Product Research and Development

Application and Practice of Replaceable Main Cable Strand Anchorage Scheme in Self-Anchored Suspension Bridges

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Abstract: The main cable strands of self-anchored suspension bridges are typically anchored directly to the back of concrete or steel girders, a construction method that has durability issues. To address this problem, a new combined anchorage structure using finished cables and a connecting shaft is proposed. This anchorage structure is connected to the end of the main cable strands via the connecting shaft. This article provides a detailed description of the design concept and specifics of this new anchorage structure, including installation methods and procedures for removal and reinstallation during bridge operation. Full-scale static load tests validated the feasibility of the proposed design. This new structure improves the durability of the main cable anchorage section, allows for its replaceability, and can be extended to other similar applications, offering considerable reference value.

Keywords: self-anchored suspension bridge; main cable; cable strands; anchorage structure; finished cable

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1 Engineering Background

The newly constructed Hongzhou Bridge is an important river crossing in the southern area of Nanchang City. It is located approximately 1.5 km downstream from the Shatian Railway Bridge and approximately 3 km upstream from the Fuxing Bridge. The Hongzhou Bridge is oriented east–west, connecting the Jiulong Lake area on the west bank with the Xiaolan Industrial Park in Nanchang County on the east bank, with a total length of 4.34 km. The construction of the Hongzhou Bridge is significant for promoting the implementation of Nanchang's "One River, Two Banks" layout and accelerating the development of both banks of the Ganjiang River [1].

The river-crossing section of the Hongzhou Bridge is approximately 1.5 km long, with the main bridge being a self-anchored suspension bridge featuring spans of 50 m + 120 m + 252 m + 120 m + 50 m = 592 m and a standard width of 41.5 m (see Figure 1). The approach bridge uses 50 m prefabricated T-beam bridges with a standard width of 38 m [2].

The height of the tower above the main bridge deck is 63.2 m, and the total height of the whole tower is 83.8 m after the upper decoration is included (see Figure 2). The main cables have a rise height of 54 m and a rise span ratio of 1/4.67. The main cable cross-section consists of 37 strands of PPWS φ5.5-127-1860 MPa steel wires anchored to concrete bumps on the main girder, with Z-shaped wire wrapping for external protection. The suspension cables use two specifications of 7mm-1860MPa parallel steel wires, with 73 bundles and 91 bundles respectively, and a spacing of 8 m in the bridge direction. The main girder adopts the hybrid structure form of composite beam and concrete beam, and the girder height is 3.54 ~ 3.85 m. The composite beam is composed of a separated twin steel box, steel crossbeams, and a 30 cm concrete deck.

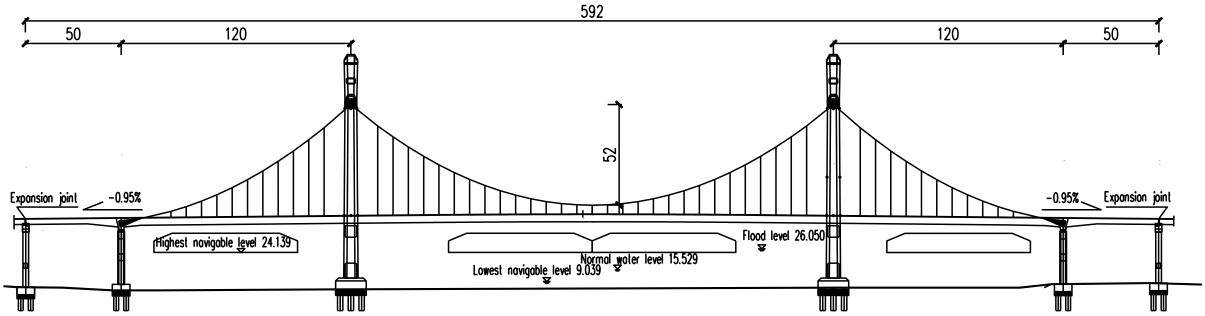

Figure 1 Elevation layout of the main bridge of Hongzhou Bridge (Unit: m)

