KEY CONSTRUCTION TECHNOLOGY OF A LARGE-SPAN DOUBLE-LEG STEEL-BOX ARCH BRIDGE USING CABLE CRANE SYSTEM

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SUMMARY

The technical standard, the general arrangement and the design of the bridge are introduced briefly. Then the construction technology of the bridge is illustrated. Trestle works are used for transporting and lifting of the segments in side-span area and the steel part of arch seat. A large-span cable crane with its hoisting capability 400t, combined with the cable-stayed cantilever assembly system, is adopted for erection of the mid-span segments. The design and erection of the cable crane, hoisting and matching of the rib, synchronous installation of the upper rib and the lower rib, closure of the rib, and installation of the girder are presented in the paper. The innovative cable crane brings great convenient and economic benefits; The Flexible connection technology guarantees the relative lineshape and inner force of the double-leg arch ribs; Suitable method of closure is helpful to the realization of the reasonable as-built state of the bridge.

Keywords: *Double-leg rib; arch bridge; design; construction; cable crane; cable-stayed.*

1. INTRODUCTION

As a conventional structure type, arch bridge plays an important role in the development of the global economy. In the past, arch bridge was usually constructed by concrete which spans over no more than 400 m, except for Wanxian Yangtze River Bridge (420 m) in china. In order to span more, steel arch bridge is needed to be constructed, in which about 60% is designed as steel box type in china. The most classic and characteristic one we have to mention here is Lupu Bridge in Shanghai, with its span 550 m. The bridge we will discuss in the following sections is similar to Lupu Bridge, called Mingzhou Bridge in Ningbo city, but it has its own peculiarity especially the double-leg rib and construction method integrating the way to construct suspension bridge, cable-stayed bridge and arch bridge. Both the design and the construction of Mingzhou Bridge is a big challenge and presents a new trend of the steel arch bridge in china.

Mingzhou Bridge is totally 1.33 km (including approach bridge), and the main bridge is 650m, with its center span 450m and two side spans 100 m (Fig. 1). The rib is a steel box structure, composed of two sub-ribs, the lower rib (in the center span) and the upper rib (from the side span to the vault). The main girder is orthotropic panel steel box beam and the mid-span beam is separated from the side-span beam. The mid-span beam is supported by the cross beam at the interchange of the main girder and the arch rib, end bearings is longitudinal sliding, with damping peneumatied device in transverse and longitudinal direction. The side-span beam is consolidated with the rib. The tie bar (horizontal cable) is anchored at the end floor beam, so as to balance the horizontal thrust.

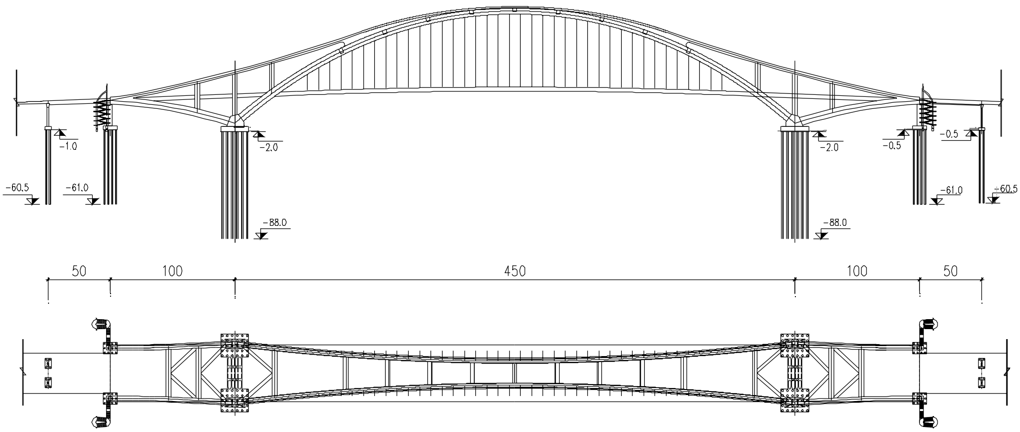

Fig. 1. *Plan and elevation of Mingzhou Bridge (dimension in meter).*

2. INNOVATIVE CABLE CRANE

Cable crane is a special type of hoisting device, usually composed of towers, cables (supported by the tower), crown blocks (moving on the cables), cable saddles and anchorages. In this project the cable crane method is combined with the cable-stayed cantilever assembly technology. The two towers (one is for cable crane, called the hoisting tower, the other is for stayed cable, called the fixing tower) are constructed together on the arch seat, with their height 20 m and 130 m. The hoisting tower is hinged with the fixing tower. The most important problem is to control the displacement of the hoisting tower during the operation period. For large span cable crane under large load, to control the operating displacement is more difficult, so we put forward an ingenious way called "inverted main cable system". And other innovations of the cable crane are: self-balanced cable saddle, light crown blocks, independent arrangement of traction and hoisting system.

