Field load test and Performance Evaluation of Rainbow Bridge with Sling and Leaning Tower Curved Arch

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Abstract. Finite element model of a suspension inclined tower arch composite structure pedestrian bridge was established based on Midas Civil. The bearing capacity was calculation and static and dynamic numerical analysis were carried out, and load capacity, loading position and field test cases were developed. The test results under various load cases were obtained based on field dynamic and static load test, and compared with the calculated values. Results show that: test values have good consistency with the calculated values. The bridge keep in elastic state during the test process, means that the bridge can better meet the current design load demand, but with low bearing capacity redundancy.

1. Project overview
The Rainbow Landscape Bridge of Qingdao Olympic Sailing Center is located at the estuary of Fushan Bay in Qingdao. It is a dedicated pedestrian bridge with a leaning tower-sling-curved arch combined structure system. The bridge tower is a 26.981m concrete leaning tower. The bridge span structure consists of internal, external and The three arches of the main girder form a truss structure. The straight line length between the two abutments is 59.5m, the standard width of the cross section is 6.0m, and the width of the pedestrian passage is 5.0m. In order to facilitate on-site measurement and statistics, as well as the description of the subsequent disease location, the main components of the bridge are numbered. The basic structure, size and number are shown in Figure 1.

![Fig. 1 Schematic of Rainbow Bridge](image-url)
2. Carrying capacity check
After investigation, the main components of the bridge are made of materials: GQ01～GQ06 and the anchorage area of the cable tower are all Q345D, the remaining steel components are Q235B, the main tower concrete is C50, and the stay cables are \( \Phi 5 \times 31 \) steel strands. Midas Civil was used to establish a three-dimensional finite element model of the bridge [1], and the bridge's bearing capacity was checked. The calculation results under the basic load combination are shown in Figure 2. The maximum is 198.46MPa<275.00MPa, and the structure is safe. The calculation results of the main components are listed in the table.

![Fig. 2 Schematic diagram of stress under fundamental combination](image)

| Component number | Component name          | Stress calculation value /MPa | Material design strength /MPa | Is it satisfied |
|------------------|-------------------------|-------------------------------|-----------------------------|----------------|
| GQ01             | Main arch               | 192.32                        | 275                         | Yes            |
| GQ02/GQ03        | Inside/outside beam     | 59.44                         | 275                         | Yes            |
| GQ04             | Vertical support        | 198.46                        | 275                         | Yes            |
| GQ05             | Horizontal support      | 32.43                         | 275                         | Yes            |
| GQ06             | Longitudinal beam       | 50.20                         | 275                         | Yes            |

3. Static load test
3.1. Measuring point layout
The principle of the arrangement of monitoring points is to reasonably optimize the number of measuring points on the premise that the observation quality requirements must be met. The arrangement of the measuring points should reflect the maximum stress (strain) and displacement of the structure [2].
3.1.1. Strain measuring point layout. The stress measurement points of this bridge are mainly arranged on the main arch, side beam and main tower. Among them, three sections (1-1 to 3-3) are selected for the main arch, which are the vault, L/4 and the arch toe (as shown in Figure 3), and 3 measuring points are arranged on each surface of the square arch. (Except the bottom surface of the arch toe), a total of 33 measuring points are arranged; the inner and outer side beams are also each selected three sections, each section is arranged with 4 measuring points, a total of 24 measuring points are arranged; the main tower selects one section (4-4), located 3m above the main tower, 3 measuring points are arranged on each surface, a total of 12 measuring points are arranged. Therefore, 57 steel strain measuring points and 12 concrete strain measuring points are arranged in this bridge.

![Fig 3 Schematic diagram of stress control section and strain measuring point](image)

3.1.2. Displacement measuring point layout
Since the bridge is a special-shaped bridge, the overall deformation of the bridge under load is translational + torsion, that is, during the test, each component of the bridge not only has vertical displacement, but also has a large horizontal displacement [3]. Combined with the finite element calculation results, the displacement measurement points of the bridge are mainly arranged at the L/4, (vault) mid-span and 3L/4 of the main arch, the inner side beam, and the anchor point of the main tower. Arrange 7 displacement measuring points, the specific numbers are shown in Figure 4.

