Design and Physical Detection of Bridge Tower and Externally Prestressing Cable for Existing Bridge Strengthened by A Cable-Stayed System

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Abstract. With the continuous development of economy, the increasing traffic volume has brought greater burden to highway bridges. In this paper, a Yellow River Bridge is taken as an example. The cracking and deflection of the box girder of the main bridge have affected the structural performance requirements of the bridge operation. Based on this situation, the cable-stayed system is used to reinforce the bridge, and the construction process of bridge tower, cable saddle, steel anchor box and external beam is described in detail. The theoretical calculation and practice show that this method can effectively strengthen the bridge structure, and the cable-stayed system reinforcement method, as a mature, reasonable and operable construction technology, provides relevant reference for the reinforcement research of similar bridges.

Keywords: Cable stayed system, Bridge reinforcement, Extracorporeal bundle.

1. Introduction
Prestressed concrete continuous rigid frame continuous beam structure has good integrity and continuity [1], and the design theory and construction technology are relatively mature, which is widely used in the 1990s. Due to the lack of early management and detection, this kind of bridge is prone to disease. In order to ensure the safe operation of the bridge, the box girder integrity is usually enhanced by adding external cables in the box, increasing the cross section of the web and setting diaphragms. Although it can alleviate the cracking and deflection of the bridge to a certain extent [2-3], it cannot effectively solve the problem. Therefore, the reinforcement design of the cable-stayed system with pylons, steel anchor boxes, stay cables and external tendons is adopted, and provide new research ideas for the key construction technology of this kind of bridge.

2. Project overview
Dongming Yellow River Highway Bridge is located on the Yellow River between Dongming County, Heze City, Shandong Province and Puyang City, Henan Province. After years of operation, it was found that the beam cracked and deflected, and the preliminary test was carried out in 2009. The results showed that the main tensile stress and section normal stress of the main bridge box girder
could not meet the requirements of the specification. Considering the geological conditions and construction environment of the site, the cable-stayed system is adopted for reinforcement construction, with a total length of 0.99 km from 57 # pier to 66 # pier. The main bridge adopts cable-stayed system for reinforcement transformation, replacement of bridge deck system, concrete defect treatment and durability protection treatment.

Figure 1. Reinforcement effect of bridge cable stayed system.

3. Overall construction of cable tower
The pylons are of single column type, with a total height of 43.529-45.779 m. There are 16 pylons, of which 58, 59, 64 and 65 are side pylons, and 60, 61, 62 and 63 are middle pylons. The height of pylons above the bridge deck is 28 m. The side tower is prestressed reinforced concrete tower, and the middle tower is reinforced concrete tower.

3.1. Tower column construction
The tower column is constructed by turnover formwork, which is composed of a variety of molds, including three section large combined formwork, support, internal and external working platform, truck crane, etc. Due to the high pier body, in order to effectively reduce the segmental construction time, reduce the consumption of machines and materials, the height of 2 sections of formwork is poured each time, that is, 2 layers of formwork are turned each time, and 4.5 m high concrete is poured.

Figure 2. Schematic diagram of segmental pouring division of main tower
3.2. Concrete pouring
During the construction of the first section, the formwork (2.25m high) shall be erected on the top of the bearing platform, the formwork of the second section (2.25m high) and the formwork of the third section (2.25m high) shall be erected on the formwork of the previous section respectively, and shall be poured once after the measurement and positioning are completed.

When the compressive strength of the concrete in the third stage meets the requirements, the formwork of the first section can be removed, and the bottom tie rod of the formwork of the second section can be removed at the same time. After the first section of formwork is polished and adjusted, it can be turned up to the third layer, so it can realize the cyclic breaking operation of formwork removal, turning up and erecting, formwork assembly and pouring until it reaches the design height.

![Figure 3. Structure of field turnover formwork.](image_url)

3.3. Formwork construction
(1) Template fabrication and accuracy requirements
The formwork is made of Q235A steel, and it needs to meet the requirements of size, flatness, process quality and service performance. The specific standards are as follows.

| Table 1. Quality standard of template production. |
|-----------------------------------------------|
| Project                                      | Allowable deviation (mm) |
| Dimensions                                   |                            |
| Long and high                                | 0. -1                      |
| Rib height                                   | ±5                         |
| Panel end deflection                         | ≤0.5                       |
| Hole position of connecting fittings (bolts)  |                            |
| Distance between hole center and plate surface| ±0.3                       |
| Distance between plate end hole center and plate end | 0. -0.5                   |
| Holes along the length and width of the plate| ±0.6                       |
| The surface of the board is locally uneven   | 1.0                        |
| Deflection of plate surface and side         | ±1.0                       |
(2) Installation of formwork
Before the installation of the formwork, the cushion block and embedded parts of the reinforcement protective layer shall be inspected, and those that do not meet the requirements shall be replaced; When the tower column formwork and beam bottom formwork are installed, they should be fixed in time and meet the quality standards of elevation and axis deviation.