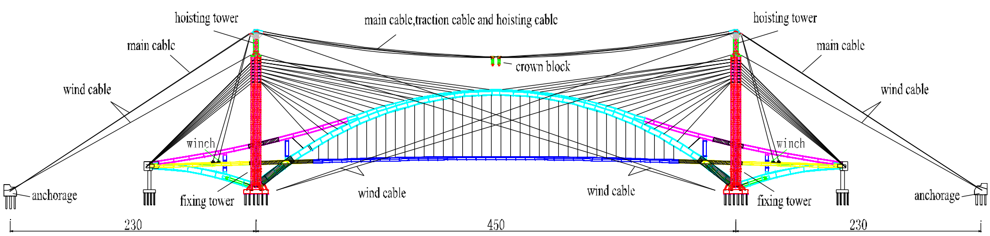

Fig. 2. *Plan of the cable crane (dimension in meter).*

The conventional main cable system is un-inverted type, in which main cables bypass the saddle and are anchored at the anchorage. While the "inverted main cable system" involves part of the main cables inverted, which bypass the saddle and the anchorage, then are inverted drag to the top of the tower and anchored (Fig. 2). The "inverted main cable system" could significantly reduce the unbalanced horizontal force caused by the difference of the horizontal angle of the main cable, thus easily control the operating displacement of the hoisting tower.

Another innovation of the cable crane is self-balanced cable saddle. For the limitation of the construction site, the anchorage should be placed deviating from the bridge axis different distance, respectively 35m and 20m. The main cable of the cable crane is not a longitudinal straight line , so the conventional cable saddle would bear lateral force, which would cause attrition to the main cable and damage to the pulley. Thus we design a self-balanced cable saddle, composed of three saddle-beams located on top of the hoisting tower according to a certain position and angle (Fig. 3), which let the mid-span cables turn to the side-span anchorage freely. Through optimization of the position and angle of the saddle-beams, we could minimize the lateral force and achieve the state that the pulley bears compression only.

Fig. 3. *Self-balanced cable saddle.*

How to reduce the weight of the crown block is a problem puzzling engineers. For the large-span large-load cable crane, the main cable system usually consists of many cables (24 in two groups in this project). In order to pass on the weight of the ribs or the girders to the cables, the crown block is normally designed as a multi-layer structure, thus increase its weight. Through adopting a two-layer structure and enhancing its lateral rigidity, the weight of the crown block could be reduced by 50% to about 10.5 t.

Although independent arrangement of traction and hoisting system could not be regarded as a standard practice, it brings great convenience during the operation period of the cable crane because of noninterference between the traction cable and the hoisting cable and less interruption to the operating of the cable crane.

The most difficult and time-consuming procedure is to set up the cable system comprising the main cable (24-Φ62 steel wire ropes), wind cable, traction cable and the hoisting cable. Because the unbalanced horizontal force during the erection period of the cable crane is very small owing to the adopting of the inverted main cable system, we could set up all the cables (especially the 24 main cables) in one time and fine adjust part of the cables. So we carry out installation analysis of the cable crane using MATLAB to ensure the displacement of the hoisting tower controlled in a safety range. It reveals that the displacement of the hoisting tower during the erection period of the cable crane could be controlled in ±25 cm, while the operation period in ±10 cm. In order to adjust the sag of the main cables we adopt pulleys instead of jack (Fig. 5), for the former is faster and its adjusting range is larger. Installation of other part of the cable crane is more or less conventional and is not discussed here.

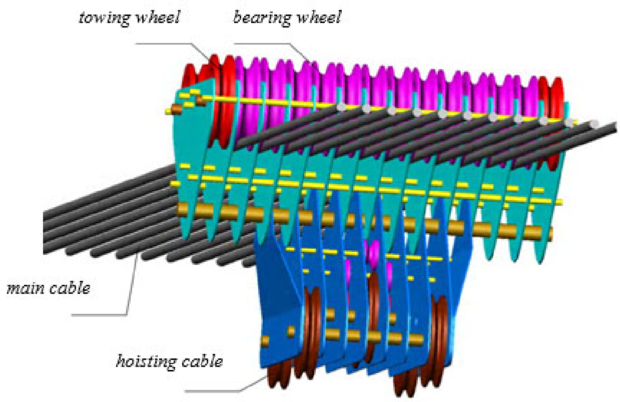

Fig. 4. *The crown block of the cable crane.*

Fig. 5. *Adjusting device of the main cable.*

3. SYNCHRONOUS INSTALLATION OF THE UPPER RIB AND THE LOWER RIB

The upper rib is crucial to the rationality of the stress state of the bridge. In order to achieve the design state, we should install the upper rib and the lower rib simultaneously. The ribs near the columns could be installed with scaffolds, while it's not convenient for the ribs away from the columns, so we have to make decision on how to connect the upper ribs and the lower ribs away from the columns. Here are three alternative solutions: rigid connection, screw connection and flexible connection.

