Analysis of Ultimate Bearing Capacity of Large Span Continuous Rigid Frame Curved Bridge

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Abstract. In order to study the ultimate bearing capacity of the large span continuous rigid frame curved bridge, a three-dimensional solid finite element model of a curved bridge was established based on ANSYS software. Different load cases were considered in analysing the ultimate bearing capacity. The results show that the loading process of the selected background curved bridge can be divided into elastic, elastoplastic and failure stages. Besides, under the most unfavourable load case, the living load coefficient and the safety factor is are 20.40 and 2.94, respectively. This indicates that the calculation formula of ultimate bearing capacity provided by the current standard has enough safety degree. In addition, because of the coupling effect of bending and torsion, the tensile stress and compressive stress on the outside of girder are larger than those on the inner part. Moreover, the ultimate bearing capacity of vehicle eccentric loading is lower than that of medium load, which should be considered in the design.

1. Introduction
Influenced by factors such as topography and road selection, there will be large span continuous rigid frame curved bridge when the bridge structure is selected. Compared with the straight bridge, when the radius of curvature of the large span curved bridge is small, bending-torsion coupling effect is more obvious[1], and its ultimate carrying capacity calculation is more complex. Therefore, it is important to define the ultimate carrying capacity of the large span continuous rigid frame curved bridge.

Today, ultimate bearing capacity of the curved bridge is numerically calculated and analysed by beam element and plate shell element, most of which do not consider the impact of the specific arrangement of steel bars and prestressed steel bars in the curved bridge box beam on its ultimate bearing capacity, so it is not possible to accurately assess the ultimate bearing capacity of the large span curved bridge. The numerical calculation and analysis of ultimate bearing capacity by using 3D solid finite elements are concentrated in small span bridges and local structural analysis, which are rarely applied to large span curved bridges. In this paper, an entity finite element model of the background curved bridge is established by ANSYS software, and the whole process of destruction of the curved bridge structure under different load conditions is analysed in order to obtain the ultimate bearing capacity of the large span continuous rigid curved bridge.

2. Engineering background
A curved bridge is a multi-span rigid-continuous beam combination system bridge with 1 unit of 9 spans, and the span is arranged as (64m+6×119m+75m). The main beam is a single box of double chamber cross-section, the beam width is 20.88m. Influenced by the surrounding environment and terrain, the 8th to 10th bridge span structure is a continuous rigid curved bridge part, with a flat linear curvature...
radius of 350m. The 9th to 11th pies are double thin-walled piers, with heights of 28.88m, 34.48m and 39.33m, respectively. The layout diagram is shown in Figure 1.

Because the background curved bridge is more complex, the eighth to tenth span is selected as the object of study, as shown in Figure 2. According to the principle of Saint-Venant[2], three more construction sections are intercepted from the right side of the 11th pier, and the force boundary can better simulate the actual condition of the continuous rigid curved bridge part of the background curved bridge.

3. Finite element model

3.1. Basic assumption
In order to study the extreme carrying capacity of the background curved bridge, the calculation and analysis in this paper follow the following assumptions[3]:

(1) It is assumed that the support, pre-stressed anchoring area, slug, etc. will not be partially damaged before the main beam.

(2) Regardless of temperature, concrete shrinkage and change, only consider the following loads: self-weight, secondary dead load, pre-stress and vehicle load.

3.2. Model introduction

3.2.1. Finite element model of bar system.
Using MIDAS software to establish the finite element model of bar system of the background curved bridge, through its internal force envelope diagram and resistance attempt to select the middle section A of ninth span and section B near tenth pier as the design control section, as shown in Figure 2. The force inside the right-hand section of the study object calculated under the most adverse load condition is used as the force boundary of the solid finite element model, as shown in Figure 3.

