Journal of Asian Concrete Federation
Vol. 3, No. 1, pp. 12-19, June 2017
ISSN 2465-7964 / eISSN 2465-7972
http://dx.doi.org/10.18702/acf.2017.06.3.1.12

Technical report

Development and application of concrete arch bridges in China

Baochun CHEN*; Jiazhan SU; Shangshun LIN; Guodong CHEN; Yizhou ZHUANG; and Habib TABATABAI

(Received: December 29, 2016; Accepted: May 20, 2017; Published online: July 05, 2017)

Abstract: The arch bridge is one of the main bridge types utilized in China, and many concrete arch bridges have been built there. Concrete with its high strength in compression and limited strength in tension is an ideal construction material for the arch since its primary internal force is compression. This paper briefly introduces the construction of concrete arch bridges in China in recent years, provides basic statistics on concrete arch bridges worldwide with a span of more than 200 m, analyses the development of concrete arch bridges, and focuses on the Nanpanjiang and Beipanjian Railway Bridges. Furthermore, this study introduces the common construction methods for concrete arch bridges, and describes the recent progress of research on concrete arch bridges using new materials and structures. Finally, future trends in the research and development of concrete arch bridges are discussed including applications of new materials, structures and construction methods.

Keywords: concrete arch bridge, construction method, steel webs, ultra-high performance concrete.

1. Introduction

China is a country with vast mountainous areas that cover 69 % of the country's land area, and is thus well suited for the construction of arch bridges. China has a long history of application of arch bridges as one of its main bridge types. Thanks to its relatively high compressive strength, concrete can be used economically in an arch bridge, which is primarily subjected to compressive forces. Concrete arch bridges in China first appeared in railway applications in the 1940s. In 1965, the Hong-du bridge in Du-an county of Guangxi province reached the longest span of 100 m. According to Chen and Ye [1], there were 199 concrete arch bridges built or under construction with spans of no less than 100 m at the end of August 2007, with 56 of those structures having spans of no less than 150 m. The construction of concrete arch bridges continued thereafter, especially for the high-speed railway networks. With their great development, concrete arch bridges in China have achieved acclaim and prestige worldwide for their structural innovations and construction methods. In this paper, results of an investigation on concrete arch bridges in China are presented. Some typical concrete arch bridges are briefly introduced. New technologies and research on concrete arch bridges in China are summarized, and potential future developments are discussed.

2. Concrete arch bridges in China

2.1 General

As of February 2016, a total of 253 concrete arch bridges in China were built with a span of no less than 100 m, an increase of 54 over the number obtained in 2007 [1]. Among them, 76 bridges have a span of no less than 150 m, or an increase of 20 since 2007. As shown in Fig. 1, the number of concrete arch bridges with a span of no less than 150 m has been increasing since 1965 in China, most significantly in the period from 1993 to 2008.

At present, there are 44 bridges in the world with a span of 200 m or greater, as listed in Table 1 [2–4]. Among them, 11 bridges are in China, accounting for 25%. The current long-span world rec ord belongs to the Beipanjiang Bridge (445-m-long main span, completed in 2016 in China).

Corresponding author B. Chen is a professor in the College of Civil Engineering, Fuzhou University, China.