Rigid connection method is to connect the upper rib and the lower with scaffold (temporary welded). The linear of the lower rib is controlled by the stayed-cable, while the linear of the upper rib is controlled by the jack putted on the scaffold.

Screw connection is to connect the upper rib and the lower rib with screw. The upper rib is fastened by the stayed-cable, and the lower rib is fastened by the screw. The screw is designed as a two-way hinge so as to connect with the upper and the lower rib easily.

Flexible connection is to connect the upper rib and the lower rib with steel strand. Firstly the anchor beam at the upper rib is widen, then set up an anchor box at the widen beam and the steel strand is connect with the lug of the lower rib. The jack is arranged at the upper rib.

The advantages and disadvantages of the three alternatives are as the following table:

Table 1. *advantages and disadvantages of the three alternatives.*

Connection Type	Advantages	Disadvantages
Rigid Connection	1) Relative linear of the ribs could be controlled easily 2) No Lateral braces for upper brace	1) More time to install the scaffold 2) Force transmission not clear 3) More enhancement work
Screw Connection	1) Force transmission clear 2) Fine adjustment allowable	1) Not convenient to install 2) Difficult to remove after installed
Flexible Connection	1) Force transmission clear 2) Operation Convenient ; 3) lower costs.	1) Difficult to tense the steel strand 2) Difficult to control the linear

As you can see in the above table, Flexible Connection has more advantages, so it was final adopted (Fig. 6).

Fig.6. *Flexible connection between the upper rib and the low rib.*

4. HOISTING AND MATCHING OF THE RIB

The distance between the upstream rib and the downstream rib varies from 18.5m to 5.76m, thus we have to either change the distance between the two group cables or adopt carrying pole beam. To change the distance between the two group cables involves special consideration about the saddle and the anchorage, a great deal of reinforcement work and higher costs. So we design a carrying pole beam connecting the two crown blocks (one upstream and one downstream) together, with a box-girder type (web hollowed) other than a truss type. As for the adjusting device, we compare the fixed one and the adjustable one. The fixed adjusting device comprises screw and steel wire, the length is fixed and un-adjustable after the rib is hoisted vertically. The adjustable device comprises hand gourd, pulley and steel wires (Fig.7), we could adjust the position of the rib with hand gourd after the rib is hoisted horizontally. The adjustable device is more superior in operability, cost performance and security, thus adopted.

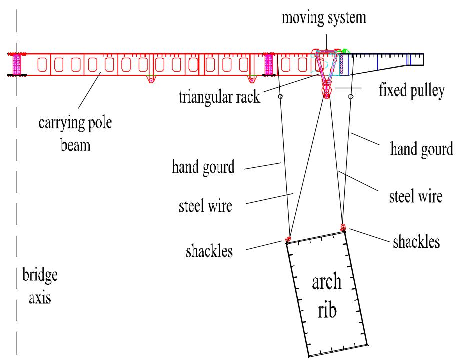

Fig. 7. *Carrying Pole Beam and Adjusting Device.*

Adjusting the position of the rib involves two steps, one is finished before the rib is lifted up on the boat and the other is accomplished after the rib reaches the specified position. To match the ribs we should first solve the following two problems: (1) selection of the matching time; (2) how to reduce the influence of the cable crane to the linear of the rib.

The material of the temporary tower, stayed cable and the ribs is steel, so the global linear of the ribs is influenced by the temperature especially the sunshine. Although we could estimate the influence of the temperature, it's still difficult to simulate the real temperature field. The best way is to accurately adjust the linear at night. However the adjusting work could only be arranged during the specific time which the temperature is stable. It is found through monitoring that the stable time of the temperature is only 6 hours (0:00~6:00). It's hard to adjust two ribs in 6 hours and this will produce influence to the construction progress. So we adopt local measurement method, thus the adjusting time could be extended to 10 hours (21:00~6:00) , the influence of wind, refraction and fog could also be eliminated.

When the new rib is close to the installed rib, the load beard by the cable crane would be transferred to the installed rib and will influence the linear of the rib. Through finite element analysis it is found that the influence of the cable crane increases along with the elongation of the arch segment. An effective way is to adopt the local measurement method mentioned above.

