Evaluation and analysis of bearing capacity of bridges based on structure checking

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Abstract. To assess the bearing capacity of a bridge, this paper modified the structural resistance and load effect in the limit state equation by using the checking coefficient of bearing capacity, deterioration coefficient of bearing capacity and section reduction coefficient. Additionally, the paper compared the bearing capacity of the decision structure or the element and provided reference for evaluation and analysis of similar beam bridges.

1. Introduction
The health state of bridges is the key to guarantee the safety and smoothness of highway traffic. With the transformation from the developing period to curing period gradually, the first problem faced by maintenance management is how to evaluate the bearing capacity of existing bridges accurately and dig out the bearing potential of the structure of the existing bridges to the utmost extent, thus ensuring that it meets the growing demand of transportation and reducing the cost of reinforcement and maintenance of the bridges. To solve this problem, the first step is to assess the bearing capacity of the bridges correctly.

2. Checking analysis method
The permanent action of bridges was calculated based on the current situation of the bridges while the variable action of bridges was calculated according to the original design of bridge and the requirements after construction. On the basis of Specification for inspection and evaluation of load-bearing capacity of highway bridges (JTG/T J21-2011), the checking coefficient of bearing capacity, deterioration coefficient of bearing capacity, section reduction coefficient and correction factor of live load were used for the assessment of the ultimate state of bearing capacity of reinforced concrete, thus modifying the structural resistance and load effect in the limit state equation respectively and determining the decision structure or bearing capacity of element via comparisons.

2.1. Checking of ultimate state of bearing capacity
The ultimate state of bearing capacity of reinforced concrete was calculated and evaluated by the checking results as

\[ \gamma_0 S \leq R(f_d, \xi, a_{de}, \xi, a_{de})Z_t(1-\xi) \]

where \(\gamma_0\) represents structure importance coefficient; 
\(S\) represents function of load effect;
$R(\cdot)$ represents function of resistance effect;

$f_d$ represents design value of material strength;

$a_{dc}$ represents geometric parameter values of concrete;

$a_{ds}$ represents geometric parameter values of steel;

$Z_1$ represents checking coefficient of bearing capacity;

$\xi_r$ represents deterioration coefficient of bearing capacity;

$\xi_c$ represents reduction coefficient of concrete section;

$\xi_s$ represents reduction coefficient of steel section.

The value of resistance effect was calculated by the current design standard, and $Z_1$, $\xi_r$, $\xi_c$, and $\xi_s$ were determined by relevant stipulations of Specification for inspection and evaluation of load-bearing capacity of highway bridges.

Masonry and concrete bridge should make an overall consideration of the structure of bridges or the test and evaluation results of apparent deficit condition of components, strength of materials and structural frequency of bridges, thereby comprehensively adjusting the theoretical calculation of resistance effect of components.

2.2. Determining checking coefficient of bearing capacity $Z_1$

Based on the standards, the checking coefficient of bearing capacity $Z_1$ of concrete bridges based on the following stipulations:

1) The evaluation scale of checking coefficient of bearing capacity of structure or component $D$ was determined by

$$D = \sum \alpha_j D_j$$

where $\alpha_j$ is the weighted value of detection index of one item, whose values are determined by the Table 1; $D_j$ is the rating scale of detection index of one item in structure or component, whose values are determined by relative criteria.

Table 1. The weighted value of detection index of checking coefficient of bearing capacity

| Items | Deficit condition | Strength of materials | Structural frequency |
|-------|-------------------|-----------------------|---------------------|
| $\alpha_j$ | 0.4 | 0.3 | 0.3 |

2) Based on the evaluation scale of checking coefficient of bearing capacity of structure or component $D$, the value of checking coefficient of bearing capacity of bridges $Z_1$ could be determined according to the following table.
Table 2. The value of checking coefficient of bearing capacity

| D | Bent | Axial compression | Axis tension | Eccentric compression | Eccentric tension | Torsion | Partial pressure |
|---|------|-------------------|--------------|-----------------------|-------------------|---------|-----------------|
| 1 | 1.15 | 1.20              | 1.05         | 1.15                  | 1.15              | 1.10    | 1.15            |
| 2 | 1.10 | 1.15              | 1.00         | 1.10                  | 1.10              | 1.05    | 1.10            |
| 3 | 1.00 | 1.05              | 0.95         | 1.00                  | 1.00              | 0.95    | 1.00            |
| 4 | 0.90 | 0.95              | 0.85         | 0.90                  | 0.90              | 0.85    | 0.90            |
| 5 | 0.80 | 0.85              | 0.75         | 0.80                  | 0.80              | 0.75    | 0.80            |

2.3. Determining deterioration coefficient of bearing capacity $\xi_e$

The deterioration coefficient of bearing capacity is used to consider the adverse effect of the deterioration of the quality of the bridge structure on the resistance effect of the bridges during the evaluation period.

