ANALYSIS AND EVALUATION ON STRENGTHENING AND WIDENING OF A CATENARY STONE ARCH BRIDGE WITH SOLID SPANDRELS

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Abstract: *This paper examines the bearing capacity and stability of a catenary axis uniform cross-section multi-span stone arch bridge with solid spandrels after strengthening and widening, in the light of the Code for Design of Highway Masonry Bridges and Culverts (JTG D61-2005) published by the Ministry of Communications of the People's Republic of China. Taking the West Ulanhot Large Bridge built in cold area of Inner Mongolia in 1960s as an example, the effect of dead load, live load and temperature variation after and before strengthening as well as multi-arch action were considered. Through calculating the bearing capacity and stability of stone multiple arch bridge, compared with the results of loading test and follow-up survey on operation condition for many years, the safety and effectiveness of strengthening scheme are evaluated.*

1 INTRODUCTION

The West Ulanhot Large Bridge was built in cold area of Inner Mongolia in 1960s. It is a hingeless, catenary, uniform section, multi-span stone arch bridge with solid spandrels in a unite with four spans of 35 meters before retrofitting, as shown in Figure 1, with the total length of 166.28m, the bridge width of 8.5m (lanes of 7 m + pedestrians of 2 x 0.75 m), the rise-span ratio of 1/5, the thickness of main arch ring of 0.8 m and the width of 7.3 m, and design load of Truck 13 and check load of Trailer 60. Since the beginning of 1980s, design specifications and construction technology standards have been continuously upgraded along with the rapid development of China's economy.This bridge was faced with some problems such as low load standards, narrow deck width, and was for long years out of repair, not to meet the needs of the development of the local economy and modern transportation [1,2]. The field tests on the old bridge had shown that the work stone of arch ring is regularity, with good in integral structure, no settlements of piers and abutments supported on the rock stratum, stable foundation bed, enough bearing capacity and potential anti-overloading. After the assessment, the bridge was considered to be with implementation conditions of strengthening and retrofitting, but it would be neither economic nor practical if demolished and reconstructed.

To improve the design load level, the traffic capacity and the bearing capacity for old bridge, the design and construction of retrofitting project for strengthening and widening (Figure 2) were implemented in 1991[3,4]. The deck width of new bridge after reconstruction is 15.0 m (lanes of 9 m + pedestrians of 2 x 3.0 m) with design load of Highway II used in *JTG D61-2005* . The execution scheme was that the concrete spandrel walls in thickness of 0.45m and back haunch fillet of arch at the springing were placed within the spandrel construction of new bridge, on the basis of keeping the appearance of old bridge and carrying all load action on the structure, provided with built-in filler between cross walls, while the reinforced concrete in thickness of 0.6 m was placed in situ on the segments of solid spandrels near to the crown of arch and at the top of side walls and cross walls, to increase the integrity between the main arch ring and the spandrels. The prestressed concrete cantilever beams were provided in the form of consolidated structure on the spandrel cross walls, with total length of cantilever beams of 15.6 m, with cantilever length of 4.15 m, height of 0.3-0.5 m, width of 0.45 m and spacing of 2.5 m. The reinforced concrete covering slabs were installed longitudinally to widen the bridge deck.

This paper examines the bearing capacity and stability of strengthened and widened stone arch bridge through taking the West Ulanhot Large Bridge as a study case, in the light of the Code for Design of Highway Masonry Bridges and Culverts（JTG D61-2005） published by the Ministry of Communications under the People's Republic of China, thus evaluating the safety and the effectiveness of such bridge retrofitting.