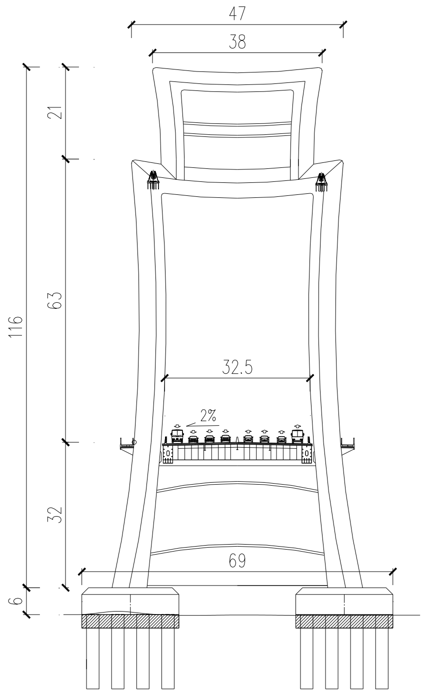

Figure 2 Cross-sectional layout of the main bridge of Hongzhou Bridge (Unit: m)

2 Problems of Existing Technical Solutions

At home and abroad, many self-anchored suspension bridges have been built, and there are cases in which the main span ranges from 100 m to 608 m [3]. The anchoring method of the main cable on the main girder is usually to directly thread the cable strands through the holes of the concrete bump and then extend to the back for anchoring.

From the perspective of force, this structure is safe and reliable, but it has two durability defects: (1) The end of the main cable strand extends to the lowest point of the bottom of the girder for anchoring. In this structural form, the condensate formed inside the side span main cable will flow down along the steel wire under the action of gravity and eventually accumulate at the anchor head. (2) Most of the holes of the concrete bump are down along the cable strand. Due to the presence of a certain space in the anchor chamber on the girder, the water vapor in the anchor chamber will enter the holes of the concrete bump. These water vapors will form condensates when the temperature drops and then accumulate at the anchor head at the lowest point.

At present, the domestic main cable strand anchor heads are usually equipped with drain holes, which can solve the first problem to a certain extent, but there will still be a certain amount of water accumulated in the anchor head. To alleviate this problem, the manufacturer usually adds a portion of the material, and once the main cable anchor head is rusted, it is descaled and then properly protected. This is essentially a way to increase the material to offset rust to increase the service life of the cable strand. However, when the maintenance environment is harsh or insufficient, the amount of rust will exceed expectations, which seriously affects the structural life.

Some bridges use the method of filling concrete holes with polymer materials to improve durability, but this method only solves the second problem and cannot solve the first problem. Combined with the design plan of the Hongzhou Bridge, this paper proposes a new type of cable strand anchoring structure that solves the above two problems from different perspectives.

3 Design Ideas of New Anchorage Structures

Since the ends of the cable strands always extend downward, water accumulation at the anchor head is inevitable and difficult to avoid. Therefore, the anchor head and the end segments of the cable strands are designed to be replaceable, allowing rapid replacement when they become irreparably damaged.

After the main cable passes through the splay saddle on the girder, it spreads out. Before the strands enter the concrete holes, their end segments are broken off and connected to replaceable finished cables by a connecting shaft [4]. The finished cables pass through the concrete holes and are anchored at the rear anchor surface of the concrete girder. This design maintains the load-transferring capacity of the cable strands while enabling the end segments to be replaceable.

Drawing inspiration from the main cable anchorage structure of ground-anchored suspension bridges and the hanger connection structure of arch bridges, a detailed anchorage connection scheme for the end segments of the main cable strands was designed, as shown in the Figure 3 and Figure 4 [4]. The key components include the main cable strand anchor cup, connecting shaft, finished cables, pre-embedded spreading tube group, wedge-shaped steel plates, anti-corrosion materials, and waterproof caps. The connecting shaft is made of 42CrMo with an ultimate strength f_b of 750 MPa and a design strength f_y of 550 MPa, with a diameter specification of 165 mm. The finished cables used were φ15.2-22-1860 MPa steel strand cables.

