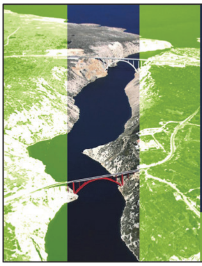

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RETROFIT OF A DOUBLE-CURVED ARCH BRIDGE IN CHINA

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Abstract: *The double-curved arch bridge was invented by Chinese bridge engineers in 1960's, and then spread all over the country because it features simple structure, easy construction, and low cost. Most of the existing double-curved arch bridges were built in 1960's and 1970's. Quite a few of them are damaged to some level and retrofit is needed to meet the increasing traffic demand. Damages of a sample double-curved arch bridge are presented, and the causes are analyzed. Due to the lack of transverse stiffness and load bearing capacity of the arch main ring, two strengthening methods named "enlarge section" and "double-curved arch convert to plate arch" are proposed, the feasibility, advantages and disadvantages of which are studied by using the internal force superposition method and stress superposition method, respectively. The paper can help bridge engineers to solve practical damages of double-curved arch bridges.*

1 INTRODUCTION

In 1964 the double-curved arch bridge, as a new bridge type, was created by the engineers of Wuxi country in Jiangxi Province. Because of its advantages, such as simple structure, easy construction, and low cost, the double-curved arch bridge was widely used in China during 1960's and 1970's, especially in highway bridge system. According to statistics [1], there are more than 3300 double-curved arch bridges built in 17 provinces in China until 1972. However, most of the double-curved arch bridges were constructed decades ago, and low standard, poor capacity and various damages are common problems for this kind of bridges in current traffic conditions. Therefore, double-curved arch bridges make up a substantial portion of retrofitted bridges in China, and the research on double-curved arch bridge retrofit develops into a new stage.

2 DOUBLE-CURVED ARCH BRIDGE DAMAGES AND THE CAUSE ANALYSIS

2.1 Double-curved arch bridge damages

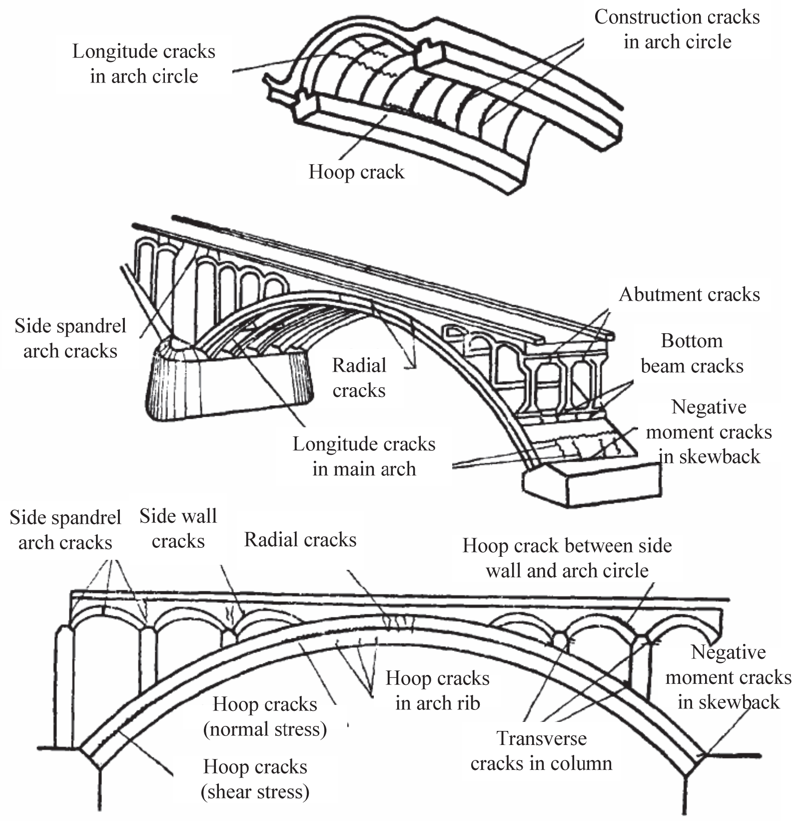


Figure 1: Double-curved arch bridge cracks

The damages of double-curved arch bridge are mainly in a form of cracking, as shown in Figure 1. According to the position, the damages are grouped into four classes, i.e., bridge deck damage, spandrel arch damage, main arch damage and abutment foundation damage.