| Project                        | Allowable deviation 9(mm) |
|--------------------------------|---------------------------|
| Formwork elevation             | ±10                       |
| Internal dimension of formwork  | ±20                       |
| Axis deviation                 | 8                         |
| Surface height difference between two adjacent plates of formwork | 2                         |
| The surface of formwork is smooth | 3                         |

(3) Removal of formwork
The removal of formwork requires the concrete to reach the specified strength, and the anti-swing measures should be prepared before the removal; After the formwork is removed, the embedded parts on the surface of the tower column shall be filled in time.

4. Prestress control of tower column

4.1. Calculation of theoretical elongation value of prestressed steel strand

The theoretical elongation value \( \triangle L \) (mm) of prestressed tendon can be calculated according to the following formula [1]:

\[
\triangle L = \frac{P_p L}{A_p E_p}
\]

Where, \( P_p \) is the average tensile force of prestressed tendon (n). Among them, the tension at the tension end is taken as the linear reinforcement, and the average value of the tension at the tension end and the tension at the middle of the span after deducting the friction loss of the channel is taken as the curve reinforcement; According to the design requirements: \( P_p = 1116 \text{MPa} \times 140 \text{mm}^2 = 156.24 \text{KN} \); \( L \) is the length of prestressed reinforcement (mm), \( L_1 = 17029 \text{mm}, \ L_2 = 17809 \text{mm} \); The elastic modulus \( E_p \) (n / mm) of prestressed tendons; The sectional area of prestressed reinforcement \( A_p = 140 \text{(mm)}^2 \); The results show that \( \triangle L_1 = 96.12 \text{mm}, \ \triangle L_2 = 100.53 \text{mm} \).

| Inspection items                                      | Allowable deviation (mm) | Inspection frequency |
|-------------------------------------------------------|--------------------------|----------------------|
| Tensile stress value                                  |                          |                      |
| Tensile elongation                                    | Meet the design requirements | Whole 100%          |
| Inspection items                                      | ±6%                      |                      |
| Number of broken and sliding wires                    |                          |                      |
| Steel strand                                          | One per bundle, and the cross section shall not exceed 1% of the total number of steel wires | |
| A steel bar                                           | Not allow                |                      |

4.2. Measurement and calculation of actual elongation of prestressed steel strand
Before the installation of the jack, the exposure of the clip at the tension end \( \triangle l_0 \) (mm) shall be measured.
Tension to initial stress $\sigma_0$ (take 15% of the control stress as the initial stress), then start the tension and measure the elongation value. The elongation from 15% to 30% of the stress can be used to control the initial stress $\sigma_0$, which is expressed as $\Delta L_1$. The actual tension control stress should consider the dead weight of steel strand. When $L = 17029mm$, $PP = 156.47kn$; When $L = 17809mm$, $PP = 156.48kn$; The elongation of prestressing tendon measured from 15% control stress to the completion of tensioning is $\Delta L_2$, and the actual total elongation $\Delta L$ is:

$$\Delta L = \Delta L_1 + \Delta L_2 - (\Delta L_0 - n)$$  \hspace{1cm} (2)

Where, $\Delta L_1$ denotes elongation from 0 to initial stress (mm); $\Delta L_2$ denotes actual elongation from initial stress to maximum stress (mm); $\Delta L_0$ denotes exposure of clip before tensioning (mm); $N$ denotes exposure of clip after tensioning (mm), generally 2-3mm.

5. Construction technology of cable saddle and stay cable

5.1. Design of sliding cable saddle
The side tower and secondary tower columns (58 #, 59 #, 64 #, 65 #) adopt three-layer sliding cable saddles, which are from bottom to top: type B cable saddles, type a cable saddles and spare cable saddles; The saddle body is connected with the saddle bottom plate through the roller assembly, and bears the vertical force of the cable; The bottom plate of the saddle body and the bottom plate of the cable saddle are connected by high-strength bolts, and the vertical force transmitted by the saddle body is borne by the bottom plate of the cable saddle.

