# Dynamic control technique research of dongping bridge during the rotation stage

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ABSTRACT: Dongping Bridge with a main span of 300m is located in the south of Foshan city and it is a cooperative-system steel box tied-arch bridge cooperating with prestressed concrete continuous beam. Dongping Bridge was constructed by two-step rotary method including vertical rotation followed by horizontal rotation. It is the first time in China that the vertical rotation method without buckles was adopted in vertical rotation construction process. The weight of the horizontal rotation is 14800t which is the heaviest in the world. Taking the construction monitor and control in rotation process as engineering background this paper represents some key technologies such as optimizing calculation of the cable force of the vertical lifting, the calculation of lifting force in the horizontal rotation, the analysis of stability in the course of rotation, the dynamic measurement of the deformation at important location during the rotation process and the real-time control of line shape of the arch rib, etc.

## 1 GENERAL INSTRUCTION

Dongping Bridge crossing the Dongping River is located in the south of Chancheng District of Foshan City, Guangdong province. The total span of the Bridge is 578m with a main span of 300m and side combine span of 95.5m. The main bridge is a cooperative-system steel box tied-arch bridge cooperating with prestressed concrete continuous beam. The arch axis of the main arch rib is funicular curve which net rise span ratio is 1/4.55 and the coefficient of arch axis is 1.1. The width of this bridge is 48.6m and the design load is Truck-Load over 20 and trailer 100. The bridge adopted the construction method of vertical lifting rotation technology without buckles followed by horizontal rotation. It is a creative method that using sub-arch instead of the buckle rope during the rotation construction and then the self-balance system was formed. In the process of construction, at first the arch rib is assembled on the low bear frame according to the manufacture line shape stage by stage, and the articulation was set in position of arch rib spring for vertical rotation. The assembled half arch rib was lifted to the design elevation by using lifting tower and the hydraulic system , and then it was flat turn to design placement. Side arch rib was assembled according to design line. For the convenience of unloading before horizontal rotation, sand buckets were installed on support frame beam. After vertical lifting rotation to the demand location, in order to adjust the actual arch rib to meet the design request the vertical raising force was exerted through support frame at L/8 main arch rib. Then sub-arch and the tie bar box were closure and the vertical rotation articulation is rigidly fixed. By placing suitable counterweight on the end cross beam of side arch the half main arch forms the self-equilibrating system with the side arch. Before horizontal rotation the lifting force was hierarchically and symmetrically unloaded and hoisting tower and balancing cable were taken down. The horizontal rotation was carried out through horizontal rotation facilities such as revolving tray setting in arch seat, the central revolution axis, the kickstand, the circuit and the hydraulic synchronization lifting jack. After horizontal rotation finishing the main arch rib was closure under the suitable temperature (Fig.2). The weight of vertical rotation is approximate 3000t and the angle of vertical rotation is 25°. The weight of horizontal rotation is 14800t and the angle of horizontal rotation is 104.6° on the north bank and 180° on the south bank.

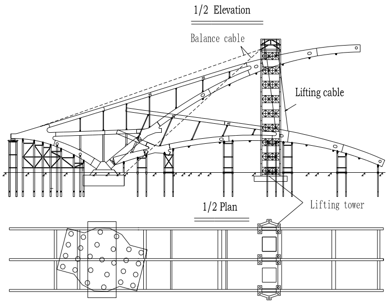



Fig. 1 : Sketch of vertical rotation system

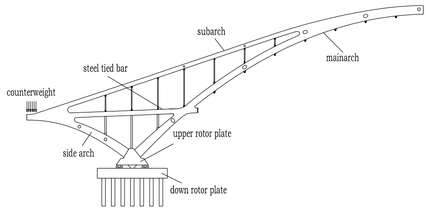



Fig. 2 : Sketch of horizontal rotation system

## 2 CHARACTERS OF THE CONSTRUCTION MONITORING CONTROL

Dongping Bridge embodied the highest achievements of the Chinese bridge rotation construction method. The characteristics of the structure analysis and the construction monitoring control technologies in construction processes are as follows:

(1)The construction method of vertical lifting rotation without buckles was used in bridge construction for the first time. There are several new problems in the construction monitor such as the stability of the lifting tower, the local safety of lifting system and the calculation of the lifting cable force and so on. According to the characteristics of the project, the special methods of structural analysis and monitoring were adopted which are closely related to design and the construction.

(2)The main bridge is a steel box arch bridge with three ribs and sub-arch. The rigid tie bar and rigid hanger were also adopted in this bridge. The complex construction technology of Dongping Bridge includes multiple system transformation and there are 12 closures (vertical rotation closures in sub-arch and side arch and horizontal rotation closures in main arch and tie bar box). Structure analysis and computation of construction control must be quite accurate because there are seldom methods of adjusting internal force and arch axis geometry in the construction process.