2.2 Damage causes

Firstly, the double-curved arch bridge has a composite sectional main arch and its transverse stiffness is very small, which results in poor structural integrity. Secondly, the difference in concrete ages between bridge components leads to the cracks caused by creep and shrinkage. Besides, due to low steel ratio, the effective cross-sectional area will be reduced after cracking, the cracks develop, and the bridge structure continues to deteriorate [2].

On one hand, low rib strength caused by small cross section, insufficient transverse joints, unreasonable superstructure dimensions and inappropriate foundation treatment account for the design reasons. On the other hand, material quality and construction control are the construction reasons. What's more, the increasing traffic load worsens the bridge damage.

3 RETROFIT MEASURES FOR DOUBLE-CURVED ARCH BRIDGE

The strengthening of concrete structure involves upgrading of the strength and stiffness of structural members, and the repair process involves re-establishing the strength and function of the damaged members. The strengthening of the bridge structural members can be carried out by replacing poor quality or defective materials by better quality materials, attaching additional load-bearing materials, and redistribution of the loading actions through imposed deformation on the structural system. The new load bearing materials will usually be high quality concrete, reinforcing steel bars, thin steel plates, straps (externally bonded by epoxy), and various combination of these materials. The strengthening of reinforcement concrete bridge to required strength can be adopted by replacing of damaged reinforcement (reinforcement corrosion) and mechanically tying-in additional reinforcement in the old cross-section and replacing it in an additional concrete layer, and using epoxy-bonded steel plates [3-6]. There are many retrofit measures for double-curved arch bridge. For substructure, the retrofit focuses on foundations. And for superstructure, the retrofit involves reinforcing the ribs, strengthening the transverse joints, adjusting superstructure fillers and changing of the structural system. Anchor spray cement concrete and changing structural system are the most common retrofit measures in recent years.

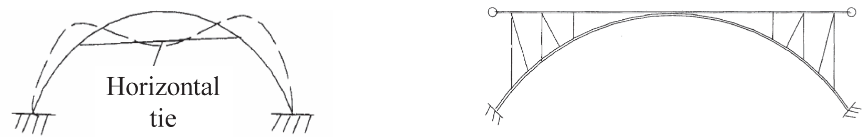
3.1 Anchor spray cement concrete

The procedure consists of two steps: First, place the reinforcement in the weak members of the structure; Second, spray the concrete. The original structure strengthened by anchor spray cement concrete works as a composite structure under the action of outer loads.

The essence of the retrofit measure using anchor spray cement concrete is to enlarge the section area, increase the steel ratio and improve the structure integrity, so that the bridge structure can bear more loads. Added reinforcement works together with the original structure to sustain tension, and it acts as the skeleton of new sprayed concrete. The sprayed concrete can combine the added reinforcement and original structure as an integral structure, and it can transmit the tensile and shear stresses, as well.

3.2 Changing structural system

Changing structural system leads to the redistribution of the member internal forces, so that the structure mechanical behavior can be improved. Following are the measures: adding horizontal ties below arch ribs (Figure 2a), enhancing the arch abutments by braces and ties (Figure 2b). It should be noted that once the bridge structure is changed, the internal forces should be carefully recalculated.



