CONSTRUCTION AND CONTROL TECHNOLOGY OF LONG-SPAN STEEL ARCH BRIDGE CONSTRUCTED BY CANTILEVER ASSEMBLY METHOD WITH CABLE-STAYED PULLING AND BUCKLING SYSTEM

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SUMMARY

Cantilever assembly method with cable-stayed pulling and buckling system is usually used for long-span truss arch bridge construction. The complex structural mechanical behaviors and construction technologies bring difficulties to bridge construction. This paper briefly introduces the main technical characteristics in construction and control of the Second Zhuhai Hengqin Bridge, such as general construction scheme, geometry control methods, unstressed closure of arch and rigid tie bar, cable-stayed pulling and buckling system erection, etc. The results provide a reference for construction of similar bridges henceforth.

Keywords: *Long-span steel truss arch bridge, cantilever assembly method, cable-stayed system, geometry control, closure method.*

1. INTRODUCTION

Steel truss arch bridges have the advantages of convenient constructing, short construction period, magnificent shape and the materials' mechanical properties were used to its full extent due to good vertical rigidity and most of the members were axially loaded. Several construction methods can be used for steel truss arch bridge such as scaffold support method, cable-hoisting method, large segment integral lifting method, and the most popular method — cantilever assembly method with cable-stayed pulling and buckling system. For example, Wanzhou Yangtze River Bridge (168 m + 360 m + 168 m) completed in 2005, Chaotianmen Yangtze River Bridge (190 mm + 552 m + 190 m) completed in 2009 and The Second Zhuhai Hengqin Bridge (100 mm + 400 m + 100 m) completed in 2015 are all steel truss arch bridge constructed by this method. The side span of Hengqin Bridge was constructed by cantilever assembling with temporary support, and the mid-span of it was constructed by cantilever assembling with cable-stayed system.

Because of the long span, complex loading, and various construction technology, It is extremely difficult for geometry control and structural internal forces control when it comes to the cantilever assembling construction of long-span steel arch bridge. Based the background of The Second Zhuhai Hengqin Bridge, this article mainly discussed the main techniques including selection of general construction method, change of the structure system, closure of arch and rigid tie bar, cable-stayed pulling and buckling system and internal force control of the main truss and temporary structure, etc.

2. PROJECT BACKGROUND

2.1. Structure type of the bridge

The Second Zhuhai Hengqin Bridge is a steel truss tied-arch bridge with a span distribution of 100 m + 400 m + 100 m. The rise of arch is 90 m and the bridge deck is 36m wide. The height of arch ring is 7m at arch crown and 11 m at side piers. It is a mixed system of rigid tie bar and flexible tie bar. The "H" shaped edge stringer over navigable span, also known as rigid tie bar, is connected to the arch by 27 couples of suspender. The steel strand flexible tie bar, passing through rigid tie bar, is anchored between arch-beam junction joints. The bridge floor system consists of longitudinal beams at a spacing of 4 m and cross beams at a spacing 12~14 m, with an upper concrete slab of 0.26 m thickness.

2.2. Selection of general construction method

Construction scheme select should consider bridge site condition as well as structure feature. Take the Second Zhuhai Hengqin Bridge over Hongwan waterway as example, scaffold support method is infeasible since Hongwan waterway has to provide 3000 tons navigation capacity and keep high traffic flow every day. Large segment lifting method is difficult to accomplish since the lifting height of main truss arch needs to reach to 120 m and the general floating crane cannot meet requirement. Considering strong wind attacks Zhuhai every year, cable-hoisting method is inappropriate because of its weak wind resistant stability. At last, cantilever assembly method with cable inclined pulling and buckling system was adopted. Girder erection crane was used to lift and assembly members at cantilever end and cable inclined pulling and buckling system was erected for mid-span arch force control.

There are two ways for long span steel truss arch closure. One is arch and beam erect together method, which was used in Wanzhou Yangtze River Bridge construction. The other is arch first and beam late method, which was used in Chongqing Chaotianmen Yangtze River Bridge and the Second Zhuhai Hengqin Bridge. Arch and beam erect together method has the advantage of fast transformation from long cantilever state to tied-arch state, few times of construction system transformation and short construction period. Arch first and beam late method is suitable for long span bridges under heavy wind load or bridges that will possess large moment during cantilever erection.

