Evaluation and Analysis of Bearing Capacity of Masonry Arch Bridge Based on Structure Detection and Checking Analysis

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Abstract. In this paper, on the basis of structure detection and technical status evaluation, the load effect and bearing capacity of the key section of masonry arch bridge under the most adverse load were calculated based on the theoretical model, and then the bearing capacity was evaluated comprehensively. The results of the project can be used for reference for similar bridge detection and evaluation.

1. Introduction
The rapid development of traffic construction in China provides a good opportunity for the development of highway and bridge. With the growth of time and the increase of load, the bridge gradually ages, and various diseases appear, which lead to the decline of the bridge structure's carrying capacity. The evaluation of bridge bearing capacity involves many factors, such as structural type and degradation mechanism, etc. At present, the evaluation methods mainly include design theory method, empirical method and load test method, among which load test method is the most direct and commonly used method. [1] However, due to the low design grade of some reinforced concrete arch Bridges and the loss of design data, it is advisable to evaluate the bearing capacity according to the inspection status of the structure and its actual function in the structure.

2. Case analysis
A masonry arch bridge, 80.4m in length, with u-shaped abutment as its substructure to expand the foundation; the bridge deck is paved with asphalt concrete. The designed load class of the bridge is car-20, and the designed safety class is grade 2.

2.1. Structure detection
On the basis of “Road bridge maintenance specification” (JTG H11-2004) [2], "The standard of assessment of highway bridge technology status " (JTG/T H21-2011) [3], " Inspection and assessment procedures for bearing capacity of highway Bridges " (JTG/T J21- 2011) [4] to regularly check the provisions of the masonry arch bridge, a comprehensive check checked bridge deck system, the structure of the upper structure and lower the appearance quality of the visible parts of the situation, the main disease is: transverse crack, deformation and breakage of the deck surfacing; Vertical cracks in guardrail; Crack and water seepage crystallization of main arch ring; The side wall of the arch ring is disintegrated, horizontal crack of the side wall is broken, and water ooze is crystallized. Bridge abutment seepage...
crystallization. According to him standard of assessment of highway bridge technology status (JTG/T H21-2011), the technical status assessment is shown in table 1.

| The bridge site  | The weight | Technical status score | Technical status | Technical status of the whole bridge | Technical status of the whole bridge |
|------------------|------------|------------------------|------------------|-------------------------------------|-------------------------------------|
| The upper structure | 0.4        | 63.0                   | 3                |                                     |                                     |
| The lower structure | 0.4        | 93.9                   | 2                |                                     |                                     |
| Floor system      | 0.2        | 69.9                   | 3                | 76.8                                | 3                                   |

2.2. Calculation and analysis of carrying capacity

2.2.1. Determination of calculation parameters. Limit state of bearing capacity of masonry arch bridge is calculated and evaluated according to the following formula according to the tested structure:

\[ \gamma_0 S \leq R (f_d, \xi_c) Z_1 \]  

Where, \( \gamma_0 \) -- the importance coefficient of the structure; 
\( S \) -- load utility function; 
\( R () \) -- resistance effect function; 
\( f_d \) -- design value of material strength; 
\( a_d \) -- geometric dimensions of the structure; 
\( Z_1 \) -- bearing capacity check coefficient; 
\( \xi_c \) -- the cross-section reduction coefficient of the structure.

1) Determination of the bearing capacity check coefficient \( Z_1 \)

The bearing capacity check coefficient \( Z_1 \) reduces or increases the resistance of the structure or component according to the actual technical status of the structure or component. According to the current overall technical status, the structure's technical status evaluation value \( D \) is first determined according to formula 2. On this basis, the bearing capacity evaluation coefficient \( Z_1 \) is determined based on the stress mode of members in accordance with the highway and bridge load capacity test and evaluation code (JTG/T 21-2011) [4], as shown in table 3.

\[ D = \sum \alpha_j D_j \]  

Where: \( \alpha_j \) -- the weight value of a certain test index, \( \sum_{j=1}^{3} \alpha_j = 1 \); 
\( D_j \) -- evaluation scale value of a test index of a structure or component.

| Test indicator name | The defect status | The material strength | Natural frequency of vibration |
|---------------------|-------------------|-----------------------|-------------------------------|
| The weight \( \alpha_j \) | 0.4               | 0.3                   | 0.3                           |
Table 3. Determination of the bearing capacity check coefficient $Z_1$

| The serial number | project                      | The weight | Rating scale | Technical status assessment value $D$ | The check coefficient determined by eccentric compression member |
|-------------------|------------------------------|------------|--------------|---------------------------------------|---------------------------------------------------------------|
| 1                 | The defect status           | 0.4        | 2            | 2                                     | 1.1                                                            |
| 2                 | The material strength       | 0.3        | 2            |                                       |                                                                |
| 3                 | Natural frequency of vibration | 0.3        | 2            |                                       |                                                                |

2) Determination of section reduction coefficient $c_e$

For masonry arch bridge, the effective section loss of the structure or member caused by material weathering and physical and chemical damage will have an impact on the section resistance effect of the structural member. The section reduction coefficient can be used to calculate the resistance effect of the structure. The calculated results are shown in table 4.

