Design and application of 9000KN hydraulic lifting cable-borne crane for suspension bridge steel girder erection

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Abstract. Based on the steel girder hoisting construction of Yangsi Port Yangtze River Bridge, the bearing capacity, applicability, safety and operation efficiency of 9000KN hydraulic hoisting cable-borne crane are studied. Considering the structural characteristics and parameters of the bridge, the hoisting methods of special beam segment and the construction cost and safety of double cable-borne cranes, the main parameters of the cable-borne crane of the bridge are determined. Then, the structure of cable-borne crane is checked by ANSYS. Finally, the cable-borne crane has been verified by experiment and applied in engineering. The results show that the structure of 9000KN hydraulic lifting cable-borne cranes is safe, reliable, excellent-performance, energy-saving and environmental. The whole structure of the cable-borne cranes adopts modular design and has strong versatility, which is conducive to installation, transportation and turnover utilization, and has brought better economic benefits to society.

1. Introduction

Cable crane is a kind of lifting machine which uses cable as its bearing body to lift heavy loads. It has been widely used in the construction of suspension bridges. The theory and concept of cable crane technology in the field of lifting were initially formed in the mid-19th century. Cable crane originated from developed countries such as Britain and the United States, and the hoister-type cable crane was the earliest one. Sanluo Bay Bridge in the United States first uses a ship to transport the truss stiffening girder weighing about 2,000 KN to anchor under the bridge, and then lifts the stiffening girder in place with four hoisting points by hoister-type Cable-borne crane, with four hoisters on each side of the tower. The Velazano Bridge in the United States is a three-span suspension bridge with truss sections weighing 1630 KN to 3570 KN. There were two hoisters under each tower. The hoisting force of the hoister was 270 KN and 159 KN respectively. The hoister was lifted by wire rope through the fixed pulley group of the cable crane along the top of the tower and along the head of the cat. The section weight of stiffening girder of steel box girder on Saiwen suspension bridge was 1300KN. There were 88 sections of box girder and two 100KN double-roll hoist cross-cable cranes. Danish small Belt three middle suspension bridge, lifting section of steel box girder weighs 2800KN, using 4 lifting points hoist type Cable-borne
crane. In Japan, hoisters are widely used. The hoister-type cable-cutting crane was used in Toyoshima Bridge. The cable-mounted crane was driven directly by four drum-shaped rollers installed on the main cable, using the method of strong winding wire of the hoister. There is also the Bosporus Strait Suspension Bridge in Turkey, which used hoister-type cable-mounted cranes. The level of research and development and application of foreign hydraulic lifting Cable cranes has been improved, the most prominent representative of which is Duomolang Company in Britain. The most typical construction case is the steel box girder hoisting of the East Bridge of Dabei Shanghai Bridge in Denmark. The Shantou Bay Bridge in Guangdong, completed in China at the end of 1995, is a prestressed concrete stiffened girder suspension bridge with a main span of 452 m, a box girder width of 26.25 m, a length of 5.7 m and a height of 2.2 M. Each section weighs about 1600 KN and 1800 KN is erected by a hoisting Cable crane. The standard beam section of Guangzhou Pearl River Huangpu Bridge built in 2008 weighs 2150 KN and the heaviest beam section 2300 KN. The hoisting cable-supported crane with the maximum lifting capacity of 2800 KN is adopted. The hoist is used as the lifting power device. The Qingma Bridge in Hong Kong, completed in 1997, and the Jiangyin Yangtze River Bridge, which opened to traffic in 1999, all or most of the stiffening beams were erected vertically by 3700KN crawler hydraulic cable crane. The steel box girder was hoisted by four cable cranes, two cable-crossing cranes in a group, one steel box girder is hoisted from mid-span to North-South sides. The maximum weight of the section completed in 2012 is 2820 KN, and a walking hydraulic cable crane with a lifting weight of 4000KN was used for erection and installation. The superstructure of the main bridge of the Quanzhou Yangtze River Bridge in Wuhan completed in 2014 is composed of steel-concrete composite beams with a width of 38m, a height of 3m, a standard section length of 15m and a maximum section weight of 4500KN. A cable-mounted crane with hydraulic traction of 5000KN and roller walking was used for erection and installation. The construction of Dongting Lake Bridge of Hangzhou-Rui High Speed completed in 2017 was carried out by a cable-loaded crane with a single 6000KN hydraulic traction combined with roller walking. The main truss is 9.0m high, the truss width is 35.4m, the length of a standard section steel truss is 16.8m, the bridge width is 33.5m, the lifting weight of the standard section is 3200KN, and the maximum lifting weight of the non-standard section is 54KN. The current development direction of cable crane is composed of the original main cable and a moving load. It gradually develops into a complex whole composed of main cable, main truss beam, lifting system, walking system, control system and auxiliary system. The lifting control system is developed from manpower winch, traditional hoist to automatic hydraulic synchronous system. The lifting capacity is from several tons to several tons. Dozens of tons have grown to hundreds and hundreds of tons today. Steel girder hoisting construction is an important stage of suspension bridge construction. Cable-loaded crane is a special equipment for steel girder hoisting and installation. Its carrying capacity and operation efficiency are directly related to construction quality, progress and safety. Steel girder hoisting construction is an important stage of suspension bridge construction. Cable crane is a special equipment for steel girder hoisting and installation. Its carrying capacity and operation efficiency are directly related to construction quality, progress and safety.

