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Research paper

Research on reinforcement technology of existing double-way curved arch bridge

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Abstract: Two-way curved arch bridges inherit the fine tradition of masonry structures, making full use of the advantages of prefabricated assembly, it adapts to the situation of no support construction and no large lifting machine and tools, and has the characteristics of convenient construction method and saving material consumption. In appearance, the two-way curved arch bridge has strong national cultural characteristics. The prefabricated components of the two-way curved arch bridge are fragmentary, complicated in bearing and poor in integrity. Most of the two-way curved arch bridges in service have been built for a long time and lack of maintenance and management. Increasing the cross-section reinforcement method is one of the two-way curved arch reinforcement methods. It has a significant effect, convenient construction, good rigidity and stability characteristics after the reinforcement. Through theoretical analysis, combined with a static load test results of the assessment of the bridge reinforcement effect. Through load test, it is found that the deflection of the arch rib after reinforcement is reduced by 9%~19% and the strain of the arch rib is reduced by 12%~22%. Through finite element calculation, the crack width of the reinforced arch rib decreases by 8.3%~14.2%. The results show that the stress and deflection are greatly improved by the method of increasing section.

Keywords: increasing the cross-section reinforcement method, two-way curved arch bridge, reinforcement effect

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1. Introduction

Two-way curved arch bridge is composed of arch rib, arch wave, arch plate, and transverse connection components. The shape of the bridge is an arc curve in both vertical and horizontal directions. Because the arch wave between the arch ribs is also curved and orthogonal to the curve of the main arch ring, it is called a double curved arch bridge. Two-way curved arch bridge inherit the fine tradition of masonry structures, making full use of the advantages of prefabricated assembly, it adapts to the situation of no support construction and no large lifting machine and tools, and has the characteristics of convenient construction method and saving material consumption. In appearance, the two-way curved arch bridge has strong national cultural characteristics. In the construction of the main arch ring of the two-way curved arch bridge, the construction method of “breaking up into parts and integrating into parts” is adopted, resulting in the lack of transverse stability of the arch ring in structure and the occurrence of crack [1]. Under the condition of increasing traffic volume and increasing load, most of the two-way curved arch bridges suffer from diseases of different degrees, and even have too many accidents of span collapse [2]. At present, the Ministry of Communications is in the peak period of dangerous bridge renovation. Governments at all levels attach great importance to the progress of dangerous bridge renovation project [3]. How to strengthen and transform the two-way curved arch bridge which has already appeared the disease is an important task that the highway department faces. This paper discusses the reinforcement design of the two-way curved arch bridge through an engineering example, which provides reference and reference for the reinforcement design of this type of bridge.

Fig. 1. Bridge elevation

2. Project profile

The two-way curved arch bridge is located in Foshan city. The central pile number is K3+691.000. The bridge is 121.5 meters long and 7.9 meters wide with a span of 37.5m +36m +37m. Each span is provided with 12 ventral arches, 5 arch ribs and 7 transverse girders. The bridge was completed and opened to traffic in November 1978. The horizontal arrangement of the bridge deck is 0.5m collision guardrail +6.9m driveway +0.5m collision guardrail. The bridge shall be equipped with a two-way transverse slope of 1.5% and be longitudinally connected with the approach road on both sides. The panoramic view of the bridge before reinforcement is shown in Fig. 1, and the superstructure drawing was shown in Fig.2.

Fig. 2. Elevated view of the superstructure

3. Disease status

(1) After field investigation and detection, the main diseases and causes of the two-way curved arch bridge are analyzed as follows:

Arch rib is an important part of arch ring of arch bridge. It bears all dead load and live load together with arch ring and is the main force member. Therefore, when its flexural strength and stiffness are insufficient, its bearing capacity is often reduced and other components are damaged. When the abutment has too large horizontal displacement, the positive bending moment at the arch top, the negative bending moment at the arch foot increases greatly, or the section of the member degenerates, resulting in the insufficient bearing capacity of the arch rib, the arch rib cracks will appear. The arch rib cracks are mainly manifested as the radial cracks at the arch bottom and the radial cracks at the arch back that are perpendicular to the arch axis.

