Experimental Study on Load of Concrete Filled Steel Tubular Double-rib Tied-arch Bridge

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Abstract: By taking a concrete filled steel tubular tied-arch bridge along Jiefang Road in Jiaozuo City, China as the research object and comparing the measured values and the theoretical values of static and dynamic load tests of the bridge, the overall mechanical performance and load-bearing capacity of the bridge are evaluated, and the research method can be used as a reference for the design and load test of the same type of bridge.

1. Description of the Bridge
The bridge described in this article is located at the intersection of Jiefang Road and the main canal of South-to-North Water Diversion Project in Jiaozuo City. With a single span of 85m, it crosses the canal and is the largest span concrete filled steel tubular arch bridge in Jiaozuo City. The bridge has two arch ribs in total. Its main rib is a concrete-filled truss structure and the spacing between centers of the middle ribs is 25.5m. The cross section of the bridge is rectangular with the same sectional height of 3.6m. The calculated rise-span ratio is 1: 4.25, the height from the center of arch rib to the center of tie beam is 20.1 m, and the arch axis has a shape of quadratic parabolic line. The main chord members are steel tubes filled with slightly expanded or non-shrinkage C50 concrete, and the upper and lower horizontal chords and the web members are steel tube structures. With a size of 3.0 m × 2.6m, the tie beam is a cast-in-situ prestressed concrete box structure and has a single box and single room box section. Its top and bottom plates are 0.3 m thick and its web plate walls are 0.5 m thick. A 1.2 m transverse diaphragm plate is provided at the location of the corresponding hanger. The vehicle load is designed to be Class I for highway. The elevation view of the bridge is shown in figure 1.

2. Theoretical Calculation Model
MIDAS/Civil-2012 finite element software is used for calculation of static forces of the bridge and a three-dimensional finite element model is established as shown in figure 2. During modeling in MIDAS/Civil-2012 software, tie beams, cross beams, arch ribs, transverse bracing and other components are discretized by spatial beam elements; the hanger is simulated by a spatial truss element that only bears tensile force, the bridge deck by plate-shell element, and the abutment by solid element. The model established has a total of 2540 nodes and 3183 elements including 2499 spatial beam elements, 30 spatial rod elements and 704 solid elements.
3. Static Load Test

3.1. Load Cases

According to the structural characteristics of the bridge and in consideration of the actual construction process, a model for analysis and calculation of static forces of the bridge is established to calculate the internal forces and displacement of the completed bridge and the response of the bridge structures to live loads, and then the following five cases are determined as load control cases, as shown in Table 1.

| Load Cases | Control of Section And Parameters | Load Distribution Mode | Calculated Test Value | Design Value for Normal Service Condition | Efficiency Coefficient |
|------------|-----------------------------------|------------------------|-----------------------|------------------------------------------|------------------------|
| Case 1     | Mid-span of arch rib Deflection   | Symmetrical load distribution in midspan | -4.4mm | -4.3mm | 1.02 |
| Case 2     | Abutment Negative moment          | Eccentric load distribution in midspan | -5.1mm | -5.0mm | 1.02 |
| Case 3     | Arch rib 1/4 L Sum of absolute values of positive and negative deflections | Eccentric loading | -2615.8kN·m | -2724.8kN·m | 0.96 |
| Case 4     | Arch rib 3/4 L Sum of absolute values of positive and negative deflections | Near 1/4 L Symmetrical loading | 3.4mm | 3.5mm | 0.97 |
| Case 5     | Arch rib 3/4 L Sum of absolute values of positive and negative deflections | Near 3/4 L Eccentric loading | 4.0mm | 3.9mm | 1.03 |

3.2. Layout of Measuring Points

3.2.1. Deflection Measuring Points. 18 reflective tapes for total station were pasted at two abutments, 1/8L, 1/4L, 3/8L, arch crown, 5/8L, 3/4L and 7/8L of the north and south arch ribs to measure their
deformation. HY65 type wireless digital displacement meters are arranged at 1/4 L, mid-span and 3/4 L of the north and south tie beams, with a total of 6 measuring points (see figure 3).

