Segmental Intelligent Model Test of Box Girder Bridge Strengthened By a Cable-Stayed System by Mathematical Calculation

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Abstract. Dongming Yellow River Highway Bridge is an important super large bridge across the Yellow River on national highway 106. In order to effectively improve the cracking and deflection of the bridge, the cable-stayed system is used to reinforce the main girder of the project. In order to analyze the stress state of joist, bracket and box girder, the static loading of cable is carried out through scale model test to study the mechanical properties of concrete box girder segment, joist and bracket, verify the reliability of bracket and concrete box girder anchorage, and optimize the reinforcement method of cable-stayed system according to the test results.

Keywords: Cable stayed system, Reinforcement, model test.

1. Introduction
In the long-term traffic operation, it will lead to the bridge cracking and deflection disease, affect the safety of the bridge structure, at this time the bridge reinforcement and maintenance is particularly important [1]. At present, there are many researches on bridge reinforcement by scholars at home and abroad, but there are few researches on model test to verify the reinforcement technology. In order to ensure the reliability and long-term use effect of the main bridge reconstruction, and understand the matching force and local adverse stress of joist and bracket, this paper verifies the rationality of construction technology, the feasibility of synchronous tension and the material performance of steel members through scale model test, and simulates the assembly process of joist, bracket and concrete box girder, It provides reasonable suggestions for the design and construction of cable-stayed reinforcement system.

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. The variable section box girder of the main bridge adopts No. 50 concrete, which is a three item prestressed structure. After many times of bridge detection and reinforcement maintenance, there is still the phenomenon of continuous cracking and deflection of the beam, and it is accompanied by concrete damage, exposed reinforcement, steel
corrosion and expansion crack and other disasters. Therefore, it is necessary to take further reinforcement measures, and through the assembly process of test model components, reasonable suggestions for construction and maintenance are put forward.

3. Model design and production

3.1. Model test
Taking the prestressed concrete continuous rigid frame composite Bridge of Dongming Yellow River Highway Bridge in Shandong Province as the prototype, considering the model material, structural parameters and construction technology, the geometric scale ratio of the model test is 1:3. In the model test, one end of the box girder is connected with the section steel, the other end is arranged freely, and the end of the section steel is fixed with the reaction wall of the laboratory. One end of the cable is connected with the anchorage end of the joist, and the other end is connected with the lifting lug. The similarity between Model Bridge and real bridge is shown in Table 1.

| Physical quantity       | Real bridge | Model bridge | Similarity relation |
|-------------------------|-------------|--------------|---------------------|
| Elastic modulus         | Ep          | Em           | SE=1                |
| Compressive stiffness   | EpAp        | EmAm         | SEA=32              |
| Bending stiffness       | EpIp        | EmIm         | SEI=34              |
| Stress                  | σp          | σm           | Sσ=SE=1             |
| Strain                  | εp          | εm           | Sε=Sε/SE=1          |
| Displacement            | lp          | lm           | SI=3                |
| Concentrated load       | pp          | pm           | Sp=SeSI2=9          |

3.2. Joist and bracket model
The width of the original bridge deck is 18.34m, the width of the box girder bottom plate is 9.00m, and the height of the box girder at the connection between the cable and the main girder is 3.19M. The joist is 23.50m in length, 0.045m in flange thickness and 0.9m in length, and the upper and lower flange are designed symmetrically. The joist and bracket are made of steel structure, and the longest cable joist is selected for the test, and the scale ratio of the model is 1:3. The main beam and bracket are connected by high-strength bolts, and holes are opened in the bearing plate of bracket to form an integral structure with joist [2-3].