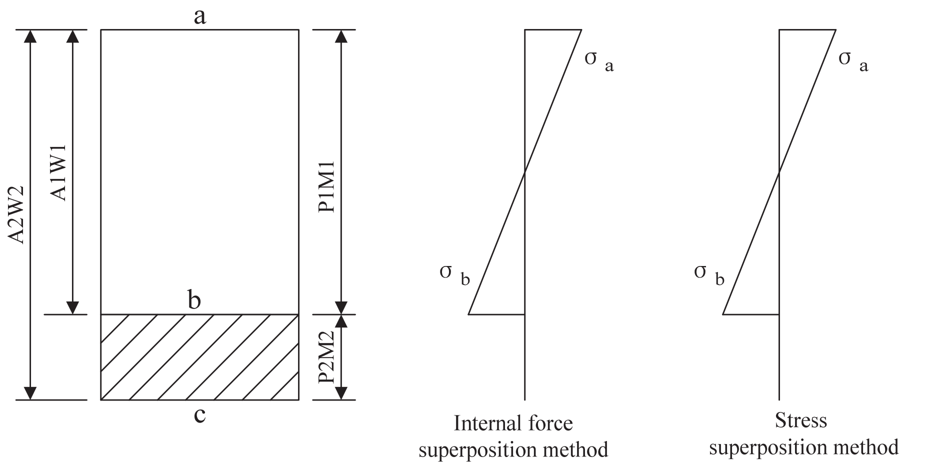
(a) Adding horizontal ties (b) Enhancing the arch abutment by braces and ties

Figure 2: Changing structural system

4 CALCULATION METHODS FOR DOUBLE-CURVED ARCH BRIDGE

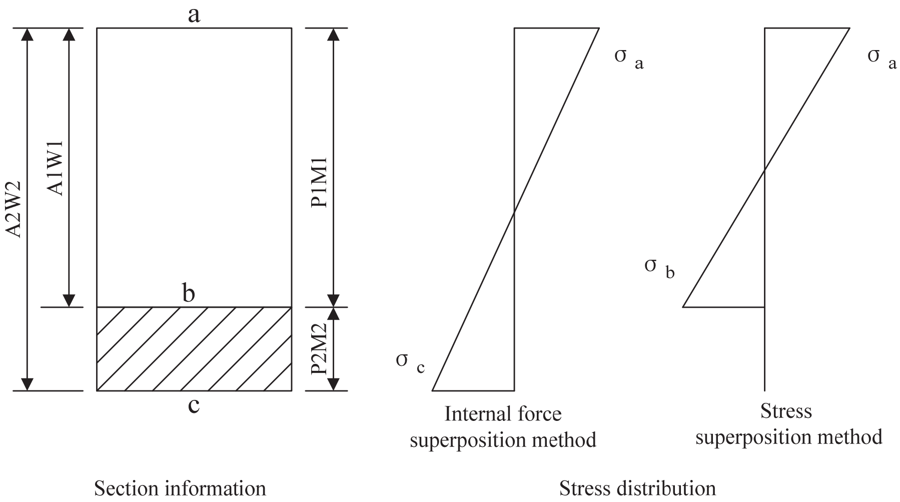
Section enlargement method, attaching additional material method and changing structural system method are commonly used in double-curved arch bridge retrofit. Generally, the weight of both original structure and reinforcing material is carried by original structure, while the live load is shared by original structure and added reinforcing structure.

There are two calculation methods for double-curved arch bridge: internal force superposition method and stress superposition method. The selection between these two methods is decided by construction sequence.

