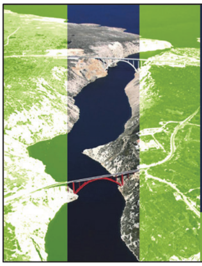

7th International Conference on Arch Bridges
ARCH'13
2 - 4 October 2013 Trogir - Split, Croatia
MAINTENANCE, ASSESSMENT AND REPAIR

STRUCTURAL PERFORMANCE AND REMAINING LIFE ASSESSMENT FOR A STRENGTHENED DOUBLE-CURVED ARCH BRIDGE

Shangguan P.[*], Huang X. Y.[+] & Zhuo W. D.[#]

[*]College of Civil Engineering of Fuzhou University, Fuzhou, P.R. China
shgping@fzu.edu.cn

[+]College of Civil Engineering of Fuzhou University, Fuzhou, P.R. China
hxinyi@126.co

[#]College of Civil Engineering of Fuzhou University, Fuzhou, P.R. China
zhuowd@fzu.edu.cn

Keywords: Double-curved arch bridge, strengthening, structural performance, reliability, remaining life

Abstract: *The strengthening technique for an existing double-curved arch bridge built in 1970's in China is briefly introduced. Both ambient vibration test and static load test were carried out for the strengthened bridge. A refined finite element (FE) model was obtained by updating the initial FE model of the strengthened bridge using the objective function containing both the measured dynamic frequencies and static deflections. The internal forces and deformation of the strengthened bridge structure were calculated by the refined FE model, and the structural performance and reliability were then evaluated based on current Chinese specifications. The remaining life of the strengthened bridge was predicted by the concept of time-varying structural reliability. The numerical results show that, after being strengthened by an appropriate technique, the old double-curved arch bridge can meet the carrying capacity demand, and has sufficient reliability and remaining life.*

1 INTRODUCTION

Two-way curved arch bridge was first constructed at Wuxi in Jiangsu province, China, in 1964 [1]. This kind of bridge takes full advantage of the compressive performance of concrete and thus can be built using only a small amount of steel. It can be built by the precast assembling method without falseworks, resulting in the reduced material consumption, smaller costs and shortened construction period. In the 1970s, a large number of two-way curved arch bridges were built in China. However, due to the localizations of design requirements and construction techniques, the design loads were relatively low and the integrity of the structures was inferior due to insufficient use of steel reinforcement. The extant two-way curved arch bridges can no longer adapt to the increasing traffic loading especially when the over-loading cases arise with the development of the economy and highway construction. Herein diseases appear in those bridges and lack of maintenance and repairs decreases the bearing capacity and endangers the safety and service lives of the bridges [2-6]. Now how can we deal with the diseases of the in-service two-way curved arch bridges becomes a big concern [7-8]. The scheme of dismantlement and reconstruction in site needs an enormous sum of money and also brings about many disadvantageous effects on the traffic and the public society. Hence effective strengthening measures are required to improve the performances of the bridges so that they can serve properly.

In this paper a representative two-way curved arch bridge named Luoyuan Wuli Bridge in Fujian province, China, is investigated. Firstly, effective measures are taken to strengthen the bridge according to the characteristics of the extant diseases. And then the ambient vibration experiment, static experiment and corresponding finite element analysis are carried out on the strengthened bridge. Finally, according to the numerical and experimental results, the reliability of the bridge after strengthening is evaluated, and a structure performance evaluation method useful for bridge health monitoring and maintenance is also presented, based on the dynamic properties of the bridge.

2 STRUCTURE PERFORMANCE EVALUATION AFTER STRENGTHENING

2.1 Strengthening techniques for two-way curved arch bridges

The main diseases occuring in two-way curved arch bridges are the cracks. They can be categorized into bridge deck system diseases, spandrel arch diseases, arch rib diseases and pier-abutment- foundation diseases according to the position of the occurred cracks [2-7].