2.3. General Construction technology

The steel truss arch is erected symmetrically from side span to middle span. There are 3 temporary piers being set up to help side span construction. 1# and 2# segments are erected by 500 t truck crane and the 80 t girder erection crane is assembled on their upper chords for the other elements erection. Before 3# segment were completed, the main piers were formed. The 1# temporary piers were disengaged when the girders reaching to 3# temporary piers. The 2# temporary piers were disengaged when the girders reaching to main piers. Then arch first and beam late method is adopted during middle span bridge construction. When 10# segments were completed, the north girder were precisely located to middle bearing and the 3# temporary piers were disengaged. The 1~6# deck slabs were installed on side span. When girder reaching to 16# segments, 1# cables were installed and tensioned. When girder reaching to 20# segments, 2# cables were installed and tensioned. When girder cantilever assembling to 23# segments, the truss arch was closed. And then the rigid tie bars were closed and counter weight were removed. The bridge was then completed. Figure 1 shows the construction plan of the Second Hengqin Bridge.

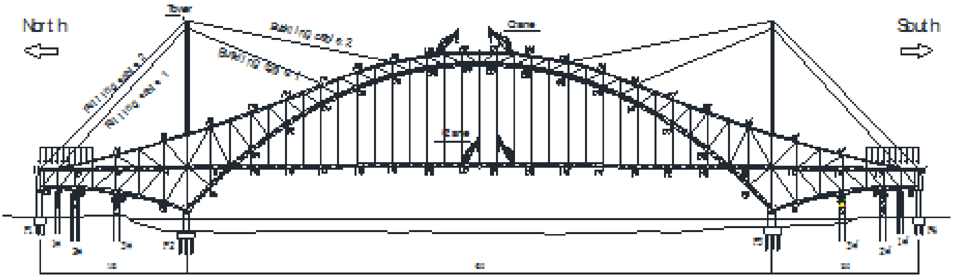

Fig. 1. *Construction Plan of the Second Hengqin Bridge (units: m).*

3. ERECTION OF THE MID-SPAN CABLE-STAYED SYSTEM

In order to control the internal forces and geometry of the girder, cable-stayed system was used during the mid-span girder erection. The design of cable-stayed system should take several factors into account, such as the height of tower, the arrangement and angle of pulling cable and buckling cable, maximum cable force and tension method. The cable-stayed pulling and buckling system is composed of tower, lateral linkage, pulling cable, buckling cable, anchor box, etc. The tower is 80m high, using 4φ800×20 mm lattice steel column which is made of Q345B steel.

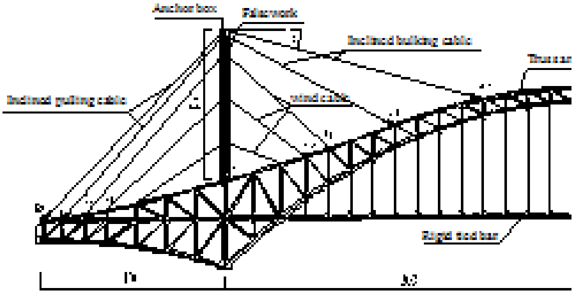

Fig. 2. *Cable-stayed System.*

The tower foot is hinged on the upper chord. There are 2 couples of cables stretching from steel anchor box. These cables were 4×37φ15.24 steel strand of high strength and low relaxation, with an ultimate tensile strength of 1860 MPa. The maximum cable force is 16500 kN, and the maximum safety factor is 2.3. To secure the stability of cable-stayed system during its erection, 3 sets of wind cable were applied.

Cables were single tensioned to its strength at one time by equivalent tensioning method. The cable tension force can be precisely controlled by equivalent tensioning method. the force of cable-stayed system would maintain and there is no need to adjust the cable force within following procedures. Figure 2 shows the cable-stayed system, Fig. 3 shows the photo of the cable-stayed system.