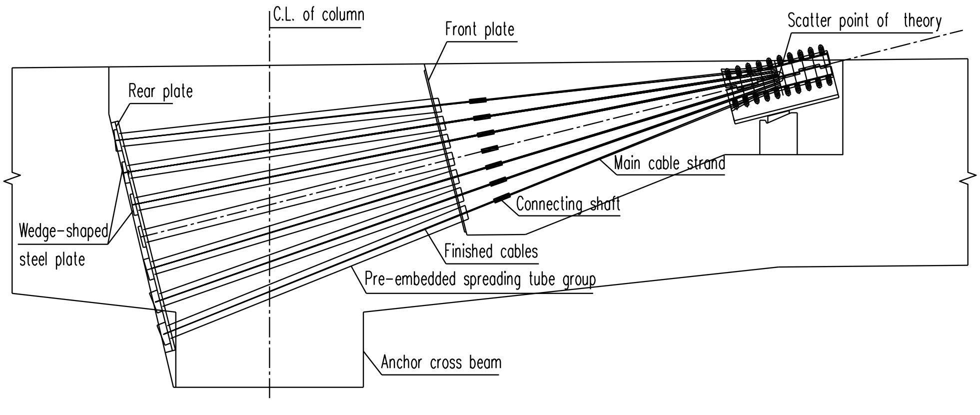

Figure 3 Elevation layout of the scattered cable area of the self-anchored suspension bridge

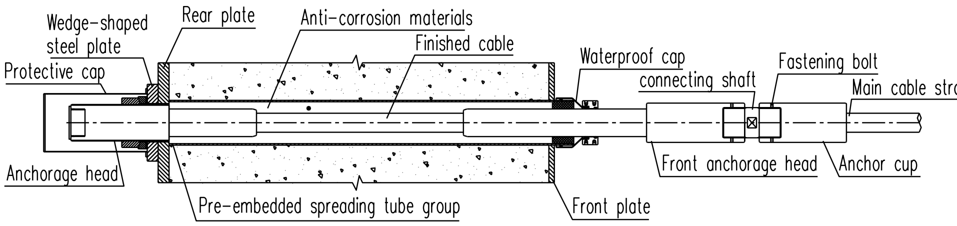

Figure 4 Layout diagram of the cable connection and anchorage structure

4 Design details

The ends of the main cable strands in the anchorage zone on the girder are designed with an anchor cup structure [5]. The cable strands and the anchor cup are connected using a "steel wire separation + hot casting" method. The rear end of the anchor cup has an open cup shape with internal threads, and the internal diameter of the cup matches the external diameter of the connecting shaft (Figure 5).

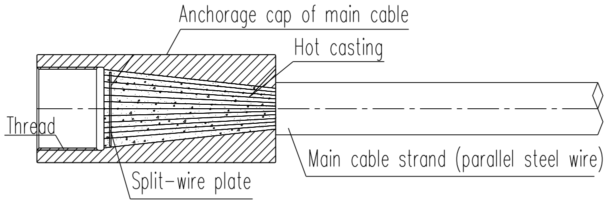

Figure 5 Structure of the anchorage head of main cable strand

The finished cables (Figure 6) include the cable body, front anchorage head, rear anchorage head, and rear protective cap. The cable body and front anchorage head are connected using either an "extrusion steel wire head + cold casting" or a "steel wire separation + hot casting" method. The front anchorage head is equipped with an anchor cup on the side of the connecting shaft. The front end of the anchor cup also has an open cup shape with internal threads, and the internal diameter of the cup matches the external diameter of the connecting shaft. The rear anchorage head uses conventional cable anchoring devices. The front anchorage head of the finished cable has two more threads in its anchor cup than in the anchor cup of the main cable strands.