The methods we can choose in the strengthening of two-way curved arch bridges are [9-13]: enlargement of the rib section, spraying concrete strengthening, external bonding strengthening, adjustment of arch axis and thrust axis geometry, alteration of structural system, box arch rib strengthening, prestressed steel arch rib strengthening, etc. The strengthening principles are different for every strengthening method; we can choose the proper method according to the characteristics of the diseases in practice. Special attention in strengthening must be paid to the main supporting member, the arch rib. According to the diseases of Luoyuan Wuli Bridge, combined methods of enlargement of the rib section, external bonding carbon fiber strengthening, spraying concrete strengthening and external bonding steel plate strengthening are taken.

2.2 Ambient vibration experiments and static load experiments

2.2.1 Ambient vibration experiment

Luoyuan Wuli Bridge is to be still in service after strengthening and repair. In order to observe the long term performances of the bridge after strengthening, correlative bearing evaluation tests were carried out in service period and the health conditions of the bridge were estimated from the test results. Table 1 presents the first five vibration frequencies and periods of the bridge before and after strengthening. Table 1 shows the first five frequencies and periods before and after strengthening for two spans, and Table 2 shows the first five frequencies before and after strengthening for the first span.

No.	frequency (Hz)		period (s)	
	before	after	before	after
1	2.818	3.178	0.354	0.314
2	3.020	4.395	0.331	0.227
3	3.149	5.102	0.317	0.196
4	5.712	5.812	0.175	0.172
5	5.725	5.973	0.174	0.167

Table 1: First five frequencies and periods before and after strengthening for two spans

No.	property	before	after
1	frequency	3.246	4.283
	damping	4.50%	3.50%
2	frequency	4.403	6.877
	damping	10.20%	7.00%
3	frequency	6.956	8.885
	damping	5.30%	2.50%
4	frequency	8.881	10.425
	damping	2.70%	2.70%
5	frequency	12.804	14.078
	damping	6.20%	2.20%

Table 2: First five frequencies before and after strengthening for the first span

The results indicate that the experimental frequencies are in good agreement with the numerical results, the first transverse mode of the bridge is anti-symmetric and the corresponding experimental frequency is higher than the calculated. Other experiment frequencies are higher than the numerical results also which denote that the integral stiffness of the bridge has been enhanced to meet the requirements of the strengthening design.

2.2.2 Static load experiments

The stress, strain and deflection at the key sections of the bridge under trial loads were determined by static load experiments, and the structural performances and working condition were evaluated by those data. The loading modes of the key sections are illustrated in Fig.1 and Fig.2, and the measured stress-strains are given in Table 3.

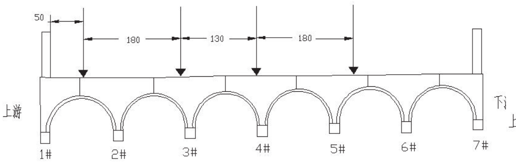

Figure 1: Transversely eccentric arrangement of two vehicles

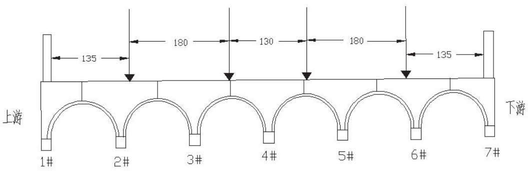

Figure 2: Transversely symmetric arrangement of two vehicles

Case		Point number						
		1	2	3	4	5	6	7
Case one (1)	experiment	-	-	-	-	-	-	-
	calculation	-	-	-	-	-	-	-
	testing	0.700	0.913	1.174	1.174	1.174	0.609	0.567
Case one (2)	experiment	-	-	-	-	-	-	-
	calculation	-	-	-	-	-	-	-
	testing	0.683	0.938	1.085	1.106	1.064	0.808	0.661
Case two	experiment	-	-	-	-	-	-	-
	calculation	-	-	-	-	-	-	-
	testing	0.904	1.200	1.140	0.978	0.875	0.784	0.565
Case three	experiment	-	-	-	-	-	-	-
	calculation	-	-	-	-	-	-	-
	testing	0.429	0.614	0.614	0.614	0.614	0.443	0.411

Table 3: Stress of the observation points for the first skewback section (MPa)

The results in Table 3 reveal that the stresses at the bottom edge of the skewback soffit section of the arch ribs are overally compressive. The stresses of the arch ribs, distributed symmetrically in transverse direction, increase proportionally with the increase of grade of symmetric load arrangement, which indicates that the ribs function elastically. While in the case of eccentric loading arrangement, the measured stresses distribute asymmetrically. Almost all the measured results are smaller than the numerical results, which indicates that the bearing capacity of the bridge can meet the requirements of service and the chosen strengthening methods are proven to be effective in that the sectional stresses reduce significantly.