Fig. 3. *Construction Photo.*

4. CLOSURE OF ARCH AND RIGID TIE BAR

4.1. Closure of arch

The arch closure of The Second Zhuhai Hengqin Bridge is carried out by method of “Longitudinal displacement compensation + beam jacking”, In which beam jacking could eliminate vertical error and angular error of final closure, while longitudinal displacement compensation could eliminate longitudinal error of final closure. In construction of The Second Zhuhai Hengqin Bridge the side bearing lowered down 0.9 m, and the girder offset 1.53 m to mid-span in the beginning erection, 1# 2# segment were constructed under a degree of 0.65°. This method avoided the risk of semi-arch overall move before arch closure. Figure 3 shows the bridge under construction.

4.2. Closure of rigid tie bar

Rigid tie bar closure was adopted by limiting middle bearing method. After arch closure, it became a three span continuous beam system. In order to avoid the influence of temperature change, the south middle bearing’s longitudinal constraint should be unlocked and start to erect rigid tie bar. The longitudinally movable support at south main pier was refitted into longitudinal regulation equipment to control arch longitudinal displacement. Several steel blocks were introduced to the equipment to adjust the longitudinal displacement of support at south main pier. The number of blocks could be increased or decreased according to theoretical analysis. When the support moved towards side span along with rigid tie bar erection, it could be naturally locked in the theoretical position. Then keep on erection until rigid tie bar closure, the distance of final closure would be almost fit for the length of closure segment and it is not necessary to push the support at main pier for rigid tie bar closure. Figure 4 demonstrates the south movable bearing.

Fig. 4. *South Movable Bearing.*

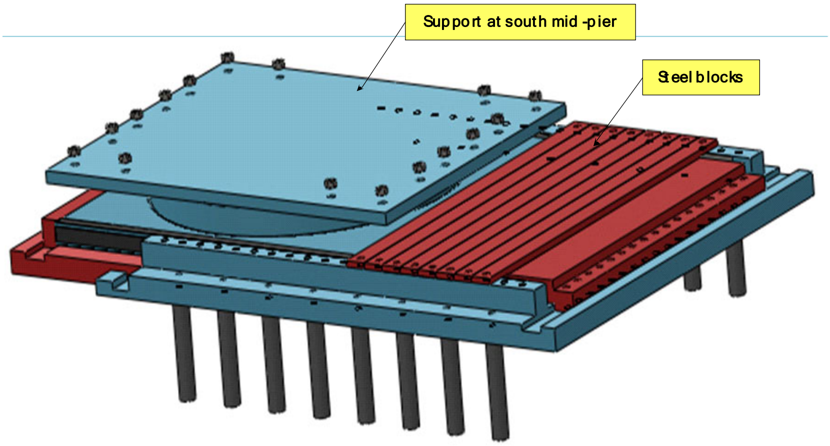

Fig. 5. *Construction of the south bearing support.*

5. GEOMETRY CONTROL OF THE MAIN TRUSS

Most of steel truss arch bridges are bolted and welded structure, so the assembly geometry is mainly determined by prefabricated geometry. This means high-precision of bolt hole must be ensured so as to get correct truss member length and angle between truss members. Unstressed length of hangers is determined by reasonable completed bridge state with practical load. Besides, the prefabricated geometry has to be verified by rolling pre-assembly of 3~4 segments in the manufactory.

During construction, the field assembly geometry can be controlled through the following technologies:

1) Coincidence degree control of bolt hole. The coincidence degree of bolt hole is determined by diameter and number of position drift pins. During truss members assembly or pre-assembly, the gusset plate of main truss needs 60%~70% position drift pins quincuncially driven in so as to control axis of the new truss member.
2) Control of cantilever setting elevation: Cantilever truss member assembly follows the sequence from bottom to top. 15% bolts can be driven in gusset plate after enough connection drift pins are ready. As truss arch assembly, the truss member of cantilever end may meet temporary pier or main pier. The bottom of truss member and the top of pier should keep 2~5cm distance before this truss segment is completed. As long as final screw of bolts in this segment is completed, the distance can be filled with steel plates, and the pier start to bear reaction force when the next segment start to erect.
3) Control of screwing progress. The bolt final screw at main truss should fall behind segment assembly not more than two segments.
4) Control of axis deviation. Axis deviation could be induced by truss member assembly sequence, imbalance load, gusset plate torsion, partial sunning, altitude difference or planimetric misregistration of supports, etc. Geometry test and evaluation must be done after single segment completed. Once the deviation exceeds the tolerance range, rectification measure such as bolt screw sequence should be adopted, to prevent accumulated divergence of the assembly error.