The radial cracks of the arch bottom mainly occur at the lower margin of the arch rib in the section with large positive moment of the arch top, extending from the bottom to the top, and from the bottom to the top with wide width and narrow width. Extrados radial cracks near the arch foot arch back radial cracks in negative bending section, especially when larger displacement of the abutment, the cracks often appear back arch, arch back radial cracks will weaken the arch of the foot fixed function to make the main arch ring happen internal force redistribution and force the assumptions and design different arch rib, and at the same time, make arch section stress increases speed dome craze.

The transverse cracking of arch rib and the subsidence of arch roof generally occur at the same time. The main reasons are as follows: First, foundation subsidence or inclination. Secondly, the bearing capacity of arch rib itself is insufficient due to insufficient design and construction or concrete deterioration. Third, due to the lack of stiffness of the transverse connection, the arch rib stress is not uniform, leading to a single rib stress too large.

（2）Part of the arch wave is cracked longitually, the crack extends from L/4 span to 3L/4 span, and the crack width is between 0.3 and 0.7mm. Due to the serious longitudinal crack of the bridge arch wave, the transverse load distribution will be affected, the structural integrity will be reduced, the internal force of the main arch element will be increased, and the bearing capacity of the main arch ring will be reduced. In addition, the hyperbolic arch bridge has weak transverse connection stiffness, poor transverse distribution of live load, and uneven stress on arch ribs, which results in great difference in deformation of arch ribs and accelerates the generation of arch wave cracks. The damage of arch wave is caused by longitudinal crack of arch wave (longitudinal crack of main arch ring), crack of micro-bending plate and corrosion of reinforcement.

Arch wave longitudinal cracks (main arch ring longitudinal cracks) appear at the top of the arch wave along the direction of the arch axis, mostly near the arch, and sometimes near the arch foot. Due to the serious longitudinal cracks, the arch rib becomes several separate arch rings, which seriously weakens the transverse integrity of the arch ring, and the stress on the arch rib is not uniform.

Due to the weakness of the micro-bending plate, poor vertical and horizontal connectivity, and the use of more medium-weight vehicles, large traffic volume, micro-bending plate diseases are very common. Especially, the micro-bending plate near the arch foot, located in the transition area of the road and the bridge deck, bears a great impact force. In severe cases, the micro-bending plate can lead to the fracture of the bridge deck pavement layer, network crack, breakage and gradual expansion, as well as the serious diseases such as pits and grooves, steel reinforcement exposed to rust.

(3) Two-way curved arch bridge are set transverse link between arch rib beam, which not only make each piece of arch rib in the concentrated load under the action of vehicle load, share the load, and the establishment of horizontal linkages, the single arch rib in the transverse together as whole, forming an arch framework, thus greatly strengthened the lateral stiffness of the arch rib, to ensure the lateral stability of the arch rib. However, the cross beam (diaphragm) of the two-way curved arch bridge is generally small in cross section, and the number of sets is also small, and the shear strength of the joint with the cross rib is also small. When subjected to a large external load, a large internal force and deformation will occur, leading to cracking and falling off of the transverse beam, weakening stiffness, and unable to effectively transfer the transverse load, and causing uneven stress and deformation of the arch rib, which aggravates the disease of the transverse beam. Because the transverse connection cracking is serious, it will lead to arch wave cracking and arch plate cracking, which will reduce the overall stress performance and stability of arch ring.

(4) The main cracks of the arch are the belly arch and the column. The damage of the arch is mainly caused by the deformation of the main arch, which is equivalent to the displacement of the abutment of the abdominal arch.

The main cracking of the ventral arch is transverse and circumferential, among which the transverse cracking is the most serious. In terms of structure, the belly arch is mostly concrete slab arch. For the multi-arch constituted by multiple holes, there is no hinge according to the need of main arch deformation, or only a simple hinge is set, but it can't play the role of hinge. In the process of use, due to the action of load, temperature change, main arch deformation and concrete shrinkage, so that the abdominal arch produced a greater internal force and led to cracking. The cracking of flank arch without hinge is especially serious, some series of cracks appear dislocation, and has reached the degree of destruction. The annular cracking of the arch is generally caused by the shrinkage of concrete and temperature change, and it is mainly caused by the non-uniform transverse deformation of the main arch, which causes the non-uniform subsidence and displacement deformation of the abutment and the annular cracking of the arch.