3.3. High strength bolt
(1) Original design
The original design value of bearing capacity of high-strength bolt is 8977.5kN. After reduction according to the 1:3 model, the design value of bearing capacity of high-strength bolt is 8977.5kN
\[ F_o / 9 = 8977.5 / 9 = 997.5 \text{kN} \tag{1} \]

(2) Model
The customized grade 8.8 high-strength bolt is used in the test. According to the specification requirements, the preload value of high-strength bolt is calculated as follows:

\[ P_s = (0.9 \times 0.9 \times 0.9 / 1.2) \times f_y \times A_y = (0.9 \times 0.9 \times 0.9 / 1.2) \times 1040 \times 36.6 = 23124 \text{N} \tag{2} \]

\[ F_m = 0.9 \cdot P \cdot \mu \cdot \eta \cdot n = 0.9 \times 23124 \times 0.5 \times 1 \times 105 = 1092.5 \text{kN} \tag{3} \]

Complete assembly:
1092.6kN > 997.5kN, it needs to be reduced.

(3) Reduction
\[ F_o / 9 = 0.9 \times 23124 \times 0.5 \times n \]
\[ n = 95.9 \tag{4} \]

During the calculation, the number of bolts is 95, and the actual number of planting bars is 99 (including 4 positioning bolts).

(4) The tensile ultimate load test results of high strength bolts are shown in the figure.

4. Scheme of model test

4.1. Test items and arrangement
(1) Arrangement of joist strain gauge
According to the experimental simulation and theoretical calculation of domestic and foreign scholars, the strain gauges are arranged at the interface between joist and bracket, and the key position of joist web during the scale test [4].

(2) Layout of bracket measuring points
Three direction strain gauge and one-way strain gauge are arranged in the key parts of the bracket to determine the stress state of the bracket.

(3) Layout of measuring points for concrete box girder
Because the stress of concrete box girder is relatively complex, the strain gauge and dial indicator are arranged at the main stress points of the box girder to analyze the stress state of the box girder.

4.2. Test loading process
(1) Static loading test
Under the condition of keeping the experimental material unchanged, the load similarity ratio is the square of the scale ratio of the model, i.e. 1:9. Before the test, the clearance between model parts should be eliminated by preloading.

![Figure 3. Laboratory layout.](image-url)
(2) Loading rules

① Before the indoor test, the temperature should be kept as constant as possible, and the temperature difference should be strictly controlled to eliminate the error of test components.

② Before loading, the measuring instrument should be cleared in advance, and the reading should be made immediately after each loading and unloading, and the next reading should be made after the structural displacement tends to be stable.

③ After the test loading, it is necessary to check whether there are cracks in the structure and the development of cracks. And pay special attention to the loading stage before the cracks appear, and make records.

④ During the loading process, the stability of the loading device should be checked frequently [5], [6].

(3) Test termination conditions

The static loading and unbalanced loading tests are carried out in order to achieve the ultimate loading value at the anchorage end of the joist.

5. Test process and result analysis

5.1. Hoisting and planting reinforcement

(1) Lifting of ear plate
When lifting the ear plate, it is necessary to lift and position through the reserved holes, adjust the hole position of the reaction wall and the upper reserved holes, and then fix them with bolts.

(2) Steel bar planting and hoisting of concrete box girder
Firstly, the joist and bracket are preassembled, and the position of the bracket in the bottom plate of the concrete box girder is determined. And before positioning, drilling should be carried out according to the ink line. The specific schematic diagram is as follows.

![Figure 4. Schematic diagram of the original positioning plate.](image)

When drilling, the number of designed holes in the original positioning plate and bracket bottom plate is 109 respectively, while in the actual drilling, the number of holes in the positioning plate will be more, and the more affected by the box girder reinforcement. Therefore, before the actual drilling construction, in order to reduce the construction difficulty, we can use the steel detector to detect the distribution position of steel bars [7].

When the number of holes is large, there will be holes that do not correspond to each other. Therefore, after the completion of drilling, the steel plate should be accurately positioned and carefully checked until the corresponding accurate position, otherwise the quality of drilling will be affected.

(3) Pre assembly of section steel and box girder
Before the formal hoisting of the section steel and box girder, the pre installation test should be carried out first. When there are problems in the connection, the reasons should be analyzed in time, and the treatment should be carried out according to the site conditions. When solving the problem, it is necessary to operate according to the relevant specifications and carry out the cyclic test until the hoisting is successful [8].

(4) Assembly of section steel, box girder and reaction wall
During the assembly stage, the section steel should be hoisted to the design height by gantry crane, and the operation should refer to the installation process of lifting lug. As the section steel structure is an important part, it needs many workers to complete the assembly to meet the higher accuracy.

