Study on the Calculation Method of Bearing Capacity of Old Steel Arch Bridge

Yebin Xiang¹*, Yong Ding¹b, Xinlei Shi²c

¹Department of Civil Engineering, Ningbo University, Ningbo 315211, China
²Ningbo Traffic Planning and Design Institute Limited, Ningbo, Zhejiang 315000, China
*dingyong@nbu.edu.cn, bdingyong@nbu.edu.cn, c624102541@qq.com

Abstract—Due to the long-term action of load, the material properties and structural shape of bridge structure will gradually change during service, resulting in the change of bearing capacity. In this paper, a calculation method of maximum bearing capacity is proposed for old steel arch bridges. The calculation method considers the material nonlinearity and geometric nonlinearity, as well as the residual deformation of the structure of the old bridge caused by the overload vehicle, collision of the vehicle and ship, resulting in the difference between the actual structure and the design drawing. Taking an 85 year old steel arch bridge in Ningbo as an example, the current material properties and the current configuration of the structure are actually tested, and the bearing capacity is calculated. The results show that: (1) The steel used in the bridge is well protected, and the properties of steel still meet the requirements; (2) For steel arch bridges, the deformation of arch ribs, especially the deformation out of plane, may greatly weaken the bearing capacity of the bridge; (3) It is necessary to consider the material nonlinearity and geometric nonlinearity for the calculation of the maximum bearing capacity of the old bridge.

1. Introduction

The ultimate bearing capacity of arch bridges has always been one of the concerns in bridge engineering. The research on the ultimate bearing capacity of arch bridge has been developed from linear analysis to nonlinear analysis, from plane theory to space theory, from bare arch to full bridge. With the rapid development of calculation technology, it has become a trend to study the actual ultimate bearing capacity of full bridge with nonlinear finite element method (FEM) [1-2]. In recent years, with the increasing service life of arch bridges, the arch ribs and other structural components are deformed or even destroyed, and the nonlinear stability problem becomes particularly prominent, so it is of great significance to study the ultimate bearing capacity of old arch bridges [3].

In this paper, taking the Ling bridge in Ningbo, a steel arch bridge built in 1932, as an example, the calculation method of the ultimate bearing capacity of the old steel arch bridge is proposed. The finite element analysis is carried out according to the bridge ultimate bearing capacity theory [4-9], during which the material nonlinearity and geometric nonlinearity are considered. By calculating the whole process of load increasing from 0 to the maximum, the mechanical characteristics and instability modes of bridge failure are determined. In the above calculation process, the current material properties and the arch rib deformation caused by war, hull collision and traffic accident are considered, and the influence of this deformation on the ultimate bearing capacity is analyzed. The calculation results of ultimate bearing capacity provide a basis for the safety evaluation and
reinforcement of old steel arch bridges.

2. Ultimate bearing capacity analysis method

Considering geometric nonlinearity and material nonlinearity, the finite element equilibrium equation of arch bridge structure can be obtained as follows

\[ \left[ K \right]_e + \lambda \left[ K \right]_g d\delta = dF, \]

in which \([K]_e\) is the elastic-plastic stiffness matrix of structure, \([K]_g\) is the geometric stiffness matrix of structure at the time of \(t\), \(d\delta\) is the displacement increment, and \(dF\) is the load increment. In nonlinear analysis, the total load can be divided into multiple stages according to Eq. (1). The arc-length method was used to solve each load step iteratively, and the whole process of structural response from the beginning of loading to instability and after instability was obtained. The load-displacement relationship of the structure and the maximum load on the load-displacement curve were obtained. In order to ensure the accuracy of the calculation, two convergence criteria of force and displacement were adopted.

3. Finite element model of Ling bridge

Ling Bridge is a single-span, three-hinged steel arch bridge with a span of 97.536 m. The width of the bridge is 25.056 m, and the structure is shown in Fig.1 and Fig. 2. The main arch ring is a circular arc line with a radius of 88.201 m and a ratio of 1/6.5. There are 12 pairs of suspenders in the arch bridge, that are H-shaped in cross section. The center distance between two neighbour suspenders is 7.925 m. The bridge deck system is made of steel beam and plate.

![Fig. 1 Cross section of Ling bridge structure](image1)

![Fig. 2 plan and elevation views of Ling bridge](image2)

According to the structural characteristics of the bridge, the FEM software, ANSYS, is adopted. The specific modeling process is as follows.

(1) In order to obtain the permanent deformation of the arch rib of Ling bridge due to war, ship collision and other accidents accurately, the position of the arch rib of Ling bridge was measured, and the measuring points were evenly distributed along the bridge span. The lateral permanent deformation of the arch rib is shown in Fig.3.

(2) The arch rib of Ling bridge is a box-shaped thin-walled section. In order to analyze its bearing
capacity more accurately, the main arch rib is accurately simulated by SHELL181 element. Two finite element models are established according to the principle of permanent deformation and non-permanent deformation.

(3) The suspenders, wind braces, longitudinal beams of the bridge deck system, transverse beams of the bridge deck system and other transverse connection systems of the main bridge are still simulated by the spatial beam element BEAM188.

(4) The deck system is simplified to the grid system. The vehicle load is taken as the concentrated force and added to the bridge deck nodes according to the distribution.

The three-dimensional finite element model of Ling bridge based on the above modeling principles is shown in Fig. 4.