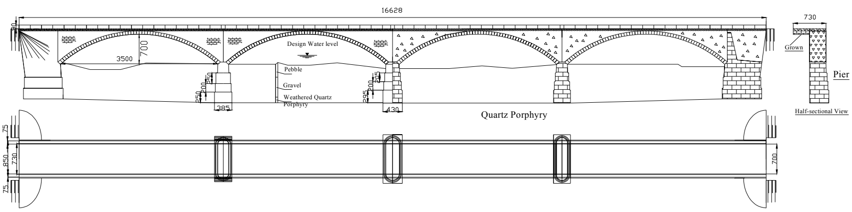

Figure 1: Overall layout of old bridge before strengthening and reconstruction

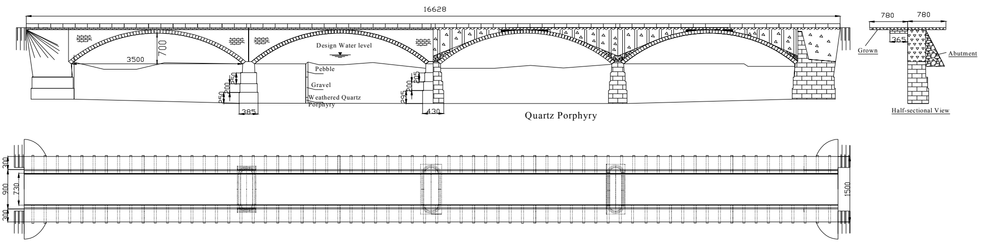

Figure 2: New bridge layout after strengthening and reconstruction

2 DETERMINATION OF ARCH AXIS COEFFICIENT

2.1 Arch axis coefficient of old bridge

Since the old bridge was a stone arch with solid spandrels, the distribution of dead load on structure from the crown to the springing of arch ring before strengthened is continuous, but not evenly distributed. The dead load pressure line, a catenary line, was used for the design arch axis (without consideration of elastic compression). By using the successive approximation method, the arch axis coefficient before strengthening was determined as: $m = 6.094$, and the corresponding arch axis equation was [5]:

$$y_1 = \frac{7.12}{(6.094-1)}(ch2.494\xi - 1) \tag{1}$$

2.2 Arch axis coefficient of new bridge

In consideration with being the entirely different in interior structures of spandrel construction between old and new bridges, the dead loads of span structure of stone arch ,i.e. the dead weight of bridge span structure, include the irregularly distributed loads of solid-web section, the concentrated forces transferred down from spandrel cross walls, and the uneven distributed dead loads of filler between cross walls. The distribution of dead loads on the new bridge was closer to that of open-spandrel arch, the reasonable axis coefficient of the bridge after strengthened was determined by using Five Points Coincidence Method as: $m' = 3.505$, so the catenary arch axis line used for new bridge was closer to the pressure line of its dead load.

3 INTERNAL FORCE CALCULATION OF ARCH BRIDGE

3.1 Dead load internal forces

The dead load internal forces of arch bridge (taking into account the elastic compression) were calculated according to the arch axis coefficient, $m' = 3.505$, in consideration with the influence of deviation between actual arch axis of new bridge ($m = 6.094$) and reasonable arch axis ($m' = 3.505$) [6,7] , the dead load internal forces of arch bridge after strengthening were given in Table 1.

Items		Crown	L/4 Point	Springing
Axial force	N_G (kN)	1740.03	1556.25	2125.21
Bending moment	M_G (kN·m)	40.48	-262.56	-83.07

Table 1: Dead load internal forces

3.2 Live load internal forces

The design load standard for new bridge after strengthening was upgraded to the Highway II Load. The live load internal forces (taking into account the elastic compression) were calculated through using the internal force influence line and determining the most unfavorable positions of live load [8], as shown in Table 2.

Items		Crown		L/4 Point		Springing	
		M_{max}	M_{min}	M_{max}	M_{min}	M_{max}	M_{min}
Lane load	N_P（kN）	101.92	54.04	79.71	104.18	96.42	99.97
	M（kN·m）	161.10	-28.87	151.70	-102.31	190.77	-154.43
Crowd load	N_P（kN）	34.64	21.90	24.91	42.09	42.87	26.96
	M（kN·m）	30.03	-10.24	26.81	-35.90	70.40	-37.62

Table 2: Internal force of live load

3.3 Internal force of changes in temperature

The arch bridge is located in the cold region. The highest temperature is 34 ℃, while the lowest temperature of minus 23 ℃. The closure temperature was10 ~ 15℃ [9]. The internal forces caused by the temperature variation are presented in Table 3.