5.2. Test results and analysis

(1) Test results and analysis of bracket stress

| Test type | Measuring point | Strain value (×10^-6) |
|-----------|----------------|----------------------|
| Load (kN) | 0  | 0.25P | 0.5P | 0.75P | P | 1.25P | 1.5P | 1.75P | 2.0P | 2.5P |
| Right TJ1 | 1-1 | 0 | -32 | -37 | -43 | -61 | -89 | -121 | -170 | -258 | -392 |
|           | 1-2 | 0 | -2 | -2 | -7 | -9 | -11 | -10 | 0 | 59 | 211 |
|           | 1-3 | Missing data |
| Left TJ10 | 10-1 | 0 | -21 | -40 | -52 | -68 | -105 | -151 | -44 | -300 | -302 |
|           | 10-2 | 0 | 0 | -7 | -15 | -20 | -24 | -35 | 110 | 41 | 10 |
|           | 10-3 | 0 | 0 | 0 | -1 | -1 | 0 | 0 | 154 | 93 | 31 |
| Right TJ2 | 2-1 | 2 | 8 | 2 | 0 | 34 | 12 | -1 | -29 | -22 | -113 |
|           | 2-2 | Missing data |
|           | 2-3 | Missing data |
| Left TJ11 | 11-1 | 1 | -9 | -15 | -27 | -43 | -72 | -98 | -129 | -151 | -206 |
|           | 11-2 | 0 | 0 | 3 | 6 | 8 | 26 | 58 | 69 | 98 | 111 |
|           | 11-3 | 0 | -1 | -2 | -7 | -10 | -1 | 12 | 10 | 18 | 30 |
| Right TJ3 | 3-1 | 0 | -40 | -75 | -104 | -104 | -152 | -212 | -279 | -325 | -236 |
|           | 3-2 | 1 | 33 | 56 | 83 | 127 | 146 | 178 | 207 | 140 | 104 |
|           | 3-3 | 0 | 9 | 11 | 12 | 18 | 18 | 25 | 27 | 29 | -135 |
| Left TJ12 | 12-1 | 1 | -199 | -293 | -553 | -858 | -726 | -674 | 302 | 732 | 659 |
|           | 12-2 | 0 | 26 | 65 | 96 | 115 | 111 | 104 | 68 | 20 | -67 |
|           | 12-3 | 0 | 21 | 40 | 62 | 52 | 104 | 110 | 100 | 10 | -102 |
| Right TJ4 | 3-1 | 1 | -100 | -119 | -129 | -163 | -210 | -248 | -334 | 787 | -1029 |
| Left TJ14 | 1 | -44 | -84 | -101 | -109 | -190 | -254 | -238 | -352 | -471 |
| Right TJ6 | 3-1 | 1 | -44 | -84 | -101 | -109 | -190 | -254 | -238 | -352 | -471 |
| Left TJ15 | 16-1 | 0 | 15 | 17 | 20 | 38 | 26 | 45 | -27 | -25 | -3 |
|           | 16-2 | 14 | 3 | 27 | 38 | 54 | 84 | 87 | 89 | 55 | 120 |
|           | 16-3 | Missing data |
| Right TJ7 | 7-1 | 1 | -7 | -18 | -22 | -21 | -13 | -19 | -16 | -3 | 30 |
|           | 7-2 | 1 | 6 | 21 | 40 | 54 | 65 | 69 | 120 | 28 | -23 |
|           | 7-3 | 1 | 0 | -6 | -22 | -37 | -45 | -52 | -58 | -32 | 12 |
| Left TJ16 | 16-1 | 0 | 15 | 17 | 20 | 38 | 26 | 45 | -27 | -25 | -3 |
|           | 16-2 | 14 | 3 | 27 | 38 | 54 | 84 | 87 | 89 | 55 | 120 |
|           | 16-3 | Missing data |
| Right TJ8 | 16-1 | 0 | 15 | 17 | 20 | 38 | 26 | 45 | -27 | -25 | -3 |
| Left TJ17 | 6 | -9 | -6 | -16 | -28 | -29 | -30 | -50 | -53 | -53 |
| Right TJ9 | 0 | 0 | -16 | -28 | -27 | -31 | -35 | 116 | -16 | 55 |
| Left TJ13 | 0 | 0 | 0 | -1 | -10 | -41 | -53 | -117 | -144 | -302 |