Table 4. Calculation results of section reduction coefficient of superstructure $c_e$

| The serial number | project                        | The weight | To evaluate the value of | Section reduction coefficient |
|-------------------|--------------------------------|------------|-------------------------|-------------------------------|
| 1                 | The material of weathering     | 0.20       | 2                       | 0.98                          |
| 2                 | Physical and chemical damage   | 0.80       | 2                       |                               |

2.2.2. Determination of finite element model and calculation parameters. In this calculation, the influence of loads on the bearing capacity of the structure from the aspects of constant load, moving load and overall rising and cooling was taken into account, and various load standard values were selected with reference to the general code for design of Highway Bridge and culvert (JTG D60-2004). [5]

1) Main mechanical properties of materials and relevant calculation parameters

According to the on-site measurement, the main structure of the bridge adopts masonry structure, the main arch ring is M10 mortar MU60 stone, the vertical wall is M10 mortar MU60 stone, and the abdominal arch ring is M10 mortar MU60 stone. Main parameters of masonry materials are shown in table 5.

Table 5. Parameters of masonry materials

| Mechanical properties of materials | Block stone mortar masonry | MU60, M10 | MU60, M10 | MU60, M10 |
|-----------------------------------|-----------------------------|-----------|-----------|-----------|
|                                   | The application structure   | The main arch ring | Vertical wall | Abdomen arch |
| Elastic modulus (MPa)             | 7300                        | 7300      | 7300      |           |
| Poisson's ratio                   | 0.17                        | 0.17      | 0.17      |           |
| Axial compressive strength design value (MPa) | 4.22                      | 4.22      | 4.22      |           |
| Bending tensile strength design value (MPa) | 0.086                      | 0.086    | 0.086     |           |
| Linear expansion coefficient (1/℃) | 0.000008                   | 0.000008 | 0.000008 |           |

2) Load calculation

(1) Constant load

First stage constant load: the dead weight of the structure is calculated according to the actual size of the bridge, and the bulk density is 25KN/m³;
Arch packing: calculated at 22KN/ m³;
Guardrail: calculated at 25KN/ m³.

(2) Moving load

Load level in accordance with the highway - I to load, consider two lanes partial load arrangement to calculate. For full belly arch Bridges and hollow arch Bridges with arch structures, it is calculated that the live load is evenly distributed in the full width of the arch ring. The impact coefficient is derived by
calculating the in-plane first-order antisymmetric fundamental frequency, which is $f = 2.357$ hz, so as to calculate the impact coefficient of tihugou bridge according to relevant provisions of the general code for highway bridge and culvert design.

(3) Temperature load
   System heating: consider the overall heating; 20℃
   System cooling: consider overall cooling. 18℃

(4) The importance coefficient of the structure is 1.0.

2.2.3. Calculation and analysis of bearing capacity. According to the theoretical model, the load effect and the bearing capacity of the bridge under the most unfavorable load of the critical section of the bridge are calculated. Based on the reasonable reduction of the bearing capacity of the bridge, the existing bearing capacity of the bridge is checked and analyzed.

1) Finite element model
   The finite element model is used for calculation and analysis in this paper. The beam element is used to discretethe whole bridge. The arch filler is applied to the main arch ring and the abdominal arch in the form of beam element load.
   The bridge structure importance coefficient is 1.0, bridge deck width, so the moving load calculation according to two lanes, two lanes are calculated by way of partial load, according to the relevant articles, masonry highway bridge and culvert design specifications calculation highway - 1 class under the action of the main arch ring of arch feet, eight points and vaults of eccentric compression bearing limit state whether meet the requirements.7.7mWhen checking the calculation, the internal force value of the corresponding element of the main arch ring with the maximum force is taken. Load combination working conditions are as follows:
   Working conditions: 1:1.2 constant load +1.4 vehicle load +1.12 overall temperature rise;
   Working conditions: 2:1.2 constant load +1.4 vehicle load +1.12 overall cooling;