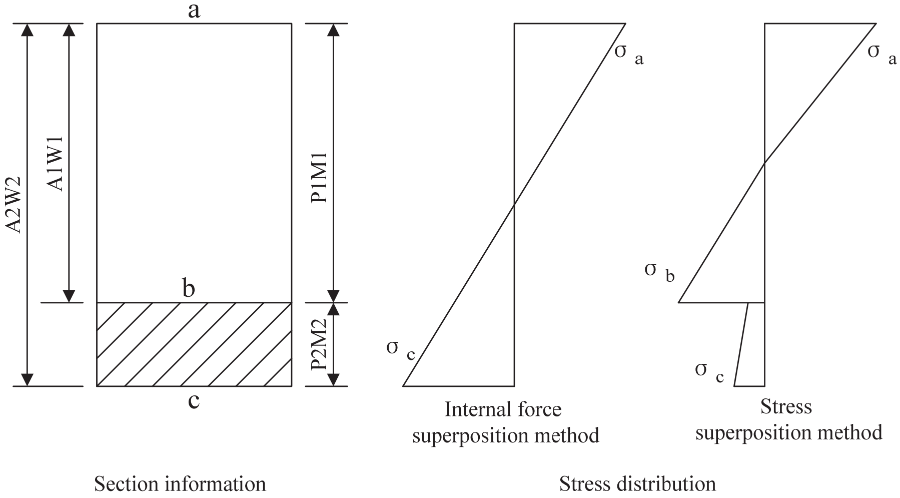


Section information Stress distribution

(a) First phase: reinforcing structure construction



(b) Second phase: after reinforcing structure construction



(c) Third phase: applying live load

Figure 3: Comparison of two calculation methods

Internal force superposition method does not take the construction procedure into consideration, regards the original structure and added reinforcing structure as a monolithic structure. Loads are applied to the combined structure to calculate the internal forces of all members. Based on the calculated internal forces, the stresses in steel reinforcement, concrete and attached reinforcing material can be obtained. Stress superposition method considers both section properties and load case in whole bridge retrofit procedure, then

calculates the internal force and adds up all stress. The comparison of above mentioned two methods is shown in Figure 3.
In the first phase, the stress distributions of internal force superposition method and stress superposition method are the same:

$$\sigma_{a,b} = \frac{P_1 + P_2}{A_1} \pm \frac{M_1 + M_2}{W_1} \tag{1}$$

In the second phase, the stress distributions are different.

(a) Internal force superposition method:

$$\sigma_{a,c} = \frac{P_1 + P_2}{A_2} \pm \frac{M_1 + M_2}{W_2} \tag{2}$$

(b) Internal stress superposition method:

$$\sigma_{a,b} = \frac{P_1 + P_2}{A_1} \pm \frac{M_1 + M_2}{W_1} \tag{3a}$$

$$\sigma_c = 0 \tag{3b}$$

In the third phase, the stress distributions are different.

(a) Internal force superposition method:

$$\sigma_{a,c} = \frac{P_1 + P_2 + P_3}{A_2} \pm \frac{M_1 + M_2 + M_3}{W_2} \tag{4}$$

(b) Internal stress superposition method:

$$\sigma_{a,b} = \left(\frac{P_1 + P_2}{A_1} \pm \frac{M_1 + M_2}{W_1}\right) \pm \left(\frac{P_3}{A_2} + \frac{M_3}{W_2}\right) \tag{5a}$$

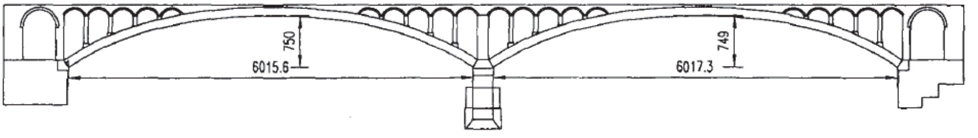
$$\sigma_c = \frac{P_2}{A_2} \pm \frac{M_3}{W_2} \tag{5b}$$

By comparing these two calculation methods, it is easily concluded that:
(1) In internal force superposition method, concrete is assumed to be an elastic-plastic material, so that the sectional stress in construction can be redistributed by plastic deformation. There is no difference between composite section and monolithic section. However, this method does not reflect the actual load case and the structure will be provided by inadequate safety margin.
(2) In stress superposition method, concrete is assumed to be elastic, so that the sectional stress in each construction phase is cumulative, besides, concrete creep is neglected. Therefore, the method reflects the construction procedure to some extent. However, this method will lead to excessively high stress in several fibers.