![Figure 4. Structural drawing of cable saddle floor.](image)

5.2. Design of steel anchor box
The section size of the steel anchor box is 3.48M (along the bridge direction) × 58m (transverse to the bridge), which is divided into three sections, namely 3, 2 and 1 anchor box from bottom to top. 1 anchor box is the spare anchor box, and there is no cable in this reinforcement; The height of anchor box varies with the angle of stay cable. The height of 1 $\sigma$ anchor box is 1.85M, the height of 2 $\sigma$ anchor box is 1.50M, and the height of 3 $\sigma$ anchor box is 1.80m. In the steel anchor box stage, the plates are welded, and the lowest support needs to be fixed on the concrete bottom.

| Table 4. Installation accuracy of steel anchor box. |
|-----------------------------------------------|
| Project                                      | Permissible error |
| Perpendicularity of four side axes           | 1/4000            |
| Contact rate of cross section                | >30%              |
| Horizontal contact clearance of four side panels | 0.2mm            |
| Sidewall misalignment                        | 2mm               |
5.3. Design of stay cables

The stay cables are made of stainless steel and consist of 289 and 217 stainless steel wires with a diameter of 5.6 mm. Among them, the middle tower of the bridge is in the form of single end tension, which is tensioned at the joist and anchored in the anchor box on the top of the tower; The side tower and secondary side tower are tensioned at both ends and anchored at the joist [5].

(1) Traction calculation of stay cable installation.

![Figure 5. Calculation diagram of installation traction of stay cable.](image)

The calculation formula is [3]:

$$F_1 \times \text{two} \times \cos \theta = F_2$$

(3)

Where, $F_{1w}$ denotes traction cable force; $F_{2w}$ denotes total gravity of stay cable and joist bracket; $\theta_w$ denotes the angle between stay cable and tower column.

The pulling force of stay cable is calculated separately according to the length of each stay cable, and the additional stress of steel members on the original bridge can be reduced by offsetting the dead weight of joist bracket and stay cable. According to the design requirements, the initial tension force of the cable is required to be 30%, which fully meets the requirements of offsetting the relevant additional gravity [7].

(2) Tension control of stay cable

In the process of cable tension, the stress of the main beam will change, and the stress concentration phenomenon will be caused when the tension is increasing, which may have a safety impact on the whole construction process. Therefore, the tension control of stay cable is an important process in the cable-stayed reinforcement system, and certain methods can be adopted to test the cable force when necessary [8].

| Stage number | Job content |
|--------------|-------------|
| 1            | Bridge completion stage |
| 2            | Bridge tower construction (divided by construction stage) |
| 3            | The bridge deck system needs to be replaced when it is demolished |
| 4            | Hoisting joist bracket and installing steel support in box |
| 5            | Simultaneously tension the stay cables of each pier to 30% tension control cable force |
| 6            | Repeat construction step 5 according to 65%, 85%, 95% and 100% tension level |
| 7            | Adjust the external prestressing force that needs to be replaced in the box |
| 8            | Phase II pavement |
Notes:
1. During the construction process, the tension level is adjusted according to the collected data and the site construction situation.
2. The tension of stay cable and external prestressing inside the box shall be carried out alternately according to the data collected and the site construction situation.

During the tensioning, the cable force should meet the requirements, the design tensioning sequence of stay cables should be strictly implemented, and the deviation of the top of tower column along the bridge should be monitored at all times. In order to ensure the normal stress of the bridge tower, the cable force should be adjusted in time according to the monitoring data [9].

6. Research on key construction technology
At present, it is the first time to reinforce long-span PC continuous box girder bridge by cable-stayed system in China. The actual engineering cases show that the process of cable-stayed reinforcement system is more complex, the construction is more difficult, and there are more unknown safety hazards. In order to meet the internal force requirements of the main bridge cable tension process, but also to ensure the tension internal force of other cables, it will cause the uneven stress of the bridge, resulting in the existence of these uncertain problems in the process of cable tension. Therefore, in order to reduce the risk of construction, the monitoring of main beam, tower column, joist bracket and cable body should be strengthened during the tension control, and the stress and strain of each structural part should be tracked in real time:

(1) The cable can be tensioned symmetrically to avoid the uneven stress of the main girder, and the tension stress can be adjusted in time according to the change of the monitoring value.

(2) At present, the k-value method is mainly used to calculate the tension of stay cables. Its working principle is to compare the tension of cables measured by cable tension meter and anchor cable meter with the reading of jack oil pump, and calculate the k-value through the linear relationship among the three, so as to obtain more accurate actual cable force [10].

(3) In the process of bridge construction, after the completion of a stay cable tension, it is necessary to measure the cable force after tension, and compare the actual measured value with the theoretical calculated value. When the error is large, the calculation model or tension process should be optimized in time.

7. Conclusions
As the cable-stayed system strengthening the bridge is the first time in China, there is no similar experience to follow in the construction of new pylons, cable saddles, steel anchor boxes and external tendons. By adopting effective design and construction key technology to reinforce the bridge, it can be found that the main beam cracking and midspan deflection can be obviously controlled, so that the technology has been successfully applied in this project, and a set of mature, operable, efficient and reasonable construction technology is summarized. Therefore, in the face of long-span continuous beam continuous rigid frame bridge, cable-stayed reinforcement system can be preferred. Through the research on the key technology of design and construction, the poor effect of external beam reinforcement method can be solved.

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