Effect	Crown		L/4 Point		Springing	
	Bending moment（kN·m）	Axial force（kN）	Bending moment（kN·m）	Axial force（kN）	Bending moment（kN·m）	Axial force（kN）
Temperature-rise	-22.97	11.90	-8.28	11.36	61.77	7.70
Temperature-drop	36.37	-18.85	13.10	-17.98	-97.81	-12.19

Table 3: Thermal internal forces

3.4 Live load internal forces with multi-arch action

The old bridge was built in 1965, the multi-arch action effect was not considered at that time in the design calculation of multi-span stone arch. In order to reflect more accurately the actual condition of forces on the bridge after strengthening and retrofitting, the multi-arch action effect has been taken into account in the scheme design of the new bridge. The live load internal forces in multi-arch action were calculated by using the summation method, which took into account simultaneously the effect of nodal displacement and rotation angles at the top of piers [10].

Elastic constant for arch ring. This bridge is a multi-arch bridge of equal four spans. The elastic constants for arch ring of all four spans are the same, and they are calculated as:

Thrust stiffness is:

$$K = \frac{1}{\delta} = 1762.274 \tag{2}$$

Bending stiffness:

$$S = \frac{1}{\alpha} + \frac{C^2}{\delta} + \frac{L^2}{4\beta} = 60285.527 \tag{3}$$

Correlation coefficient:

$$T = \frac{c}{\delta} = 9146.202 \tag{4}$$

Bending stiffness:

$$CS = \frac{1}{\alpha} + \frac{C^2}{\delta} - \frac{L^2}{4\beta} = 541184.606 \tag{5}$$

Where $\alpha, \delta, \beta,$ are the coefficients of constant displacement for arch rings.

Elastic constants for piers. Three piers of this bridge are the gravity type piers with uniform cross-section in dividing parts, the elastic constants of piers are presented in Table 4.

Items		No. 1 pier	No. 2 pier	No. 3 pier
Anti-pushing rigidity	$\bar{K}_i = \frac{\varepsilon}{\varepsilon\lambda - \lambda'^2}$	1633781.47	3552780.39	2177325.22
Coherent coefficient	$\bar{T}_i = \frac{\lambda'}{\varepsilon\lambda - \lambda'^2}$	4537016.53	9929494.31	4865973.45
Bending rigidity	$\bar{S}_i = \frac{\lambda}{\varepsilon\lambda - \lambda'^2}$	28216390.46	65399013.48	30243515.95

Note: $\varepsilon, \lambda, \lambda',$ are the coefficients of displacement for piers.

Table 4: Elastic constants for piers

Horizontal thrusts for arch and piers. For the multi-arch bridge of equal four spans, if the horizontal thrust were calculated when all external loads acting on the third span, the three-thrust equation is expressed as follows:

$$\begin{cases}(1+\phi_{11})H_1-\phi_{11}H_2=0\\(1+\phi_{12}+\phi_{22})H_2-\phi_{12}H_1-\phi_{22}H_3=0\\(1+\phi_{23}+\phi_{33})H_3-\phi_{23}H_2-\phi_{33}H_4=H_3^p\\(1+\phi_{34})H_4-\phi_{34}H_3=0\end{cases} \tag{6}$$

It was calculated that:

$$\phi_{12}=\phi_{11}=3.552634125\times10^{-3} \tag{7}$$

$$\phi_{23}=\phi_{22}=1.533998157\times10^{-3} \tag{8}$$

$$\phi_{34}=\phi_{33}=2.301010266\times10^{-3} \tag{9}$$

$$\xi_H^3 H_3=H_3^p \tag{10}$$

$$\xi_H^3=1.003827385 \tag{11}$$

Live load internal force in multi-arch action. The internal forces in multi-arch calculation can be considered as those in fixed arch with the influence of multi-arch action, while the imposed horizontal force produced by the action is: $\Delta H=(\xi_H^3-1)H$, and the live load internal forces included in multi-arch action as given in Table 5.