3.2.2. Solid finite element model.
In order to reduce the computational difficulty and speed up convergence, the entity finite element model of the research object is established by ANSYS universal finite element software, as shown in Figure 4. Among them, the main beam and bridge pier choose SOLID65 element, steel strands choose LINK8 element. The constraint equation is used to establish a constraint between the concrete element and the prestressed rib element, which assumes that the concrete and the steel bar are bonded well, regardless of the slip effect between the two[4]. Using the initial strain simulation prestress, pre-stress loss is
considered by the folding coefficient, and the ordinary rebar is simulated by the SOLID65 element input reinforcement ratio.

\[
\begin{align*}
\text{Axis Force:} & \quad -1.476 \times 10^5 \text{kN} \\
\text{Shear Force:} & \quad 3.064 \times 10^4 \text{kN} \\
\text{Torsion:} & \quad 1.047 \times 10^5 \text{kN} \cdot \text{m} \\
\text{Bending Moment:} & \quad 3.962 \times 10^5 \text{kN} \cdot \text{m}
\end{align*}
\]

Figure 3. A finite element model of bar system

The bottom of pier 9 to 11 is consolidation restraint, and the end of side span beam releases rotation restraint around the transverse direction and horizontal restraint along the longitudinal direction. The force boundary on the right section of pier 11 is shown in Figure 3. The corresponding axial force, bending moment, shear force and torsion are added to the right section of pier 11 of solid finite element model through a mass element MASS21.

Figure 4. Solid finite element model of the object of study

The main beam and bridge is made of C50 concrete, using the Willam-Warnke destruction guidelines[5] and the constitutive mode of French Rüsch[6]. Steel bars label HRB400, the structure relationship chooses the ideal bullet-plastic model, the pre-stressed ribs use the standard steel strand, the structure relationship adopts the three-fold line model[7]. The parameters of the specific material are shown in Table 1.

|             | elastic modulus /GPa | compressive strength /MPa | tensile strength /MPa | yield strength /MPa |
|-------------|----------------------|---------------------------|-----------------------|---------------------|
| C50         | 34.5                 | 32.4                      | 2.65                  | —                   |
| steel strand| 195                  | —                         | —                     | 1860                |
| steel bars  | 200                  | —                         | —                     | 400                 |

3.3. load cases

The initial constant load is kept unchanged during loading, the lane load is increased until the structural damage is destroyed, and the ratio of the applied lane load and the design lane load is defined as the live load coefficient $\lambda$[8]. Lane load level for highway I, two-way 4 lanes, wherein the cloth load using face force loading, concentrated force $(360 \times 4 \times 1.05 \times 0.67 = 1013.04 \text{kN})$ equivalent to the vertical 2m range of the average cloth load. According to the bending moment impact line of each design control cross-
section, the corresponding most adverse lane load loading condition is determined, the specific condition can be seen in Table 2.

| load case | failure Section | vehicle loading                      | lane load | force characteristics |
|-----------|-----------------|--------------------------------------|-----------|-----------------------|
| 1         | section A       | vehicle medium load                  | λ times   | sagging moment         |
| 2         | section A       | vehicle outward eccentric loading     | λ times   | sagging moment         |
| 3         | section A       | vehicle inward eccentric loading      | λ times   | sagging moment         |
| 4         | section B       | vehicle inward eccentric loading      | λ times   | hogging moment         |

4. Analysis and discussion of results
Under the load case 1~4, the background curved bridge is loaded step by step, and the ultimate bearing capacity calculation and analysis are carried out.

4.1. Analysis of the whole loading process
Live load coefficient-displacement (\(\lambda-\Delta\)) curve of the design control section A under condition load case 1~3 is shown in Figure 5. The design control sections A and B are shown in Figure 5 of the steel strand stress-live load coefficient (\(\sigma-\lambda\)) curve of the concrete pulled area under load case 1~4. As you can see, \(\lambda-\Delta\) and \(\sigma-\lambda\) curves of the four load cases have the same trend of change:

Stage 1: When the live load coefficient is less than 7, the background curve bridge is basically in the elastic state, the vertical displacement of cross-section A with the live load coefficient, the load coefficient of section A and the section B concrete pulled area steel strand stress with the live load coefficient also grows in a linear way;

Stage 2: With the increase of lane load, cracks appear in the pulled area of concrete, the stiffness of the bridge decreases, and the \(\lambda-\Delta\) curve gradually slows down. When the lane load is increased to about \(\lambda=14\) (section B is about \(\lambda=18\)) and the pulled-up concrete in the section A gradually exits the work, the stress of the steel strand increases suddenly, and the \(\sigma-\lambda\) curve gradually becomes steeper;

Stage 3: When the cross-section A reaches the limit load, with the weak growth of the live load coefficient, the vertical displacement of the base of the beam is growing rapidly, the slope of the crucible curve is almost zero, the steel strand has yielded, and the structure reaches the ultimate bearing capacity state.

