Analysis of the effect of cable replacement and reconstruction of a single-tower cable-stayed bridge based on cable force optimization

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Abstract—Taking a single-tower cable-stayed bridge as the engineering background, this paper simulates the cable replacement process of the bridge by finite element analysis method, and improves the structural stress state by optimizing the cable force. Combined with the construction technology of demolishing old cables and installing new cables, the force of stay cables is controlled. The results of construction control and load test are compared and analyzed. It is found that bridge structure is safely stressed in the construction process, with no excessive displacement for main girder and bridge tower. Furthermore, after the cable is replaced, the overall stiffness of the bridge is significantly improved, and the load-bearing capacity and reinforcement effect are increased.

1. Introduction

Stay cables are divided into parallel wire cables and strand cables. The parallel wire cables are composed of multiple high-strength steel wires bundled in parallel, with the outermost layer directly extruded with high-density polyethylene as a protective cover. The parallel strand cables are composed of a single galvanized or epoxy-sprayed steel strand with a heat-extruded polyethylene sheath, which is then bundled in parallel to form a cable with a high-density polyethylene sheath as a protective cover. With a service life of generally 20 years, stay cables are the main force-bearing components that can be replaced. The cable replaceable and maintenance convenience were not considered in the early cable-stayed bridges. However, with the continuous development of cable-stayed bridge design and construction, existing cable-stayed bridge structure can generally be replaced during operation and use, or even can be replaced safely while maintaining normal traffic conditions. In recent years, with the increasing number of cable replacement projects for cable-stayed bridge, scholars at home and abroad have conducted more and more research on cable replacement and construction technologies and construction control$^{[1-5]}$. However, currently there is no systematic research on the structural mechanical behavior in the process of cable replacement, the optimization of structural force by adjusting cable force, the major construction technologies of cable replacement and the impact of bridge reconstruction after cable replacement, and there are few theoretical analyses and engineering practices. Taking a single tower concrete cable-stayed bridge project as an example, this paper analyzes the construction steps and plans of the cable replacement applying numerical methods, and improves the force of the bridge structure by optimizing cable force. Based on the disassembly of old cables and the installation of new cables and tension construction, the key construction technologies and procedures of stay cable
replacement are discussed and studied. Lastly, the reinforcement effect is evaluated and analyzed by comparing with load test results.

2. Engineering background and construction principles of cable replacement

2.1. Engineering background

The supporting project is a (60+90)-m single-tower single-cable plane cable-stayed bridge, which was completed in 1997. The facade layout of the bridge is shown in Fig.1. The bridge is consolidated by bridge tower and main girder, both of which are made of No. 50 concrete. The bridge tower is diamond-shaped, 64.31 m above the platform and 50.71 m above the bridge deck. As shown in Fig.2, the bridge has a full section width of 19 m and a beam height of 1.8 m, whose main span is a concrete single-box double-chamber section, and side span is a solid concrete section. The design load is -super 20 for automobiles and -120 for trailers. The stayed cables of the bridge are galvanized high-strength parallel steel cables with a standard tensile strength of 1,670 MPa. The bridge has a total of 24 stayed cables, which are arranged in a single-cable-plane sector, with each 12 cables for the side span and the main span. The cable number increases outward from the main tower, where the cables for the side span are numbered by B1~B12, and those of the main span are numbered by Z1~Z12.

Fig.1 The layout of the bridge elevation (unit: cm)

Fig.2 Standard cross-section view of span main beam with a length of 90 m (unit: cm)

The bridge was inspected in 2014, and it was found that there were extensive diseases and problems of the stay cables of the bridge, which were specifically manifested as follows: 1) The general caps and steel sleeves of the stay cables on the beam as well as the built-in shock absorbers at the end of the stay cables were seriously corroded. 2) Components such as anchor cups, nuts and anchor pads in the anchorage area of the beams were severely corroded, the grease inside the anchor cups was dry and there was water in the cups. The typical diseases of the anchoring end are shown in Fig.3. 3) The cable guards
on the pylons were severely corroded, concrete near individual cable conduits fell off, and the corners of the cable anchoring tooth blocks were damaged. 4) The measured cable force was greatly deviated from how it was originally designed. For example, the deviation between Z4 cable and the original design was 33.4%, and that between B2 cable and the original design was -21.7%. In order to ensure the safe operation of the bridge, the bridge needs to be overhauled, and it is recommended to replace all the stay cables.

