Current Situation Detection and Performance Evaluation Analysis of Existing Double-curved arch bridge

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Abstract: The existing design load level of the existing double-curved arch bridge is generally low, the old-fashioned inferiority and the poor overall integrity, which are likely to cause structural damage and affect the normal use of such structures. Based on the appearance inspection and static and dynamic load test of a dangerous three span double-curved arch bridge without original design data, this paper discusses the methods of structural modeling, load test and structural performance evaluation of this kind of bridge, which provides reference to the current situation evaluation of similar bridges. Through the inspection of bridge appearance defects, component cracks, deformation displacement, steel protective layer thickness, concrete carbonization depth and material strength, combined with the load test results, the comprehensive technical status of the bridge is determined to be 4 types of bridges. The bearing capacity meets the requirements of load grade Automobile-10 class, but the safety reserve is insufficient.

1. Introduction

Double curved arch bridge is a new type of arch bridge, which was first created by the staff of Wuxi Transportation Bureau in 1960s [1]. It is a new type of arch bridge structure that fully reflects the background of the times and the characteristics of nationality. The double curved arch bridge is usually composed of the main arch ring and the building on the arch. The main arch ring is composed of the arch rib, arch wave, arch plate and transverse connection. The cross section of the main arch ring is made up of several small transverse arches connected by transverse connection, so that the main arch ring presents a curve shape in both longitudinal and transverse directions, so it is called double curvature arch bridge [2]. This type of bridge not only makes full use of the pressure resistance of masonry materials, but also has the characteristics of material saving, simple construction, low cost and beautiful appearance. Therefore, the bridge type has been widely used in the whole country since it was proposed, which lays a foundation for the development of highway transportation in China. According to incomplete statistics, by 1972, only 17 provinces and cities in the South had built more than 3300 double curvature arch bridges with a total length of 193km [3]. Due to the problems of low design level and design load class, insufficient material strength, low structural reinforcement ratio, which were difficult to guarantee construction quality and poor overall performance caused by too thin section division of main arch ring of double curvature arch bridge, almost all double curvature arch bridges have presented different degrees of diseases after nearly 40 years of use, especially, in recent years with large traffic volume and heavy load. Under the action of vehicles, the disease of double curved arch bridge is not optimistic. Some double curved arch bridges have developed into dangerous bridges or been demolished for reconstruction [4].
For these bridges with diseases, if all of them are demolished and rebuilt, not only a lot of money needs to be invested, but also the road traffic will be seriously affected, especially some bridges with historical significance are more difficult to demolish and rebuild. At present, in the face of this kind of bridge, we mainly test and evaluate the appearance and structural performance of the bridge, and then formulate corresponding maintenance and reinforcement measures to ensure the safe use of the bridge.

2. Engineering summary
The total length of a double curved arch bridge is 111 m, and the span combination is 3×31.5 m. The main arch ring is composed of four rectangular section arch ribs connected by arch waves and diaphragms. Each span is set with 13 diaphragms along the longitudinal direction of the bridge. The bridge deck width is 5.4 m, the rise span ratio is 1/6 and the asphalt concrete bridge deck. Due to the long history of bridge construction and the lack of design data, the detailed structure size and design load level are unknown. The above data are obtained by field measurement and combined with similar bridge types in the same age. Bridge superstructure adopts three span hollow reinforced concrete double curvature arch, the arch rib and arch wave are reinforced concrete structures, and the spandrel arch and column adopt masonry structure. The substructure is gravity masonry pier and abutment. According to the investigation, the bridge was completed and opened to traffic in 1981. See Figure 1 and Figure 2 for the longitudinal layout of bridge structure and cross section layout of main arch ring.