3.2.2. Strain Measuring Points. Strain measuring points are located at 7 cross sections of both the north and south arch ribs as shown in figure 4, with a total of 14 strain gauges arranged on the upper surface of the upper chord of the steel pipe inside the arch ribs. Other strain measuring points were provided at 3 cross sections of 1/4L, midspan and 3/4L of the north and south tie beams, with a total of 12 strain gauges symmetrically arranged on the left and right sides of these three sections, as shown in figure 4.

3.2.3. Hanger Force. Prior to application of test loads and before and after application of load cases 1 to 5, the initial tensile force and the force increment of each hanger are tested separately.

3.3 Analysis and Comparison of Test Results

3.3.1. Deflection. Under each load case, the measured deflection obtained from the measuring points at the control sections of the north and south tie beams is less than the theoretical one. The maximum deflection of the tie beams appears in the span of the north tie beams under 1/2 L eccentric loading case (figure 5). The maximum measured deflection is -6.518 mm, which is less than the theoretically calculated value of -8.645 mm and is also far less than L/600 specified in Chinese specification. The measured deflection of arch ribs is small, which is less than the theoretically calculated deflection value. The maximum measured deflection of the arch rib appears at the side crown under 1/2 L eccentric loading case (figure 6) and is less than the theoretically calculated value of -5.1mm. The deflection check coefficient of tie beam and arch rib is between 0.71 and 0.86, which meets the stipulation that the deflection check coefficient shall be less than 1 as specified in Code for Testing and Evaluation of Load-bearing Capacity of Highway Bridges (JTG/T J21-2011). The test data shows that under the test loads, the structural rigidity of the bridge meets the requirements and has a certain safety and recovery performance.

3.3.2. Strain. The strain of arch rib and tie beam is less than the theoretically calculated value, and the strain change trend is basically the same as the theoretically calculated one. The maximum
compressive strain of the arch rib is 48.5 $\mu \varepsilon$, which occurs at the cross section of 1/2L of south arch rib under symmetrical loading case and is less than the theoretically calculated strain of 62.9 $\mu \varepsilon$ of this section. The maximum tensile strain of the tie beam is 40.2 $\mu \varepsilon$, which occurs at the cross section of 3/4L under eccentric loading case and the maximum positive strain of the tie beam is less than the theoretically calculated strain of 67.5 $\mu \varepsilon$ of this section. The strain check coefficient of key measuring points of arch rib is between 0.59 and 0.79 and that of key measuring points of tie-beam is between 0.33 and 0.61, both meeting the stipulation that the strain check coefficient shall be less than 1 as specified in Code for Testing and Evaluation of Load-bearing Capacity of Highway Bridges (JTG/T J21-2011). The relative residual strain of the tie beam is between 3.9% and 9.6%, which meets the stipulation that the residual strain shall be not more than 20% as specified in Code for Testing and Evaluation of Load-bearing Capacity of Highway Bridges (JTG/T J21-2011). This shows that the deformation of the bridge is basically restored after the test load is removed, and the concrete filled steel tube arch bridge is in an elastic working state.

Table 2. Arch Rib Strain Measurement Table.

| Location of Cross Section | Load case 1 Symmetrically applied load at the cross section of 1/2L | Measured Strain | Theoretical Strain | Check Coefficient |
|--------------------------|-------------------------------------------------|-----------------|--------------------|-------------------|
| Crown of North Rib       | -37.3                                           | -62.9           | 0.59               |
| Crown of South Rib       | -48.5                                           | -62.9           | 0.77               |