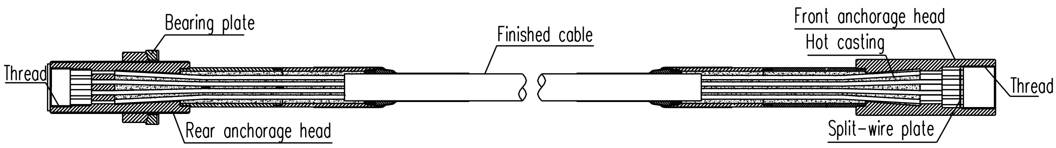

Figure 6 Structure of the finished cable

The connecting shaft (Figure 7) has a cylindrical outer contour, with connection zones at both ends and a nonconnection zone in the middle. The surface of the connection zones is threaded, connecting to the anchor cup of the main cable strands at one end and to the anchor cup of the finished cable at the other end. The exposed area of the connecting shaft has four flat surfaces, each perpendicular to the cross-section of the shaft. Any two adjacent flat surfaces are perpendicular to each other, with each flat surface forming a chord of the circular cross-section of the shaft. These chords do not intersect. The length of each flat surface in the axial direction does not exceed the length of the nonconnection zone. The threads at both ends of the connection zones are set as reverse threads.

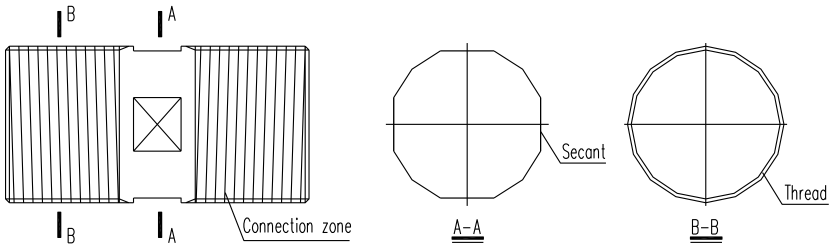

Figure 7 Connecting shaft details

The pre-embedded spreading tube group consists of a set of steel tubes with a spreading spatial configuration. Steel plates with holes are used to embed the tubes at the intersection with the crossbeam sides, with the front plate on the main cable strand side and the rear plate on the finished cable rear anchorage head side. The lower end of the steel tubes is flush with the rear plate, while the upper end passes through the front plate and is symmetrically arranged in multiple layers on the front plate, as shown in Figure 8. The internal diameter of the steel tubes must be larger than the diameter of the anchor cup of the main cable strands and the front anchorage head of the finished cable.

The wedge-shaped steel plate is a spatially configured steel plate with a central circular hole, placed between the rear anchorage head of the finished cable and the rear plate, used to level the rear anchorage head of the finished cable. The wedge-shaped steel plate is welded to the rear plate, as shown in Figure 5. The waterproof cap is a "half conical tube", fixed in place using fastening bolts, and installed at the upper end of the steel tubes, as shown in Figure 4. Anti-corrosion material fills the gaps between the steel tubes and the finished cable, and is applied to the finished cable, waterproof cap, connecting shaft, and exposed surfaces of the main cable strands. The assembly tool for the finished cable is a steel tie rod with threads at both ends. The front end thread connects to the internal thread of the anchor cup in the rear anchorage head of the finished cable, while the rear end thread is used to install a big nut for tensioning with a jack. The diameter of the steel tie rod matches the internal diameter of the anchor cup in the rear anchorage head of the finished cable.

The anchor cup of the main cable strands has four fastening bolt holes for installing fastening bolts. Similarly, the front anchorage head of the finished cable also has four fastening bolt holes for installing fastening bolts. These fastening bolts are installed after the connection of the connecting shaft with the main cable strand anchor cup and the finished cable front anchor cup is completed and are used to prevent the stress loss caused by the spin of the connecting shaft.