![Figure 1. Longitudinal layout of bridge structure (unit: cm).](image1)

![Figure 2. Transverse structure of main arch ring (unit: cm).](image2)

3. Detection of structural appearance defect and material condition
According to the relevant standards and specifications [5-8], the appearance defects and material conditions of the bridge are detected, which is one of the bases for evaluating the bearing capacity of the existing bridge. Through the appearance inspection, it is found that the bridge deck pavement is seriously worn and accompanied with a large number of longitudinal and transverse cracks, the whole bridge drain holes are blocked by sundries, and the bridge deck is seriously watered. In the upper structure, there are more than 20 places of steel bar corrosion and concrete peeling off in the arch rib, with a total area of \( S = 2.21 \text{ m}^2 \), in which the largest area of steel bar corrosion and concrete peeling off in a single place is \( S_{\text{max}} = 0.6 \text{ m}^2 \), and the mortar joint of the ventral arch falls off seriously and water erosion occurs in many places. During the inspection of substructure, it is found that the water erosion of pier and abutment is serious, no obvious erosion of pier and abutment foundation is found, and the working condition is good.
Two arch ribs are randomly selected for each span by adopting rebound method and combining with concrete core drilling correction. The strength of concrete at present age is detected at the position of arch crown, 1/4 span and arch foot respectively. Its purpose is to have a general understanding of the strength of the concrete of the whole bridge, and to provide a basis for bridge modeling, and also to understand the carbonation of concrete. The results show that the estimated strength of the arch rib is between 17.4 and 20.2 MPa. Due to the lack of original design data, the concrete grade of partial safety bridge is C20.

According to the inspection results, the technical condition grade of the superstructure of the bridge is 4; the technical condition grade of the whole bridge is 3. According to 4.1.8 of the Evaluation Standard for Technical Conditions of Highway Bridges (JTG / T H21-2011), when the overall technical condition rating of the whole bridge reaches 4 or 5 categories and affects the safety of the bridge, it can be evaluated according to the worst defect condition of the main components of the bridge, so the bridge is finally evaluated as 4 categories.

4. Linear detection of main arch ring
The main arch ring is the main bearing component of the double curved arch bridge, and the key point of the existing arch calculation is whether the actual arch axis is used for internal force calculation and analysis, so it is particularly important to measure the position of the arch axis of the main arch ring on site [9].

Take the elevation of guardrail at 0# abutment and 1# pier as reference value, and then measure 1/8 span, 2/8 span … 8/8 span successively. The distance from the guardrail at the top of pier and abutment to the upper edge of main arch ring, and finally the influence of guardrail elevation is deducted. Then, the catenary equation, the arc equation and the parabola equation are used to fit the above-mentioned elevation value of each main arch ring, and the best quadratic parabola equation is selected as the arch axis equation. The fitting degree $R^2$ of the main arch ring alignment of the measured span is greater than 0.99, indicating that the main arch ring alignment is good, and the main arch ring alignment fitting is shown in Figure 3.

![Figure 3. Line fitting diagram of main arch circle axis](image)

(a) Fitting drawing of the first span arch axis  
(b) Fitting drawing of the second span arch axis

It can be concluded that the equation of arch axis is $y = -0.02023x^2 + 0.63126x - 7.00152$, and the ratio of rise to span is approximately 1/6, which can be used as the basis for subsequent calculation and modeling.

5. Establishment of finite element model
In order to obtain the theoretical loading value of the bridge and ensure the load efficiency within the specification value of 0.95~1.05, the model of double curved arch bridge is established by Midas civil, a general finite element software of the bridge. As the gravity structure is adopted for the piers and abutments, the anti-seismic rigidity of the piers and abutments is much greater than that of the main arch ring, and the horizontal and vertical displacement of the arch foot is very small, so the continuous supply effect of the porous arch bridge can be ignored in the modeling analysis [10]. Due to the lack of design data, the on-site measured values are used for the arch axis, concrete material characteristics and the
size of each component. The analysis shows that the arch plate, arch rib and arch wave in the main arch ring are fully stressed after long-term use, so the overall stress is considered [11]. The whole bridge model includes 906 nodes and 1642 beam elements, of which 33 are single arch rib nodes. The arch structure and the main arch ring are connected by the beam element, and the bending moment is released at both ends of the beam element. The filling on the arch is applied to the bridge deck as a unit load. See Figure 4 for node division and structure dispersion.