As shown in Figure 6, when the background curve bridge reaches the limit state, the position of the neutral axis moves significantly upward, the pulled area concrete has been cracked, and the pressured area concrete is close to crushing, which is very typical plastic damage. And the pull stress and pressure stress on the outside of the beam are greater than the inside of the beam, because there is a large rotational
torque in the curved beam bridge, resulting in overloading the outside of the beam and unloading the inside of the beam.

Figure 6. Longitudinal stress distribution map of concrete nearby section A failure (unit Pa)

4.2. Comparative analysis of different load cases
Vehicle eccentric loading of the curved beam bridge will produce a larger torque, because of the bending-torsion coupling effect, the corresponding coupling bending moment will inevitably occur, which leads to its ultimate bearing capacity is lower than the medium load cases. As can be seen from Figure 5 and Figure 6, compared with the medium-load conditions, the vehicle outward eccentric and vehicle inward eccentric load cases increases faster with the increase of load; The pulled area concrete is pulled earlier, and the steel strand is separated from the concrete alone force, and the yield strength is reached earlier.

The pre-eccentricity of bearing or pier of the curved bridge can adjust the distribution of the torque peak in the beam[9]. Therefore, the pre-eccentric setting of the bearing or pier can reduce the torque of the vehicle eccentric loading, and thus improve the ultimate bearing capacity of the curved bridge.

4.3. Structural safety assessment
Because of the relatively small proportion of the live load and the constant load, the live load coefficient cannot significantly reflect to the surplus degree of the bending carrying capacity of the structure. In order to better evaluate the safety of the structure, the safety factor of the structure anti-bending carrying capacity is used k:

\[
k = \frac{M_G + \lambda M_Q}{M_G + 1.4M_Q}
\]  

(1)

In the formula, \(M_G\) is the bending moment of the bridge completion stage calculated according to the current specification, and \(M_Q\) is the bending moment generated under the design lane load. The results of the calculation are shown in Table 3.

| failure Section | vehicle loading                           | \(\lambda\) | k   |
|----------------|------------------------------------------|-------------|-----|
| load case 1    | section A                                | vehicle medium load | 22.49 | 3.16 |
| load case 2    | section A                                | vehicle outward eccentric loading | 21.35 | 3.03 |
| load case 3    | section A                                | vehicle inward eccentric loading | 20.40 | 2.94 |
| load case 4    | section B                                | vehicle inward eccentric loading | 26.71 | 2.95 |

As can be seen from Table 3, under the 4 load cases in this paper, the ultimate bearing capacity of the background curved bridge higher than the safety factor (1.98) calculated by the calculation formula of the ultimate bearing capacity provided in the current highway bridge design specification. Thus, the background curved bridge has a sufficient safety factor.
5. Conclusion

In this paper, an 3D solid finite element model of a large span continuous rigid curved bridge is established by ANSYS, which calculates its ultimate bearing capacity under different load conditions, and analyses the whole process of structural destruction. The main conclusions are as follows:

(1) The ultimate bearing capacity of the background bend bridge can be obtained by numerical calculation, the live load coefficient can reach 20.40 and the safety coefficient can reach 2.94, so it can be considered that the ultimate bearing capacity calculation formula in the current highway bridge design specification has sufficient safety degree.

(2) The whole process of loading the background curve bridge is analysed, and the destruction process can be divided into three stages of elasticity, catapult and destruction, which is typical plastic destruction.

(3) Due to bending-torsional coupling, the pull stress and pressure stress on the outside of the main beam of the background curved bridge are greater than the inside of the main beam, and the ultimate bearing capacity under the vehicle eccentric loading cases is lower than the vehicle medium load, which can be improved by the pre-eccentricity of the support or pier.

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