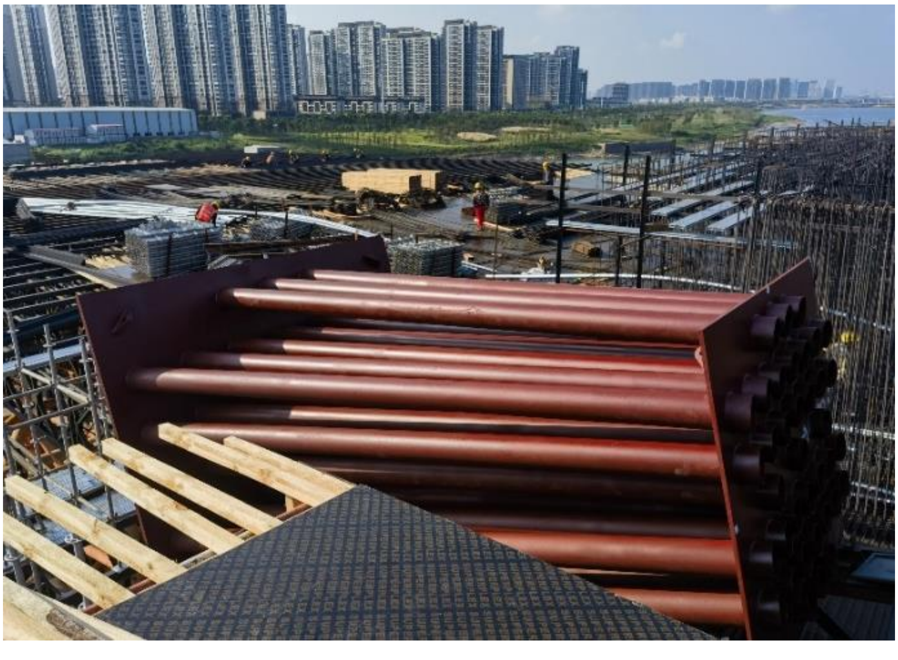

Figure 8 Pre-embedded spreading tube group

5 Full-Scale Structural Model Test

As this type of finished cable anchor structure for the ends of main cable strands is being used domestically for the first time, the design requires the main cable manufacturer (Jiangyin Fasten Group) to conduct full-scale structural model tests to verify the safety of the finished cables and the connection structure between the main cable strands and the finished cables.

Three test specimens were used, with the load fundamental combination maximum stress of 878 MPa and the load standard combination maximum stress of 663

MPa. The cross-sectional area of a single cable strand is 3,017.3 mm², with a breaking force P_b is 5,612 kN. The fundamental combination tensile force P_2 is 2,649 kN, and the standard combination maximum tensile force P_1 is 2,000 kN.

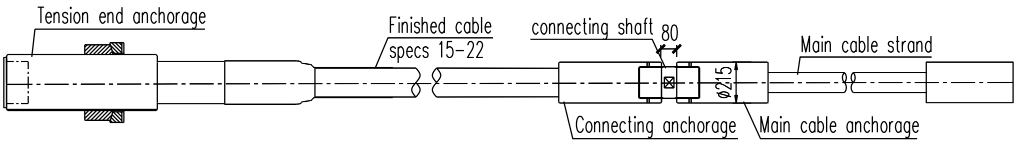

Figure 9 Test specimen details (Unit: mm)

The specific requirements for the static load test are as follows:

(1) The samples were then loaded to 1.7 times the standard combination maximum tensile force (1.7 × 2000 = 3,400 kN), held for 10 minutes, and then unloaded.

(2) The static load breaking force should not be less than 95% of the breaking force of the cable strand, which is 0.95 × 5,612 = 5,331.4 kN. After the test, there should be no damage to the anchorage devices or other auxiliary components, the anchorage devices should function normally, and the breakage rate of the steel wires in the main cable strands and parallel steel wire bundles should be less than 5%, with no breaks occurring in the anchorage zone. The residual deformation rate of the φ165 connecting shaft after unloading should not exceed 0.2% (residual deformation can be measured over a 3 m range, and when the residual deformation level difference does not exceed 30% of the average value, the average value can be used; if the level difference exceeds 30% of the average value, the number of test specimens should be increased, and the residual deformation should be reassessed based on actual conditions). All parts should rotate flexibly, and the threads at both ends should function normally.

