New type of concrete arch bridge with corrugated steel webs

B. Chen
College of Civil Engineering, Fuzhou University, 350002, China, E-mail: baochunchen@fzu.edu.cn

Y. Wang and Q. Huang
College of Civil Engineering, Fuzhou University, 350002, China

ABSTRACT: The development and research on long span concrete arch bridge is reviewed. A new type of concrete arch bridge with corrugated steel webs is proposed. The primary results of a trial design, which takes the Wanxian Yangtze River Bridge as prototype, shows that the new bridge type has the advantages on decreasing dead weight of the arch ring, rationalizing construction and shortening construction period. It is a potential bridge type for super- long span concrete arch bridge.

1 A BRIEF REVIEW OF RESEARCH ON LONG SPAN CONCRETE ARCH BRIDGE

Thanks to the greater compression strength of concrete, it is reasonable to use it in arch bridge because arch works essentially in compression. The first concrete arch bridge spanning more than 100 m, the Risorgimento Bridge in Rome, was built about 100 years ago. Along with the rapid development of construction technology and improvement of structural materials, the span record of concrete arch bridges has been refreshing continually. In 1979, the completion of Krk I Bridge in Croatia with the main span of 390m made a miracle at that time in concrete arch bridge. This bridge was constructed by temporary truss method. However, the lengthening cantilever of arch ring undoubtedly increases the difficulty of construction. Currently the KRK arch bridge still ranks as the world's longest arch bridge erected by cantilever-construction method.

Now Wanxian Yangtze River Bridge with span of 420m in China is the longest concrete arch bridge in the world. It was built by embedded formwork comprising a latticework structure of concrete-filled steel tubes (CFST). The scaffolding was erected by cantilever cable-stayed method (Yan and Yang 1997). The concrete was cast in situ ring by ring transversally and section by section longitudinally to avoid overloading of the formwork and hence also very labor consuming. Therefore, these construction methods are only suitable for the countries with very cheap labor costs. Theoretical studies show that limit spans for concrete arches will not exceed those already built (Wanxian- Yangtz, Krk I), especially if complicated construction of these bridges is accounted for, unless the weight of the superstructure is reduced (Radic et al 2005).

Although the long span concrete arch bridge are not built commonly in recent years, research on it is considerably active.

Croatia has technological advantages on construction for long span concrete arch bridge. Recently, a series of conceptual designs for concrete arch bridge with the span range from 432m to 1000m were carried out (Candrlic et al 2001, 2004). In these trial designs, Reactive Powder Concrete (RPC) was applied in the arch rings and other members to decrease structural self-weight. In addition, some valuable discussions about construction and design method were carried out as well.

Japan is a land country. Until Mar., 2003, there were 38 reinforced concrete arch bridges with clean span over 100m in Japan, and another 13 bridges are under construction. The Japan Society of Civil Engineering Institute has carried out the study on reinforced concrete arch bridges spanning 600m, and the research results was published in Design and Construction of Long Span Concrete Arch Bridges -the 600m Class Span in 2003.

The main bridge of Millau Viaduct (France), completed in Dec.2004 and has a span arrangement as 204m + 6×342m + 204m, is a cable-stayed bridge. In its international design bid, the famous Jean Muller International Consulting Engineers Inc. and Alian Spielmann Consulting Architect Inc. proposed to span the river gorge with a 602 m concrete arch in order to avoid the complicated high piers' construction (Muller 2001). Despite this project was not accepted, some conceptions in this proposal have significant meanings for large span concrete arch bridge.

2 CONCEPTION OF CONCRETE ARCH BRIDGE WITH CORRUGATED STEEL WEBS

The basic problem with concrete arch is its construction because it is heavier than steel one. The arch itself does not work until closed at crown and so intermediate structures should be formed during the construction process. One of the effective way to decrease the structural dead-weight is to use light-weight and high-strength material, such as the abovementioned that make use of Reactive Powder Concrete (RPC).

