Trial design of a reactive powder concrete (RPC) arch bridge with a span of 420m

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ABSTRACT: Taking Wanxian Yangtze River Bridge with a main span of 420m as prototype, trial design of Reactive Powder Concrete (RPC) arch bridge was carried out. Analysis results show that much thinner cross section can be adopted due to its high performance and strength, the self-weight of the arch ring can be reduced effectively, subsequently the internal forces caused by the self-weight and the difficulty in construction decrease notability. Preliminary research indicates that it is possible to use Reactive Powder Concrete (RPC) in long span arch bridge.

1 INTRODUCTION

Arch is a natural and appropriate structural solution, which is both aesthetically pleasing and clearly shows its function. It is ideal for concrete with higher compression strength and limited tensile strength. Many concrete arch bridges have been built in world, in which more than 40 bridges with a span equal or longer than 200m, among them the Wanxian Yangtze River Bridge in China with a main span of 420m is the longest one (Z Šavor and J Bleiziffer 2008; Baochun Chen et al. 2007). However, the construction difficulty and cost will increase with the heavy self-weight of long span concrete arch bridges. Hence, there are few long span concrete arch bridges to be built commonly in recent years, while research on it is considerably active. Many researchers have carried out trial design of concrete arch bridges with a span exceeds the present span record of 420m, in which Reactive Powder Concrete (RPC) with high strength is adopted as the main materials in order to decrease the structural dead-weight and make the construction possible (Japan society of civil engineers 2003; V. Candrlic et al. 2001; V. Candrlic et al.2004). On the premise of having the same flexural strength, RPC structures may weigh only one-third or one-half as much as corresponding concrete structures, and almost as light as steel structure.

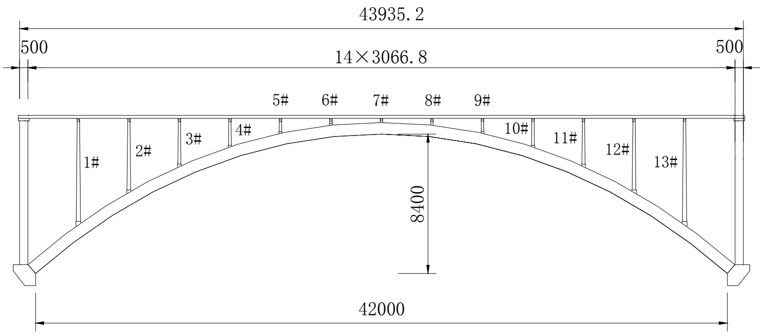
Reactive powder concrete (RPC) is a kind of cement-based composites with super-high compressive strength, high toughness, good durability and stability. Since developed successfully from 1993, there were many researches on RPC; it was used in bridge fields, but not yet widely. Sun-Yu Pedestrian Arch Bridge was built with RPC in 2002; its span was 120m (SukBum Huh and YoonJoo Byun 2005). Wildbrücke Völkermarkt arch bridge is the first road arch bridge with an arch consisting ultra high performance concrete. The project was awarded in Austria with ZT AWARD 2007(W. Zimmermann 2008).

The advantage of RPC arch bridge is mainly in terms of long span concrete arch bridge. In recent years, Croatia professors have proposed trial design of arch bridges with main spans of 432m, 500m, 750m and 1000m respectively. The weight of the main arch ring was reduced by using RPC as building materials, the research of construction method and preliminary calculations were also carried out (V. Candrlic et al. 2001, 2004).

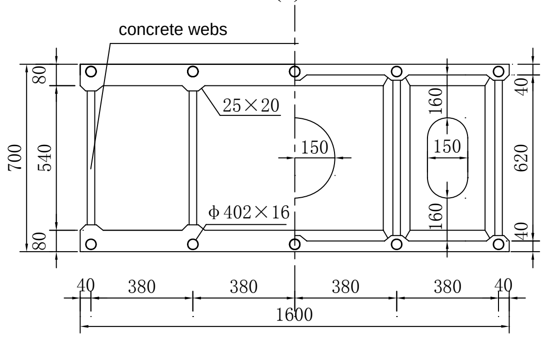
In this paper, taking Wanxian Yangtze River Bridge with a main span of 420m as prototype, trial design of RPC arch bridge was carried out, and its potential in engineering application was explored.

