Research on the special lifting devices for steel box girders of Sutong Bridge

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Abstract: Sutong Bridge is a cable-stayed bridge with a steel box girder and a main span of 1 088 m. The steel box girder of main span includes five portions: back span large unit, large block of pylon, standard girder, back span closure girder and middle span closure girder. Each back span large unit is fabricated by welding several deck segments together in factory, and is erected by floating crane. As navigational clearance of the main bridge is high, the traditional truss lifting device can't satisfy the requirement of domestic lifting cranes for this kind of lifting height and weight. Hence, a kind of lighter lifting device for the erection of back span large units was accepted for this bridge. In this paper, the design and use of this lifting device is introduced.

The upper structure used lifting gantry to install the standard girder segment by cantilever method. Because the bridge's navigation clearance is high, and the girder segment is wide and heavy, the meteorology and hydrology condition of the bridge district is abominable, and the requirements of long cable girder side pull-in, structure and performance propose high request to the lifting gantry. In this paper, the design and use key point of long cable pull-in angle adjustment device integrate into lifting gantry is introduced.
Key words: Sutong Bridge; large units; lifting devices; cantilever installation; lifting gantry; design and use

1 Introduction

The main bridge of Sutong Bridge has two pylons and two cable planes, which is a cable-stayed bridge with steel box girders and has the first steel span in the world. Its span combination is (2 × 100 + 300 + 1 088 + 300 + 2 × 100) m. The steel box girder of main bridge adopts fully welded stream lined structure and is divided into 17 types of 141 segments, with a total weight of about 50 000 t. The steel box girder containing wind fairing is 41 m wide, 4 m high at its center line (Fig. 1).

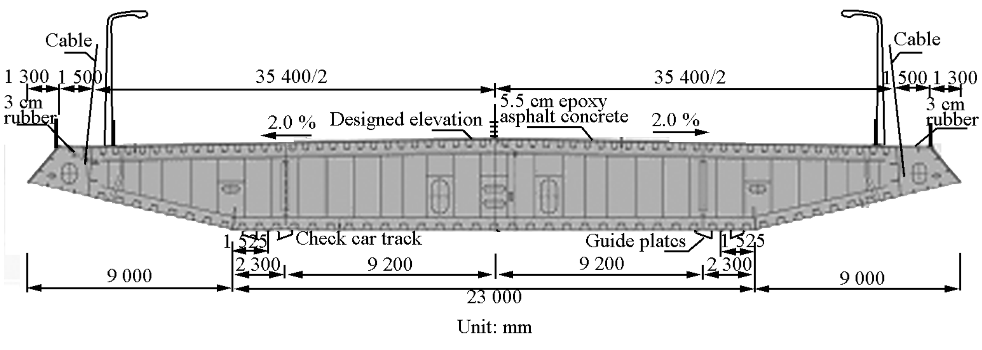

Fig. 1 The cross section of main bridge steel box girder

The main bridge steel box girder of Sutong Bridge included five portions: back span large unit, large block of pylon, standard girder, back span closure girder and middle span closure girder, and the large unit is erected by floating crane, the upper structure used lifting gantry to install the standard girder segment by cantilever.

2 Research on lifting equipment of back span, side span large unit

2.1 Overall layout of large unit

According to structure design of steel box girder,

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the location of temporary supports and lifting performance of existing floating crane in China, the steel box girders of side span and back span were butt welded into 9 girder segments, with the length of 16 ~ 60 m and the weight of 380 ~ 1 208 t.

Large units of pylon are marked NA1-2, NT0, and NJ1-2 from bank side to river side, their length respectively is 22.2 m, 13.2 m and 22.2 m, with the biggest lifting weight of more or less 695 t.

2.2 Performance parameter of floating crane and layout of lifting-point

In view of lifting weight and lifting height, domestic floating crane that can be used to install large unit of Sutong Bridge is Zhenfu No. 4[1,2], and its main performance parameters can be seen in Table 1.

Table 1 Performance parameters of floating crane with lifting weight

Total length /m	Total width /m	Molded depth /m	Inclined angle of hanger arm /(°)	Lifting weigh /t	Lifting height /m
94	36	6.8	63	1 600	95
			60	1 500	90
			55	1 200	86
			50	1 000	80

According to the weight and length of large units, 4 lifting-points were set in unit IX, IV, II each, and 8 lifting-points to other large units.