The construction unit commissioned the Zhengzhou Metal Products Research Institute of China Steel Corporation to conduct the tests (Figure 10). The test results showed that the parameters and overall performance of the specimens met the requirements, confirming their applicability in the project.

Figure 10 Main cable strand, connecting shaft and the end of the finished cable specimen

6 Manufacturing and Installations

6.1 Initial Installation Method

For new bridges, the installation method for the finished cables at the ends of the main cable strands is as follows:

(1) The central main cable strand, connecting shaft, and finished cable in the bottom layer were installed first, and the strand was anchored. Then, other strands were alternately installed on both sides of this layer (Figure 11). Once all the main cable strands in the bottom layer are installed, the other main cable strands are installed and anchored, the shafts are connected, and the cables are finished layer by layer upward.

Figure 11 Installation of the first cable strand and finished cable

(2) The steel bearing plate of the rear anchorage head is screwed into the rear anchorage head of the finished cable. Before installing the main cable strand, the finished cable is threaded from the rear panel side of the corresponding steel tube, ensuring that the front anchorage head of the finished cable is positioned approximately two connecting shaft lengths away from the target location. After threading the finished cable, a temporary support bracket was used to hold the rear anchorage head bearing plate in place to prevent sliding.
(3) The front end of the finished cable assembly tool (steel tie rod) was screwed into the anchor cup of the rear anchorage head of the finished cable. The through-bore jack was placed over the finished cable assembly tool, and then the big nut was screwed onto the rear end of the finished cable assembly tool.
(4) The connecting shaft was hoisted to the anchor cup of the front anchorage head of the finished cable, the assembly tool was installed onto the three flat surfaces of the connecting shaft, and it was fixed. The assembly tool was used to screw the connecting shaft into the anchor cup of the front anchorage head of the finished cable, which was threaded in two turns.
(5) At the position of the rear anchorage head of the finished cable, a jack is used to push the finished cable toward the main cable strand direction. The connecting shaft assembly tool is used to screw the connecting shaft into the anchor cup of the main cable strand, threading in one turn.
(6) Check whether the alignment of the finished cable axis and the main cable end axis meets the requirements. Once confirmed, the jack is used to push the finished cable in and tighten the connecting shaft until all the threads are fully engaged.
(7) The fastening bolts were screwed into the anchor cup of the main cable strand and the anchor cup of the front anchorage head of the finished cable, and the threads were locked to prevent the connecting shaft from rotating.

(8) The temporary support bracket was removed, the jack was used to tension the finished cable assembly tool to the predetermined elongation, and the steel bearing plate of the rear anchorage head of the finished cable was rotated until it fit closely with the wedge-shaped steel plate (Figure 12).
(9) The assembly tool and the jack were removed, and the waterproof cap on the front end and the protective cap on the rear end of the finished cable were installed, completing the tensioning of one main cable strand.

Figure 12 Photo of rear anchor surface installation

6.2 Removal Method

When a finished cable exhibits durability defects, it can be removed and replaced via the following method:

