen from the engineering example that the cable-stayed bridge with long span and split girder basically adopts the all-floating system. Considering all the factors, the bridge adopts the full floating system. At the same time, in order to limit the lateral and longitudinal displacement of the structure, the horizontal wind resistance support and the longitudinal viscous damper with limiting function are set at the cable tower [6].

3. STUDY ON POSITION OF STEEL-CONCRETE JOINT SECTION

3.1 Combine segment position selection
Reasonable use of the properties of the two materials for the hybrid beam improves the structural stress, span capacity and economy greatly. However, the steel-concrete section is located at the abrupt change of material and structural characteristics, and is the key control position for the design of the
hybrid beam[7-8]. According to the different overall layout of the bridge and considering the factors of structural stress, construction and economy, the position of the steel mixing part of the main girder of the mixed girder cable-stayed bridge can be set in the middle span, the center of the bridge tower and the side span. Considering the structural force, the reasonable joint position of the mixed girder cable-stayed bridge needs to take into account the structural performance requirements from both the overall force of the bridge structure and the local force of the joint section[9-10]. For highway Bridges due to live load, the dead load are much smaller, usually less than 20% of the dead load, so this project adopts mainly considering the constant load and live load of thought to determine the bridge combined with reasonable location, design combined with the different positions of two kinds of schemes, and the whole bridge finite element model is established, the calculation and analysis are carried out, and the location of the joint section of the bridge is selected.

In order to study the position of the joint section suitable for the bridge, according to the experience of the cable-stayed bridge built, the force comparison analysis is conducted according to the position of the joint section in the side span and in the middle span. Scheme 1 is that the joint section is located at 35m from the side span to the bridge tower, and Scheme 2 is that the joint section is located at 20m from the side span to the bridge tower.

3.2 Analysis of completion state of bridge
The longitudinal bending moments of the main girder in the completed bridge state are shown in the figure below.

![Fig. 4 Longitudinal Bending Moment Diagram of Main Girder under Complete Bridge Condition (Unit: kN\cdot m)](image)

As can be seen from the above figure, under the action of dead load, the bending moment at the position of the joint section in Scheme 1 is 9310.3kN\cdot m, and the bending moment at the position of the joint section in Scheme 2 is 232,820.1kN\cdot m, much higher than that in Scheme 1. The distribution of the bending moment at the dead load of the main beam is not ideal, and meanwhile, the side span is overweight.

3.3 Operational status analysis
Under the action of live load, the longitudinal bending moment of the main girder is shown in the figure below.
It can be seen from the above figure that, under the action of live load, the internal forces in all areas are roughly the same except for the location of the binding section, where Scheme 2 is greater than Scheme 1.

3.4 Analysis of construction scheme

The bridge height at the side tower of the large pile number of the bridge is over 70m. Combine the period set in the midspan, cable tower near the bracket of cast-in-situ concrete beams is a greater risk of construction safety, and the combination set in side span, bracket of cast-in-situ concrete beams under highly reduced to 55 m, cable tower area of steel box girder, the use of the stored on lower bracket hoisting construction plan, the lower bracket construction also can reduce the affect on both sides of the road. To make the construction safety risk of the main girder in the cable tower area more controllable, so the joint section of the bridge should be set on the side span considering the construction scheme.

3.5 Support reaction force analysis

Under dead load plus live load, the reaction forces of structural support are shown in Table 1 and Table 2.

| Support position | Minimum reaction force | Maximum reaction force |
|------------------|------------------------|------------------------|
|                  | left side   | right side  | left side   | right side  |
| 0 abutment       | 10547       | 10422       | 16624       | 16481       |
| No. 1 auxiliary pier | 16380       | 16438       | 29360       | 29464       |
| No. 2 auxiliary pier | 17303       | 17605       | 29738       | 30078       |
| No. 5 auxiliary pier | 17376       | 17211       | 30047       | 29885       |
| No. 6 auxiliary pier | 7874        | 7892        | 20553       | 20568       |
| 7 abutment       | 5576        | 5581        | 11373       | 11378       |

| Support position | Minimum reaction force | Maximum reaction force |
|------------------|------------------------|------------------------|
|                  | left side   | right side  | left side   |
| 0 abutment       | 12134       | 11990       | 18138       |
| No. 1 auxiliary pier | 10453       | 10166       | 23525       |
| No. 2 auxiliary pier | 35256       | 35808       | 49157       |
| No. 5 auxiliary pier | 35191       | 34921       | 49373       |
| No. 6 auxiliary pier | 2455        | 2374        | 15221       |
| 7 abutment       | 7179        | 7151        | 12913       |

Table 1 List of a reaction force of the scheme one (unit: kN)
It can be seen from the above table that the reaction force of the second branch near the auxiliary pier of the bridge pylon is obviously greater than that of the first branch. The reserve of supporting reaction force at the auxiliary pier of the far bridge tower on the side of the second pile number is small. From the perspective of supporting reaction force, scheme 1 is better than scheme 2.