Items		Crown		L/4 Point		Springing	
		M_{max}	M_{min}	M_{max}	M_{min}	M_{max}	M_{min}
Lane load	N_P (kN)	102.31	54.24	79.93	104.54	96.68	100.15
	M_P (kN·m)	112.25	-29.27	106.08	-102.58	173.51	-152.99
Crowd load	N_P (kN)	34.78	21.99	24.97	42.23	42.98	26.99
	M_P (kN·m)	29.77	-10.40	26.76	-36.01	71.25	-37.35

Table 5: Live load internal force in multi-arch action

4 CHECKING CALCULATION OF BEARING CAPACITY AND STABILITY OF ARCH BRIDGE

4.1 Bearing capacity

The combination of dead load, live load, thermal internal forces, live load internal forces with multi-arch action was carried out in the light of the bearing capacity limit state, and the results from checking calculation of bearing capacity with the following formula are presented in Table 6.

$$\begin{cases} \gamma_0 N_d < \varphi A f_{cd} & e \le 0.6S \\ \gamma_0 N_d < \varphi \dfrac{A f_{tmd}}{\dfrac{Ae}{W} - 1} & e. > 0.6S \end{cases} \tag{12}$$

Effect	Crown				L/4 Point				Springing			
	$M_{\max}+M_t^+$	$M_{\max}+M_t^-$	$M_{\min}+M_t^+$	$M_{\min}+M_t^-$	$M_{\max}+M_t^+$	$M_{\max}+M_t^-$	$M_{\min}+M_t^+$	$M_{\min}+M_t^-$	$M_{\max}+M_t^+$	$M_{\max}+M_t^-$	$M_{\min}+M_t^+$	$M_{\min}+M_t^-$
$\gamma_0 N_d$ (kN)	1946.48	1920.66	1868.45	1842.62	2009.91	1985.26	2058.87	2034.22	2728.16	2711.46	2719.59	2702.89
$\gamma_0 M_d$ (kN·m)	211.44	261.29	-20.43	29.41	-169.97	-152.01	-499.03	-481.07	254.97	120.92	-293.35	-427.40
e_y (m)	0.11	0.14	-0.01	0.02	-0.08	-0.08	-0.24	-0.24	0.09	0.04	-0.11	-0.16
e (m)	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
φ	0.82	0.74	1.00	1.00	0.88	0.90	0.47	0.48	0.86	0.96	0.82	0.68
$\varphi A f$ (kN·m)	3835.98	3477.32	4674.31	4662.52	4130.90	4220.82	2201.86	2248.70	4025.51	4516.38	3845.69	3187.58

Note: M_t^+ —Temperature-rise， M_t^- —Temperature-drop

Table 6: Bearing capacity for arch bridge

4.2 Lateral stability

Since this strengthened and widened bridge is a deck-type arch bridge built by using the trestle construction method and the span-width ratio of arch ring is: $7.3/35 \approx 1/5 > 1/20$,so the lateral stability of arch bridge needs not to be calculated according to the stipulation of the Code（JTG D61-2005）.

5 CONCLUSIONS

The results from calculation and analysis on the scheme of strengthening and widening for the West Ulanhot Large Bridge have shown that the hinge less, catenary, constant section stone multi-arch bridge with solid spandrels, which was built in the cold region in the early stage, has a strong anti-overloading ability, it can get reasonable use through scientific design and construction, and also ensure the bearing capacity and stability of the bridge meeting the requirements of current specification of bridge service. Compared with the results of loading test and follow-up survey on operation for many years, it has been confirmed that the bridge structure is safe and reliable, working in good condition, having achieved the desired design goal.

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