Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability

Editors

Joan-Ramon Casas, Dan M. Frangopol
and **Jose Turmo**

International Association for Bridge Maintenance and Safety

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BRIDGE SAFETY, MAINTENANCE, MANAGEMENT, LIFE-CYCLE, RESILIENCE AND SUSTAINABILITY

Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability contains lectures and papers presented at the Eleventh International Conference on Bridge Maintenance, Safety and Management (IABMAS 2022, Barcelona, Spain, 11–15 July, 2022). This e-book contains the full papers of 324 contributions presented at IABMAS 2022, including the T.Y. Lin Lecture, 4 Keynote Lectures, and 319 technical papers from 36 countries all around the world.

The contributions deal with the state-of-the-art as well as emerging concepts and innovative applications related to the main aspects of safety, maintenance, management, life-cycle, resilience, sustainability and technological innovations of bridges. Major topics include: advanced bridge design, construction and maintenance approaches, safety, reliability and risk evaluation, life-cycle management, life-cycle, resilience, sustainability, standardization, analytical models, bridge management systems, service life prediction, structural health monitoring, non-destructive testing and field testing, robustness and redundancy, durability enhancement, repair and rehabilitation, fatigue and corrosion, extreme loads, needs of bridge owners, whole life costing and investment for the future, financial planning and application of information and computer technology, big data analysis and artificial intelligence for bridges, among others.

This volume provides both an up-to-date overview of the field of bridge engineering and significant contributions to the process of making more rational decisions on bridge safety, maintenance, management, life-cycle, resilience and sustainability of bridges for the purpose of enhancing the welfare of society. The volume serves as a valuable reference to all concerned with and/or involved in bridge structure and infrastructure systems, including students, researchers and practitioners from all areas of bridge engineering.

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Bridge Safety, Maintenance, Management, Life-Cycle, Resilience and Sustainability

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Preface

World economy is changing rapidly. On the one hand, issues like health and safety, quality, resilience, sustainability, climate change, social justice and environment are increasing their weight for decision makers compared with traditional pecuniary considerations. On the other hand, the advent of cheap powerful computers, smart phones and robots is changing society drastically and also the economic interactions. And on top of that, COVID came. However, one thing that seems to be stable in this turmoil is the importance given to maintenance and life-cycle evaluation in any infrastructure, making IABMAS (International Association of Bridge Maintenance and Safety) goals more and more relevant for the engineering community. In this context, academics and practitioners are rising to the challenge with research and practice focusing on innovative approaches to identify new problems and to implement solutions. IABMAS conferences bring together academic and technological developments in the fields of bridge safety, maintenance, management, life-cycle, resilience and sustainability, among others, to solve with innovative solutions both new and old problems. The most recent developments in the field are expected to be discussed at the 11th International Conference on Bridge Maintenance, Safety and Management (IABMAS 2022), held in Barcelona, Spain, 11–15 July, 2022 (https://congress.cimne.com/iabmas2022/frontal/default.asp).

The First (IABMAS'02), Second (IABMAS'04), Third (IABMAS'06), Fourth (IABMAS'08), Fifth (IABMAS'10), Sixth (IABMAS'12), Seventh (IABMAS'14), Eighth (IABMAS'16), Ninth (IABMAS'18) and Tenth (IABMAS'20) International Conferences on Bridge Maintenance, Safety and Management were held in Barcelona, Spain, July 14–17, 2002, Kyoto, Japan, October 18–22, 2004, Porto, Portugal, July 16–19, 2006, Seoul, Korea, July 13–17, 2008, Philadelphia, USA, July 11–15, 2010, Stresa, Lake Maggiore, Italy, July 8–12, 2012, Shanghai, China, July 7–11, 2014, Foz do Iguaçu, Brazil, June 26–30, 2016, Melbourne, Australia, July 9–13, 2018 and, online, Sapporo, Hokkaido, Japan, April 11–15, 2021.