J. Su is an assistant professor in the College of Civil Engineering, Fuzhou University, China.

S. Lin is an associate professor in the College of Civil Engineering, Fujian University of Technology, China.

G. Chen is a master degree candidate in the College of Civil Engineering, Fuzhou University, China.

Y. Zhuang is a professor in the College of Civil Engineering, Fuzhou University, China.

H. Tabatabai is an associate professor in the Department of Civil Engineering, University of Wisconsin-Milwaukee,

Table 1 – Concrete arch bridges worldwide with a span of no less than 200 m

Rank	Bridge Name	Country	Year	Span (m)
1	Beipanjiang Bridge	China	2016	445
2	Wanxian Yangtze River Bridge	China	1997	420
3	Nanpanjiang Bridge	China	2016	416
4	Krk I Bridge	Croatia	1980	390
5	Almonte Bridge	Spain	Under construction	384
6	Jialingjiang Bridge	China	2012	350
7	Jiangjiehe Bridge	China	1995	330
8	Colorado Bridge	America	2010	323
9	Yongjiang Bridge	China	1996	312
10	Gladesville Bridge	Australia	1964	305
11	Amizade Bridge	Brazil	1965	290
12	Chishi Datong Bridge	China	1997	280
13	Infante D. Henrique Bridge	Portugal	2002	280
14	Bloukrans Bridge	South Africa	1983	272
15	Arrabida Bridge	Portugal	1963	270
16	Fujikawa Bridge	Japan	2003	265
17	Sando Bridge	Sweden	1943	264
18	Chateaubriand Bridge	France	1991	261
19	Tensho Bridge	Japan	2000	260
20	Los Tilos Bridge	Spain	2004	255
21	Wilde Gera	Germany	2000	252
22	Svinesund II	Norway and Sweden	2005	247
23	Sibenik Bridge	Croatia	1966	246
24	Barelang Bridge	Indonesia	1998	245
25	Krk II Bridge	Croatia	1980	244
26	Xiaonanmen Bridge	China	1990	240
27	Beppu-Myouban Bridge	Japan	1989	235
28	Fiumarella Bridge	Italy	1961	231
29	Zaporoze Bridge	Ukraine	1952	228
30	Rio Zezere Bridge	Portugal	1993	224
31	Kyll Valley Bridge	Germany	1999	223
32	Xuguo Bridge	China	2001	220
33	Kashirajima Bridge	Japan	2003	218
34	Tercer Milenio	Spain	2008	216
35	Esla Bridge	Spain	1942	210
36	Lingenau Bridge	Austria	1969	210
37	Xingduicha Bridge	China	2007	205
38	Usagawa Bridge	Japan	1982	204
39	Krka Bridge	Croatia	2004	204
40	Morbihan Bridge	France	1995	201
41	Pfaffenberg Zwenberg Bridge	Austria	1971	200
42	Maslenica Bridge	Croatia	1997	200
43	FuLing Bridge	China	1989	200
44	Ikeda Bridge	Japan	2000	200

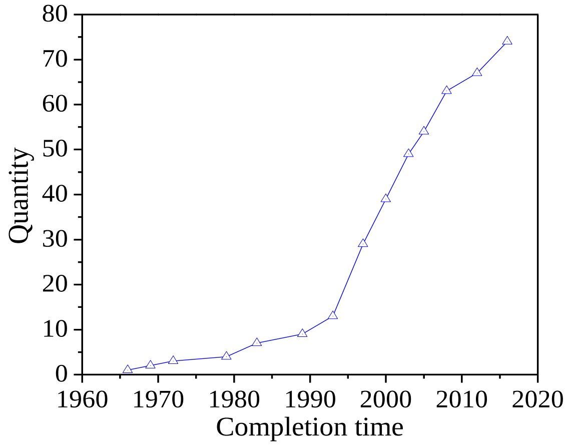


Fig. 1 – Number of concrete arch bridges in China

2.2 Case studies

2.2.1 Beipanjiang Railway Bridge in Guizhou

The Beipanjiang Railway Bridge is located in Anshun City, Guizhou Province. It is the key project of the Shanghai-Kunming high-speed railway, which has a design train speed of 350 km/h. The railway bridge crosses over the Beipan river and has a total length of 721.25 m. The main structure is a concrete arch bridge with a span of 445 m and a rise of 100 m, giving a rise-to-span ratio of 1/4.45. The bridge deck is approximately 300 m above the water surface. The arch axis is in the shape of a catenary. The strength of concrete in the main arch is 60 MPa. The arch cross-section is a box containing three cells, with a constant depth of 9.0 m, but varying in width and wall thickness to improve the transverse stability for the structure. This is important because the width of the bridge deck is only 13.4 m resulting in a small width-to-span ratio in this super-long span arch.

In each adjacent pier, the two 65-m girders are rigidly connected to the pier and form a T-shape rigid frame structure. The overall superstructure is in the form of a (2×65m+8×42m +2×65m) prestressed concrete rigid-frame/ continuous girder with a total length of 599.6m. Such a continuous structure would effectively improve the vertical and transverse stiffness and help assure effective operation of the high-speed train. Each pier and spandrel column has twin members that are connected with bracing. The tallest column has a height of 102m.

The main arch was constructed by the embedded Concrete-Filled Steel Tube (CFST) scaffolding method. The 40-segment, 445-m-span steel tube truss arch was first erected, then hoisted by cable-crane, and erected by the cable-stayed cantilever method [5]. Concrete grade of C80 was injected into the steel tubes after the closure of the steel tube truss arch to make the truss arch a CFST structure, resulting in significant improvement in the stiffness and strength of the trussed arch. Subsequently, the CFST trussed arch was encased in concrete to form a concrete box section arch ring. All the construction works were completed in early 2016 (Fig. 2).