According to the standards, the deterioration coefficient of bearing capacity $\xi_e$ could be determined via following methods:

1) Based on the detection results, the evaluation scale of the deterioration state E was determined by the standards as shown in the following table.

Table 3. The evaluation scale of the deterioration state

| Serial number | Detection index           | $\alpha_j$ | Evaluation method                                                                 |
|---------------|---------------------------|------------|-----------------------------------------------------------------------------------|
| 1             | Deficit condition         | 0.32       | The evaluation scale of the deterioration state E was calculated by $E = \sum_{j=1}^{7} E_j \alpha_j$ where $E_j$ is the rating scale of detection index of one item in structure or component; $\alpha_j$ is the weighted value of detection index of one item $\sum_{j=1}^{7} \alpha_j = 1$. |
| 2             | Steel corrosion potential | 0.11       |                                                                                   |
| 3             | Concrete resistivity      | 0.05       |                                                                                   |
| 4             | Concrete carbonation      | 0.20       |                                                                                   |
| 5             | Reinforced protective layer thickness | 0.12 |                                                                                   |
| 6             | Chloride ion content      | 0.15       |                                                                                   |
| 7             | Concrete strength         | 0.05       |                                                                                   |

2) Based on the evaluation scale of the deterioration state E and the environmental conditions, the deterioration coefficient of bearing capacity $\xi_e$ could be determined according to the following table.
Table 4. The deterioration coefficient of bearing capacity

| E | Environmental conditions          | 1 | 2 | 3 | 4 | 5 |
|---|----------------------------------|---|---|---|---|---|
|   | Dry Not frozen Non-aggressive medium | 0.00 | 0.02 | 0.05 | 0.06 |
| 1 | Dry and wet alternate Not frozen Non-aggressive medium | 0.04 | 0.07 | 0.10 | 0.12 |
| 2 | Dry and wet alternate Frozen Non-aggressive medium | 0.12 | 0.14 | 0.20 | 0.25 |
| 3 | Dry and wet alternate Frozen Aggressive medium | | | | |

2.4. Determining reduction coefficient of concrete section $\xi_c$

Based on the standards, section reduction coefficient of the masonry and reinforced concrete bridge structures or components was determined via following stipulations:

According to evaluation scale of three testing indexes including material weathering, carbonation as well as physical and chemical damage, synthesized assess of the deterioration of structure or component sections $R$ was determined by

$$R = \sum_{j=1}^{N} R_j \alpha_j$$

where $R_j$ represents evaluation scale of one detection index;

$\alpha_j$ represents weight value of a certain detection index, whose values were determined by the specification as shown in following table.

When $N$ represents the structure of brick and stone, $N=2$; when $N$ represents concrete and reinforced concrete structure, $N=3$.

Table 5. The weight value of material of weathering, carbonation as well as physical and chemical damage

| Structure type                              | Detection index          | $\alpha_j$ |
|--------------------------------------------|--------------------------|------------|
| Structure of brick and stone               | Material of weathering    | 0.20       |
|                                            | Physical and chemical damage | 0.80      |
| Concrete and reinforced concrete structure | Material of weathering    | 0.10       |
|                                            | Concrete carbonation      | 0.35       |
|                                            | Physical and chemical damage | 0.55      |

Section reduction coefficient of masonry arch bridge or component $\xi_c$ was determined by following table based on comprehensive evaluation scale of section damage.