![Fig 4 Schematic diagram of displacement measuring points and numbers](image)
3.2. Test load and loading position

The code [4-5] pointed out that the actual test load and loading position can be controlled by the load test efficiency. The static load test efficiency is calculated as follows:

$$\eta_s = \frac{S_{stat}}{S_k \times (1 + \mu)}$$

(1)

$S_{stat}$ — The calculated value of the maximum internal force or displacement of the control section under the actual load of the static test;

$S_k$ — The most unfavorable internal force or displacement calculation value of the control section under the control load;

$\mu$ — Impact coefficient value taken according to the specification;

$\eta_s$ — For static load test efficiency, for acceptance load test, its value should be greater than or equal to 0.85 and not greater than 1.05, and for appraisal load test, its value should be greater than or equal to 0.95 and not greater than 1.05.

Bridge static load test includes two test types: acceptance load test and appraisal load test. This load test is a qualitative load test, and the control load of the qualitative load test should be selected according to the original design load or the target load. Compared with ordinary bridges, the structure of this bridge is a complex special-shaped structure system, including multiple redundant constraint statically indeterminate systems. When specific indicators meet the load test requirements, some indicators have a large degree of excess, which is difficult to meet through conventional loading Load test requirements. After structural inspection and considering the safety of the bridge, 90% of the design load is taken as the target control load of the bridge [6].

The static load test adopts concrete counterweight to load. The load at all levels and the number and weight of the loaded counterweight are shown in Table 2. The loading position of the counterweight is within 4m of the bridge span. The specific loading sequence and position are shown in Figure 5.

The schematic plan is shown in Figure 4 below. The internal force and test efficiency of the bridge control section under live load and proposed test load are shown in Table 3.

| Load classification | Number of counterweights | Counterweight volume (m$^3$) | Weight (t) | Load weight (t) |
|---------------------|--------------------------|-----------------------------|------------|----------------|
| 1                   | 2                        | $3.0 \times 1.0 \times 0.5$ | 3.75       | 7.50           |
| 2                   | 4                        | $3.0 \times 1.0 \times 0.5$ | 3.75       | 15.00          |
| 3                   | 6                        | $3.0 \times 1.0 \times 0.5$ | 3.75       | 22.50          |
| 4                   | 7                        | $3.0 \times 1.0 \times 0.5$ | 3.75       | 26.25          |

Fig. 5 Loading position and sequence of concrete weights
Tab. 3 Static load test load efficiency of Rainbow Bridge at Olympic Sailing Center

| Structure type | Pilot projects | Target load effect (kN•m) | Test load effect (kN•m) | Efficiency factor η_s | Loaded counterweight |
|----------------|----------------|---------------------------|------------------------|----------------------|---------------------|
| Leaning tower-sling-curved arch combined structure system | Maximum positive bending moment in span | 863.90 | 868.16 | 1.005 | 7 |

It can be seen from the table that the static load test efficiency of the Rainbow Bridge of the Olympic Sailing Center is 1.05, which meets the specification [5].

3.3. Loading conditions
According to the test requirements, a total of 16 working conditions are selected. The working conditions of the load test are strictly in accordance with Table 4 below.

Tab. 4 Loading conditions

| category | Numbering | Working condition | Measurement content |
|----------|-----------|-------------------|---------------------|
| Static load test | 1 | Initial reading | Bridge deformation, strain and cable force increment |
| | 2 | Load with two counterweights | Bridge deformation, strain and cable force increment |
| | 3 | Uninstall all | Bridge deformation, strain and cable force increment |
| | 4 | Load with two counterweights | Bridge deformation, strain and cable force increment |
| | 5 | Four counterweight loading | Bridge deformation, strain and cable force increment |
| | 6 | Six counterweight loading | Bridge deformation, strain and cable force increment |
| | 7 | Seven counterweight loading | Bridge deformation, strain and cable force increment |
| | 8 | Uninstall all | Bridge deformation, strain and cable force increment |
| | 9 | Load with two counterweights | Bridge deformation, strain and cable force increment |
| | 10 | Four counterweight loading | Bridge deformation, strain and cable force increment |
| | 11 | Six counterweight loading | Bridge deformation, strain and cable force increment |
| | 12 | Seven counterweight loading | Bridge deformation, strain and cable force increment |
| | 13 | Uninstall all | Bridge deformation, strain and cable force increment |
| | 14 | Partial load loading for cars 1, 2, and 3 | Bridge deformation, strain and cable force increment |
| | 15 | Uninstall all | Bridge deformation, strain and cable force increment |
| Dynamic load test | 16 | Environmental incentives | Acceleration time history curve within bridge span |
3.4. Data analysis of static load test results

The static load test mainly analyzes the two parts of the data of the check coefficient and the residual coefficient. Among them, the check coefficient is less than 1 indicates that the bearing capacity of the structure can meet the requirements of the test load. The smaller the value, the higher the surplus of the bearing capacity of the structure [7]. The smaller the relative residual displacement (or strain) is, the closer the structure is to the elastic working state. Generally, the required value is not more than 20%.