Fig. 2 – Beipanjiang Railway Bridge

2.2.2 Nanpanjiang Railway Bridge in Yunnan

The Nanpanjiang River Bridge is located in Mile City, Yunnan Province (Fig. 3). The main bridge is a concrete arch bridge with a span of 416 m. The arch axis is a catenary curve, with a rise of 99 m and rise-to-span ratio of 1/4.2. The arch ring is a box section with three cells. The depth of the section is constant at 8.5 m, while the width varies from 18 m at the crown to 28 m at the springing. The width of the central cell is unchanged at 9.80 m, while the width of the two side cells is changed from 3.5 m at the crown to 8.5 m at the springing. The concrete arch ring of the bridge was constructed with the same method as that in Beipanjiang Railway Bridge [6].

Fig. 3 – Nanpanjiang Railway Bridge

3. Construction method

3.1 General description

It is well known that the basic problem of arch bridge lies in its construction difficulty. This is because the entire structure is not an arch until the closure is done. With thousands of arch bridges built in China from ancient times till today, almost all the construction methods employed in arch bridges in other countries have been adopted in China. These include the cantilever method, the embedded scaffolding method, the swing method, and the scaffolding method. The scaffolding method is a classical construction method for arch bridges, however, it is seldom used in other countries now due to its high costs. Some innovative construction methods with high prestige have been proposed and developed, such as the horizontal swing method, and the embedded CFST scaffolding method [7].

3.2 Cantilever method

The cantilever method is the most popular construction method for concrete arch bridges. The cantilevered arch ribs are generally cable stayed using temporary pylons, while they are rarely truss cantilevered in China. Among the 50 concrete arch bridges with a span of no less than 150 m, 29 bridges (58%) used cable-stayed cantilever method. Arch rib segments are mostly prefabricated before erection, and then hoisted by cable crane and assembled with stayed cable to form two half arches that are eventually integrated with each other at the crown (Fig. 4). In only a few bridges (such as the Baishaguo Bridge), the cast-in-situ arch ribs were constructed segment-by-segment on the traveling formwork carriage (Fig. 5).

Fig. 4 – Cantilever assembling method in the Modong Bridge in Guangxi

Fig. 5 – Cantilever cast-in-situ method in the Baishaguo Bridge in Sichuan

3.3 Embedded scaffolding method

The embedded scaffolding method for concrete arch was developed from the scaffolding method. This method was invented by Josef Melan at the end of the 19th century and is sometimes referred to as Melan Method. The main disadvantage of this method is the large consumption of steel scaffolding, resulting in increased construction costs. Therefore, it is seldom utilized nowadays even in developed countries with high steel production where steel bridges are popular. To use less steel materials in the scaffoldings, the steel truss arch is generally encased in concrete using complex procedures so that various components can work together to resist loads during each construction phase. Concrete casting procedures should be carefully designed and sufficient time should be provided for each stage. This may complicate the construction sequence and prolong its duration.

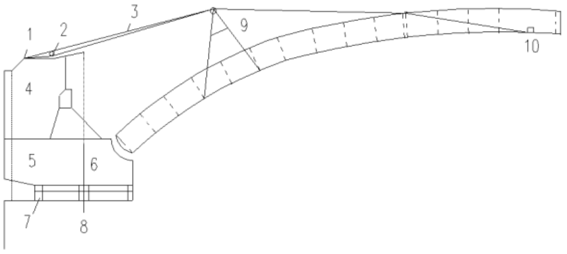
Employing CFST in the embedded scaffolding for concrete arch bridges is a great innovation by China, which is the result of a large-scale construction of long-span concrete arch bridges in recent years. Generally, the self-weight of the steel truss arches is only about 1/15 of the self-weight of the concrete arch ribs. For example, in the Beipanjiang Bridge (445 m), the steel truss arch is 41,800 kN, the concrete in the arch ring is 26,500 m^3 with a weight of 662,500 kN (25 kN/m^3 for concrete), so the steel weight is only 1/15.8 of the concrete weight. For the Nanpanjiang Bridge (416 m), 40,000 kN of steel truss arch is only 1/15 of 600,000 kN of concrete (24,000 m^3).

In the 50 concrete arch bridges with a span no less than 150 m, 13 bridges or 26% used this method. For the five concrete arch bridges with a span no less than 300 m built in the last two decades, all were constructed by the embedded CFST scaffolding method.