Table 6. The value of section reduction coefficient

| $R$         | Section reduction coefficient |
|-------------|------------------------------|
| 1≤$R$<2     | (0.98,1.00)                  |
| 2≤$R$<3     | (0.93,0.98)                  |
| 3≤$R$<4     | (0.85,0.93)                  |
| 4≤$R$<5     | ≤0.85                        |
2.5. Determining reduction coefficient of steel section \( \xi_s \)

In reinforced concrete structures, the reduction coefficient of steel section \( \xi_s \) with corrosion, was determined according to the following table.

| Evaluation scale | Description                                                                                     | \( \xi_s \)     |
|------------------|-------------------------------------------------------------------------------------------------|-----------------|
| 1                | Cracks appear along the steel bars and the width is less than the limit                         | \( (0.98,1.00) \) |
| 2                | Cracks appear along the steel bars and the width is greater than the limit, or the rust of the steel causes delamination of the concrete | \( (0.95,0.98) \) |
| 3                | Corrosion of steel bars causes concrete to peel off, steel bars are exposed, and there is an expanded thin rust layer or corrosion on the surface. | \( (0.90,0.95) \) |
| 4                | The steel corrosion causes the concrete to peel off, the steel bars are exposed, the surface has a swelling rust layer, and the steel section loss is less than 10%. | \( (0.80,0.90) \) |
| 5                | Corrosion of steel bars causes concrete to peel off, steel bars are exposed, rust and peeling occur, and the section loss of steel bars is more than 10%. | \( \leq 0.80 \)  |

3. Case analysis

The main highway bridges in China are the beam bridges. Taking concrete beam bridge as an example, this paper introduced the bridge bearing capacity check coefficient, section reduction coefficient and other coefficients, analyzed the structure of bridges and calculated its bearing capacity based on the checking methods in Section 2, which provides scientific basis for the maintenance and reinforcement of similar bridges.

3.1. Engineering background

The span of the bridge studied in this paper is 3-13m, whose superstructure is ordinary concrete precast hollow slab. Every span has 12 beams, the substructure is double-column bridge pier, bridge platform is a double-ribbed bridge platform and the foundation is enlargement base. The support form is ordinary plate rubber bearing. The bridge deck has a anti-collision wall whose net width is 11.0m+2×0.50m and two MZL-80 expansion joints. The design load of the bridge is automobile -20 and trailer -100. The earthquake intensity is 8 degrees.

3.2. Checking and calculation of superstructure

On the basis of stress condition of the bridge, min-span was selected as the control section to make the calculation of the limit state of bearing capacity of structure.

3.2.1. Determining relative parameters for load capacity checking and calculation. According to Specification for Inspection and Evaluation of Load-bearing Capacity of Highway Bridges (JTG/T J21-2011) and the testing results of the bridge, the related parameters for load capacity checking and calculation were determined as follows:
Table 8. The related parameters for load capacity checking

| Parameters                        | Value          | Description                                      |
|-----------------------------------|----------------|--------------------------------------------------|
| Structure type                    | /              | Ordinary reinforced concrete hollow slab bridge  |
| Span combination                  | /              | 3x13m                                            |
| Main beam structure parameters    | /              | 12 hollow slab beams with a beam height of 65cm and a beam width of 1.0m. |
| Original bridge design load level | /              | car-20,trailer -100                              |
| Load level after reconstruction   | /              | highway- I                                       |
| Concrete axial compressive strength design value $f_{cd}$(MPa) | 23.0 | /                                                 |
| Ordinary steel tensile (pressure) strength design value $f_{sd}$(MPa) | 340 | /                                                 |
| Evaluation scale of bearing capacity of structure D | 3 | Poor state                                       |
| Checking coefficient of bearing capacity $Z_1$ | 0.95 | For bent component, when D=3                     |
| Deterioration coefficient of bearing capacity $\xi_e$ | 0.08 | Mainly based on the deficit condition of the component, the carbonization condition of the concrete, the corrosion potential of the steel, and the carbonization condition of the concrete, taking $E=1.32$, in the dry and wet alternate, frozen environment, and aggressive medium, determine |
| Reduction coefficient of concrete section $\xi_c$ | 0.95 | Based on material of weathering, concrete carbonation, and physical and chemical damage, taking $2\leq R <3$ |
| Reduction coefficient of steel section $\xi_s$ | 0.98 | When cracks appear along the steel bars and the width is less than the limit |