Fig.3 Corrosion and accumulation of water on the anchor cup on the stayed cable beam

2.2. Construction control principles for cable replacement
The principles of cable replacement construction are as follows: 1) Ensure the safety of the bridge structure during and after construction; 2) The main girder and main tower shall not be excessively displaced during and after construction; 3) By optimizing the tension cable force, the stress condition of the bridge during operation can be improved; 4) A reasonable construction sequence should be selected for cable replacement to facilitate construction and minimize the impact on the change of structural force and displacement; 5) Under the premise of safe force without excessive displacement, stay cable should be placed once, and should not be adjusted after replacement.

3. Finite element analysis and cable force optimization

3.1. Finite element simulation of cable replacement construction
Cable replacement is generally divided into two construction schemes, namely positive-sequence cable replacement and reverse-sequence cable replacement, the former of which is to replace the cables one by one from the two sides of the bridge tower, and the latter is to replace the cables one by one from both sides to the bridge tower[6-8]. Considering the convenience of construction and combining with the preliminary simulation calculation and analysis results, positive-sequence cable replacement was adopted. As shown in Fig.4, Midas/Civil was used to build the bridge model, the main beam was divided into 40 units, the main tower into 92 units, and the cable into 24 units. According to the construction steps, simulation calculations were performed in 29 stages. See Table 1 for details.
Tab.1 Division of finite element simulation construction stages

| construction stage | simulation construction content                                                                 | duration of this phase (d) |
|--------------------|---------------------------------------------------------------------------------------------------|----------------------------|
| 1                  | The bridge unit is fully activated, and the cable force is the original design cable force.        | 365                        |
| 2                  | Simulate bridge shrinkage and creep for 17 years.                                                  | 6200                       |
| 3                  | Adjust the cable force to the actual measured cable force in 2014 as the internal force state before the cable replacement. | 3                          |
| 4                  | Remove the railings and deck paving of the bridge, and reinforce the main girder.                   | 45                         |
| 5                  | Symmetrically remove the cable stays B1 and Z1 of the bridge.                                     | 2                          |
| 6                  | Install and tension the new B1 and Z1 stay cables symmetrically.                                   | 2                          |
| 7–28               | Remove the cable stays B2–B12 and Z2–Z12 in pairs, then install and tension the new stay cables B2–B12 and Z2–Z12 symmetrically. | 44 (2 days for each stage, 22 stages in total) |
| 29                 | Construction of new bridge deck paving and ancillary facilities, adjustment of cable force.         | 30                         |

3.2. Optimization and adjustment of cable force

The cable force of the bridge deviated greatly from the original design, so did the internal force of the structure. According to the current state of internal forces, in the most unfavorable load combination state, the tensile stress of the main girder bottom plate of the main span exceeded the limit, and the main girder bottom plate of the main span cracked. Considering the increased dead load of bridge deck pavement, railing and main beam, the cable type and cable force were optimized and adjusted by combining finite element calculation. The parallel wire rope with the original tensile strength standard value of 1,670 MPa was replaced with the stay cable with a tensile strength standard value of 1,770 MPa. The comparison of the cable force before and after adjustment is shown in Tab.2. According to finite element calculations, the minimum safety factor of stay cables during and after cable replacement was 2.60 and 2.71, while that during use was 2.52, and the stay cables were stressed safely, which all met the requirements.

Tab.2 Comparison of cable force before and after optimization and adjustment

| stay cable number | type of stay cable | original design cable force (kN) | cable force measured in 2014 (kN) | adjusted cable force after cable replacement (kN) | cable force ratio after adjustment and original design | the ratio of adjusted cable force to the cable force in 2014 |
|-------------------|--------------------|----------------------------------|----------------------------------|-----------------------------------------------|------------------------------------------------------|----------------------------------------------------------|
| B12               | LPES7-187          | 4526                             | 4726                             | 4486                                           | 0.99                                                 | 0.95                                                     |
| B11               | LPES7-163          | 3428                             | 3841                             | 3925                                           | 1.15                                                 | 1.02                                                     |
| B10               | LPES7-163          | 3387                             | 3553                             | 3976                                           | 1.17                                                 | 1.12                                                     |
| B9                | LPES7-163          | 3320                             | 3412                             | 3988                                           | 1.20                                                 | 1.17                                                     |
| B8                | LPES7-163          | 2998                             | 3384                             | 3873                                           | 1.29                                                 | 1.14                                                     |
| B7                | LPES7-163          | 3046                             | 3301                             | 3320                                           | 1.09                                                 | 1.01                                                     |
| B6                | LPES7-163          | 3097                             | 3286                             | 3978                                           | 1.28                                                 | 1.21                                                     |
| B5                | LPES7-163          | 2841                             | 2981                             | 3597                                           | 1.27                                                 | 1.21                                                     |
| B4                | LPES7-163          | 2894                             | 2991                             | 3575                                           | 1.24                                                 | 1.20                                                     |
| B3                | LPES7-163          | 2779                             | 2893                             | 2804                                           | 1.01                                                 | 0.97                                                     |
| B2                | LPES7-163          | 2806                             | 2198                             | 2813                                           | 1.00                                                 | 1.28                                                     |
| B1                | LPES7-187          | 3691                             | 3466                             | 3983                                           | 1.08                                                 | 1.15                                                     |
| Z1                | LPES7-163          | 2683                             | 2709                             | 3525                                           | 1.31                                                 | 1.30                                                     |
4. The main construction process of cable replacement