3.4 Swing method

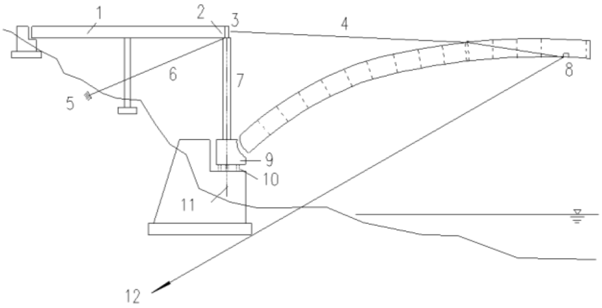
In the swing method, two half arches are fabricated on easy construction position or level, and then they are rotated horizontally or vertically into the design closure position on temporary pivots. The horizontal swing method (Fig. 6) for concrete arch bridge is a special technique only used in China, and it is more often adopted than the vertical swing method. The horizontal swing technique with counterweight abutment was first adopted in 1975 for the construction of concrete arch bridges (Fig. 7(a)). However, this method is limited by the self-weight of the concrete arch ribs when the span is large. Therefore, a swing system without counterweight was developed, in which only the arch ribs on the pivot were rotated to closure (Fig. 7(b)).

Fig. 6 – Horizontal Swing method in Fuling Bridge in Sichuan



1. tail cable; 2. anchor beam; 3. stayed cable; 4. counterweight; 5. upper turn plate; 6. axis; 7. loop road; 8. center support; 9. steel scaffold; 10. anchor slot

(a) With counterweight



1. approach girder; 2. anchor beam; 3. upper shaft; 4. stayed cable; 5. anchor; 6. back cable; 7. vertical prop; 8. anchor slot; 9. upper turn plate; 10. loop road; 11. lower shaft;12. guy cable (traveling rope of arch ring rotation)

(b) Without counterweight

Fig. 7 – Horizontal Swing method

4. Structures and materials

4.1 Application of new structure in concrete arch bridge

Statistics demonstrate that most of the concrete arch bridges in China are made with box sections, with a rise-span ratio between 1/5~1/8 (1/6 is mostly used), and catenary curves are popular for the arch axis.

In China, a series of research projects on new steel-concrete composite arch has been proposed and performed at Fuzhou University since 2003. In a new type arch, the arch box section is composed of upper and lower reinforced concrete flanges and steel webs. The concrete webs in conventional concrete arch structures are replaced by steel web, resulting in a smaller self-weigh for the arch and reduced construction difficulty related to hoisting and concreting. The steel webs can be in the form of corrugated plates, plane plates or tubular trusses.

Trial designs of real arch bridges as well as experimental research on arch models have been conducted (Fig. 8). Research results show that this new type of arch rib can be 30% lighter than the conventional concrete arch while still meeting the design requirements, thus indicating great possibility for application [8].

(a) With steel corrugated webs

(b) With steel plane webs

(c) With steel truss webs

(d) Concrete box arch (for comparison)

Fig. 8 – Experimental models of concrete arches with steel webs

4.2 Application of new materials in concrete arch bridges

Structures made of normal concrete with relatively low strength are heavy, resulting in large consumption of natural resources and energy. There has been a recent trend to apply high performance concrete and ultra-high performance concrete (UHPC) to arch bridges to reduce the self-weight of the structure. UHPC is a cementitious material with super-high compressive strength, high toughness, good durability, and stability, which could be an ideal material to be used in long-span arch bridges. The first pedestrian UHPC arch bridge in the world is the Sun-yu Bridge in South Korea with a span of 120 m, which was completed in 2002 [9]. The second UHPC arch bridge is the Wild Bridge, a 70-m span highway bridge in Austria completed in 2010 [10].

In China, trial designs of UHPC arch bridges with spans of 160 m, 420 m, and 600 m have been carried out to investigate whether the use of UHPC in arch bridges with different spans is economically and technically feasible, and to find out the key issues involved in their construction. This trial design study showed that by utilizing UHPC, much thinner cross sectional elements can be adopted due to the high performance and strength of the material, hence effectively reducing the self-weight of the arch ring and consequently the internal forces caused by the self-weight. This would also facilitate and simplify the construction process [11].