2 BRIEF DESCRIPTION OF THE PROPOTYE BRIDGE--THE WANXIAN YANGTZE RIVER BRIDGE

The general layout of Wanxian Yangtze River Bridge is shown in Fig.1 (a). The main arch ring has a clean span of 420m. Its rise to span ration is 1/5 and arch axis is a catenary curve with a shape coefficient of 1.6. The arch ring has a three-cell RC box section of 16m wide and 7m deep, as shown in Fig. 1 (b). One diaphragm plate with thickness of 0.25m is set every 15m in longitudinal direction. Reinforced concrete spandrel columns from height of 0.93m to 59.94m support the prestressed concrete T-shape deck girders with equal spans of 30.668m. The concrete grade is C60 and the stiff skeleton method is adopted for construction (Dowd 1999, Sichuan Provincial Communications Department Sichuan Communications Planning & Design Institute. 2001).



(a)



(b)

Figure 1 : Wanxian Yangtze River Bridge (unit: cm) : (a) General layout, (b) Cross-section of main arch ring

3 TRIAL DESIGN OF RPC ARCH BRIDGE

For the sake of contrastive analysis, according to the design of Wanxian Yangtze River Bridge, trial design still adopted the original design load, the overall layout and structure of a bridge deck system. Only the column on arch ring, bent cap and arch ring were changed from general concrete into RPC200 materials. The bridge would be erected by cantilever construction method; the large volume of steel frame as embedded scaffolding in the main arch ring of the original bridge can be cancelled. As the total weight of the trial design bridge reduced significantly, the axis of the arch was optimized by making the arch axis coincide with the dead load pressure line as much as possible, the arch-axis coefficient for the RPC arch bridge is adjusted from 1.6 in the original one to 1.410.

As a new material, RPC is lack of a common production protocols, related materials testing and acceptance criteria, structural design standard. Therefore, material properties of RPC provided in different literatures are different. In this paper, RPC with the following parameters is adopted: axial compressive strength of 130MPa, tensile strength of 20MPa, elastic modulus of 40 ~ 60GPa and Poisson's ratio of about 0.2.

While for the linear expansion coefficient of RPC200 had not yet seen in the relevant references, the value of linear expansion coefficient is assumed to be 10^{-5}. Taking (Qin Yonggang 2006) as the main reference, the design materials parameters selected in this paper were shown in Table 1.

Table 1 : Material Properties of RPC200

Raw materials	density（kg/m3）	Elastic modulus（GPa）	Poisson's ratio	Compressive strength（MPa）	Tensile strength（MPa）	Shearing strength（MPa）	coefficient of linear expansion
RPC200	2600	50	0.2	120	20	20	10-5

The arch ring with uniform section of trial design had a four-cell RPC box section of 16m wide and 7m deep, as shown in Fig. 2. Concrete top and bottom flange is both thick of 0.20m, webs of both sides of the box are 0.30m, and the rest of webs are 0.20m. The width of middle boxes is 3.8m, and each side one is 4.20m. Meanwhile, in order to enhance the stability against overall and local buckling of arch ring cross-section, diaphragm plate with thickness of 0.25m will be employed every 5m.

Analysis shows that the volume and self-weight of RPC section can be reduced about one third compared with the ordinary one. Similar for the spandrel columns, its thickness of the hollow column can also reduced one third self-weight, but the length, height, width of the column are not changed. For bent cap, its height is the same as the original one, but its cross-sectional can also reduced one third self-weight

Table 2 shows the major quantities of arch ring. As can be seen from Table 2, the consumption of concrete of RPC arch bridge reduces 40% than that of the prototype bridge; the consumption of steel is 595t, reduces 72% than that of the original bridge. The weight of arch ring changes from 29732t to 17838t, the reduction achieves 40%.

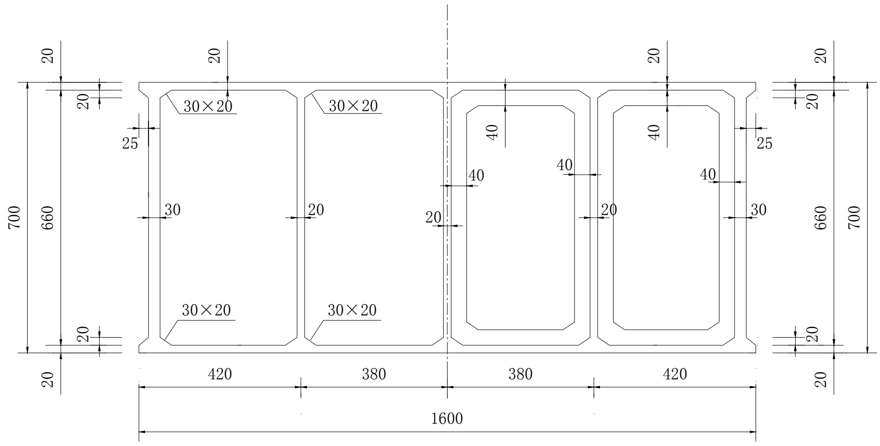


Figure 2 : Cross-section of the arch ring in the trial design bridge

Table 2 Arch Ring’s Quantity

Project	Wanxian Bridge（W）	Trial designed bridge（S）	S/W
Concrete（m3）	11054	6632	0.60
steel（t）	2095	595	0.28