According to compressive strength, RPC can be divided into RPC200 and RPC800. Taking RPC200 as the example, it can achieve high structural behavior, i.e., compressive strength (170 to 130MPa), elastic modulus (40 to 60GPa), fracture energy (20000 to 40000J/m^2). 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 structures. Due to its high flexural and shearing strength, reinforcing steel can be eliminated in RPC structure, and the range of structural shapes and forms can be broadened for the architect and designer. Sun-Yu Pedstrain Arch Bridge, Seol, in Korea with a span of 120m is the first and longest arch bridge in the world using RPC (Huh and Byun, 2005).

However, the bridge using RPC is still on trial. Some special requirements are necessary to get the material properties and strength, such as heat treatment in a vapor-saturated atmosphere (Pierre Y 1999). In addition, the material is inferior to ductility. Therefore, it is worth to carry out further research on RPC before utilizing the RPC material in long span arch bridge.

In order to lighten the arch self-weight, cut down the dimension of abutment and its foundation and simplify the construction procedure, an innovative conception is proposed by author, which substitute the concrete web in arch ring for corrugated steel web.

Corrugated steel plate has been applied in civil engineering structures for a few decades. Many PC box girder bridges with corrugated webs have been built allover the world. Compared with concrete webs, corrugated steel web is much lighter and easier to fabricate and construct. The prestressed forces can be efficiently introduced into the top and bottom concrete flanges due to so-called "accordion effects". In Japan corrugated steel web box girder has been used as the main girder of extradosed bridge and cable-stayed bridge in Rittoh Bridge and Toyota Arrows Bridge, respectively. However, it is the first time to propose concrete arch with corrugated steel web.

3 TRAIL DESIGN FOR CONCRETE ARCH BRIDGE WITH CORRUGATED STEEL WEBS

Taking the Wanxian Yangtze River Bridge as prototype, a trail design of concrete arch bridge with corrugated steel webs is carried out.

It is known that the Wanxian Yangtze River Bridge is a concrete deck arch bridge with total length of 439.35m and deck width of 24m with four traffic lanes and two sidewalks. The arch ring has a three-cell reinforced concrete box section with 16m wide and 7m deep. The arch axis is a centenary curve with a rise-to-span ratio of 0.2. Reinforced concrete spandrel columns from height of 0.93m to 59.94m support the prestressed concrete T-shape deck girders with a constant length of 30.668m.

In this trial design, except substituting the concrete webs of the arch ring for 10mm thick corrugated steel webs, the dimensions and material of the bridge structure are the same with Wanxian Yangtze River Bridge. The corrugated steel web, used Q345 steel type, is disposed perpendicularly to arch axis and connects the upper and lower steel tubes by welding which embedded in the extrados and intrados slabs of the arch box ring. Fig 1 and Fig. 2 show the layout and the arch ring cross section of the trial design.

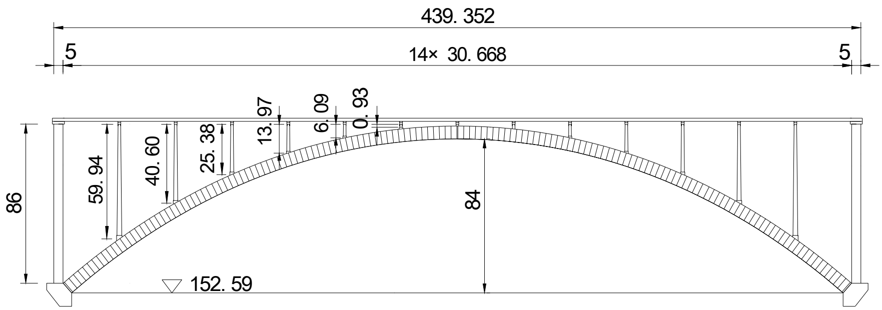

Figure 1 : Layout of the trial design (unit: m)