2. Steel truss girder
The cable-mounted crane is mainly composed of two sets of roller-type walking mechanism on the main cable, one steel main truss beam, two sets of hydraulic lifting equipment integrated with diesel generator (including lifting and traction jacks, hydraulic pump station integrated with diesel generator, control system and strand take-up device), sling flat pole beam and other parts. Its structure is shown in Figure 1.
2.1. **Steel truss girder**

The steel truss structure is composed of two box-type load-bearing beams connected by H-section steel welded truss beams, as shown in Figure 2. Intermediate truss beams are mainly rigid supports for the whole structure. The space of truss is used to install steel strand retractors, diesel engine integrated hydraulic pump station and control room, and to provide working platform for construction operation. In order to facilitate transportation, installation, disassembly and connection, and to adapt to structural changes and modifications of different main cable spacing, the intermediate truss beam is designed in five sections. The pin connection is used between segments, and the bolt connection of high-strength bolts is used for other connections, which are spliced on site to achieve modular design.

![Figure 2. Structural diagram of steel truss beam](image)

The box-type load-bearing beams at both ends are mainly equipped with hydraulic lifting jacks, and are also the main stress components. In order to facilitate transportation, box-type load-bearing beams are also bolted by high-strength bolts, which are spliced on site to achieve modular design.

2.2. **Walking mechanism**

The main body of the walking mechanism is a box structure, which is the framework of various mechanisms and structures. Load conversion device, holding device, hydraulic winch, traction cage and traction roof are installed on it, as shown in Figure 3. The replaceable supporting and clamping device is installed at the bottom of the main body of the walking mechanism, and bears the lifting gravity and sliding force when lifting the weight. In order to meet the different length of cable clamps, the crane is
precisely positioned by bolt connection, which can move the supporting position. There are four sets of load conversion devices installed on the walking mechanism. The load conversion device is controlled by a hydraulic pump station. The running wheels of the device can rise and fall independently or simultaneously. There are clearances in the axes of each wheel to compensate the spacing error of the main cables automatically. Hydraulic winch is a kind of traction device which provides auxiliary sliding force when the cable-loaded crane moves downward to the mid-span position with insufficient sliding force, as well as a traction device when the two machines walk synchronously.