3.2.2. Calculating limit state of bearing capacity. 1) Calculating load transverse distribution coefficient of main beam

Table 9. The load transverse distribution coefficient of main beam

| Beam number | 1   | 2   | 3   | 4   | 5   | 6   |
|-------------|-----|-----|-----|-----|-----|-----|
| Car         | 0.253 | 0.237 | 0.234 | 0.229 | 0.211 | 0.196 |
| Trailer     | 0.138 | 0.134 | 0.135 | 0.126 | 0.118 | 0.115 |

2) Calculating ultimate state of bearing capacity of bridge superstructure

Based on the calculation results, with the conditions that car was -20, trailer was -100 and highway was - I load, the effect combination value of the basic combination is higher than 11% and 17% of the design value of structural resistance respectively under the limit state of bearing capacity. The ultimate state of bearing capacity of bridges could not meet the requirements of the original designed load of bridges and the Specification for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG D62-2004) (Highway -I degree). The calculation results could be seen in Table 10.
Table 10. The results of ultimate state of bearing capacity of bridge (kN·m)

| Serial number                  | Type load                  | Positive bending moment |
|--------------------------------|----------------------------|-------------------------|
| 89 specification (car-20,trailer-100) | Combination I             | 866                     |
| 04 specification (highway-Ⅰ)   | Combination I             | 911                     |
| Original design bearing capacity ultimate state |  | 958                     |
| Adjusted load capacity ultimate state |  | 780                     |

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|--------------------------------|----------------------------|-------------------------|
| 89 specification (car-20,trailer-100) | Combination I             | 866                     |
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| Original design bearing capacity ultimate state |  | 958                     |
| Adjusted load capacity ultimate state |  | 780                     |

Whether to meet the ultimate state requirements of the original bridge bearing capacity: No

Whether to meet the Highway-Ⅰ load capacity ultimate state requirements: No

Conclusion: The combined value of the car-20 and the trailer-100 is greater than the adjusted ultimate state of bearing capacity of 11.2%, and the combined value of the highway-Ⅰ is greater than the adjusted ultimate state of bearing capacity of 17.3%.

3.3. Check and calculation of the stability of abutment

The stability calculation of bridge arch and abutment wall includes the calculation of the stability against overturning and sliding, both of which could be calculated by formula 4.4.1-1, 4.4.1-2, 4.4.2-3 in Code for Design of Ground Base and Foundation of Highway Bridges and Culverts (JTG D63-2007). The detailed calculation could be seen in Table 11.

Table 11. The calculation of the stability of abutment

| Content                      | Dead load+lane load | Dead load+lane load+Temperature load+Braking force | Dead load+lane load+Temperature load+Bearing friction |
|------------------------------|---------------------|---------------------------------------------------|------------------------------------------------------|
| anti-dip coefficient         | 12.85               | 13.34                                             | 12.84                                                |
| anti-sliding coefficient     | 3.29                | 3.39                                              | 3.38                                                 |
| Minimum anti-dip coefficient | 1.5                 | 1.3                                               | 1.3                                                  |
| Minimum anti-sliding coefficient | 1.3               | 1.2                                               | 1.2                                                  |
| Anti-tip safety requirements | Yes                 | Yes                                               | Yes                                                 |
| Anti-sliding safety requirements | Yes             | Yes                                               | Yes                                                 |

3.4. Calculation results

Based on the calculation results, with the conditions that car was -20, trailer was -100 and highway was -Ⅰ load, the effect combination value of the basic combination is higher than 11% and 17% of the design value of structural resistance respectively under the limit state of bearing capacity. The ultimate state of bearing capacity of bridges could not meet the requirements of the original designed load of bridges and the Specification for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTG D62-2004) (Highway -Ⅰ degree). The calculated resistive sliding factor and coefficient of sliding resistance of this bridge is larger than those of standard regulation. In addition, the stability against overturning and sliding of abutment meets the requirements of standard regulations.
4. Conclusion

The assessing technology of the bearing capacity of bridges plays a significant role in the usage of bridges and the scientific assessing method could guarantee the safety and service life of bridges. Despite the certain differences among the commonly used assessing methods, those methods could assess the bearing capacity of the current bridges relatively accurately. Based on the existing design standard of bridges, the structure checking method adopted in the paper determines the bearing capacity of the existing bridges by calculation and analysis on the basis of the investigation on the defects of the bridges. In the real practice, this method could select its appropriate evaluation ways in accordance with the specific demands.

References

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