(a) Arch rib damage and rib exposure (b) Arch rib damage and rib exposure

(c) Arch rib cracks (d) Arch wave cracks

Fig. 3. Disease diagram of two-way curved arch bridge

4. Reinforcement method and principle

4.1. Strengthening method

The following reinforcement methods are adopted for arch ribs and transverse girders of main bearing members.

（1） The concrete at the bottom and two sides of the arch rib was increased by 15cm, and the new concrete was connected with the original structure as a whole by planting bars on the arch rib and the original transverse beam, so as to improve the ability of the arch rib to resist axial force and positive moment at the top of the arch. C40 micro - expanded concrete was used to increase the section of arch rib.

（2） A layer of 15 cm thick reinforced concrete is poured on the back of the main arch ring close to each arch foot (2 belly arch areas) to increase the section of the main arch ring. The new concrete is poured with C40 micro-expansion concrete. By planting bars and the original structure to form an overall joint force, the ability of the arch rib to resist axial force and negative bending moment at the foot of the arch is improved.

(3) Increasing 15 cm thick concrete on both sides and underside. The enlarged section is poured with C40 micro-expanded concrete, and the new concrete is connected with the original structure as a whole by planting bars on the arch ribs and the original transverse beam, so as to enhance the transverse connection of the structure. The concrete with the section enlargement of main arch rib and the section enlargement of transverse beam should be poured simultaneously.

(a) superstructure (b) cross-section drawn

Fig. 4. Reinforced two-way curved arch bridge diagram

4.2. Reinforcing principle

The method of increasing section reinforcement is to increase the section area and reinforcement of the original arch rib by using the external reinforcement and concrete, so as to improve the section bearing capacity, stiffness, stability and crack resistance of the members. It can also be used to repair cracks [4]. Considering the stress characteristics of the reinforced members and the requirements of the reinforcement purpose, the parts and sizes of the members, the convenience of construction and other factors, the enlarged section can be designed as unilateral, bilateral or tripartite reinforcement, as well as the surrounding outsourcing reinforcement [5]. The advantages of increasing section reinforcement method are as follows. It can be constructed under the bridge without affecting traffic, and the reinforcement works are not large, and the reinforcement effect is relatively significant. Moreover, the stress mode of the two-way curved arch bridge is mainly to bear the bias pressure, which can make full use of the material strength of the main arch section and give full play to the compressive performance of concrete [6]. Construction technology can be used in situ concrete, shotcrete, mortar daub and other methods [7].

The arch ribs and transverse beam of this bridge are strengthened by increasing the section. Fig. 5 shows the cross-section diagram of reinforcement by increasing the section of arch rib.

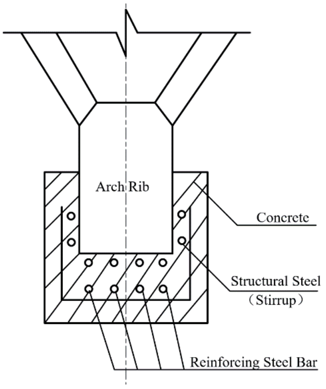

Fig. 5. Method cross-section diagram of arch rib enlargement

From the aspect of mechanics, under the vertical load, the stress calculation formula of the main arch ring is as follows [8]:

$$\sigma = \frac{N}{A} + \frac{M}{W} \tag{1.1}$$

Where:

σ – the tensile and compressive stress generated by the section under the action of load, N – the axial force on the section under load, M – the bending moment of the section under load, A – the sectional area of the main arch ring, W – the moment of section resistance of main arch ring.

Under the condition that the axial force N and bending moment M of the section do not change, increasing the height H and width B of the section can improve the resistance of the section area W and section A, thus effectively reducing the stress σ and further increasing the compressive, bending and cracking resistance of the section.