3.4.1. Analysis of displacement check coefficient. The displacement check coefficients and residual displacement coefficients of this bridge are listed in Table 5. Due to space limitations, the calibration coefficients of each measuring point are not listed in detail in the table, only the calibration coefficient range of all measuring points is given.

| Working condition number | Load classification proportion | horizontal direction | Vertically |
|--------------------------|--------------------------------|----------------------|------------|
|                          |                                | Check coefficient    | Residual displacement | Check coefficient | Residual displacement |
| 2                        | 30.38%                         | 0.61–0.79            | 0.63–0.82 |
| 3                        |                                | 0.00–0.08            | 0.00–0.11 |
| 4                        | 30.38%                         | 0.61–0.79            | 0.64–0.85 |
| 5                        | 58.05%                         | 0.61–0.73            | 0.66–0.85 |
| 6                        | 85.71%                         | 0.61–0.84            | 0.75–0.92 |
| 7                        | 100.00%                        | 0.67–0.82            | 0.71–0.92 |
| 8                        |                                | 0.00–0.06            | 0.00–0.10 |
| 9                        | 30.38%                         | 0.62–0.85            | 0.65–0.82 |
| 10                       | 58.05%                         | 0.62–0.76            | 0.67–0.86 |
| 11                       | 85.71%                         | 0.61–0.84            | 0.75–0.92 |
| 12                       | 100.00%                        | 0.70–0.93            | 0.75–0.92 |
| 13                       |                                | 0.00–0.09            | 0.00–0.13 |

It can be seen from Table 4 that the horizontal displacement check coefficient of this bridge in the preloading stage (condition 2) is between 0.61 and 0.79, and the vertical displacement check coefficient is between 0.63 and 0.82. The bridge at this loading stage is safe and the overall condition is good. In the formal loading stage (Working condition 4～Working condition 7 and Working condition 9～Working condition 12), the horizontal displacement calibration coefficient of each measuring point is between 0.61 and 0.93, and the vertical displacement correction coefficient is between 0.62 and 0.92. It shows that the overall stiffness of the bridge is acceptable [8-9], which can meet the design load requirements. However, the calibration coefficient of some main measuring points (vertical displacement of the vault and the inner side beam mid-span) exceeds 0.90, indicating that the overall bearing capacity of the bridge is relatively low. After unloading, the relative residual displacement in the horizontal direction of all measuring points is between 0.00 and 0.09, and the relative residual displacement in the vertical direction is between 0.00 and 0.13, which all meet the relative residual displacement (or strain) in the specification [5] The requirement that the allowable value is not more than 20% indicates that the bridge is in an elastic state during the test [10].
3.4.2. Strain calibration factor analysis. The stress calibration coefficients and residual coefficients of this bridge under different working conditions are listed in Table 6. Same as above, this table only gives the calibration coefficient range of all measuring points.

| Working condition number | Load classification proportion | Calibration coefficient range | Residual coefficient |
|--------------------------|--------------------------------|-------------------------------|----------------------|
| 2                        | 30.38%                         | 0.80–0.92                     | 0.02–0.06            |
| 3                        | 30.38%                         | 0.81–0.91                     |                      |
| 4                        | 58.05%                         | 0.78–0.90                     |                      |
| 5                        | 85.71%                         | 0.78–0.92                     |                      |
| 6                        | 100.00%                        | 0.82–0.90                     |                      |
| 7                        | 30.38%                         | 0.80–0.92                     | 0.01–0.11            |
| 8                        | 30.38%                         | 0.79–0.91                     |                      |
| 9                        | 58.05%                         | 0.79–0.92                     |                      |
| 10                       | 85.71%                         | 0.80–0.91                     |                      |
| 11                       | 100.00%                        | 0.81–0.90                     |                      |
| 12                       |                                |                               | 0.02–0.10            |
| 13                       |                                |                               |                      |

It can be seen from the table that in the pre-loading stage (condition 2) and the formal loading stage (condition 4–condition 7 and 9–condition 12) of this bridge, the strain calibration coefficients of all measuring points are between 0.78 and 0.92. It shows that the overall condition of the bridge during the loading stage is good, and the bearing capacity can meet the design load requirements. The relative residual strain of the strain measuring point under all unloading conditions is between 0.01 and 0.12, which meets the specification that the relative residual displacement (or strain) allowable value is not more than 20% [5], indicating that the bridge is in the test process always in a resilient state.