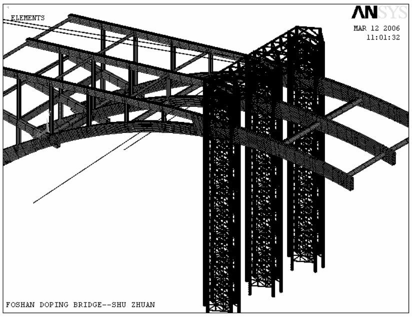
(3)The rotation weight of this bridge creates a record of 14,800t, and the flat turn angle is large (reaching 180°on the south bank). It brings a big challenge to the construction and monitoring. Moreover, because of the unique sub-arch structure of the bridge, the rotation structure forms a self-equilibrating system. During the rotation process, the controllability is very poor. Therefore, before the rotation, the judgment of the rotation-structure gravity-center position, the calculation of the draft load and the structural stability in the rotation process are especially important.

(4) The structure inner force and alignment changes along with the construction process because the rotation construction is a dynamic process. In order to make the comprehensive and correct monitor of the rotation structure stressed state, it is not only need to reasonably and scientifically arrange monitoring points, but also need to continuously measure monitoring points and collect measured data.

## 3 THE MONITORING CONTROL CONSTRUCTION ANALYSIS

### *3.1 The establishment of rotation process simulation model*

The rotation construction process was simulated by the finite element program (ANSYS) and the model mainly included three parts: the vertical rotation model (Fig.3), the flat turn model (Fig.4) and the general model (Fig.5). In the process of rotation the number and relative position of elements of main structure did not change and the main structure just rotation around the articulation. In order to avoid time-costing and complicated model construction work, the model was established by using array and parameter in this paper. The local coordinate system is based on the state that the arch rid swiveled to the correct position and the model under different rotation angle were simulated by revolving the work plane. It is greatly simplified the work of model construction in the rotation process.



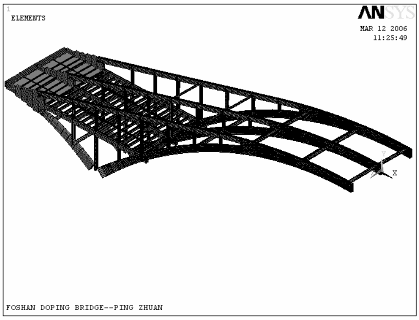




Fig.3 FEM model of the vertical rotation stage Fig.4 FEM model of the horizontal rotation stage

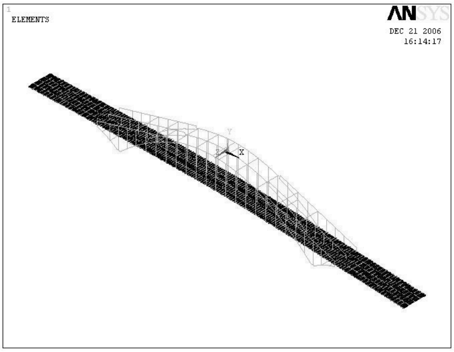



Fig.5 Finite element model of the bridge

### *3.2 The optimizing calculation of vertical rotation cable force*

The length of lifting cable and the angle between lift cable and lift tower changes with the rotation process. It leads to the force of lifting cable continuously change. The value of lifting cable force directly effect the safety of lifting process, the accuracy of the forecast of lifting state and the subsequent working conditions. Therefore, ascertaining the cable force under each working condition is an important premise to ensure the calculation accuracy of entire vertical rotation process and the arch rib well closure after horizontal rotation.

The optimizing design is a type of technique which seeks and determines the optimum design plan. The specific optimizing design includes the design variable, the state variable, the target function, the controlling condition and so on. In the course of lifting, a couple group of lifting cable forces are the design variables, the difference between the two group of cable forces is the state variables, the deformation at the midst location of the line which connects the two lifting points is the target function. The calculation process of lifting cable force is just the process that unceasingly revising the initial cable forces to guarantee the force uniform and the midst location of the line which connects the two lifting points reach the corresponding height at the same time.

The cable force is specifically calculated by the optimum design model in ANSYS and the vertical rotation structural model was shown in fig.3.The iterated algorithm was employed in the emulate calculation and the initial strain of the two group cables (define the initial rigidity of the lifting cable) was looked as design variables and the initial value got zero. The displacement of the median site between the two paralleling groups of lift cables' lifting point got zero as controlling target and the vertical rotation lifting cable force of main arch rib was calculated. The whole rotation angle varied from 0°to 25°(the final position) and the vertical lifting process of the entire bridge were discrete by 2.5°. The comparisons between theory cable force and measuring cable force in the process of the vertical rotation were shown in table 1.