5. Reinforcement effect

5.1. Theoretical reinforcement effect

After the reinforcement of the old bridge by increasing section method, the finite element software Midas /Civil was used to establish the finite element model of the whole bridge, in which the reinforced concrete structure was modeled as a whole. Beam element is used to simulate the arch wave except the plate element. According to the evaluation results of the bridge disease, the bridge disease was simulated by element stiffness reduction. The unit weight of concrete is calculated at 25kN/m^3, and bridge deck paving and arch filling are calculated at 20kN/m^3. Due to the lack of original design data, the designed load grade was according to Truck-20, Trailer -100, the checked load grade was according to Truck -15 and Trailer -80, respectively. The finite element model of the bridge is established, as shown in Fig. 6

Fig. 6. Finite element model of bridge

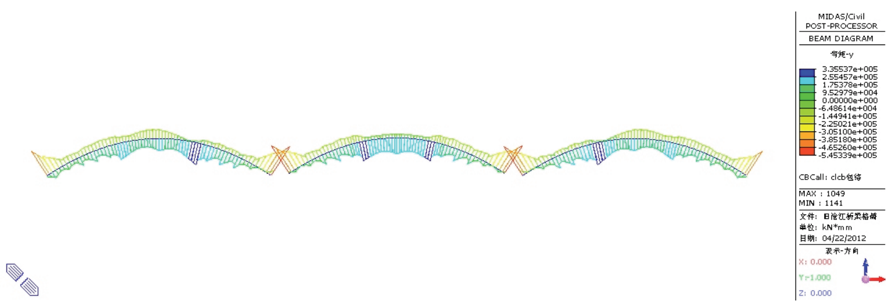

Fig. 7. Envelopment diagram of main arch bending moment in three combinations under normal use limit state - side rib

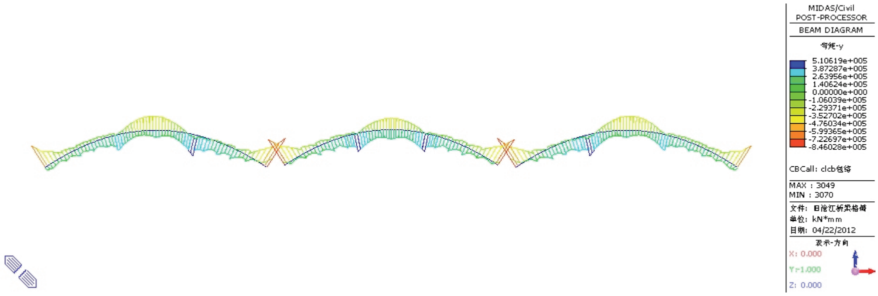

Fig. 8. Envelopment diagram of main arch bending moment in three combinations under normal use limit state - middle rib

（1）The vertical theoretical deformation before and after reinforcement is shown in Table 1.

Table 1. Vertical deformation before and after reinforcement（mm）

	Constant load -side span - side rib	Constant load -side span -middle rib	Constant load -middle span - side rib	Constant load -middle span -middle rib	Live load -middle span
Deformation before reinforcement	11.609	9.413	15.523	13.278	5.664
Deformation after reinforcement	11.184	8.822	14.869	12.634	5.130
Decrease percentage	3.8%	6.7%	4.4%	5.1%	10.4%

The theoretical deflection of live load decreases by 10.4% and is less than 1/800 of the calculated span of arch rib. By increasing the section, the overall stiffness of the bridge is improved, and the deflection under live load and constant load is reduced to some extent, but the percentage reduction of the deflection under live load is greater than that under constant load, and the theoretical effect is obvious after reinforcement.

（2）The vertical cracks before and after reinforcement are shown in Table 2.

