Evaluation of bearing capacity of reinforced stone arch bridge based on dynamic load test

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Abstract. In order to evaluate the stress and working performance of a reinforced stone arch bridge, the load test of the bridge is carried out. Dynamic load test is used to test the inherent fundamental frequency, damping ratio and impact coefficient of the bridge through pulsation test and sports car test. Under the dynamic load, the first vertical natural vibration frequency of the bridge is 5.005, the damping ratio is 0.203, the second vertical natural vibration frequency of the bridge is 6.274, the damping ratio is 0.021, the tested strain impact coefficient is between 1.03 and 1.10, the measured vertical fundamental frequency is greater than the calculated fundamental frequency, and the overall stiffness of the bridge meets the design specification. The test results show that the reinforcement method of thickening the main arch ring has good application value, can effectively improve the service level of the old bridge and prolong the safety service life, and has obvious social and economic benefits.

1. Introduction
Arch is a kind of structure bearing type with long history and wide application. Under vertical load [1], the arch is mainly under axial compression, which can make full use of masonry materials with good compressive properties to construct arch Bridges. In mountainous areas rich in stone materials, stone arch Bridges are usually preferred in order to meet local traffic needs and consider local materials, low cost and other factors, especially suitable for crossing gullies or streams.

Due to the limited span, the construction means of small and medium-sized stone arch Bridges are relatively single, that is, the masonry method [2-3] is adopted, with the arch frame or arch tire as the support, the natural stone (stone, block or stone) is gradually formed as the bearing structure according to the grouting or dry laying process. Restricted by the technical and economic conditions at that time, the load standard of such local Bridges is low, professional design is lacking, construction quality is not easy to be controlled [4], and there is a lack of maintenance during operation. As a result, structural diseases appear constantly with the increase of bridge age and the change of service conditions. A large number of investigations on stone arch Bridges show that the masonry quality of small and medium-sized span stone arch Bridges has great variability, common diseases such as poor integrity of the main arch ring, deformation or cracking of the main arch ring, cracking of the upper arch wall or displacement of the arch foot, etc.

Growing along with the economic development of traffic, local service performance of highway Bridges is generally faced with higher requirements [5], due to the open bridge economic cost is high,
the interrupt the traffic impact on the new bridge went big, to a large number of stone bridge in service, to reinforce the repaired by testing to assess its carrying capacity, improve the level of bridge service and extend the safe use fixed number of year, has obvious economic and social benefits. Based on the results of dynamic load test, this paper analyzes the load-bearing capacity of the reinforced stone arch Bridges.

2. Project summary
The bridge is located at K73+105 of a national highway. The original bridge was completed and opened to traffic in 1993. Due to the construction of road reconstruction and expansion project in this section, the bridge was reinforced with loads. Before reinforcement, the net span of the bridge is 50.00m, and the thickness of the main arch ring is 1.0m. After reinforcement of the main arch ring with C40 concrete, the net span of the bridge is 49.52m, the net vector height is 8.03m, the net vector span is 1/6.17, the width of the main arch ring is 8.5m, and the thickness is 1.3m. The cross section size of the main arch wall is 8.5×3.0m, and the cross section size of the upper arch hole is 8.5×1.0m. The original design load of the bridge is car-20, trailer -100, and the load level of the strengthened bridge is highway -1.

Midas Civil bridge finite element analysis software was used for the calculation tool, and beam element simulation was used for the main arch ring. By applying static load to the model, strain and displacement values of each measured point in each test section of the structure were obtained, and then compared with the measured values after the real bridge was loaded to evaluate the bearing capacity of the bridge.

3. Bridge dynamic load test

3.1. Test content
This dynamic load test mainly includes pulse test and sports car test [10]. The pulsation test USES DH5907N wireless modal tester to test the natural vibration characteristics of the bridge. DH5908 dynamic signal tester is used to collect and analyze dynamic strain. A 480kN truck was used to uniformly cross the bridge along the center line of the carriageway at a speed of 10~30km/h to test the dynamic strain of the bridge superstructure under the moving load. The modal test layout is shown in Figure 1.