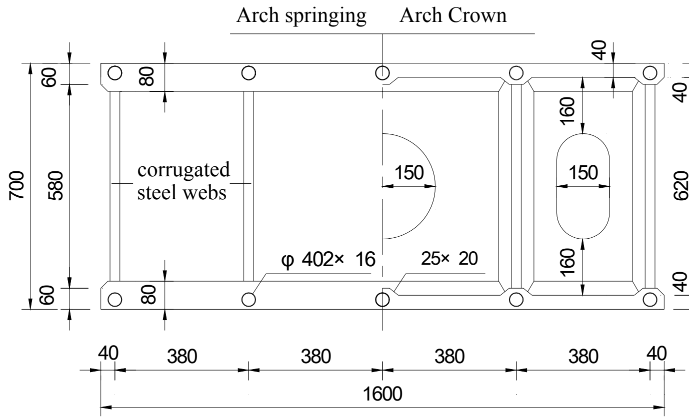

Figure 2: Arch cross section of of the trial designed bridge (unit: cm)

The dimension of the corrugated steel web is shown in Fig. 3. In order to enhance the global performance for arch ring and protect corrugated steel webs from local buckling, 25cm thick transversal diaphragms are set at every 15m interval along the arch.

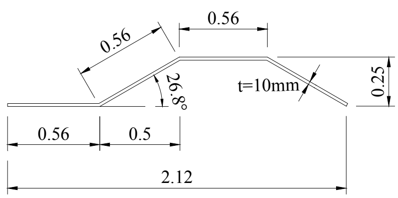

Figure 3:Dimensions of the corrugation profile

The construction method of the trial design is still the embedded CFST scaffolding method used in Wanxian Yangtze River Bridge. Therefore, the corrugated steel webs in the trial designed bridge do not only replace the concrete web but also the web tubular members of the embedded scaffolding in the prototype bridge (Fig. 4).

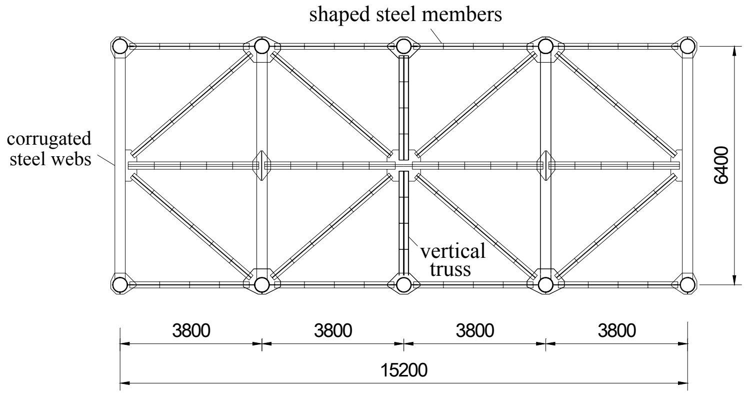

Figure 4 : Cross section of embedded scaffolding

In order to make the fabrication easy, arc axis of the embedded scaffolding is formed by short straight lines of the segments of corrugated webs, each one has a length of 13m. In this way, an angle, less than 2 degree, will exist between two segments inevitably (Fig. 5).

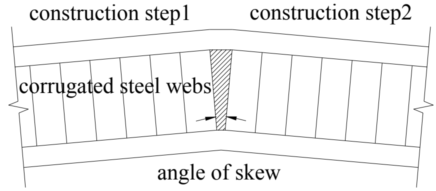

Figure 5:Angle of skew between two web segments

Table 1 compares the material consumption of the arch ring between the trial designed bridge and the Wanxian Yangtze River Bridge. It is worth to note that the concrete weight in arch ring is decreased by 31% by using corrugated steel web, while the steel weight for embedded scaffolding is increased by 19%. But in a whole, it should highlight that the self-weight of arch ring in the trial designed bridge is decreased by 27%.