Table 2. Maximum crack width before and after reinforcement (arch foot) (mm)

	Constant load -side span -side rib	Constant load -side span -middle rib	Constant load -middle span - side rib	Constant load -middle span -middle rib
Crack before reinforcement	0.07	0.12	0.09	0.10
Crack after reinforcement	0.06	0.11	0.08	0.09
Decrease percentage	14.2%	8.3%	11.1%	10.0%

Under the combination of short term effects of live load, the theoretical values of fractures under the reinforcement method of increasing section are all smaller and no more than 0.2mm. By increasing the section, the overall stiffness of the bridge is improved, and the theoretical crack resistance is obviously improved.

5.2. Static load test effect

After the reinforcement, the bridge was loaded according to the influence line of the control section. In the test, 2 triaxial loading vehicles with a load of 35 kN were used. In order to make the internal force of the control section meet the requirement of load efficiency, the main displacement control section are the 1/4L section, mid-span section and the 3/4L section of the test span. The stress test section is the section at the arch foot. The test section is shown in Fig. 9, and the layout of the measuring points in the cross section is shown in Fig. 10.

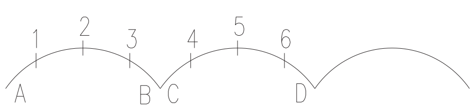

Fig. 9. Test section of arch bridge

In the loading process, the whole bridge is divided into four working conditions, which are respectively.

Working condition 1: Symmetrically loading of the bending moment influence line for the first span arch roof section.

Working condition 2: Eccentric loading of the bending moment influence line for the first span arch roof section.

Working condition 3: Symmetrically loading of the bending moment influence line for the second span arch roof section.

Working condition 4: Eccentric loading of the bending moment influence line for the second span arch roof section.

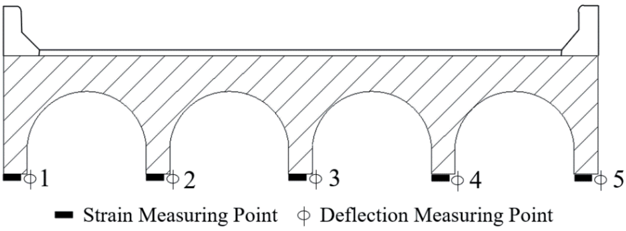

Fig. 10. The arrangement of arch rib deflection and strain measurement points

（1）Analysis of deflection measurement results

The deflection test results for the first and second spans are shown in Fig.11 and Fig.12.

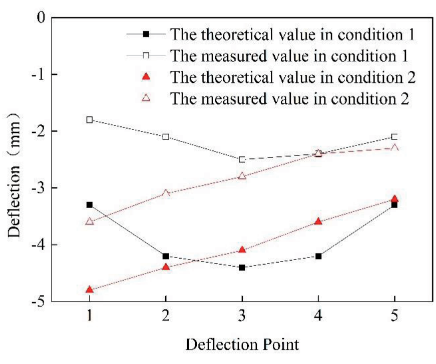

Fig. 11. Test results of deflection under working conditions 1 and 2

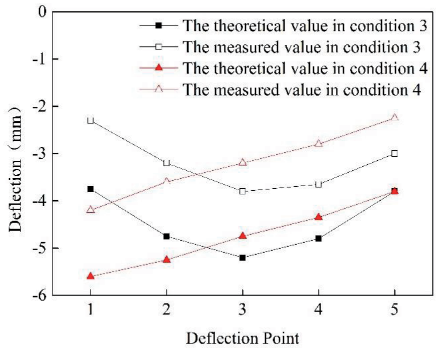

Fig. 12. Test results of deflection under working conditions 3 and 4

According to the static load data of the first span and the second span, it can be seen that the measured deflection under the action of vehicle load is less than the theoretical deflection, indicating that the stiffness of the reinforced structure meets the requirements, and the stiffness after the reinforcement is better.

(2) Analysis of strain measured results

The strain test results for the first and second spans are shown in Table 3.