![Figure 1. The modal test layout (unit: cm)](image)

3.2. Results and analysis of natural vibration characteristics
According to the dynamic response signal of the bridge under environmental excitation and the residual vibration signal of the sports car test, the natural vibration characteristics and damping ratio of the bridge can be obtained. The measured basic frequency of natural vibration of the structure and the theoretical value calculated by the finite element software are shown in Table 1.
Table 1. Theoretical and measured fundamental frequency

| Order   | Theoretical fundamental frequency /(Hz) | The measured fundamental frequency /(Hz) | Measured damping ratio /(%) | Measured/ Theoretical |
|---------|----------------------------------------|-----------------------------------------|-----------------------------|------------------------|
| Order-1 | 2.853                                  | 5.005                                   | 0.203                       | 1.754                  |
| Order-2 | 3.896                                  | 6.274                                   | 0.021                       | 1.610                  |

The calculated and measured modes of vibration of each order of vertical bending theory are shown in Figure 2~ Figure 5.

As can be seen from Table 1 and Figure 2~ Figure 5, the measured fundamental frequency is higher than the theoretical inherent fundamental frequency, indicating that the measured structural stiffness is higher than the theoretical stiffness. The ratios of the measured fundamental frequency and theoretical fundamental frequency at the first and second order vertical bends were 1.754 and 1.610 respectively, which met the requirements of literature [6] \( \geq 0.9 \), indicating that the overall structural stiffness of the bridge was stronger. The first and second order measured vertical bending modes are in good agreement with the theoretical modes, and the first two order damping ratios are 0.203 and 0.021, respectively, which are very small, indicating that the overall performance of the bridge is good and the structure has a strong anti-attenuation force.
3.3. Impact coefficient results and analysis
JM3 section 3# strain measurement point was selected for the sports car test to test the dynamic strain of the bridge superstructure under the action of vehicle load. Strain impact coefficient is calculated according to the peak and valley values of dynamic strain in sports car test, as shown in Table 2. According to the theoretical calculation of fundamental frequency, the theoretical calculation of the test bridge impact coefficient $\mu = 0.170$.

| The test section | Driving speed / (km.h$^{-1}$) | Maximum dynamic strain / ($\mu e$) | Impact factor / (1+$\mu$) |
|------------------|-----------------------------|-----------------------------|-----------------------------|
| JM3              | 10                          | 6                           | 0.030                        |
|                  | 20                          | 9                           | 0.062                        |
|                  | 30                          | 12                          | 0.101                        |

It can be seen from Table 2 that, with the increase of vehicle speed, the impact coefficient presents an obvious increasing trend with little change, and the dynamic strain shows a good change curve with time. The maximum dynamic coefficient measured in the test is 1.101, and the corresponding dynamic strain increment is 0.101, which is smaller than the theoretical calculation value of 0.170, indicating that the bridge deck is comfortable.

In the existing load-bearing capacity evaluation methods, most structures can be evaluated rapidly and effectively. According to the relationship between the static and dynamic performance of the structure, $\beta(\eta, \mu)$ was used as the comprehensive evaluation index of static and dynamic performance, which was calculated according to formula (1) [7].

$$\beta(\eta, \mu) = \frac{\eta (1+\mu_T)}{\eta (1+\mu_M)}$$

(1)

In the equation: $\beta(\eta, \mu)$ is the comprehensive evaluation index of static and dynamic function; The $\eta$ is the average value of relative check coefficient of each cross section under static load. $\mu_M$ is the measured impact coefficient; The theory $\mu_T$ is used to calculate the impact coefficient. It can be calculated that $\beta(\eta, \mu) = 0.40 < 1$, the bridge structure meets the bearing capacity requirements.

4. Conclusion of static load test
After the reinforcement of the arch bridge, the dynamic test results show that the measured and theoretical frequencies of the first and second order vertical vibrations of the bridge are 1.754 and 1.610, respectively, which meet the requirements of the code as $\geq 0.9$; In the test of sports car, the value of dynamic strain is 0.101, which is less than the theoretical value of 0.170, indicating that the bridge deck is comfortable $\beta(\eta, \mu) = 0.78 < 1.0$, the bridge structure meets the requirements of carrying capacity.

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