Figure 4. Discrete diagram of MIDAS structure of double curved arch bridge

6. Static load test

6.1 Preliminary preparation

Combined with the stress characteristics of the structure itself and the on-site inspection of the bridge, the representative mid span and the side span with relatively serious damage are selected as the test span. In addition, the most unfavorable section of the internal force of the superstructure under the Level-10 load of the highway vehicle is selected as the test section of this test [12]. For this purpose, according to the relevant provisions of Specifications for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG 3362-2018), the superstructure of the bridge is analyzed and calculated in detail by using the bridge special program, and the bending moment envelope diagram of the bridge structure under the design load is made, from which the section position of the most unfavorable bending moment of the main arch ring under the live load can be determined. This section is taken as the main test section of this load test. At the same time, combined with the actual site conditions, the section at the first span of the bridge (section I-I), the section at the horizontal distance of 1.5m from the arch foot (section II-II) (the arch foot is flooded) and the section at the second span of the bridge (section III-III) are determined as test sections. The test section is arranged along the longitudinal direction of the bridge as shown in Figure 5.

Figure 5. Longitudinal layout of test section along the bridge (unit: m)

According to the principle of internal force equivalence and load distribution at the most unfavorable position of the influence line, the value of the efficiency coefficient $\eta_q$ of the static test load shall meet the requirements of $0.95 \leq \eta_q \leq 1.05$ specified in the load test specification for highway bridges (JTG/T J21-01-2015). See table 1 for the load efficiency of each working condition in this test. The bending moment and deflection influence line of each test section are shown in Figure 6. Considering the actual situation of the site, the loaded vehicles are arranged according to the medium load. See Figure 7 for the
longitudinal and transverse layout and vehicle parameters of the loaded vehicle used in the test under various working conditions.

(a) Displacement influence line of vault section
(b) Bending moment influence line of vault section
(c) Displacement influence line of arch foot section
(d) Bending moment influence line of arch foot section

Figure 6. Bending moment and deflection influence line of each test section

(a) Elevation layout of arch loaded truck (unit: mm)
(b) Elevation layout of arch foot loaded truck (unit: mm)
(c) Layout plan of medium load of truck (unit: cm)

Figure 7. Loading diagram of heavy vehicle under various working conditions

| Condition | Section location          | Design internal force value (KN·N) | Test internal force value (KN·N) | Load efficiency |
|-----------|---------------------------|-----------------------------------|----------------------------------|-----------------|
| 1         | First span vault section  | 73.54                             | 75.88                            | 0.97            |
| 2         | First span arch foot section | -30.81                           | -32.14                           | 0.96            |
| 3         | Second span vault section | 73.54                             | 75.88                            | 0.97            |

6.2 Analysis of test results

6.2.1 Strain analysis
See Table 2, 3 and 4 for the measured and calculated values of the corresponding control section strain under each working condition. The strain is positive in tension and negative in compression.
According to the strain calibration coefficient, under the test load equivalent to the design load, the average calibration coefficient of strain of the first span vault section in condition 1 is 0.83. The average calibration coefficient of strain of the second span vault section in condition 3 is 0.74. The average calibration coefficient of strain of the first span arch foot section in condition 2 is 0.87. The calibration coefficient is in the normal range, but the quantile value is slightly higher, indicating that the safety margin of the bridge is insufficient.

6.2.2 Deflection analysis
See Table 5 and table 6 for the comparison and analysis between the theoretical calculation value and the measured value of the deflection of the structure under various working conditions. The deflection is positive for downward deformation and negative for upward deformation.
Table 5. Comparison between the measured value and the theoretical value of each deflection measuring point of the first span vault section under condition 1

| Condition | Section location | Survey point number | theoretical value (mm) | Deflection value (mm) | Check coefficient | Average value of calibration coefficient |
|-----------|-----------------|---------------------|------------------------|-----------------------|------------------|------------------------------------------|
| 1         | vault section   | 1                   | 1.0                    | 0.85, 0.83            | 0.84             | 0.84, 0.83, 0.84                         |
|           |                 | 2                   | 1.0                    | 1.02, 1.10            | 1.06             | 1.06, 1.06                               |