2) Assessment of carrying capacity
   According to the relevant provisions of code for design of highway Masonry Bridge and culverts (JTG D61-2005), for masonry members with unidirectional or bidirectional eccentric compression, under the action of basic combination, the eccentricity of compression should not exceed 0.6s, where $s$ is the distance from the center of gravity of the section to the edge of the section in the direction of eccentricity. The bearing capacity within the limitation range of compression eccentricity shall be calculated according to formula 3:
   \[
   \gamma_v N_d < \varphi A f_{cd} \tag{3}
   \]
   Where: $N_d$ - design value of axial force;
   $A$ -- section area of member;
   $f_{cd}$ -- design value of masonry axial compressive strength;
   $\varphi$ -- influence coefficient of bearing capacity of compression members.
   According to the relevant provisions of code for design of highway Masonry Bridge and culverts (JTG D61-2005), the influence of length-thickness ratio on bearing capacity of compression members can be excluded in the calculation of the strength of arch ring section.5.1.4 $\beta$ Therefore, for unidirectional eccentrically loaded members, the bearing capacity impact coefficient can be simplified as:
   \[
   \varphi = \frac{1 - \left(\frac{e}{x}\right)^{m}}{1 + \left(\frac{e}{t_x}\right)^{2}} \tag{4}
   \]
Where, \( e = \frac{M_{yd}}{N_d} \), \( M_{yd} \) is the design value of the bending moment of the X-axis;

\( m \) -- section shape coefficient is 8.0 for rectangular section;

\( i_y \) -- radius of section turning in the curved plane.

As for the bearing capacity outside the limitation range of compression eccentricity, one-way eccentricity should be calculated according to formula 5:

\[
\gamma_0 N_d < \varphi \frac{Af_{md}}{W} - 1
\]

Where, \( N_d \) -- is the design value of axial force;

\( A \) -- section area of member;

\( W \)-- the elastic resistance moment of the member’s tension edge;

\( f_{md} \)-- design value of bending tensile strength of tension edge layer of masonry;

\( \varphi \)-- influence coefficient of bearing capacity of compression members.

3) Carrying capacity check analysis

The ultimate bearing capacity of the main arch ring was checked according to the bearing capacity checking coefficient \( Z_1 \) and the section reduction coefficient. \( \xi_e \). According to the design load level highway - I, bridge structure were obtained through the finite element analysis under the action of load combination condition 1, condition 2 to the bending moment of each section, shaft as shown in figure 1, figure 2, bearing capacity calculation results shown in table 6–11.

![Figure 1](image_url)

**Figure 1.** Overall bending moment envelope diagram and overall axial force envelope diagram under the action of working condition 1
Figure 2. The envelope diagram of the whole bending moment and the whole axial force under the action of working condition 2

Table 6. Calculation results of main arch ring bearing capacity under working condition 1

| Load combination | Cross section position | N (KN)  | M (KN. M)  | E (m) | [e] | phi | Resistance of section (KN) |
|------------------|------------------------|---------|------------|-------|-----|-----|----------------------------|
|                  | The arch foot          | 42987   | 6944.2      | 0.1615| 0.36| 0.821| 42426.5                    |
| Mix 1            | 1/8                    | 40480.6 | 3920.3      | 0.0968| 0.36| 0.928| 47908.5                    |
|                  | A quarter              | 37584.8 | 5961.2      | 0.1586| 0.36| 0.827| 42701.2                    |
|                  | 3/8                    | 36384.6 | 7420.8      | 0.2040| 0.36| 0.743| 38356.7                    |
|                  | vault                  | 36061.4 | 4480.2      | 0.1242| 0.36| 0.886| 45766.1                    |

Table 7. Calculation results of bearing capacity of 1# abdominal arch arch ring under working condition 1

| Load combination | Cross section location | N (KN) | M (KN. M) | E (m) | [e] | phi | Resistance of section (KN) |
|------------------|------------------------|--------|-----------|-------|-----|-----|----------------------------|
| Mix 1            | The arch foot          | 1118.1 | 1664.7     | 1.49  | 0.135| 0.005| 0.0                         |
|                  | A quarter              | 1594.1 | 704.1      | 0.44  | 0.135| 0.050| 1.9                         |
|                  | vault                  | 1416.4 | 638.1      | 0.45  | 0.135| 0.048| 1.8                         |