Fig. 9 – Test set-up of the UHPC arch models

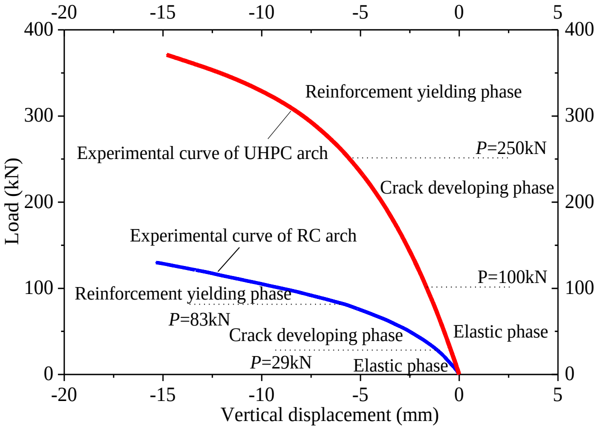


Fig. 10 – Comparison between load-displacement curves of UHPC arch and RC arch models

Experimental research on the behavior of UHPC arch models were performed at Fuzhou University, as shown in Fig. 9. Load-displacement curves, strains, crack patterns, failure modes, and ultimate load-carrying capacity of the UHPC arches were analyzed and compared with results obtained from tests on conventional reinforced concrete (RC) arch models. Except for the concrete material in the models, all other parameters were kept constant. Experimental results showed that UHPC arch models failed due to cracks developing in tensile zones (similar to RC arches). However, the initial cracking load, reinforcement yielding load, and ultimate load-carrying capacity of UHPC arches were 2~3 times larger than the RC arches, as shown in Fig. 10. Moreover, the largest crack width in UHPC arches was only 40% of the corresponding cracks in RC arches. It can be concluded that the UHPC has great technological promise for use in arch bridges [12].

Following these studies, the first UHPC arch bridge in China was built in 2015, which is located on the Fuzhou University campus [13]. The bridge has a span of 10 m, with a rise of 2.5 m, giving a rise-span ratio of 1/4. The arch axis is a segment of a circle with a radius of 6.25 m. The width of bridge is 2.1 m. The main arch ring has a depth of 100 mm, giving a depth-to-span ratio of 1/100. The elevation of the bridge is shown in Fig. 11.

The UHPC in the arch had a design compressive strength of 130 MPa, and was made using high quality local sand from the Min River with particle size of 0.3~0.5 mm (without quartz powder). UHPC for the arch ring was produced in the structural laboratory of Fuzhou University. The arch was constructed by cast-in-situ method with timber formwork as shown in Fig. 12(a) and the completed bridge is shown in Fig. 12(b).

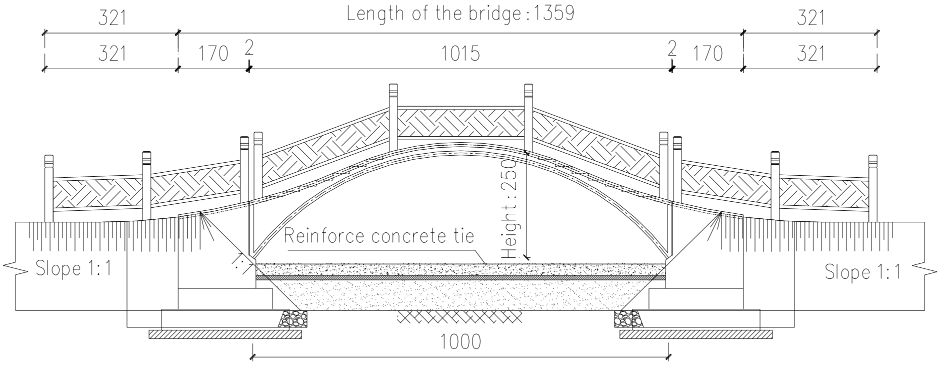


Fig. 11 – Elevation view of the pedestrian UHPC arch bridge in China (unit: cm)

(a) Under construction

(b) Completed

Fig. 12 – View of UHPC arch bridge on the Fuzhou University Campus

5. Conclusions

The investigation reported in this paper indicates that many concrete arch bridges have been built in China. Long-span concrete arch bridges are favored to be adopted in high-speed railway applications in mountain areas nowadays. As of February 2016, there are 253 concrete arch bridges with spans equal to or longer than 100 m, in which 10 of them were longer than 200 m. The present world span record is the 445-m Beipanjiang Railway Bridge in China.

In addition to the conventional scaffolding method, the main construction methods for concrete arch bridges in China are the cantilever method, the embedded scaffolding method, and the swing method. The cable-stayed cantilever method with precast segments is widely adopted in China, while the cast-in-situ method and the cantilever truss method are not commonly used. Using CFST as embedded scaffolding is a great innovation and it is a key technology for the economical construction of long-span concrete arch bridges, which is also the main reason why China has been able to build so many long-span concrete arch bridges in recent years.