Considering the structural force, construction scheme, support reaction force and other factors, the bridge joint section is designed to be located at the side span 35m away from the bridge tower.

4. RESEARCH ON SIDE SPAN LOAD DESIGN

The basic design concept of the mixed girder cable-stayed bridge is to use the gravity of the side span concrete beam to balance the gravity of the middle span steel beam, and the side span concrete main beam plays the role of compression and anchorage, thus improving the stiffness of the whole bridge on the whole[11]. When the length of the span is small, in order to ensure that no negative reaction force occurs at the fulcrum of the span and to avoid setting tension and compression supports, pressure is often configured in a certain range of the span.

After the finite element structure calculation and analysis of the whole bridge, the main girder of the side span is transited according to the conventional plate thickness, so it is necessary to properly allocate the pressure weight near the auxiliary piers and abutment, so as to ensure that the fulcrum of the side span in the completed bridge and the construction state does not appear negative reaction force and is under pressure. The specific compression scheme is to place iron sand concrete blocks in the box[12], and the bulk density of iron sand concrete is 35kN/m3. The load-bearing iron sand concrete blocks are arranged on the bottom floor of box girder and box chamber, and there are some problems of dislocation under dynamic load, so it is necessary to increase the fixed structure measures.

Considering that the thickness of the paved iron sand concrete block on the bottom plate of the box girder chamber is only 30cm, and the thickness of the concrete is about 40cm by equivalent conversion. In the range of compression, the concrete roof and bottom plate are thickened from 30cm to 50cm, so there is no need for additional compression. After the finite element analysis of the structure, the calculation results also meet the stress requirements. The use of thick slab concrete, not only can ensure that the bridge and the construction state of the side span of the fulcrum are not negative force and in a state of compression, but also has no pressure to fix measures, simplify the construction process, convenient late inspection and maintenance and other advantages.

Based on the above factors, the heavy slab concrete weight design is chosen for the side span weight.

5. CONCLUSION

In this paper, the structure system, the position of the joint section, the load of the side span and other key technologies of the 716m mixed girder cable-stayed bridge are studied, and the following conclusions are drawn.

（1）As for the main girder, the bending moment at the tower of the all-floating scheme is only 36.4% of that of the semi-floating scheme, and the bending moment of the stiffening beam in other areas is the same as that of the semi-floating scheme. In terms of main beam stiffness, there is little difference between full-floating scheme and semi-floating scheme. At the construction level, if the support is set at the cable tower of the semi-floating system, the large cantilever beam needs to be used, which will not only affect the appearance of the beam, but also cause unreasonable stress on the beam. The full floating system can avoid the problems of the large cantilever beam setting affecting the appearance of the beam, and the unreasonable stress on the beam, and also facilitate the hoisting of steel box girder.

（2）For the two schemes where the steel-concrete joint section is located in the side span and the middle span, this paper demonstrates the bridge completion state, operation state, supporting reaction force and construction scheme. When the bridge is completed, the longitudinal bending moment of the joint section located in the middle span is far greater than that in the side-span scheme, and the dead load bending moment distribution of the main girder is not ideal. Under the operation condition, the
longitudinal bending moment of the main girder of the two schemes is roughly the same under live load. In terms of construction, the construction risk of the high support located in the middle span of the joint section is higher, while the construction risk located in the side span is relatively low. In terms of supporting reaction force, the joint section is located at the middle span, and the supporting reaction force of the auxiliary pier near the bridge tower is far greater than that of the side-span scheme.

(3) In view of the design of the side span compression weight, compare and select two schemes of iron sand concrete compression weight and thick slab concrete design. Considering the design of thick slab concrete can not only ensure that the fulcrum of the bridge and the construction state of the side span does not appear negative reaction force and is in the state of compression, but also has the advantages of no load fixation measures, simplified construction process, convenient late inspection and maintenance and so on.

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