2.3 Lifting device design of large unit

2.3.1 The request to lifting device of large unit

1) The height of lifting device. Supposing water level elevation height is −1.0 m, the largest lifting height of large unit is 74.0 m. Considering that the bridge was located in the large storms and the impact of large vessels, in order to ensure the lifting unit and temporary fixtures do not collide, the elevation difference between the bottom of the segment and the top of the supports should not less than 1m. Therefore, the total height of lifting device should be less than 95 − 74 − 1 = 20 m.

2) The weight of lifting device. Except the weight of the dead weight of the beam segment (1 208 t), the counterweight for the balance of the beam segment (82 t) and local reinforcement structure for large unit installation (20 t), the total weight of the lifting device should be less than 1 600 − 1 208 − 82 − 20 = 290 t.

3) The types of lifting device. The length of the 9 large units is different. For the request of different beam segments installation and minimizing the type number of lifting devices, all large units were divided into 5 lifting-point styles. It is required that the spreader structure can adapt to every lifting-point styles.

4) The disposing of lifting device. The floating crane Zhenfu No. 4 (1 600 t) had two hooks. According to the operating requirements of the floating crane, the horizontal force between two hooks should be less than 100 t in the design of lifting device structure.

2.3.2 Design of lifting device structure

The answer to the above 4 problems conducted to the structure type of the lifting device.

1) Design of spreader structure type. At first, comparative calculations of two kinds of spreaders were carried out and the better one would be used in the project.

Spreader 1: Truss structure was considered (Fig. 2). For the characteristic of the structure type, several lifting-points were laid on bottom chord bar and the weight of the beam segment was distributed uniformly under the truss spreader bottom chord. Spreader of this kind usually has high stiffness and big deadweight. By calculating, when lifting device has a limitation of 20 m, vertical angle of lateral slings would be 57°, the total weight of lifting device would be 250 t, and the diameter of the sling 12 cm. The main problems of this kind of spreader concluded: there was only 40 t surplus of the capacity; it's difficult to manufacture and install the sling with big diameter and not accommodated by the hooks of the floating crane. Further more, there was connection difficulty between the spreader and the lifting-points, while each lifting-point was unevenly stressing. For the big vertical angle of the sling, it's difficult to control balance of the beam segment and the load of each sling, which go against the safety of the installation.

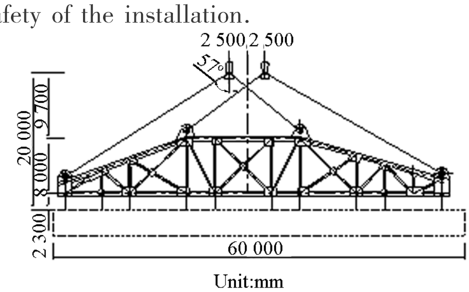

Fig. 2 Schematic diagram of the spreader structure in steel truss

Spreader 2: Structure of plane compression bar was considered (Fig. 3), which lowered the height of the structure, and decreased the weight. By computing, when the height of the lifting device was 18.3 m, vertical angle of lateral slings would be 40° and relatively reasonable. The diameter of the sling was small and the total of the lifting device was about 170 t with a surplus 120 t of the weight and 2.7 m to the height. Equipment of this kind could make the installation more save.

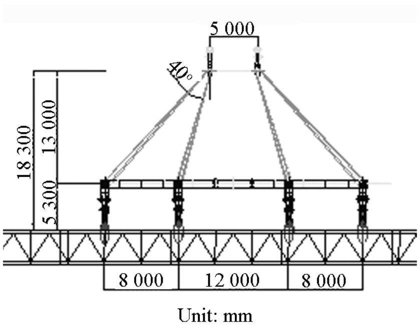

Fig. 3　Schematic diagram of the plane pressure lever spreader structure

Through the description of the two structure types, it is reasonable to adopt the latter.

2) Layout design of the sling. If sling were lay out as Fig. 3, there would be great horizontal force between hooks which exceeded the capacity of hook itself. Therefore, crossed slings shown in Fig. 4 is used to minish the horizontal force. However, it is possible that disastrous consequences occurred when there is large bending stress in spreader structure caused by the un-synchronous of two hooks or the length difference of the slings. Thus it is important to control the manufacture length and the operating synchronous strictly.

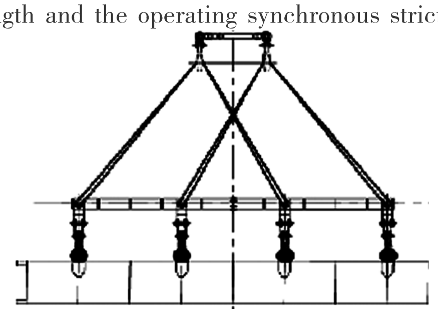

Fig. 4　Cross slings

3) Spreader structure. Spreader structure includes main hanging beam, brace and shackle, therein main hanging beam of spreader with 8 lifting-points was steel box girder structure, and brace was steel pipe structure. Main hanging beam, brace and shackle are combined by a pin. Main hanging beam was divided into three segments, and two side segments were fixed with an adjective segment in the middle, which were connected by high-strength bolt and could combined together in many ways. This method was adapted to meet the requirement of beam segments with different lengths, and therefore realize generality (Fig. 5).