Table 8. Results of checking the bearing capacity of no.2 abdominal arch arch ring under the action of working condition 1

| Load combination | Cross section location | N (KN) | M (KN. M) | E (m) | [e] | phi | Resistance of section (KN) |
|------------------|------------------------|--------|-----------|-------|-----|-----|----------------------------|
| Mix 1            | The arch foot          | 1172.4 | 1209.7     | 1.03  | 0.135| 0.009| 0.1                         |
|                  | A quarter              | 1727.1 | 509.4      | 0.29  | 0.135| 0.105| 6.6                         |
|                  | vault                  | 1722.8 | 571.1      | 0.33  | 0.135| 0.085| 4.6                         |
Table 9. Calculation results of main arch ring bearing capacity under the action of working condition 2

| Load combination | Cross section position | N (KN) | M (KN. M) | E (m) | [e] | phi | Resistance of section (KN) |
|------------------|------------------------|--------|-----------|-------|-----|-----|--------------------------|
| Combination of two | The arch foot          | 43079.1 | 9757.6    | 0.2265 | 0.36 | 0.701 | 36183.2                 |
|                  | 1/8                    | 40521.9 | 4753.5    | 0.1173 | 0.36 | 0.897 | 46338.9                 |
|                  | 1 quarter              | 36330.7 | 5193.2    | 0.1429 | 0.36 | 0.855 | 44137.5                 |
|                  | 3/8                    | 35182.9 | 8853.8    | 0.2517 | 0.36 | 0.655 | 33810.1                 |
|                  | vault                  | 34733.2 | 6893.4    | 0.1985 | 0.36 | 0.753 | 38888.1                 |

Table 10. Calculation results of bearing capacity of 1# abdominal arch arch ring under the action of working condition 2

| Load combination | Cross section position | N (KN) | M (KN. M) | E (m) | [e] | phi | Resistance of section (KN) |
|------------------|------------------------|--------|-----------|-------|-----|-----|--------------------------|
| Combination of two | The arch foot          | 1088.7 | 2414.9    | 2.22  | 0.135 | 0.002 | 0.0                    |
|                  | A quarter              | 2848.1 | 1076.5    | 0.38  | 0.135 | 0.067 | 3.1                    |
|                  | vault                  | 2528.9 | 994.5     | 0.39  | 0.135 | 0.062 | 2.8                    |

Table 11. Calculation results of bearing capacity of 2# abdominal arch arch ring under working condition 2

| Load combination | Cross section position | N (KN) | M (KN. M) | E (m) | [e] | phi | Resistance of section (KN) |
|------------------|------------------------|--------|-----------|-------|-----|-----|--------------------------|
| Combination of two | The arch foot          | 2252.7 | 1777.9    | 0.79  | 0.135 | 0.016 | 0.3                    |
|                  | A quarter              | 2892.1 | 722.8     | 0.25  | 0.135 | 0.140 | 10.9                   |
|                  | vault                  | 2957.4 | 807.5     | 0.27  | 0.135 | 0.120 | 8.4                    |

2.3. Analysis results
Bearing capacity evaluation is checked, the first of all, according to the appearance quality inspection and material conditions to determine the structure bearing capacity coefficient is checked, cross section reduction factor coefficient is checked, when determining the coefficient of carrying capacity is checked according to " Inspection and assessment procedures for bearing capacity of highway Bridges " (JTG/T J21- 2011) to determine the coefficient Z1 is checked, and on this basis the check computation was carried out on carrying capacity of bridge structure. The following conclusions are obtained through checking calculation:

Under condition 1, condition 2 respectively according to the design load level highway - I loads, main arch ring of arch foot section, 3/8 section resistance does not meet the design requirements, and other interface resistance meet the design requirements; Because the bending moment of the arch section is too large, the section resistance does not meet the design requirements.

3. Conclusion
Taking a masonry arch bridge as an example, the finite element model of the bridge is established to analyze and calculate the structural bearing capacity on the basis of appearance inspection and technical status evaluation. In view of the bridge structure, the following maintenance Suggestions are proposed:

1) Re-paving asphalt concrete bridge deck pavement according to the existing deformation, transverse crack, damage and other diseases;
2) Cement mortar or epoxy material shall be used to seal the vertical cracks in the guardrail;
3) Repair the waterproof layer of the bridge deck according to the water seepage crystallization diseases of the main arch ring, the belly arch and the abutment;
4) In view of the cracks in the main arch ring and the abdominal arch wall, high pressure grouting method is adopted to seal and reinforce the cracks;

5) Cement mortar can be sprayed on the side wall of the arch ring of the abdominal arch, and steel wire mesh can be added if necessary to increase the strength of the coating and prevent further damage and falling off of the masonry.

With the continuous development of science and technology, the emergence of new technology, new materials, new technology and new equipment will constantly promote the bridge maintenance management to a higher level, and gradually form a perfect bridge modern management system.

References
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