In this edition, the venue is located in the city were the first conference of the series was organized twenty years ago, Barcelona, and the format will be again face-to-face. IABMAS 2022 is organized on behalf of the International Association for Bridge Maintenance and Safety under the auspices of Technical University of Catalonia, Barcelona Tech, Spain (https://www.upc.edu/) and Construction Engineering -ConstruTech- research group (https://construtech.upc.edu/en) with the organizational support of the Spanish group of IABMAS. IABMAS encompasses all aspects of bridge maintenance, safety and management. Specifically, it deals with: bridge repair and rehabilitation issues; bridge management systems; needs of bridge owners; financial planning; whole life costing and investment of the future; bridge-related safety and risk issues; and economic and other implications. The objective of the Association is to promote international cooperation in the fields of bridge maintenance, safety and management for the purpose of enhancing the welfare of society (www.iabmas.org). The interest of the international bridge community in the fields covered by IABMAS has been confirmed by the large response to IABMAS 2022 call for papers. The Conference Secretariat received 616 abstracts, 540 of which were selected for presentation at the Conference within mini- symposia, special sessions, and general sessions. Finally, 324 papers were submitted for publication in this volume of proceedings.

Contributions presented at IABMAS 2022 deal with the state of the art as well as emerging concepts and innovative applications related to the main aspects of safety, maintenance, management, life-cycle, resilience, sustainability, and technological innovations of bridges. Major topics include: advanced bridge design, construction and maintenance approaches, safety, reliability and risk evaluation, life-cycle management, life-cycle, resilience, sustainability, standardization, analytical models, bridge management systems, service life prediction, structural health monitoring, non-destructive testing and field testing, robustness and redundancy, durability enhancement, repair and rehabilitation, fatigue and corrosion, extreme loads, needs of bridge owners, whole life costing and investment for the future, financial planning and application of information and computer technology, big data analysis and artificial intelligence for bridges, among others.

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Joan-R. Casas, Dan M. Frangopol and Jose Turmo
Chairs, BARCELONA IABMAS 2022
July 2022

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Moreover, the Editors wish to thank all organizations, institutions, and authorities that offered their sponsorship. A special acknowledgement has to be given to Technical University of Catalonia and Construction Engineering Research Group- ConstruTech-, from UPC for being the lead hosts and organizers of the conference. Also, special thanks go to the International Association for Bridge Maintenance and Safety (IABMAS) and Spanish group of IABMAS for endorsing and supporting the conference organization.

The conference organizers want to deeply thank the entities who support the technical visits of the conference and their personnel: Ferrocarrils de la Generalitat de Catalunya and Pere Mateu and Bernat Bellavista, FC Barcelona and Ramon Ramirez, Sara Flanagan and Jorge Laborda, Port de Barcelona and Ramon Griell, Eduardo Gonzalez and Miguel Angel Pindado. The Editors are also indebted to Enginyeria Reventos, who provided the picture of the cover of the proceedings: The Nelson Mandela bridge, and iconic structure at the Llobregat estuary near Barcelona.

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T.Y. LIN LECTURE

Bridge Safety, Maintenance, Management, Life-Cycle,
Resilience and Sustainability – Casas, Frangopol & Turmo (eds)