2.4　Lifting device of large unit

2.4.1　Installation of lifting device

It is difficult to pre-assemble and transport the

Fig. 5　Spreader structure with 8 lifting-points

lifting device because its great dimension and weight. It was the beam segment waited installed that utilized the spreader assembling and sling hook hanging, and small floating crane utilized the spreader structure assembling, and small hooks of 1 600 t floating crane for the sling hooks.

2.4.2　Monitoring of lifting device force

According to the force analysis of the lifting device, the spreader structure with 8 lifting-points force was influenced remarkably asynchrony of floating crane hooks. Because relative height difference of the measured hooks was unavailable, so the stress of key sections of the spreader structure was monitored to control the hook movement for attaining the same control effect.

3　Research of lifting device of standard beam segment

Standard beam segment includes symmetrical beam segment with double cantilevers and beam segment with single cantilever. There are 80 standard beam segments that are cantilever installed totally, therein $4 \times 8 = 32$ segments with double cantilevers and $2 \times 24 = 48$ segments with single cantilever.

The length of standard beam segments (A3 ~ A10, J3 ~ J34, total 80 segments) are 16 m, and 326 ~ 450 t in weight. The installation process is: installing deck lifting gantry symmetrically in pylon area, than it was transported to the site by ship, the deck lifting gantry was constructed from side span to the middle used double cantilevers balanced method, than constructed use single cantilever method, finally closure up.

3.1　Multi-functional deck lifting gantry design

3.1.1　Construction requirement to lifting gantry

1) Lifting height and speed. Lifting height of beam segment of middle span is about 80 m, and the bridge is located at the golden waterway of lower Yangtze River that 6 000 ships passed everyday. The installation of main span steel box girder engrossed main sea-route, and affected the transport. It is important that deck lifting gantry running in higher speed to minish the sea-

route engrossing time.

2) Lifting weight. The biggest lifting weight of standard beam segment is 450 t, this set a high goal to the performance of deck lifting gantry structure and lifting system.

3) Meteorological and hydrographic condition. The bridge is located at where the river is wide, the water is rapid and the billow insurgent and the tide are changeful. The max flow velocity is 3.86 m/s, point flow velocity is 4.47 m/s. There are more than 150 days that wind degree exceeded 6 in a year. And it is possible that typhoons attack this area from the last 10 days of May to the last 10 days of November. The meteorological and hydrographic condition of the area is complex that affects the precision of boat location and lifting device structure design remarkably.

4) Control system of the crane. Control system of the crane should monitor the force status and movement of the lifting-point in real time because of the big weight and height. At the same time, component geometric control method called for the recurrence of the pre-assembling state, which put forward higher requirements to the device location precision.

5) Dead weight of the crane structure. The structure is long and flexible. The stress and strain of the main beam are very sensitive to the construction load of cantilever front end. Therefore it was important that deck lifting gantry structure should be defter.

6) Matching of different beam segments. The width of the main beam is 41 m and the maximum weight of one single segment is 450 t. When conventional single crane structure type is adopted, the relative deformation difference between the installed beam and the waiting-for-installation beam becomes very remarkable, even to 7 cm. After matching, the residual deformation of the structure is hard to eliminate, which will affect the shape of the main beam at unstressed status.

7) The movement of the crane. Stay cables adopt twice stretching technique, namely, moved crane forward after first stretch, and then second stretch is executed. The length of the standard beam segment is 16 m, which calls for faster movement speed of the crane when the construction period is short.

8) Stay cable construction. The traction and anchorage force of the stay cable exceeds 650 t, thus combined traction and stretch techniques are used at the beam end. To avoid bending of the tension rod, angle adjust device of the anchorage tube at cantilever front-end. Because of the small spaces at the front-end of the cantilever and the requirement of controlling its load and adjusting its movement conveniently, integrative design of the angle adjust device and the deck lifting gantry was required.