2.2.3 Finite element analysis and model updating

The finite element analysis model of the Wuli Bridge after strengthening using Midas/Civil software is given in Figure 3. The sensitivity of frequencies to the modulus of elasticity of the ribs is numerically determined, and the first five frequencies of the Wuli Bridge before and after model updating are given in Table 4.

The model updating of Luoyuan Wuli Bridge includes six parameters as follows: the elasticity modulus of arch rib, arch rib mass density, deck horizontal linkage elasticity modulus, elasticity modulus of cross walls on piers, deck material elasticity modulus and elastic connections between arch ribs. The aim of adjustment is to make the calculated fundamental frequency agree well with the actual measured frequency and that the numerically obtained deflections of key sections under static load can reflect the actual measured ones.

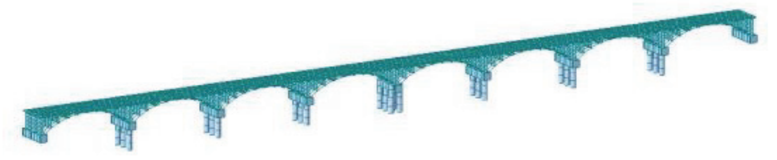

Figure 3: The FE model of Wuli bridge

Mode shape	number	measured(Hz)	calculated(Hz)	Errors
Vertical bending mode	1st	4.101 Hz	3.17Hz	22.7%
	2nd	6.647 Hz	4.40Hz	33.8%
	3rd	8.301 Hz	5.10Hz	38.6%
	4th	10.208 Hz	5.82Hz	43.0%
	5th	14.059 Hz	5.97Hz	57.5%

Table 4: Frequencies of Wuli Bridge experimental and before model updating

2.3 Performance evaluation of the double-curved arch bridge structure

In the practical application, the visual inspection, load test and analysis-checking calculation are often combined to assess the structural performance of double-curved arch bridge. The method of bearing capacity evaluations of double-curved arch bridge, which is based on the dynamic analysis can be a supplement of the evaluations of double-curved arch bridge. Judge the bridge work status according to the changes in vibration frequency, correct the standard finite element model via the changes of basic frequency, and then assess the bearing capacity.

3 REMAINING LIFE ASSESSMENT

3.1 Calculation of internal force and deformation

The deformations under the dead load are calculated according to load combination in the current “Bridge codes”. The deflection to span ratio under the most unfavorable load combination is 0.002531/22=1/8692<1/800, which meets the standard requirement, so that it may be concluded that Luoyuan Wuli Bridge’s stiffness was improved after strengthening and that it meets the design requirement of strengthening. Table 5 shows internal force calculation results of reinforced main arch rib under vehicle-13 load, trailer-60 load and temperature effect.

load types	dead load	vehicle -13Max	trailer -60Max	vehicle -13 Min	trailer -60 Min	cooling load	warming load
axial force (kN)	-301.1	28.31	40.74	-79.79	-128.75	20.92	-20.92
shear force (kN)	11.93	25.98	35.39	-19.96	-26.65	15.8	-15.8
bending moment (kN·m)	-53.77	45.86	64.19	-81.17	-95.11	-85.88	85.88

Table 5: The computed internal forces of the arch foot sections in the site rib after strengthening

3.2 Strength checking on the control sections of the main arch rib

The strength of control cross section of the main arch rib was checked, according to the internal force combinations and results are shown in Table 6..