Table.1 Material consumption of arch rings

Materials	Wanxian Bridge (W)	Trail design (T)	T/W
Concrete(m^3)	11054	7644	0.69
Steel (ton)	2095	2487	1.19
Total weight(ton)	29730	21597	0.73

Similar to Wanxian Yangtze River Bridge, the steel tube truss scaffolding are divided into 36 segments and will be erected by cantilever cable-stayed launching method with cable crane. The maximum weight of one segment is about 69 tons, which is lightly heavier than the 60ton of that in the Wanxian Yangtze River Bridge, but still under the capacity of the cable crane of 70 tons. After its closure, C60concrete is poured into chord tubes to form CFST scaffolding. Then, the top and bottom slabs of arch ring and transversal diaphragms are concreted in situ to form the concrete arch ring.

In Wanxian Yangtze River Bridge, in order to avoid overloading of the scaffolding, the concreting of arch ring was proceeded ring by ring in section with eight phases, including concreting chord tubes, bottom slab of middle cell, lower portion of interior webs, upper portion of interior webs, top slab of middle cell, bottom slabs of exterior cells, exterior webs and top slabs of exterior cells. Each ring was concreted symmetrically in longitudinally by four to twelve steps. It took 224 days to complete this concreting process. But in the trial designed bridge, 70 days is saved in concreting the arch ring because of the corrugated steel web.

4 ANALYSIS OF TRIAL DESIGNED BRIDGE

4.1 Performance under normal loading

Analyses started from the performance under normal loading and both of the 2-D finite element models of the arch ring in the trial design bridge and in the Wanxian Yangtze River Bridge were established. In these two models, the arch rings with embedded scaffoldings were simplified as reinforced concrete arch structures, i.e. steel tubes were considered as reinforcements and the confinement effect of steel tube to concrete core was ignored.

Because of the so-called “accordion effects”, the effective elastic modulus of corrugated steel web is only 1/1524 of that of steel plate. Therefore, the axial and moment stiffness of corrugated steel web in the trail designed bridge are ignored.

Distribution of bending moments in the arch under dead load is shown in Fig 6. Table 2 shows the internal forces in the arches. It is shown that the axial compression under dead load decreased substantially in the trial design, in which the compression and thrust in arch springing were -300800kN and 226753kN respectively, about 17% less than those in Wanxian Yangtze River Bridge. Moreover, additional forces produced by temperature variation and shrinkage effect will decrease with the decrease of arch stiffness. But with regard to the bending moments, there is no obvious change rule in the trial designed bridge. They increase in some sections and decrease in other sections compared with those in Wanxian Yangtze River Bridge.

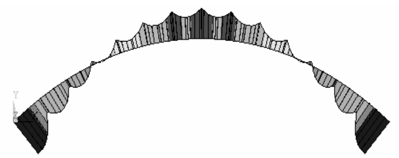

Figure 6 : Distribution of bending moment in corrugated steel webs arch under dead load

Table.2 Internal force in arches

	Sections	Dead Load		Temperature and Shrinkage Effects	
		N_g (kN)	M_g (kN-m)	N_t (kN)	M_t (kN-m)
Trail design	Springing	-300800	-214400	2080	-156560
	1/8	-268800	-83630	2336	-49829
	1/4	-243900	-738	2559	21558
	3/8	-230800	92180	2691	62511
	Crown	-227200	158200	2740	75855
Wanxian	Springing	-364200	-178500	2351	-176400

Bridge	1/8	-324500	-88900	2655	-55935
	1/4	-295100	-13290	2895	24480
	3/8	-279500	90860	3045	70635
	Crown	-275100	163200	3092	85680

Performances of the trial designed bridge under two load cases were checked out as listed in Table 3. The load case I is a combination of dead load, live load and concrete shrinkage effects and load case II is a combination of dead load, live loads, concrete shrinkage effect and temperature effect. It is found that the stress, deflection and stability of the trial design bridge were satisfied to the requirements of the Chinese Code for Design of highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts (JTJ D21-89).