3.4.3. Analysis of Cable Force Increment. Table 7 shows the check coefficients and residual coefficients of stay cables with the largest increase in cable force under various conditions in the static load test.

| Working condition number | Load classification proportion | Check coefficient | Residual coefficient |
|--------------------------|--------------------------------|-------------------|---------------------|
| 2                        | 30.38%                         | 0.81–0.94         | 0.09–0.14           |
| 3                        | 30.38%                         | 0.80–0.90         |                      |
| 4                        | 58.05%                         | 0.82–0.93         |                      |
| 5                        | 85.71%                         | 0.81–0.92         |                      |
| 6                        | 100.00%                        | 0.80–0.91         |                      |
| 7                        |                                |                   | 0.06–0.07           |
| 8                        | 30.38%                         | 0.80–0.91         |                      |
| 9                        | 58.05%                         | 0.81–0.92         |                      |
| 10                       | 85.71%                         | 0.80–0.90         |                      |
| 11                       | 100.00%                        | 0.79–0.91         |                      |
| 12                       |                                |                   | 0.04–0.07           |
| 13                       |                                |                   |                      |

It can be seen from the table that in each loading condition, the actual measured value of the stay cable increment is smaller than the calculated value and relatively close, and the check coefficient is between 0.79 and 0.94, indicating that the stay cable meets the design load requirements. The residual
coefficient of the cable force under all levels of unloading conditions is between 0.04 and 0.14, and the residual coefficient of the cable force under the formal loading and unloading conditions is small, between 0.04 and 0.07, all of which meet the relative residual displacement (or The requirement that the allowable value of strain is not greater than 20% [5] indicates that the cable stays in an elastic state during the test.

3.5. Analysis of dynamic load test results

This test uses the environmental excitation method to test the dynamic characteristics of the Rainbow Bridge at the Olympic Sailing Center, that is, in the absence of any traffic load on the bridge deck and irregular vibration sources near the bridge site, a high-sensitivity dynamic test system is used to determine the wind load and ground at the bridge site. Random loads, such as pulsation, water flow, etc., cause the small vibration response of the bridge span structure (free vibration displacement time history curve) [11]. Corresponding test parameter: the natural frequency $f_0$ of the structure. Pulsation test: The measuring points are arranged on the top of the guardrail of the test span (mid-span, quarter point and abutment fulcrum) to test the natural frequency $f_0$ of the bridge.

The first-order mode shape of the Rainbow Bridge at Olympic Sailing Center is calculated by the finite element model as shown in Figure 6. After calculation, the first-order natural frequency of the bridge is 1.2796 Hz.

![Fig 6 First-order natural frequency diagram of finite element calculation](image)

According to field measurement, the first-order natural frequency of the bridge is 1.753 as shown in Figure 7. The measured value is larger than the calculated value. The main reason may be the contribution of the accessory components and deck paving to the overall stiffness of the bridge. The test results show that the overall rigidity of the bridge structure is acceptable, the evaluation scale is greater than 1, the vertical rigidity of the structure is larger than the calculated value, and the dynamic performance of the structure is good [12].

![Fig. 7 Measured first-order natural frequency diagram](image)

4. In conclusion

1) The results of static load loading conditions show that the calibration coefficients of all measuring points of the bridge are less than 1.00, indicating that the overall performance of the bridge is good, and the bearing capacity of the bridge meets the design load requirements. However, the calibration
coefficient of some main measuring points (vertical displacement of the vault and the inner side beam mid-span) exceeds 0.90, indicating that the bearing capacity of the bridge is relatively low.

2) The static load unloading condition results show that the relative residual displacement (or strain, cable force increment) of all the measuring points of the bridge is less than the specification requirement of 0.20, indicating that the bridge is in an elastic working state during the test.

3) The results of the dynamic load test show that the measured first-order natural frequency of the bridge is 1.753 Hz, which is greater than the calculated value of 1.2796 Hz, indicating that the bridge has good dynamic performance, and the overall rigidity is acceptable, and the evaluation scale is greater than 1.

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