The checking of main combination 1					
Max and Min internal force combination			N_R	N_J	result
$N_j(kN)$	$Q_j(kN)$	$M_j(kN\cdot m)$			
231.35	50.69	15.81	1770	259	satisfied
473.02	-17.20	-178.17	811	530	satisfied
The checking of combination 3					
Max and Min internal force			N_R	N_J	result
$N_j(kN)$	$Q_j(kN)$	$M_j(kN\cdot m)$			
226.18	53.25	22.21	1530	253	satisfied
502.94	-18.57	-169.15	655	563	satisfied

Table 6: Strength checking of the site rib at arch foot

3.3 Structural reliability assessment

Based on the calculations of reinforced double-curved arch bridges we found that the main reason of section failure is the excessive bending moment, so the bending moment is used as the control internal forces of double-curved arch bridges. The arch rib and wave of double-curved arch bridge are prefabricated; the micro-expansion concrete used in strengthening has relatively low contractility. The combination of computed internal forces are used by the effect of dead loads and vehicle load, changing the structural resistance into a moment control, first eccentric moment was produced under external force, the resisted bending moment can be obtained by multiplying the resisted force in eccentric compression section with its eccentricity.

Reliability assessment was done on the strengthened double-curved arch bridge. A multi-span arch bridge model was used in the numerical analysis. The calculation results satisfy the design load level of vehicle-13. The reliability indexes of sections in the side rib are shown in Table 7.

Skewback section	section in 1/8	section in 1/4	section in 3/8	crownt section
6.8646	7.0583	7.4358	7.7221	8.7216

Table 7: The reliability indexes of side rib sections (β)

It can be established from the calculated values in Table 7, that the reinforcing double-curved arch bridges can satisfy the requirements of target reliability index (This bridge is a general model, ??? should be considered as□ductile failure), which means that the double-curved arch bridges is safe after strengthening.

3.4 Remaining life prediction of bridges after strengthening

The design load of reinforced Luoyuan Wuli Bridge is vehicle-13. By performing numerical analysis after strengthening we know that the skewback sections are the most unfavorable. According to the relevant literatures, the resistance reduction coefficient is taken as [14]:

$$r(t) = 1 - k_1 t + k_2 t^2 = 1 - 0.005t \tag{1}$$

The prediction of remaining service life for reinforcing double-curved arch bridges may be done by introducing the concept of time-dependent reliability. This concept means that as time increases, the resistance decreases and traffic loads are increasing. Reliability index decreases with the increase of the time. When the given target reliability index is reached, the reinforced double-curved arch bridge can be considered to reach its service life. By discrete calculation method, strengthened Luoyuan Wuli Bridge's remaining service life is forecast to be 50 years. Based on the modern database theory and combined with probability finite element analysis method, the decision management system of active bridge structures performance diagnosis, evaluation, maintenance and strengthening are established, providing scientific basis for the bridge's evaluation, maintenance, reinforcement, decision-making and so on.
The calculations of internal forces and deflections under loads, and checking of strength under prescribed load combinations for main arch rib control section have been performed. The results show that Luoyuan Wuli Bridge can recover the original design load level.

4 CONCLUSIONS

(1) The structural performance evaluation of the Luoyuan Wuli Bridge is mainly about the evaluation of load bearing capacity. The calculation of internal forces and deflection under dead load and internal force calculation and combination for main arch rib control section strength checking are considered, and the load bearing capacity of the strengthened bridge is evaluated. The updated finite element model is taken to analyze the vehicle load effects. The internal force combination and intensity checking results show that Luoyuan Wuli Bridge can satisfy the original design loading level.
(2) The structure safety degrees are judged by comparison between the calculating reliability index and target reliability index β of the key sections. The analysis shows that the key section reliability indexes of Luoyuan Wuli Bridge are larger than 4.2, which can

satisfy the engineering requirements after strengthening. A structural performance evaluation method which can be applied to in-service double-curved arch bridges is presented in this paper.

(3) The time-dependent reliability concept is used to predict the remaining service life of the reinforcing double-curved arch bridges. The resistance decreases as time increases, while the traffic loads are increasing, so that the reliability index decreases with the increase of the time. When the reliability index reaches the given target reliability index, the service life of the strengthened double-curved arch bridge is considered to be terminated. Our calculations predict that the remaining service life of Luoyuan Wuli Bridge is 50 years.

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