### *3.3 The stability analysis in the rotation process*

For long-span arch bridge, the stability during the construction process is very important. As there are many examples in the world that the entire bridge destroyed due to destabilization in the process of construction, we must pay sufficient emphasis on stability. The stability of the integral and partial of the major structure as well as the temporary structure in the rotation process has been detailed analyzed in Dongping Bridge. During the rotation process, the stability of the lifting tower is very important. According to calculation, when the main arch rib remove from the supporter in the vertical process, the level force of the lifting tower generated by the lifting steel strand is maximum , the first kind stability safety coefficient of the lifting tower is 13.25 and the correspond instability mode of the tower is the horizontal swing. For the first kind stability problem, the new code(JTG D-62—2004)defines that the safety coefficient should be greater than 4, so the lifting tower of Dongping Bridge in vertical process have sufficient safety stock.

### *3.4 Stress calculation during different operating mode*

With the above mentioned simulation model of the rotation process, the stress of the main arch rib under each working condition from the main arch rib remove from the supporter to the rotation accomplished has been detailed analysis. From the calculation results, in the process of rotation the position of the maximum stress of arch box is located in quarter of the main arch rib and the lifting point. The most disadvantageous stressed location of the lifting tower appears in the vertical steel tube under crane platform, which lies in the upper part of the tower.

In order to accurately analysis the structure behavior of the key component that suffered complicated stress during the vertical rotation, shell or solid model of some locations including the vertical rotation joint, the counterforce crossbeam in the lifting tower top and the lifting ear area were built. The strain and deformation of these important components also be analyzed, and then the location of the most disadvantageous stress has been found out. Major track monitor were given to these sites during field construct monitoring.

Table.1. Calculation of lifting-cable force in vertical rotation stage

| The lifting angle | The theoretical cable force kN | The real measured cable force kN | The deviation between the theoretical value and the measured value |
|---|---|---|---|
| 0° | 1086 | 1047 | 3.59% |
| 2.5° | 1075 | 1011 | 5.95% |
| 5° | 1060 | 1043 | 1.60% |
| 7.5° | 1044 | 994 | 4.79% |
| 10° | 1027 | 989 | 3.70% |
| 12.5° | 1010 | 961 | 4.85% |
| 15° | 993 | 965 | 2.82% |
| 17.5° | 976 | 970 | 0.61% |
| 20° | 960 | 896 | 6.67% |
| 22.5° | 959 | 897 | 6.47% |
| 25° | 1036 | 1013 | 2.22% |

### *3.5 Calculation of the flat turn draft load*

For accurately calculate the upper rotary plate's stress and draft load during flat turning in Dongping Bridge, the three-dimensional solid model of the abutment of arch and upper rotary plate were built. By calculation the maximum compression stress on the abutment during the flat turning is 15.3MPa and the maximum tensile stress is 1.67MPa. The weight of flat turn is 14800t and the draft load counterforce of friction is 880t in the south coast which is close to the measured value (860t). The draft load counterforce of friction is 660t in the north coast and the measured value is 640t. The results indicate that the measured value is in accord with the construction control forecast value.

## 4 ACCOMPLISHMENT OF CONSTRUCTION MONITOR

The aim of long span arch bridge construction control is to control the bridge construction process and ensure bridge structure internal force and deformation in allowed safe range in the process of construction, and also ensure the accomplished bridge line shape and internal force meet design demand. According to the characteristic of bridge type and construction method, the main contents of construction monitor are as follows:

### *4.1 Stress monitoring*

For real time track force state of structure, and avoid the dangerous of high-rise operation and low efficiency of the manpower monitor, we perfect solve the difficult problem of date collection in the rotation process with the method of wireless automation synthetic monitor system matched corded sensing element during rotation process in Dongping Bridge.

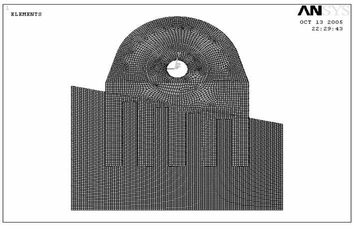


Fig.6 FEM model of the lifting eye

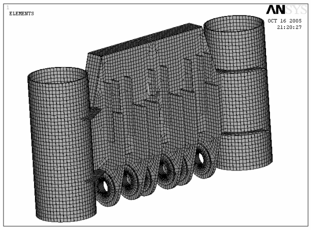


Fig.7 FEM model of crossbeam in the top of lifting-tower

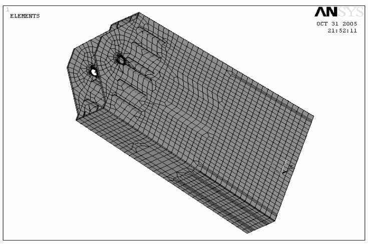


Fig.8 FEM model of the vertical rotation ream

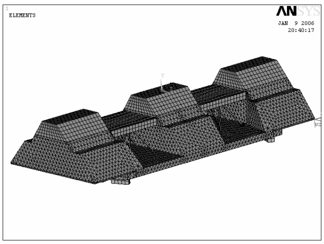


Fig.9 FEM model of the skewback of arch

Besides real-time monitor the strain of the main arch rib, the centre rotation axis of flat turn system and the strain of the kickstand are also importance of flat turn stress monitor in the process of horizontal rotation. Those values of stress not only reflect the local stress at key location but also supply foundation to judge whether the flat turn system is in self equilibrium state.