4.1. Demolition of old cables
The overall sequence of demolition construction was: install the drop limit bracket of the cable → remove the shock absorption block and other accessories of the original cable → install the jack and connect the tension rod → connect the cable-laying auxiliary traction winch → remove the anchor ring → gradually release the jack → lower the stay cable and the anchor head of the tension end to the bridge deck → remove the anchor head at the fixed end (on the beam) → cut the stay cable into small sections with a length of 4-6 m → truck hoist and transport out of the bridge deck → clean the anchor holes and protect the cable guides to prepare for the installation of the following new cables.

4.2. Installation and tension of new cables

4.2.1. Construction of hanging cables
The new cables were deployed on the bridge deck with a cable-laying trolley, the anchor head at the tension end of the cable was transported to the bottom of the bridge tower, and then the cable was lifted by the hoisting system installed on the bridge tower. The cable was lifted to a certain height by synchronously operating the vertical lifting system and the traction system, and stopped till the anchor head of the beam end was installed and fixed. Subsequently, the vertical hoisting system and the hoisting machine traction cable were started up simultaneously. When the tension rod was exposed to the upper end of the cable conduit, supporting feet were promptly installed, and then jacks, corresponding tool anchors, anchor head nuts and other equipment were immediately started up, the anchor head nut on the top of the tension rod was tightly screwed to complete the transition from soft traction to tension rod. The tensioning operation was completed by a jack, the anchor head was tightened until the upper opening of the cable guide was exposed, and then the anchor ring nut was screwed into the anchor head with no less than 4 turns of threads, so that the cable hanging at the end of the cable tower was completed. Another symmetrical stay cable was installed in the same way. After a pair of stay cables and two sets of tension jacks were installed, tensioning construction could proceed.

4.2.2. Tensioning construction of new cables
The stay cables on the tower were all tensioned in accordance with control instructions. The tension activated by the jack was graded and synchronously tensed and then anchored by the anchor nut. The tension force was mainly controlled by the pressure of the oil gauge and then reviewed according to the elongation. The jack held the load for 5 min after the tension reached the grading control force, and then the anchor nut was tightened. In order to make up for the loss of cable anchorage, overtension was up to 1% after tensioning to the final control cable force, and then the anchor nut was tightened for tensioning. After a pair of cables was replaced, the changes in the cable forces of two adjacent pairs of cables were tested and compared with the theoretical calculation values. After the replacement of all
cables and the construction of bridge reinforcement and auxiliary facilities, the maximum deviation between the measured cable force and the designed one was 8%, less than the control value of ±10%.

5. Bridge load test after cable replacement
According to the construction control principles and calculation results of cable replacement, cable force was controlled, main girder displacement, main tower deflection and key section force in the construction process were monitored to achieve the design goals of reinforcement and transformation. In order to evaluate and analyze the effect of reinforcement and reconstruction, the bridge was tested by load test before and after reinforcement with the same scheme. The bridge load test results suggested: 1) The maximum calibration coefficients for the control section strain and deflection of the span with a length of 90 m were 0.95 and 0.94 before reinforcement, respectively, and 0.83 and 0.85, respectively after reinforcement; 2) The maximum test coefficients were 0.77 and 0.86 before reinforcement, 0.69 and 0.91 respectively after reinforcement; 3) The measured fundamental frequency of the bridge before and after reinforcement was 0.88 and 0.98, respectively.

6. Conclusion
Based on the above engineering practice results and discussion, the following conclusions are drawn.
(1) Before cable replacement, the current stress state of the structure should be firstly determined, and detailed plans and steps should be formulated. The construction steps can be simulated by finite element analysis to verify the rationality of the construction methods and steps.
(2) By adjusting new cable force, the stress state of the bridge can be optimized. The cable force can be controlled in the process of cable replacement. The measured maximum deviation between the cable force of the bridge and the original design was 8%, less than the control value of ±10%.
(3) The load test results indicated that the bearing capacity and overall flexural rigidity of the bridge after cable replacement were greatly improved. The load test results before and after reinforcement were compared to evaluate the effect of the bridge reconstruction.
(4) In the construction process, the structure of the bridge was stressed safely, with no excessive replacement for main girder and bridge tower.

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