Ongoing research ranging from construction methods to structure types allow continuous progress in construction of concrete arch bridges in China. Research on new steel-concrete composite arch structures with steel webs (plates or trusses) may bring a revolution in concrete arch structures in the future.

Trial design and model tests at Fuzhou University have shown that UHPC arches with much thinner cross section can effectively reduce the overall self-weight and make the construction process easier. The first completed UHPC arch bridge in China may provide experience for Chinese engineers to encourage more UHPC arch bridges with longer spans to be constructed in the near future.

Acknowledgements

This work is supported by the National Science Foundation under Grant No. U1305245. The support is gratefully acknowledged. The opinions expressed in this paper are those of the authors and do not necessarily reflect the views of the sponsors.

References

1. Chen, B.C. and Ye, L. (2008) “An overview of long span concrete arch bridges in China,” Proceedings of Chinese-Croatian Joint Colloquium on Long Span Arch Bridges, Brijuni Islands, Croatia, July 10-14, pp. 163-170.
2. Chen, B.C. (2013) “Recent development and future trends of arch bridge,” Proceedings of 7th International Conference on Arch Bridges, October, Trogir-Split, Croatia, pp. 29-46.
3. Savor, Z. and Bleiziffer, J. (2008) “Long span concrete arch bridges of Europe,” Proceedings of 1st Chinese-Croatian Joint Colloquium on Long Span Arch Bridges, 10–14 July, Brijuni Islands, Croatia, pp. 171-180.
4. Chen, B.C.; Gao, J.; and Ye, L. (2007) “Long span concrete arch bridges in China,” Proceedings of the fib Symposium – Concrete Structures – Stimulators of Development, 20–23 May, Dubrovnik, Croatia, pp. 69-76.
5. Xu, Y.; Chen, L.; Xie, H.Q.; and Hu, J.T. (2011) “Design of the Beipanjiang Bridge on the high-speed railway between Shanghai and Kunming,” Proceedings of 3rd Chinese-Croatian Joint Colloquium on Long Span Arch Bridges, 15-16 July, Zagreb, Croatia, pp. 71-82.
6. Xu, Y.; Chen, K.J.; Wei, R.; and Hu, J.T. (2011) “Design of Nanpanjiang Grand Bridge on high-speed railway from Kunming to Nanning,” Proceedings of 3rd Chinese-Croatian Joint Colloquium on Long Span Arch Bridges, 15-16 July, Zagreb, Croatia, pp. 83-90.
7. Chen, B.C. (2009) “Construction methods of arch bridges in China,” Proceedings of 2nd Chinese-Croatian Joint Colloquium on Long Span Arch Bridges, Fuzhou, China, October 5-9.
8. Chen, B.C. and Mou, T.M. (2008) “Research on concrete arches with steel webs,” Proceedings of 1st Chinese-Croatian Joint Colloquium on Long Span Arch Bridges, Brijuni Islands, Croatia, 10-14 July, pp. 189-196.
9. Bum, H.S. and Joo, B.Y. (2005) “Sun-Yu Pedestrian Arch Bridge, Seoul, Korea,” Structural Engineering International, 15(1), pp. 32-34.
10. Sparowitz L.; Freytag B.; Reichel M.; and Zimmermann, W. (2011) “Wild Bridge – a sustainable arch made of UHPFRC,” Proceedings of 3rd Chinese-Croatian Joint Colloquium on Long Span Arch Bridges, 15-16 July, Zagreb, Croatia, pp. 45-70.
11. Chen, B.C.; Huang, Q.W.; and Du, R.Y. (2016) “Research and application of UHPC arch bridges in China,” Proceedings of 4th International Symposium on UHPC and High Performance Construction Materials, Kassel, Germany, pp. 199-200.
12. Chen, B.C.; Du, R.Y.; and Huang, Q.W. (2014) “Experimental study on the ultimate load-carrying capacity of UHPFRC arches,” 6th International Conference of Asian Concrete Federation, 21-24 Sep., Seoul, Korea, pp. 49-53.
13. Chen, B.C.; Huang, Q.W.; Shen, X.J.; and Guo, B. (2015) “Two pilot UHPFRC bridges in China,” Proceedings of the 1st International Symposium of ACF on Ultra High Performance Concrete, 7 October, Klokata, India, pp. 83-92.