RPC is not suitable for cast on site due to special curing system it needed, so it should be precast in shop and erected in situ. The only two RPC arch bridges, the Sun-Yu Pedestrian Bridge and the Wildbrücke Völkermarkt Bridge, were both built by erecting the precast segments.

In China, the cantilever erection method is very popular in construction of concrete arch bridges. Therefore, cantilever erection method is selected as the construction method in this trial designed RPC arch bridge as shown in Fig. 3.

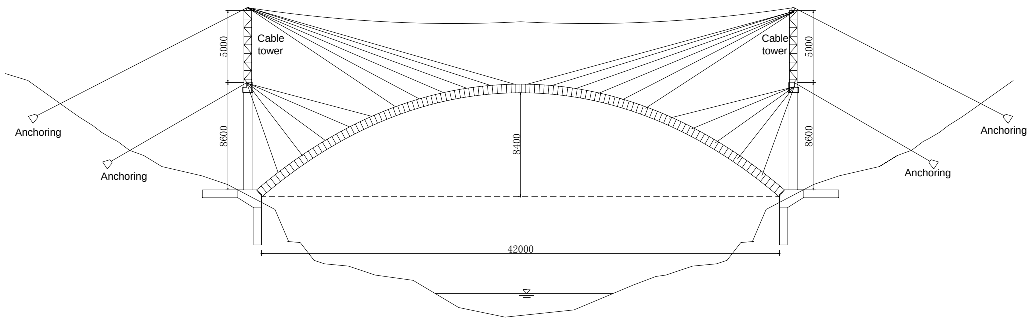


Figure 3 : Construction diagram of the main arch ring in the trial design RPC arch bridge

4 THE CALCULATION AND ANALYSIS OF INTERNAL FORCES IN RPC ARCH BRIDGE

The finite element model of RPC arch bridge was established by MIDAS / CIVIL, the overall force situation under dead load and live load was calculated. According to reference (Wang Yuanyang 2006), the calculation of internal forces in trial Design Bridge and original bridge is compared in Table 3. The results show the axial force and bending moment of every section in trial design is significantly reduced compared with original bridge. Axial force of arch foot is -251489kN, decreased by 31%, axial force of the vault is -193997 kN, reduced by 29% The moment is decreased by 39% and 41%. As the stiffness of arch ring is reduced, additional internal forces generated by change of temperature and shrinkage of concrete is also decreased.

Table 3 Inner forces in the arch ring of the trial design bridge

	Cross sections	Dead load		Temperature change（-30 °C）	
		Ng(kN)	Mg(kN •m)	Nt(kN)	Mt(kN • m)
Trial design	Arch foot	-251489	-109403	1592	-114758
	1/8	-228808	-36894	1774	-34828
	1/4	-208307	3992	1935	19657
	3/8	-196991	47796	2041	51332
	The vault	-1939970	96582	2080	61670
Wanxian bridge	Arch foot	-364200	-178500	2351	-176400
	1/8	-324500	-88900	2655	-55935
	1/4	-295100	-13290	2895	24480
	3/8	-279500	90860	3045	70635
	The vault	-275100	163200	3092	85680

Table 4 shows the design checking results of arch ring section. Two load combinations are considered:

Load combination I: self weight of structure + the vehicle load + pedestrian load + concrete shrinkage + temperature impact (-10°C) (Gu Anbang and Fang Lichu 2002).

Load combination II: self weight of structure + the vehicle load + pedestrian load + concrete shrinkage + temperature impact (-20°C).

From Table 4 it can be seen that the RPC arch ring can meet the design requirement for strength with some larger safety factors (Gu Maoqing and Shi Shaopu 2000).