6. INTERNAL FORCE CONTROL OF THE MAIN TRUSS AND TEMPORARY STRUCTURE

A finite element model of the structure system is built for simulation of the entire process of main bridge construction. The model contains 85 key operating conditions, calculating the structure stress states under different conditions. The construction technology will be optimized based on the analysis of the FE model simulation, to ensure that the structure stress under any operating conditions can meet the requirements of relevant standards and codes. In addition, an automatic wireless monitoring system (AWMS) is applied for the real-time monitoring of the structure stress states during the construction of the bridge. The monitoring system contains sensor system, data collection system, data communication and transmission system, and monitoring center which is the data analysis and processing system. The main parameters monitored are arch stress of main truss, cable stress of stayed fasten system, acceleration of vibration, temperature, etc. Monitoring points are installed at the key forced positions of structure.

The following Table 1 is showing the maximum and minimum theoretical calculated stress comparing the actual measured data under the most unfavourable operating conditions. Generally table 1 shows that: the maximum stress of main truss occurs at the A13-A14 member before installing 2# buckle cable to be 247.5 MPa; the minimum stress is located on the steel pipe to be -184.6 MPa as the closure of the rigid tie bar. The main steels used for main structure are Q420qD and Q345qD, and for temporary structure are Q345B. The corresponding construction allowable stresses are 299 MPa, 260 MPa, and 260 MPa according to Bridge Structural Steel (GB/T 714-2000). It could be concluded that: (1) the theoretical calculated and actual measured stresses are less than the construction allowable stresses, and (2) there are limited deviation between the theoretical calculated and actual measured values.

Table 1. *Maximum and Minimum stresses of main truss and temporary structures.*

Main cases	**No. of member**	**Theoretical [MPa]**	**Measured [MPa]**	**Differences [MPa]**
Before 1# cables erection	North A8-A9	236.7	231.5	-5.2
	North G7-G8	-95.2	-101.2	-6
	North Tower	-59.5	-52.3	7.2
	South A8-A9	239.2	230.5	-8.7
	South G7-G8	-106.2	-102.3	3.9
	South Tower	-62.3	-57.1	5.2
Before 2# cables erection	North A13-A14	247.5	239.1	-8.4
	North G7-G8	-113.6	-106.2	7.4
	North Tower	-100.1	-105.4	-5.3
	South A13-A14	240.9	231.6	-9.3
	South G7-G8	-102.2	-107.3	-5.1
	South Tower	110.9	104.7	-6.2
Before arch closure	North E2-G2	195.8	191.2	-4.6
	North G7-G8	-93	-97.5	-4.5
	North Tower	-155.4	-150.0	5.4
	South E2-G2	205.5	212.8	7.3
	South G7-G8	-97.4	-104.3	-6.9
	South Tower	-173.1	-181.6	-8.5
Before rigid tie bar closure	North A20-G21	211.7	207.3	-4.4
	North G7-G8	-120.0	-113.4	6.6
	North Tower	-167.8	-172.3	-4.5
	South A20-G21	224.5	216.2	-8.3
	South G7-G8	-121.6	-128.1	-6.5
	South Tower	-184.6	-180.1	4.5

7. SIDE AND MIDDLE BEARING SETTINGS

Jacking and pushing devices were arranged in order to implement exchanges of structure systems during construction.

7.1. Side bearing setting

Longitudinal and transverse moving and limiting devices were arranged on side pier as well as elevation adjusting device. Side bearing of both north and south lowered down 0.9m in advance. The maximum reaction force of side bearing is 2200 kN during construction. Maximum longitudinal wind force is 600 kN and maximum transverse wind force is 1000 kN. Side bearing need to be restricted longitudinally and transversely. Elevation adjusting were accomplished by 4 vertical jacks of 800 t. Longitudinal moving were accomplished by 4 horizontal jacks of 150 t, and 150 t jack was used for transverse moving. Figure 6 shows the side Bearing Setting.