2.3. Hydraulic lifting jack
The lifting mechanism adopts two sets of 5700kN hydraulic lifting jacks. As shown in Figure 4, the jack can lift and drop heavy objects. The integral clamping mechanism can effectively ensure the opening/closing of all clamps. The use of steel strand with diameter of 18 mm can reduce the number of lifting strands. A safety clamp is placed under the lifting jack. When the lifting jack or other emergencies occur, all the clamps of the safety clamp are clamped. When working normally, all clamps of safety gripper are loosened.
2.4. Steel strand retractor
In order to reduce the influence of hoisting on the waterway, steel strands and hangers are retracted and put in by hydraulic motor type take-up device. The lowest speed of setting-off can reach 80 m/h. Hydraulic motor, planetary gear and steel structure combined take-up disc is a take-up device which integrates machine, electricity and fluid. It uses gear transmission pair to decelerate and hydraulic motor back pressure to restrict the over-range rotation of take-up disc. The braking moment can reach 4 to 5 times of the input moment. The device includes installation of chassis, steel tube drum, hydraulic motor drive system, rope arranger, etc.

2.5. Hydraulic pumping station
Hydraulic pump station is specially designed to meet the requirements of 900 tons cable-loaded crane. The system uses diesel engine as power, drives plunger pump and high-pressure gear pump to provide pressure oil for the system, and forms pressure and flow circuits with hydraulic components such as relief valve and solenoid reversing valve to drive the tightening anchor, loose anchor, expansion cylinder, contraction cylinder of lifting jack, and other execution. The action of the mechanism. At the same time, the hydraulic pump station can also use the control system to control its output flow and pressure. Through the coordination of the control system, the speed of the jack can be accurately adjusted, and the cable-mounted crane can walk up and position and hoist. The output flow and pressure of the hydraulic pump station can ensure that the maximum comprehensive speed of lifting jack synchronously lifting and descending can reach 30m/h, and the maximum speed of crane cable can reach 30m/h. The control system can adjust the output flow of the main pump of hoisting (traction) steplessly, so as to realize the speed change of the actuator and improve the synchronization accuracy of hoisting. The system consists of three independent loop systems: lifting (traction) system, clamping system and walking system. The three systems all output hydraulic oil by independent pump head, independent hydraulic valves and related hydraulic components to control the pressure and flow direction of hydraulic oil. They are all in one way, and they do not interfere with each other. They simplify the hydraulic circuit and are easy to control.

2.6. Spreader
The suspension structure mainly includes cylindrical cylinder, flat pole beam, flat pole beam slide box, lifting anchor support and lifting steel strand, etc. Each cable crane is equipped with two hangers. The hanger can adjust the center of gravity of the section beam through the hydraulic cylinder, adjust the vertical rotation and alignment, and move along the bridge to the suspension point.

2.7. Other hydraulic control systems
The cable crane is equipped with a central control room, and a diesel engine-driven hydraulic pump station is arranged on both sides of it, which are lifting mechanism, walking mechanism and traction mechanism on the left and right sides respectively. The steel strand retracting and releasing device provides hydraulic power. The lifting mechanism adopts two sets of 5700kN hydraulic lifting jacks, which can lift the falling weight.

3. Structural check of cable crane
In order to ensure the structural safety of 9000KN hydraulic lifting cable crane, the structural checking of the steel structure of cable crane is carried out.

1) Checking calculation of steel truss
   The truss structure of cable-mounted crane is calculated by finite element method with three different load combinations. 1) windless working condition; 2) windy working condition; 3) non-working condition. According to different load combinations, their safety factors are taken separately. Considering the construction condition, according to the position of the main cable of the cable-loaded crane, the cable-loaded crane is selected to operate at the main cable level and 30 degree inclined position of the main cable, and the main girder swing construction condition is also considered.
Structural strength checking, stiffness checking, stability checking and node checking under working conditions are carried out, and constraints are imposed at the corresponding locations. Beam element is adopted, elastic modulus is 2.06×10^5 MPa, Poisson's ratio is 0.3 and density is 7850 kg/m^3. The main pole material of cable-mounted crane is Q345B [5], and the pin shaft is 40Cr. The calculation shows that the swing hoisting condition with wind (25 m/s wind speed) is the most disadvantageous. Under this condition, the maximum stress of the bar is 204.1 MPa, less than the allowable stress of Q345B 215.6 MPa, which meets the requirements; the maximum vertical displacement is 59.5 mm, which does not exceed the allowable deflection value of 71.7 mm, which meets the requirements.