3.1.2 The determination of the structure type for the deck derrick crane

As for the selection of the structure of the deck derrick crane, it needs to make decisions for the following two main issues:

1) The selection of the upgrade system. The first one is hoister upgrade system whose representative engineering is Tatara Bridge in Japan. The second one is steel hinge line upgrade system whose representative engineering is Nanjing No. 2 Bridge and Nanjing No. 3 Bridge[3,4]. The comparison of the two systems is shown in Table 2.

Table 2 The comparison of the upgrade system

Project	The hoister upgrade system	The steel hinge line upgrade system
Hoisting weight and height	No restriction	No restriction
Hoisting speed	Up to 100 m/h, with the increase of the lifting weight and the wire rope it will lower	Up to 30 m/h, related to the hydraulic, fundamentally constant
The structure dead weight of the hanging machine	Heavier	Lighter
Hoist controlling	Computer control	Computer control
Positioning precision	Lower	High, three direction all can be up to 1 mm
System security	The key of the security is the brake performance of wire rope and hoister; the damage of the wire rope will lead to the collapse of the whole system.	The key of the security is the anchorage of the steel hinge line; a single strand's wear and tear does not affect the safety of lifting, it can be replaced before the next section's hoisting.

Comprehensive consideration, the using of the steel hinge line jack upgrade system is more in line with the standards of the Sutong Bridge cantilever beam assembly requirements.

2) The deformation of the main beam. The main beam's deformation had something to do with the bearing point disposal. As a result, doing contrast through a single crane and double crane (Table 3).

Table 3 The contrast of the single crane and double crane

Project	Single crane (4 fulcrums)	Double crane (8 fulcrums)
The structure size of the hanging machine	Large size of the bar structure	Relatively small size of the bar structure
Wind-resistant and hoisting stability of the crane	Lower	Higher
Stress-free match between the beams	The number of points is small and focus, the local stress of the diaphragm is big, the local deformation of the beam segments is big, the adding steel of the main beams is much, when matching it is not easy to achieve stress-free match	The number of points is big and dispersion, the local stress of the diaphragm is small, the local deformation of the beam segments is small, the adding steel of the main beams is little, when matching it is easy to achieve stress-free match

Comprehensive consideration, the using of double crane was more in line with the standards of the Sutong Bridge cantilever beam assembly requirements. Double-bridge crane was consisted of steel framework, upgrade system, walking system, positioning system, spreader and work platform and other components.

3.1.3 The main performance index of the deck derrick crane and design parameters

Considering the above requirements to identify the main performance index of the derrick crane and design parameters as follows (Table 4).

Table 4 The main performance index of the deck derrick crane and design parameters

Project	Parameters	Remarks
The average lifting speed	40 m/h	To enhance the formation of a single hoisting speed through jack raised
Segment positioning accuracy	±1 mm	In any direction
During the lifting the maximum allowable wind speed	20 m/s	Deck elevation department
The maximum allowable wind speed during the walk	25 m/s	Deck elevation department
The maximum allowable speed during the non-operating (once in every 30 years)	34.5 m/s	10 m elevation service
In the water the plane positioning accuracy of the Yun Liang-boat	±2.5 m	

3.1.4 The main function of the bridge crane design

1) The overall node. In order to ensure the bridge crane's versatility, ease of processing and assembly, the crane steel frame used bolt connection, the complexity of the main nodes designed as a whole in order to ensure reliable power by the node.

2) The anterior fulcrum. For the convenience of walking and leveling, the anterior fulcrum of the bridge crane was designed to carrying-pole structure under which setting up cylinder (the cylinder was to set a fixed nut to prevent the hydraulic failure) under the cylinder setting up supporting leg to spread the reaction of the support. At the same time, in order to avoid the tow anterior fulcrums' elevation difference of the single crane causing additional stress, the former pole fulcrum beam structure used articulated.

3) Back anchor. The back anchor was the key parts bearing force of the deck derrick crane, because of the processing errors and the structural deformation after the installation of the main beam, the back anchor used to connect directly to anchor to the bridge will be very difficult, if expanded the hole diameter of the back anchor it might cause unevenly stressing and arise the lifting security issues. As a result, post designing the back anchor for the structure of multi-hinge rod could expand the horizontal and vertical tolerance of the back anchor's connecting and realize the fast connections and ensure the uniformly stressed.

4) Spreader. Spreader has tow functions, one is to connect beams suspended above points and the other one is to regulate the beam segment's longitudinal slope. a. Connection: as the beam manufacturing error, as well as the transport ship remains in bump, it can not use pin connection between the spreader and the beam segment hanging points, flexible steel cables used to connecting can solve this problem. b. Transfer slope: setting up adjust tilt jack on the spreader can realize longitudinal adjustment to meet the level lifting of the beam segments and the need for longitudinal adjustment when matching.