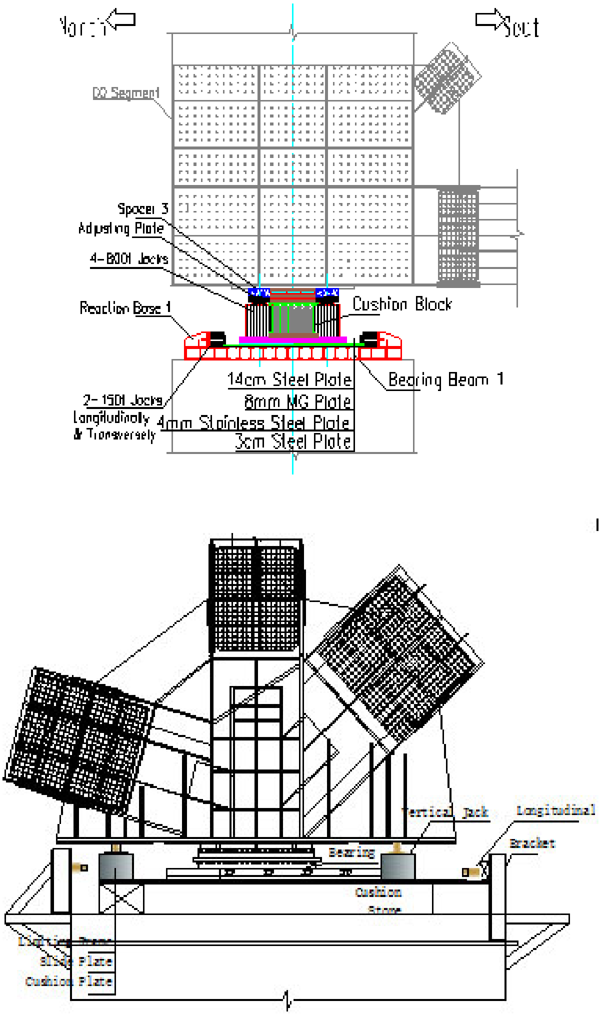

Fig. 6. *Side Bearing Setting (above) and Middle Bearing Setting (below).*

7.2. Middle bearing setting

Vertical jacking devices, longitudinal and transverse moving and limiting devices were used to adjust geometry and precisely locate middle bearing when constructing truss arch. The jacking device consists of 4 vertical jacks of 8000 kN, 4 longitudinal jacks of 2000 kN and 4 transverse jacks of 2000 kN. Longitudinal and transverse moving and limiting devices were made of pre-embedded steel plate, limiting frame, limiting bracket, Teflon slide plate, moving jacks. Steel plate of 20mm embedded on top of bearing stone within the flatness error of 2 mm/m^2. Limiting frame was made of H800 welded to steel plate. Teflon slide plate lied between limiting frame and steel plate. Vertical jacks were fixed onto the steel plate within working range. Limiting frame was moving on Teflon slide plate as a whole. The slide plate bearing of south main pier was temporarily extended 1.8 m to adjusting the error of mid span closure. Figure 7 shows the middle Bearing Setting.

8. CONCLUSIONS

In the construction of the Second Hengqin Bridge, key construction technologies are summarized and investigated as the following.

1) Construction safety was guaranteed by cable-stayed system of cantilever assembling and arch first beam later for mid span method. During construction, structure systems changed smoothly by jacking and limiting devices of side and middle bearing.
2) The members of truss arch were welded in factory and bolted on site. The manufacturing precision is the key to assembling geometry. In-situ control of geometry is accomplished by camber and deck axial deviation control.
3) Mid span closure adopted "Longitudinal displacement compensation + beam jacking" method, which avoided the risk of semi-arch overall move. No stress arch closure were achieved by adjusting side bearing's angle and height. The blocks of middle bearing are adjustable to achieve rigid tie bar closure.
4) Cables were single tensioned to its strength at one time. So that the force of cable-stayed system would maintain and there is no need to adjusting the cable force within following procedures, thus construction time is reduced.
5) The whole construction process is analyzed and optimized through a finite model. Automatic wireless monitoring system contributes to the structure safety during construction.

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