In the process of the vertical rotation, the chief monitoring are the stress of main-arch rib、lifting tower and the vertical rotation articulation and so on. The deformation measuring points of the main-arch rib are laid at 0、L/8、L/4、3L/8、L/2 and the lifting point cross-section. Before the vertical rotation, we will make the stress dynamic test of the measuring points in the main-arch rib, and identify the stress performance of the vertical rotation system by comparing with the theoretical value. In the formal process of vertical rotation, the major work is the global real-time monitoring of the key-position (lifting point、lift-up point) stress. The stress monitoring of the lifting tower is the major of the vertical rotation stress monitoring. According to the calculated result, the measuring points are laid at the vertical steel pipe below the lifting platform in the lifting tower top, the cross beam of the lifting tower top and the vertical steel pipe in the lifting tower bottom. There are many strain transducers nearby the steel box cross-section of the vertical rotation articulation to make global real-time stress monitor of the vertical rotation articulation in the process of the vertical rotation.

### *4.2 Arch axis line shape monitoring*

In the process of main arch vertical rotation, emphases were paid on the space coordinate of the mid-span cross-section, the mid-point of the line which connect the two lifting points, the closure of the sub arch, the closure of the tied box and the lifting control point, and use the space coordinate of the mid-point of the line to control the angle of the vertical rotation. Before vertical rotation, all measure points in the low bearer were measured. After the vertical swivel reach the right position, the actual deviations of measure points were adjusted according to the actual deviation of each measuring point in the main arch assembling, which provided reference for the accurate regulation of the main arch rib's target line shape. The lifting tower is the main stress structure in the process of arch rib vertical rotation, and the monitoring of the tower top deviation is very important to the security and the stability in the process of the vertical rotation. In order to control the tower top deviation in the scope of the designed permission, the total station instrument was used to observe the tower top deviation in the process of the vertical rotation and regulate the dorsal cord force of the lifting tower.

In the process of the horizontal rotation, the space coordinate variation of the mid-span and the side span were real-time tracked by high-accuracy total station instrument. Judging the horizontal rotation structure whether has the phenomenon of longitudinal banking by comparing coordinate values of measure points. According to the relative height difference, judging the arch ribs has the phenomenon of cross direction banking. According to the space coordinate of measure point, we can judge the horizontal rotation whether reach the right position.

In the process of the rotation, the compression force which the kickstand was suffered deliver to the rotor plate inevitably cause the local deformation and the uneven settlement of the rotor plate and then the Leica digital precision level was adopted in real-time measurement.

### *4.3 Cable force and temperature monitoring*

The cable force of lift cable and balancing cable are major factors effect the deviation of the lifting tower top in the process of the vertical rotation, so the cable monitoring is the key of cable force monitoring. In the vertical rotation, the hydromantic in-step hoisting system controlled by the computer can make automatic regulation according to the locale practical situation.

Before the formal vertical rotation of the main arch, the intellectual temperature bulb was used to make temperature measurement of the main arch rib and atmosphere. Several attention cross sections were selected as measuring points and the relative curve of the arch temperature and the atmosphere temperature was obtained by coordinating digital information. It offered the reference for amending coordinate of the measuring points while closing of sub-arch and tie bar box.

## 5 CONCLUSIONS

(1)The vertical rotation method without buckles combined with the horizontal rotation method is very advanced and safe. If only the rotation system designed reasonable, it's possible to achieve larger rotation weight and longer span according to the present construction level and material technique.

(2)Through researching of key techniques in the rotation construction control and emulating calculation in the construction process of the Foshan Dongping Bridge, we can draw the conclusion that Dongping Bridge has many remarkable advantages such as reasonable rotation system stress, high stability factor of vertical system, reasonably drafting system of horizontal rotation. But stress concentration also exists in part of the vertical articulation and the lifting tower and more attention must pay on it.

(3)The construction monitor and control was increasingly applied in the larger bridge construction. Owing to design concept is more advanced in the modern bridge, the risk in the construction stage is always larger than the service stage. Particularly for the rotation construction, the constructions process is various and the calculation is complex, so the construction monitor and control is absolutely necessarily. There are many innovations in the structural design and rotation construction technology in Dongping Bridge, which brings a lot of challenges to the construction control. Based on the theoretical calculation, the construction monitor and control assure the rotation construction accomplished successful by using advanced instruments and testing methods.

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