5) Operating system. In order to reduce the weight of the cranes, the track will be shortened and separated to anterior walk track and after walk track of tow sections, there are tow anterior walk tracks, symmetrically arranged in the bottom of the first point and there is one after walk track arranged in the middle of the back anchor beam, setting a single tank in the after walking track, pushing forward crane.

6) The main jack and the control system. The tow main jacks used DL-290 steel hinge line jack, with the stress and displacement sensor, it used a computer for centralized control and setting configuration-specific control software.

During the hoisting process, the control system interface displaces tow jacks' itinerary, load and status to diagnose the main fault of the system to achieve the tow main jacks' sport automatically and manually. The jack is equipped with double-layer self-anchored system; even in the hydraulic failure the strand jack can be safely anchored.

7) Positioning system. The precision of the positioning system for the beam to ensure no stress is a key match. The positioning system is divided into 3 parts, one is longitudinal adjustment and the other is height adjustment and the third one is the position adjustment of the beam segments. a. Longitudinal adjustment: changing the hanging position through telescopic the spreader to realize the beam longitudinal adjustment. b. Height adjustment: changing the elevation of the hanging position by micro-changes the main jack to achieve the elevation adjustment. c. Adjust the location of the plane: the main jack and the crane is separated and they can slide, by setting the expansion of the vertical and horizontal jacks up the crane changes the plane location of the main jack to realize the plane position adjustment of the beams.

Through some combination of the adjustment it can quickly achieve the three directions of the positioning accuracy of 1 mm.

8) The angle adjustment of the cable stay. Using the first quarter of the deck hanging machine to set cantilever beam on its slide, set up track under the cantilever beam, set up hand chain hoist on the track as a mobile hanging point, adjust the angle of the cable stay into the anchor pipe, after the deck derrick crane setting up a 50 t crane, it can be used to solve the problem of short-track and improve the traction point of view.

To achieve the above-mentioned functions of the bridge crane after the completion of the design of the total weight is less than 110 t (including studios, hydraulic equipment and support to adjust the angle) which realized the light.

3.2 The use of the deck derrick crane

3.2.1 The installation of the deck derrick crane

According to the lifting capacity of the equipment, the installation procedures of the Sutong Bridge's deck derrick crane are as follows:

1) Assembling the steel framework in the bridge;

2) Crane hoisting the steel framework as a whole to the bridge deck;

3) The crane to install the main jack's upgrade module, install other components, horizontal and vertical to transfer the crane in place to complete the installation;

4) The test of static load, dynamic load and hydraulic sea test at the scene of the bridge crane.

3.2.2 The using main points of the deck crane

1) The anchorage system maintenance. One of the main using points of the crane is to well maintain the anchorage system of the main jack to ensure the uniform force of the strand and the good anchor performance. Catching out the main jack clip before lifting for each time to check and in time to replace of the excessive wear and tear, for the waste in the chips, using steel grinding wheel to clean, reinstall after the maintenance of waxing.

2) The caring of the lifting system. Another important point for the using of the crane is that in the process of lifting, keeping a close watch on the work situation of the jack and reel strand for once come out abnormal situation it can be immediately identified and dealt with.

3) The walking of the crane. The use of the separate operating system and a single point of push technology, the cranes are divided into 4^{th} place to walk, each forward 4 m. The concrete steps are:

Step 1: the former walking crane moves forward 4 m, the push crane moves forward 4 m, repeat Step 1, the crane moves another 4 m;

Step 2: the latter walking crane moves forward 4 m, repeat Step 1 and Step 2, the crane moves forward 2×4 m, complete the forward moving of the crane.

4 Conclusion

There are a total of 18 beam segments for the side span and aided span for the Sutong Bridge, it lasts 4 months before and after the lifting, and the total lifting time is 28 days. In the lifting process of the large beam, based on the existing national capacity of floating, through in-depth study, it puts forward a new spreader scheme for the plane combination compression structure which overcomes the shortcomings of high degree and big self-weight for the traditional steel truss structure, greatly reduces the height of the crane, increases the well-off hoist, in the process of the lifting, the introduction of stress real-time monitoring system is to guide the process of the lifting and realize the whole process of controlling and information-based construction, it has played a crucial role for ensuring the safety of the lifting. With the continuous improvement in the performance of the large-scale floating crane, using large floating crane to install the main beam of the length and weight are also growing for the water of the long-span bridges. The successful application of a light plane combination spreader bar in the Sutong Bridge has a reference to a certain extent for other long-span bridge girder installation of a large segment.

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