It can be seen from the above table that before 0.75P, the bracket strain is generally small; When the cable force P is loaded, the strain of tj12 is the largest (-551×10^-6); At 1.5P, the strain of tj12 is the largest (-836×10^-6); When loading to 2p and 2.5P, the strain of tj4 is the largest, and its strain value is only -786×10^-6 and -1029×10^-6, all of them did not reach yield strain 1504×10^-6.
The above data show that the strain of the bracket is very small after loading to the cable force P; At 2.5P, the bracket is still in the elastic deformation stage, which indicates that the bearing capacity of the bracket is reliable and has great bearing potential.

(2) Stress test results and analysis of concrete box girder.

Table 3. Strain test results of box girder web (micro strain).

| Measuring point | 0.5P | 0.88P | P     | 1.25P | 1.5P |
|-----------------|------|-------|-------|-------|------|
| FB5             |      |       |       |       |      |
| Level FB5-1     | -4   | -6    | -5    | -5    | -33  |
| Vertical FB5-2  | 16   | 54    | 70    | 73    | 67   |
| FB6             |      |       |       |       |      |
| Level FB6-1     | -19  | -24   | -20   | -35   | -51  |
| Vertical FB6-2  | 10   | 30    | 38    | 47    | 52   |
| FB8             |      |       |       |       |      |
| Level FB8-1     | 0    | 0     | 1     | 0     | -62  |
| Vertical FB8-2  | 10   | 28    | 41    | 57    | 14   |

The above test data show that the web strain is generally small before 0.5p; When the cable force P is reached, the compressive strain of the box girder web along the horizontal direction is normal, and the tensile strain of some measuring points along the vertical direction is larger, and the strain value of fb5-2 is 70 × 10^{-6}; 25p ~ 1.5p, the compressive strain is normal, the tensile strain in the vertical direction of each measuring point generally increases, and the strain value of fb5-2 is 73 × 10^{-6}, fb8-2 strain value 57 × 10^{-6}; After 2p, the tensile strain increases further.

(3) Stress test results and analysis of high strength bolt.

Through the observation of four measuring points of high-strength bolt, the stress variation range of design cable force before the completion of bridge is small, so it can be considered that the high-strength bolt only loses a small part of the stress, and the anchorage performance between box girder and bracket is very good. When the load continues to increase, the speed of stress loss of high strength bolt begins to increase. From the load-strain curve of high-strength bolt, the change curve of LS3 measuring point is the steepest, and the stress loss speed of bolt is the fastest, but the high-strength bolt still plays a good role in fixing [9-10].

6. Conclusions

In this paper, the simulation test is carried out on the basis of similarity theory. Through the simulation test of box girder segment, the anchorage performance between steel joist, steel bracket, steel support in box and concrete box girder under the condition of symmetrical tension cable is mainly studied:
1) Under the static loading test, the cable bearing capacity and deformation meet the requirements of the code under the design cable force \( P \) (342KN).

2) The stress and deformation of joist, bracket and steel support in box girder are in the elastic stage under the designed cable force, which basically meets the requirements of the code.

3) Under the design cable force \( P \), the bracket and the concrete box girder are anchored reliably. The stress and deformation of the concrete and reinforcement of the box girder section under the design cable force meet the requirements of the specification. The construction technology is basically reasonable, and the cable can be tensioned synchronously.

4) If there is a gap between the bracket and the joist side joint (non pressure bearing surface), it needs to be filled with a backing plate. Reduce the number of bolts at the side connection (non pressure bearing surface) of bracket and joist to facilitate the position adjustment of bracket and joist during installation. It can be connected by welding or bolt welding. The test data show that the joist at the joint of joist and bracket begins to yield first, so it is suggested to increase the stiffening rib of joist at this part appropriately.

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