Table 6. Comparison between the measured value and the theoretical value of each deflection measuring point of the second span vault section under condition 3

| Condition | Section location | Survey point number | theoretical value (mm) | Deflection value (mm) | Check coefficient | Average value of calibration coefficient |
|-----------|-----------------|---------------------|------------------------|-----------------------|------------------|------------------------------------------|
| 3         | vault section   | 1                   | 1.0                    | 0.81, 0.83            | 0.82             | 0.82, 0.83                               |
|           |                 | 2                   | 1.0                    | 0.98, 1.02            | 1.00             | 1.00, 1.00                               |

It can be seen that the average deflection calibration coefficient of the first span of the arch top section is 0.95, and the deflection value at the guardrail on the left side of the bridge is obviously smaller than that at the guardrail on the right side; the average deflection calibration coefficient of the second span of the arch top section is 0.91, and the deflection value at the guardrail on the left side of the bridge is obviously smaller than that at the guardrail on the right side. It shows that the bridge span structure has a slight torsional effect under the test load, and the bridge span has a slight torsional effect. Under the design load, the connection performance of each part of the structure is poor. The deflection calibration coefficients are all within the normal range, but the quantile value is slightly higher, indicating that the safety margin of the bridge is insufficient. In addition, no other abnormal phenomena were found during the whole static load test.

7. Dynamic load test

7.1 Comparison of natural frequencies

With environmental excitation, the measured time history signal and natural vibration power spectrum are shown in Figure 8. The measured and theoretical natural frequencies are shown in Table 7. The basic mode shapes calculated by the program are shown in Figure 9.

![Time domain signal](image1)

![Self-vibration power spectrum](image2)

Figure 8. Bridge vibration signal

Table 7. Comparison between test value and calculation value of self-vibration frequency

| Mode of vibration | Measured frequency (Hz) | Calculated frequency (Hz) | Mode feature description |
|-------------------|-------------------------|---------------------------|-------------------------|
| 1                 | 5.72                    | 5.35                      | Symmetrical vertical bending vibration of main arch ring |
Antisymmetric vertical bending vibration of main arch ring

Symmetrical vertical bending vibration of main arch ring

(a) One order vibration mode

(b) Two order vibration mode

(c) Three order vibration mode

Figure 9. Vibration mode of bridge structure

7.2 Conclusion of dynamic load test
Under the dynamic excitation, the dynamic response performance of the superstructure shows that the overall performance of the structure is good. The measured first-order natural frequency is 5.72 HZ, which is greater than the theoretical calculation frequency of 5.35 HZ, and the ratio of the measured natural frequency to the theoretical calculation frequency: \( \frac{f_{mi}}{f_{di}} = \frac{5.72}{5.35} = 1.07 \), and the technical condition of the bridge is evaluated as scale 2. Therefore, the actual dynamic stiffness of the bridge is greater than the theoretical stiffness.

8. Conclusions
Through the appearance inspection, static and dynamic load test and evaluation analysis of the double curved arch bridge, the following conclusions can be obtained:

(1) The comprehensive technical condition evaluation grade of the bridge is 4 categories. The main diseases of the superstructure are corrosion and exposure of the steel bars of the arch ring, large area peeling of the concrete and falling off of the mortar joints of the arch web; the deck pavement is damaged, the coarse aggregate is exposed and accompanied by a large number of longitudinal and transverse cracks.

(2) Through the static load test, it is known that the strain and deflection calibration coefficient of the control section of the test span are larger than the constant value, indicating that the bearing capacity of the bridge meets the requirements of the target identification load level, but the safety reserve is not sufficient.

(3) The measured vertical vibration frequency of the main arch ring is greater than the theoretical analysis value, indicating that the actual dynamic stiffness of the bridge is greater than the theoretical value.

(4) It is recommended to strengthen and repair the bridge, including the treatment of concrete peeling, joint peeling, poor drainage of the bridge deck and poor integrity of the bridge, and it is also recommended to carry out load limiting and traffic limiting measures for the bridge.

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