Table 4 Checking results of the cross-section of the arch ring

Sections	Projects		Axial force N/kN	eccentricity e/m	Resistance Nu/kN	Nu/N
Arch foot	load combination	I	-3336234	1.270	-864501	2.57
		II	-267739	1.612	-755834	2.82
1/8	load combination	I	-327973	0.588	-840932	2.56
		II	-260987	0.696	-831887	3.19
1/4	load combination	I	-279766	-0.524	-849678	3.04
		II	-222296	-0.597	-839280	3.78
3/8	load combination	I	-275315	-0.858	-818544	2.97
		II	-218652	-1.049	-719537	3.29
The vault	load combination	I	-267619	-1.410	-755451	2.82
		II	-221465	-1.648	-683682	3.22

5 THE STRESS CHECKING OF RPC ARCH BRIDGE IN CONSTRUCTION PHASE

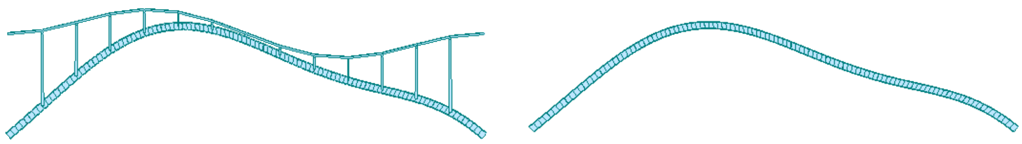
According to the design code, the arch should also be checked from strength to stiffness in its construction phase. Two phases in construction is checked herein. One is the stage when the two half arches has united in the crown, waiting for erection of spandrel structures, which is called as naked arch stage. In this stage though the dead load of the arch is not large, but the bending moment in the arch could be very large caused by the large deviation of the arch axis from the compression line by the uniform self-weight of the arch without spandrel and deck structure after the bridge completed. The second case is the bridge completed with the heaviest self-weight. The calculation results shown in table 5 indicate that the bridge subject to much smaller stress in both top and bottom flange of the arch section than the allowable stress value, moreover all cross sections are in compression without tension stress.

Table 5 Checking results of the arch ring during construction

Projects		Arch foot		1/8		1/4		3/8		The vault	
		Top flange	Bottom flange	Top flange	Bottom flange	Top flange	Bottom flange	Top flange	Bottom flange	Top flange	Bottom flange
Margin yield stress(MPa）	Naked arch	8.39	10.6	13.0	14.8	16.3	15.8	12.8	10.4	9.31	6.35
	The arch bridge	17.1	25.2	18.0	20.5	17.80	17.20	17.8	15.0	19.6	13.0
Concrete Allowable compressive Stress(MPa)		96	96	96	96	96	96	96	96	96	96

6 STABILITY CHECKING

In this paper, the MIDAS / CIVIL software was used to establish a spatial finite element model and to calculate the stability factors under dead load for in-plane buckling (Fig.4) and out-of-plane buckling (Fig.5). Table 6 shows the stability factors of in-plane and out-plane are greater than 4 to 5, and can meet the requirements.



(a) (b)

Figure 4 : In-plane buckling models: (a) Safety factor of Stability 17.02 of arch bridge, (b) Safety factor of Stability 7.11 of naked arch

(a) (b)

Figure 5 : Out-of-plane Buckling models: (a) Safety factor of Stability 22.11 of arch bridg (b) Safety factor of Stability 9.49 of naked arch

Table 6 Checking results of stability

Projects		*[N]*（kN）	*N*（kN）	K= *N/[N]*
In-plane	The arch bridge	269722	1917723	7.11
	Naked arch	109652	1866277	17.02
Out-of-plane	The arch bridge	269722	2559662	9.49
	Naked arch	109652	2424406	22.11

7 CONCLUSION

Taking Wanxian Yangtze River Bridge as the prototype, trial design of RPC arch bridge with a span of 420m was carried out. Analysis results show that much thinner cross section can be adopted due to its high performance and strength of RPC, the self-weight of the rib can be reduced effectively. Compared with original bridge, the weight of arch ring of RPC arch bridge can be reduced about 40%

Compared with original bridge, the internal forces caused by the self-weight reduce efficiently. Axial compressive force at arch spring and crown section are reduced by 31% and 29% respectively; while the bending moment at arch spring and crown section are reduced by 39% and 41% respectively.

Because of reduction of self-weight, cantilever erection method can be adopted in construction of the trial design RPC arch bridge. Compared with original bridge constructed by stiff reinforcement, all of the embedded steel scaffolding, weight of 1500t, would can be saved and make the construction more economic.

The preliminary study in this paper shows RPC arch has great potential application and is worth for further study.

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