(1) The waterproof cap was removed from the front end, and the protective cap was removed from the rear end of the finished cable. Install the finished cable assembly tool without the big nut onto the anchor cup of the rear anchorage head of the finished cable. The through-bore jack was installed onto the finished cable assembly tool, and then the big nut was installed onto the rear end of the finished cable assembly tool.
(2) The jack was used to tension and separate the steel bearing plate of the rear anchorage head from the wedge-shaped plate.
(3) The bearing plate of the finished cable was unscrewed to the end of the rear anchorage head of the finished cable.
(4) Install fasteners at the junction of the jack and the big nut of the finished cable assembly tool to fix them together. The tension of the jack is slowly released, and the cable force of the finished cable is unloaded.
(5) The four fastening bolts on the anchor cup of the main cable strand were loosened, and the fastening bolts of the waterproof cap were removed.
(6) The connecting shaft assembly tool was installed and fixed firmly. Slowly tension the jack while rotating the connecting shaft assembly tool, loosening the thread connection between the connecting shaft and the anchor cup of the main cable strand and the anchor cup of the front anchorage head of the finished cable until the connecting shaft is completely detached from the anchor cup of the main cable strand.
(7) A temporary support bracket was used to hold the rear anchorage head bearing plate of the finished cable to prevent sliding.

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(8) The finished cable assembly tool and the jack were removed.
(9) The temporary support bracket was removed, the rear anchorage head of the finished cable was slowly removed, and the finished cable and the connecting shaft were subsequently removed.

6.3 Reinstallation Method

After the removal of a finished cable, if a new finished cable needs to be installed, the operation can be performed as follows:

(1) The new finished cable was prepared on-site and placed on one side of the rear plate.
(2) The connecting shaft was installed into the anchor cup of the front anchorage head of the finished cable. The connecting shaft assembly tool was installed and used to screw the connecting shaft into the anchor cup of the front anchorage head of the finished cable, which was threaded in two turns to integrate it with the finished cable. The connecting shaft assembly tool was removed.
(3) The rear anchorage head bearing plate of the finished cable is screwed into the rear anchorage head.
(4) The finished cable (including the connecting shaft) is threaded from the rear plate side of the corresponding steel tube, ensuring that the end of the connecting shaft is close to the anchor cup of the main cable strand. After threading the finished cable, a temporary support bracket is used to hold the rear anchorage head bearing plate of the finished cable to prevent sliding.
(5) The front end of the finished cable assembly tool (steel tie rod) was screwed into the anchor cup of the rear anchorage head of the finished cable. The through-bore jack was placed over the finished cable assembly tool. Then, the big nut is screwed onto the rear end of the finished cable assembly tool.
(6) Steps 4 to 9 of the initial installation method are described in section 6.1.

7 Conclusions

After the design, testing, and subsequent construction, the development and application of the new type of main cable strand anchorage structure have been completed, providing valuable references for future designs of similar structures. Through the research and development of this type of main cable strand anchorage structure, the following conclusions have been drawn:

(1) The use of a replaceable connecting shaft + finished cable anchorage form at the end of the main cable strand facilitates the improvement of durability in the anchorage area on the girder of the main cable strand.
(2) The design of the connecting shaft with grooves facilitates the use of assembly tools to tighten the connecting shaft, aiding in rotating the threads. Additionally, under tension, the stress concentration in the grooved structure is significantly lower than that in the protruding structure.
(3) The design of the rear anchorage head of the finished cable as a cup with internal threads facilitates the installation of tools for tensioning the main cable, which can be removed after use without affecting the aesthetics.
(4) The construction where the inner diameter of the pre-embedded steel tube is larger than the diameter of the anchor head of the main cable strand and the front anchor head of the finished cable facilitates the installation, removal, and replacement of the finished cable.

Conflict of Interest: All authors disclosed no relevant relationships.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, Hu, upon reasonable request.

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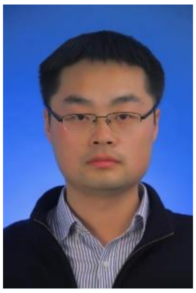	**Fangjian Hu** Ph.D. Senior Engineer. Shanghai Urban Construction Design & Research Institute (Group) Co., Ltd. Research Direction: Bridge Design and Research, BIM Technology R&D. Email: hufangjian@sucdri.com		**Long Chen** Engineer. Shanghai Urban Construction Design & Research Institute (Group) Co., Ltd. Research Direction: Bridge Design and Research. Email: chenlong@sucdri.com
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