3.3.3. Hanger Force. Under load cases 1 and 2, the hanger force increases by 3710kN and 3433kN respectively, which is basically consistent with 3440kN applied by total weight of 8 loaded vehicles. The change of hanger force increment under such two cases ranges from -47kN to 344kN, and the maximum force increment occurs on the SY7 hanger under symmetrical loads (see figure 7), which corresponds to location of vehicle load. Under load cases 4 and 5, the hanger force increases by 2921kN and 1532kN respectively, which is less than that under the mid-span load by 789kN and 1901kN. The reason for this is that when the vehicle is loaded at 1/4 L cross section, the load is directly transferred to the support, thus reducing the load borne by the hanger. Under load case 4, the maximum hanger force increment of 298kN occurs on the SY7 hanger and under load case 5, the maximum increment of 192kN occurs on the XY11 hanger, which corresponds to actual location of vehicle load. When the test load of 8 vehicles is applied, the maximum hanger force of 3131kN appears on the SY8 hanger under load symmetrically applied in the mid-span section, and the minimum calculated safety factor is 3.8, which meets the requirements of not less than 2.5 in the specification.

Figure 7. Analysis of Change in Hanger Force (unit: kN).
4. Dynamic Load Test

4.1 Test Method
Under the condition that there is no heavy traffic load (or random non-motor vehicle flow with small traffic volume) on the bridge deck and strong vibration sources near the bridge site, the micro-amplitude vibration response of the bridge span structure caused by random loads such as wind load, ground pulsation and water flow at the bridge site is determined by high-sensitivity vibration pickup, so as to measure the dynamic characteristics such as natural vibration frequency and damping ratio of the bridge. For effective measurement of natural vibration frequencies of the bridge such as horizontal and longitudinal vibration frequencies, three vertical vibration pickup are respectively installed at 1/4 span, mid-span and 3/4 span of both north and south tie beams, and one transverse vibration pickup is arranged at the crown of north arch rib.

4.2. Analysis of Test Results
The horizontal and longitudinal vibration frequencies of the bridge is shown in table 3. The first-order measured horizontal and longitudinal vibration frequencies is 1.09 to 1.29 times larger than the theoretical value, and the first-order measured longitudinal vibration frequency is close to the theoretical value, showing that the bridge has good dynamic rigidity and can meet the normal service requirements under design load. In this paper, the damping ratio is calculated according to the half-power bandwidth method, and the calculation results are shown in table 4. The damping ratio of the bridge falls between 0.518% and 0.735%, which is within the normal range of long-span concrete filled steel tube bridges.

Table 3. List of Measured Vibration Frequencies of the Bridge.

| Frequency Order     | Natural Vibration Frequency | f_{mi}/f_{di} |
|---------------------|-----------------------------|---------------|
|                     | Measured value \( f_{mi} \) (Hz) | Theoretical Value \( f_{di} \) (Hz) |                |
| Horizontal first-order | 1.06                        | 0.86          | 1.29          |
| Longitudinal first-order | 2.28                        | 2.09          | 1.09          |

Table 4. List of Damping Ratio of the Bridge.

| Location of measuring point | Measured value \( f_{mi} \) (Hz) | Damping ratio (%) | Remarks                             |
|-----------------------------|----------------------------------|-------------------|-------------------------------------|
| 1/4 L of Tie beam           | 2.28                             | 0.518             | Measuring point for longitudinal vibration |
| 1/2 L of Tie beam           | 2.28                             | 0.559             | Measuring point for longitudinal vibration |
| 3/4 L of Tie beam           | 2.28                             | 0.585             | Measuring point for longitudinal vibration |
| 1/2 L of Arch rib           | 1.05                             | 0.735             | Measuring point for horizontal vibration |

5. Conclusions
(1) During the static load test, the measured deflection and strain data of each control section of arch rib and tie beam are consistent with the normal change law of the bridge, and each check coefficient is less than 1, indicating that the bridge is in an elastic working state. The safety factor of hanger force meets the specification requirements.

(2) During the dynamic load test, the measured frequency is slightly higher than the theoretical value, the damping ratio is also within the normal range, and the structural stiffness can meet the normal operation requirements.

(3) The static load and dynamic load test results mutually support each other, which shows that the test results are reliable.
(4) According to the test results, the bearing capacity and overall dynamic performance of the bridge meet the design requirements and can meet the normal service requirements under design load.

References
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