5. CLOSURE OF THE RIB

There are multiple closures of the rib: the closure of the side-span girder and the rib, the closure of the upper rib and the lower rib, the closure of the mid-span rib, the closure of the mid-span girder. Here we mainly discuss the middle two closures, which is more important to the bridge.

First is the closure of the upper rib and the lower rib. Two methods are considered: synchronous closure and asynchronous closure. Synchronous closure method is to weld the three ends of the upper rib (U12), the lower rib (M7) and the mid-span rib (M8) at the same time. Asynchronous closure method is to first weld M7 and M8, then weld U12 and M8. Another asynchronous closure way (first U12-M8, then M7-M8) is not allowed. The advantage of synchronous closure method is its security, but it's difficult to match the three ends meanwhile, and the cable crane is occupied when matching and welding. On the contrary, asynchronous closure method could release the cable to hoist other ribs and it is easier to adjust the elevation of the cantilever, however the bracket and the fittings should be reinforced. Finally the Asynchronous closure method is adopted.

Second is the closure of the mid-span rib (Fig. 8). There are three alternative methods: bolting, welding and bolt welding combination. It's needed to accurately calculate appropriate closure temperature for the bolting method and produce the rib especially the bolting hole with high precision, meanwhile to drill in the splice plate on-site. Bolt welding combination method is to connect the rib with bolt first and then cut the closure segment according to the width and shape of the final closure, while to release the bolt connection when welding the other end of the final closure, and to tight the bolt again after welding finished, resulting poor appearance and waterproof for the existing of a wide connection seam. The welding method only needs to select an appropriate weather and weld the final closure in a short time in order to avoid temperature variation. Based on the discussion above, we know that the bolting method is most demanding and difficult, the bolt welding combination method is more or less complex, and the welding method is the best way.

Fig. 8. *Closure of the mid-span rib.*

6. INSTALLATION OF THE GIRDER

During the installation of the girder, we should remove the temporary stayed-cable and tense the tie bar (horizontal cable) in stages. The installation of the girder will last at least 3 months, so the mean temperature changes greatly. After the closure of the rib, the linear of the rib is more sensitive to the temperature, thus it's difficult to adjust the linear of the girder.

After installing one girder, we mainly control the relative elevation of the girder, that's to ensure the relative slope between the two girders welded together. After all the girders installed, we begin to adjust the integrated linear. In order to reduce the workload, the absolute elevation of the girder is controlled by the outside allowance of the rib anchor.

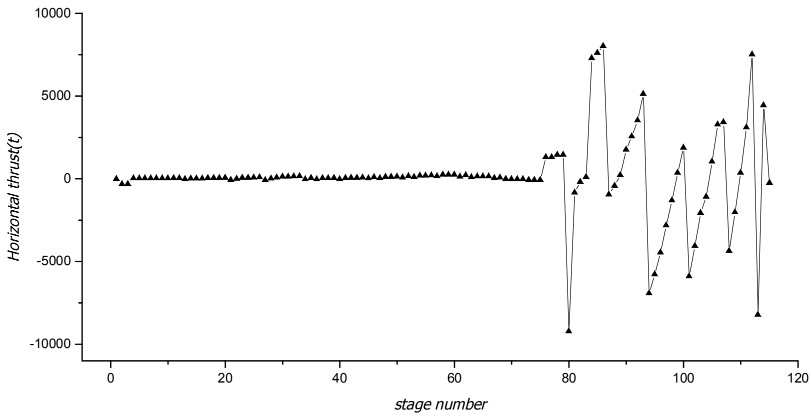

Fig. 9. *The horizontal thrust at the arch seat during the construction period.*

Before adjusting the integrated linear of the girder, we have to calculate the target linear first. It will last at least 10 days for adjusting the integrated linear, so the influence of the temperature to the linear should be taken into account, and the positioning coordinate of the girder should be revised.

The most demanding and tough work is to decide when to remove the temporary stayed-cable and how much force the tie bar tensed. Through installation analysis we guarantee the horizontal thrust of the arch feet is less than 1000t, and the counterforce of the side pier is less than 1500t for the pressure load at the side pier is totally1600t.

7. CONCLUSION

Mingzhou Bridge is a double-leg steel box rib tie bar arch bridge, constructed by a combined way to construct suspension bridge, cable-stayed bridge and arch bridge. The innovative cable crane brings great convenient and economic benefits; The flexible connection technology guarantees the relative lineshape and inner force of the double-leg arch ribs; Suitable method of closure is helpful to the realization of the reasonable state of the completed bridge. The design and construction of Mingzhou Bridge provides reference and help for the similar projects.