(2) Checking calculation of steel truss

Through ANSYS finite element software, solid calculation unit Solid185 and Solid187 are used to establish the model, and the working conditions of cable-loaded crane in horizontal position of main cable without load, in 30 degree position of main cable without load, in horizontal position of main cable with load, in 30 degree position of main cable with load, and in exciting position of main cable with 30 degree of load are fixed. The stress, deformation and pin stress of walking mechanism steel structure are analyzed. The calculation shows that the maximum stress of the walking mechanism is 196 MPa (< Q345B material allowable stress, meet the requirements) and the maximum deformation is 2.9 mm (meet the requirements) when the main cable is fixed at 30.

4. Engineering application

Yangsi port Yangtze River Bridge is a single-span suspension double-deck steel truss suspension bridge with a main span of 1700m. It is the largest double-deck highway suspension bridge in the world. There are two main cables in the bridge. The span of the main cables is (465+1700+465) m, the distance between the main cables and the center of the bridge is 28m, the diameter of the main cables is 1088m, and the maximum clamp size (length × height of the clamp) is 2460mm × 182mm. The stiffening girder of the main bridge is a truss structure with a truss height of 10 m and a standard segment length of 9 m. There are four types of stiffening girders (L1-L4). Adopt large segment (the maximum length is 36 m) integral hoisting, the net weight (without suspension) of the heaviest beam segment is about 10500KN . There are 49 segments in the whole bridge. The bridge uses two 9000KN hydraulic lifting cable-mounted cranes. Considering the actual working condition of the structure, because of the curvature of the main cable, may only two of the three hags of a single walking mechanism actually participate in the work, and there is a large eccentricity, which makes the bearing force of one hug much larger than that of the other. For the sake of structural safety, the whole machine is checked and calculated. ANSYS is used and the entity element Solid185 is adopted. According to the actual constraints, full constraints are applied on the arc surface contacting the main cable.

The most unfavorable condition is that the cable-loaded crane is swinging on the main cable at 30 degrees. The contact elements Target170 and Contact17 were adopted between the big roller and the big roller shaft of the walking mechanism and between the big roller and the main cable, and the friction coefficient was 0.15, and contact constraints are used between the large roller and the large roller shaft and between the large roller and the main cable; Full restraint is applied on the bottom of the main cable. There are three kinds of materials involved in the model analysis, among which the large roller adopts nylon MC901, the main cable adopts high-strength steel wire, and the large roller shaft adopts alloy structural steel 40Cr. After calculation, the overall comprehensive stress of the traveling wheel structure is 180 MPa and the maximum stress of the large roller is 47.1 MPa. The large roller shaft is made of alloy steel with yield strength of 785 MPa. According to the calculation, the maximum stress of the large roller is 47.1 MPa, less than the yield strength of nylon material 81.5 MPa, which meets the engineering requirements. In December 2018, two 9000KN hydraulic lift cable-borne cranes on the bridge successfully completed the lifting of steel beams of the whole bridge.
5. Conclusion

Based on the hoisting of large tonnage stiffening girder of long span suspension bridges in China, a new model of cable crane is established by using Solidworks, a three-dimensional mechanical design software, and a new cable-loaded crane is developed which can adapt to large tonnage hoisting. The practical results of the 9000KN hydraulic lifting cable-mounted crane of Yangsi Port Yangtze River Bridge show that its structure is safe, reliable, excellent performance, energy-saving and environmental protection. The whole structure of the crane adopts modular design and has strong versatility, which is conducive to installation, transportation and turnaround utilization. The practical results of the 9000KN hydraulic lifting cable-mounted crane of Yangsi Port Yangtze River Bridge show that its structure is safe, reliable, excellent performance, energy-saving and environmental protection. The whole structure of the crane adopts modular design and has strong versatility, which is conducive to installation, transportation and turnaround utilization.

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