Table.3 Strength calculation for normal-section

Sections	Load Combinations	Compressive Force *N*(kN)	Eccentric Distance *e*(m)	Allowable Compressive Force *Nu*(kN)	*Nu*/*N*
Springing	I	-390045	1.58	-555071	1.42
	II	-313676	1.96	-499193	1.59
1/8	I	-356021	0.55	-370705	1.04
	II	-286670	0.68	-365245	1.27
1/4	I	-313878	-0.47	-373651	1.19
	II	-249082	-0.54	-371168	1.49
3/8	I	-300481	-0.94	-352143	1.17
	II	-238258	-1.15	-338906	1.42
Crown	I	-296785	-1.19	-336324	1.13
	II	-235270	-1.46	-317828	1.35

4.2 Performance during construction

It is proposed to use the embedded scaffolding method to construct the trial design bridge, similar to Wanxian Yangtze River Bridge. The steel tube-corrugated steel web scaffolding (see Fig. 4) is only 9t per unit heavier than that used in Wanxian Yangtze River Bridge, and can be erected by cantilever method with cable crane. After the closure, concrete will filled into steel tubular chords to from a CFST arch with corrugated steel web. Then concreting can be carried out to form the box ring.

In the analysis of the performance of the arch ring during construction from steel arch ring closure to formed concrete ring, a 3-D finite element models of the arch ring both for the trial design bridge as shown in Fig. 7 was developed.

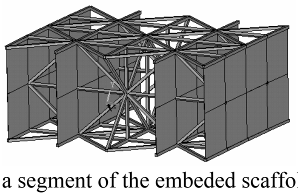

Figure 7 : 3-D FE model of a segment of the embeded scaffolding in the trial design bridge

Analysis results show that the inner forces and the deflections of the embedded scaffolding in the trial design bridge are about 20% larger than those in the proto type bridge when fill concrete is pouring into the steel tubular chords, because the self-weight of the former by replacing the corrugated web to the shaped steel web members is about 19% heavier than the latter's.

If it is divided into eight sections to concreting the upper and bottom slabs to form the concrete arch ring symmetrically from two arch ring sides to the crown, performances of the embedded CFST-corrugated steel web scaffolding can satisfy the design requirements.

4.3 Performance under seismic loading

In order to check the performance under seismic loading, a 3-D finite element model of the whole structure including the arch ring, the spandrel columns and the deck system was established, as shown in Fig. 8.

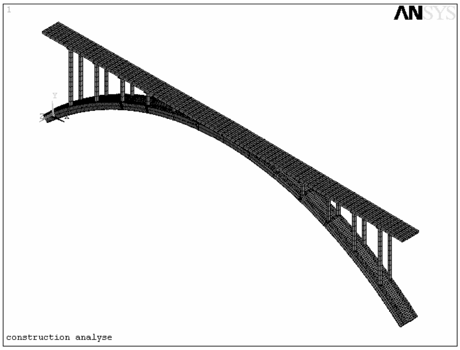

Figure 8 : 3-D FE model of the whole structure

The anti-seismic performance of this new bridge type is analyzed by the time-history method. It shows that by comparing the dynamic and seismic response characteristics with concrete arch bridge with concrete webs, the new bridge type is superior in earthquake-resistance performance. The basic frequencies out-of-plan of the trial design bridge decrease about 14% to those in the concrete arch bridge, while the basic frequencies in-plan do not change too much.

Comparing with the concrete arch bridge--the Wanxian Yangtze River Bridge, the bending moment and the torsion moment are still the dominate forces in the transverse direction of the structure but they decrease about 40% when it subjected to three direction ground motions by EL-Centro Wave without taking phase difference into account. In the direction of the bridge axis, the bending moments and axial forces are dominate ones in concrete arch ring with corrugated steel web and will decrease about 10%--20% to concrete arch ring with concrete web.

5. CONCLUSIONS

A new type of concrete arch bridge with corrugated steel webs is proposed in this paper. A trial design, took the Wanxian Yangtze River Bridge as prototype, shows that self-weight of arch ring is decrease by 27% and 70 days are saved for concreting.

Preliminary analyses by FE method confirm that the trial design of this new bridge type can meet general design requirement during construction and after it completed under both normal and earthquake loading. Further numerical analyses and experimental researches on model arches will be carried out soon. A real bridge adopted this new type bridge is under design now. It is expected that this new type of concrete arch bridge will be applied to mountainous area of China in the near future.

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