4. Ultimate bearing capacity analysis

4.1 Basic assumptions

(1) In order to get the current mechanical properties of structural steel of Ling bridge, some accessory components of the bridge are tested. The results are shown in Table 1 and Table 2.

| Sample No. | Yield strength /MPa | Ultimate strength /MPa | Elongation/% |
|------------|----------------------|------------------------|--------------|
| 1#         | 295                  | 395                    | 34.5         |
| 2#         | 285                  | 400                    | 37.0         |
| 3#         | 290                  | 405                    | 32.5         |

(2) Because the bearing capacity of the deformed arch rib is the focus of attention. According to the influence line of the stress at the corner of the arch rib section, the load of the vehicle is arranged, and the maximum stress is obtained.

4.2 Ultimate bearing capacity analysis

As the main bearing member, the deformed arch rib will greatly weaken the ultimate bearing capacity of the structure. Therefore, it is necessary to study the influence of the arch deformation on the bearing
capacity of the structure.

On the basis of permanent arch rib deformation model I and non permanent arch rib deformation model II, and considering the material and geometric nonlinearity, the ultimate bearing capacities of the structure are calculated. When calculating the ultimate bearing capacity of the structure, the dead loads are kept as constant values, and the live loads are increased continuously until the main arch rib yields.

The results indicate that both finite element models yield at the arch foot firstly. Then the arch crown and other parts of arch yield with the increase of load. Finally the whole structure fails. In model I, due to the consideration of the initial deformation of the arch rib, the arch foot yields when the structural displacement is very small. But in model II, the initial deformation of arch rib is not considered, and the arch foot does not yield until the structure has a large displacement.

The maximum lateral displacement curve of arch rib is shown in Fig.5, and the maximum vertical displacement of arch rib increases with the load is shown in Fig.6. The comparison of calculation results of the two models is shown in Table 3. Fig. 5 and Fig. 6 indicate that the lateral deformation of arch rib is much larger when the initial deformation is considered. Table 3 indicates that when the initial deformation of the arch rib is considered, the maximum lateral displacement of the arch rib is increased by 1.97 times and the vertical displacement is increased by 1.31 times. The above results indicates that when Ling bridge has initial deformation, its ultimate bearing capacity is reduced to about half of that without initial deformation. The initial deformation outside the arch rib plane greatly weakens the ultimate bearing capacity of Ling bridge.

| Model     | Stability coefficient | Maximum deformation under ultimate load /m | Lateral displacement /mm | Vertical displacement/mm |
|-----------|-----------------------|------------------------------------------|--------------------------|--------------------------|
| Model I   | 2.28                  | 0.175                                    | 6.5                      | 64                       |
| Model II  | 5.14                  | 0.543                                    | 3.3                      | 49                       |
5. Conclusion

(1) For evaluating the ultimate bearing capacity of old bridges, the permanent deformation of arch ribs and other important components must be considered, and a correct finite element model should be established;

(2) The stability coefficient of Ling bridge is 2.28 when the initial deformation of arch rib is considered, and 5.14 when the initial deformation is not considered. The out-of-plane initial deformation of the arch rib of Ling bridge plays important role in the ultimate bearing capacity of Ling bridge.

(3) Finite element analysis considering material nonlinearity and geometric nonlinearity is an effective method to calculate the ultimate bearing capacity of arch bridge.

Acknowledgement

This work has been supported by the Natural Science Foundation of Zhejiang Province (LY19E080009), the Comprehensive Insurance for Country Road in Haishu District of Ningbo City, and Ningbo Transportation Science and Technology Project (202104).

References:

[1] Cheng J, Jiang J.H, Xiao R. Research status and development of ultimate bearing capacity of arch bridge structure [J]. Highway Traffic Science and Technology, 2002(4):57-59.

[2] Brandon Lee. Stability and vibration of bridge structure [M]. Beijing: China Railway Press, 1992.

[3] Pan J, Zhang G, Cheng Q. Nonlinear coupling analysis of geometric and material for ultimate bearing capacity of long-span bridges [J]. Journal of Civil Engineering, 2000(1):5-8.

[4] Yan Q, Xu S. Stability analysis of long-span concrete-filled steel tubular arch bridge [J]. Bridges, 2003(7):16-18.

[5] Shen Y, Zhao Z.J, Hua Xugang. Stability analysis of long-span concrete-filled steel tubular arch bridge [J]. Journal of Southwest Jiaotong University, 2003(12):655-657.

[6] Cui J, Wang J, Sun B. Nonlinear stability analysis of long-span concrete-filled steel tubular arch bridge [J]. Journal of Harbin Institute of Technology, 2003(7):876-878.

[7] Wu G, Yang S, WANG Jinfeng, et al. Journal of Nanchang University: Science Edition, 2013, 037(002):198-204.

[8] XU Jia. Study on Force Analysis and Ultimate Bearing Capacity calculation of Steel truss Arch Bridge in service Stage [D]. Southwest Jiaotong University, 2016.

[9] WU F. Study on mechanical Properties and Optimal Design of new orthotropic steel Bridge Deck [D]. Changsha University of Science and Technology, 2018.

[10] Zienkiewicz O C, Taylor R L. The finite element method for solid and structural mechanics[M]. 6th ed. New York: Baker & Taylor Books, 2005.