5 APPLICATION OF RETROFIT METHOD

5.1 Description of Shuiwen Bridge

(a) Photo



(b) Longitudinal layout (dimensions in cm)

Figure 4: Shuiwen Bridge

Shuiwen concrete double-curved arch bridge, built in 1977, is located in Guangxi Province of China. The width of the bridge is 7.8 m and it has 2 spans. The clear length of each span is about 60 m and the arch rise is 7.5 m. The bridge is designed as a constant section, open spandrel catenary double-curved arch bridge with an arch-axis coefficient of 3.5. The longitudinal layout of Shuiwen Bridge is shown in Figure 4 and Figure 5 shows the transverse section of the bridge.

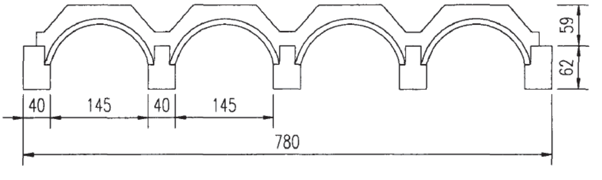


Figure 5: Transverse section of Shuiwen Bridge (dimensions in cm)

5.2 Strengthening measure

The actual arch axis of Shuiwen Bridge does not match well with the designed one due to construction errors, especially at skewback and vault of the arch. In this case, following two respects should be taken into consideration: (1) Enlarging the section to increase the resistance of skewback; (2) Adjusting dead load thrust line to reduce the offset of arch axis. To ensure that the added reinforcing structure can work well with the original structure, the following retrofit construction procedure is adopted: (1) Defusing the bridge deck and removing superstructure fillers; (2) casting skewback concrete; (3) attaching carbon fiber reinforcement on the bottom of arch vault; (4) casting concrete at top of arch vault; (5)

strengthening arch circle; (6) constructing superstructure fillers symmetrically; (7) constructing bridge deck.

5.3 Finite element simulation

The numerical simulation of the double- curved arch bridge retrofit was carried out by use of Finite element program MIDAS/Civil. As shown in Figure 6, the bridge was modeled with 784 beam elements.

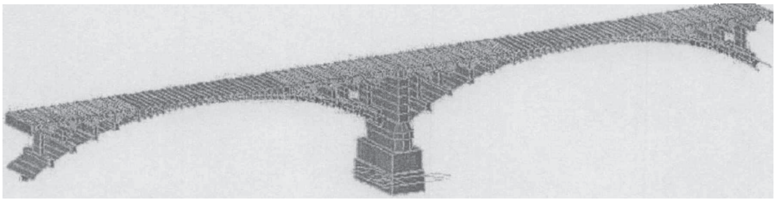


Figure 6: Finite element model

In order to meet the requirement of construction procedure, the safety in each retrofit phase should be considered. Therefore, construction phase simulation provided by MIDAS/Civil was employed.

5.4 Result

By reconstructing superstructure filler and enlarging skewback section, the actual arch axis of Shuiwen Bridge matches well with the designed one after retrofit.
The capacity of the bridge arch has been improved by attaching carbon fiber reinforcement and recasting concrete.

6 CONCLUSION

This paper summarizes the retrofit measures and calculation methods for strengthening double-curved arch bridge. A retrofit scheme was proposed for Shuiwen Bridge, and corresponding calculation was carried out on the basis of stress superposition method. The results show that:
1) For double-curved arch bridges with long span and small arch-axis coefficient like Shuiwen Bridge, enlarging section with additional measures is an effective way to repair the bridge and improve its structural capacity.
2) The influence of construction procedure on bridge structure internal forces should be considered. And the stress superposition method can well reflect the stress state of the structure in each retrofit phase.

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