Table 3. Strain test results (MPa)

	1	2	3	4	5
Measured value under condition 1	-0.8	-1.2	-1.8	-1.6	-1.0
Theoretical value under condition 1	-2.0	-3.2	-4.0	-3.2	-2.0
Measured value under condition 2	-0.7	-1.3	-1.9	-2.2	-2.5
Theoretical value under condition 2	-1.8	-3.0	-4.2	-4.6	-5.4
Measured value under condition 3	-1.1	-1.6	-2.1	-1.4	-1.0
Theoretical value under condition 3	-2.2	-3.4	-4.5	-3.4	-2.2
Measured value under condition 4	-0.9	-1.6	-2.2	-2.1	-2.3
Theoretical value under condition 5	-2.0	-3.3	-4.5	-4.8	-5.9

According to the static load data of the first span and the second span, it can be seen that the measured strain under the action of vehicle load is smaller than the theoretical strain, indicating that the strength of the reinforced structure meets the requirements and the strength is better after the reinforcement.

(3) Effect analysis before and after reinforcement

The test results of girder rib deflection before and after reinforcement are shown in Tab. 4.

Table 4. Results of deflection before and after reinforcement

	Middle load of edge span	Eccentric load of side span	Middle load of middle span	Eccentric load of middle span
Before strengthening	-3.1	-4.2	-4.2	-4.6
After strengthening	-2.5	-3.6	-3.8	-4.1
Percentage change	19%	14%	9%	11%

The rib strain test results of the main beam before and after reinforcement are shown in Table 5.

Table 5. Results of strain before and after reinforcement

	Middle load of side span	Eccentric load of side span	Middle load of middle span	Eccentric load of middle span
Before strengthening	-2.1	-2.8	-2.4	-2.8
After strengthening	-1.8	-2.5	-2.1	-2.3
Percentage change	17%	12%	14%	22%

6. Conclusion

According to the application and evaluation of reinforcement effect of increasing arch rib and cross beam section method in the old Cangjiang bridge, the deflection and stress of the two-way curved arch bridge are greatly improved and the bearing capacity is greatly increased after the reinforcement method of increasing cross section. After the reinforcement, the bridge can meet the requirements of the current load standard and achieve the expected reinforcement effect. The deflection and strain under the symmetric load of the side span are reduced by 19% and 17% compared with those before reinforcement. The deflection and strain of the middle span under symmetric load are reduced by 9% and 14% compared with those before reinforcement. Through finite element calculation, the crack width of the reinforced arch rib decreases by 8.3%~14.2%. It shows that the method of increasing section has obvious advantages in the reinforcement of two-way curved arch bridges

References

[1] Huo B R , Yang G N , Zhang X D . Internal Force Calculation of Two-Way Curved Arch Bridge[J]. Advanced Materials Research, 2012, 594-597:1561-1564. https://doi.org/10.4028/www.scientific.net/AMR.594-597.1561

[2] Yu, Tong-Hua. Structural Design of Two-Way Curved Arch Bridges[J]. Structural Engineering International, 1992, 2(1).

[3] Yang, Jun. Disease analysis and reninforcement methods discussion of several sorts of arch bridges[J]. 2010:1321-1324.

[4] Naser A F , Zonglin W . Damage Investigation, Strengthening, and Repair of Jilin Highway Double-Curved Arch Concrete Bridge in China[J]. Procedia Engineering, 2011, 14(none): 2294-2300.

[5] Huo B R,Zhang X D.Research of Two-Way Curved Arch Bridge Reinforced by BFRP[J].Applied Mechanics&Materials,2012,166-169:873-876. https://doi.org/10.4028/www.scientific.net/AMM.166-169.873

[6] Chen X Y , Liao B , Li J . Research on Optimization Design for Reinforcing Method of Irregular Cross-Section Arch[J].Applied Mechanics&Materials,2012,166-169:1684-1688.https://doi.org/10.4028/www.scientific.net

[7] /AMM.166-169.1684

[8] Du S W , Li S S . The Effect of Different Warm Additives on Performance Properties of HMA[J]. Applied Mechanics and Materials, 2012, 178-181:1369-1372. https://doi.org/10.4028/www.scientific.net/AMM.178-181.1369

[9] Chiou W J , Slaw R A . Somerset County Bridge: A Precast Replacement Solution[J]. Pci Journal, 1998, 43(2):22-30.

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