Recent development of long-span arch bridges in China

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ABSTRACT: The Lupu Bridge in Shanghai, opened to traffic in 2003 with a 520m span, was the first world-record span arch bridge in China. The span record was superseded by the 552m-span, Chaotianmen Bridge in Chongqing in 2009. These two bridges are steel arch bridges. Concrete filled steel tube arch bridges and steel-frame reinforced concrete arch bridges have high load-carrying capacity, good durability, high stiffness, and are more economical. They are especially suitable for long-span bridges. The cantilever construction method using stay cables without any falsework support is well suited for this type of structures. This method, developed by Professor J.L. Zheng's team, was first successfully employed for the construction of the Sanlijiang Bridge in China in 1968. It has been used for many subsequent arch bridges and is now very popular in China. Concrete filled steel tube arch bridges are very popular in China too. To date, almost 500 of these bridges have been built. Their performance is good and their development has been aided by advancements in design and construction methods such as integrated design and prefabricated construction methods, which accelerated steel truss assembly, and vacuum grouting with shrinkage compensated, high-strength concrete, which addressed concrete debonding inside the steel tubes. These new technologies have significantly advanced bridge construction and have been successfully applied to the construction of many long-span arch bridges in China, including the 575m-span, Pingnan Third Bridge in Guangxi, China, opened to traffic in 2020, and presently the world-record span for arch bridges. To build a steel-frame reinforced concrete arch bridge, a light steel-truss arch consisting of steel-tube members is built first. The concrete arch rib, usually a multi-cell box section, is poured using the steel-truss arch frame as a support. For example, this construction method was used to build the 420m-span, concrete arch bridge in Wanzhou, Chongqing. This bridge, a world record for concrete arch bridges, was opened to traffic in 1997. Now, this method is being used to build the 600m-span, Longtan Bridge in Tian E. When the bridge is opened to traffic in 2023, it will be a new world-record span for an arch bridge. This paper will discuss the development of these arch bridge technologies.

1 INSTRUCTION

Arch is one of the most common shapes in nature. The birth of the arch bridge comes from human observation and practice of natural phenomena. The arch bridge built with natural stone is beautiful, strong and durable, which is widely used in ancient Rome and China. Zhaozhou Bridge built in 618 AD is one of the outstanding representatives. Since modern times, with the invention and application of high-quality artificial materials such as concrete, iron and steel in arch bridges, the span of arch bridges has been increasing rapidly. The concrete arch bridge was born in 1875 and the span of Wanzhou Yangtze River Bridge exceeded 400 meters in 1997. This process has gone through 122 years; the Beipanjiang Bridge of Shanghai-Kunming High-speed Railway built in 2016 raised the span record to 445 m, creating a new world record. At present, the Tian'e Longtan Bridge under construction is upgrading the record to 600 m (Zheng 2019).

Concrete-filled steel tube (CFST) arch bridge chords adopt a concrete-filled steel tube section, which is an excellent composite structure of steel and concrete. Among them, the concrete in the tube

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improves the local stability of the steel tube wall, and the hoop effect of the steel tube enhances the toughness and bearing capacity of the concrete in the tube (Chen et al. 2020). In addition, the steel tube arch truss is light and easy to install, and the concrete in the tube is filled with vacuum-assisted pouring with good quality and fast construction speed. Therefore, in the past 30 years, nearly 500 CFST arch bridges have been built in China. It can also be considered that CFST arch bridges are developed from steel arch bridges. The steel is replaced by cheap concrete partly in the arch ring, which reduces the cost and accelerates the construction of the arch ring. CFST arch bridge originated from the former Soviet Union. Two CFST arch bridges were built in 1937 and 1939. The construction method was that the segmented steel tube was filled with concrete in the precast yard and assembled into an arch on the full support. The structural advantages, construction advantages and economic advantages of the CFST arch bridge were not brought into play. Whereafter, the arch bridge has never been built with this method in the following 80 years (Zheng & Wang 2018). Chinese engineers set up cable-stayed fastening-hanging cantilever assembly and rotation assembly of steel tube arch-truss (Zheng et al. 2018), and vacuum-assisted continuous pouring concrete pipe (Zheng et al. 2013) by using their own technology, which improves the quality of CFST arch bridge, while reduces the cost, shortens the construction period and enhances the competitiveness. Nearly 500 CFST arch bridges have been built in the past 30 years and have maintained a high-speed development trend (see Figure 1 for some CFST arch bridges). The maximum span is 575 m, which exceeds the span of all arch bridges in the world. In China, the number of CFST arch bridges built and the rapid growth of span are rare in the development history of arch bridges in the world. Therefore, it is well-founded to say that the CFST arch bridge with engineering value is developed by Chinese engineers.

The development of CFST arch bridges has also promoted the breakthrough of the span of concrete arch bridges with concrete-filled steel tubular as the rigid skeleton. There are four concrete arch bridges with a span of more than 400 m all over the world, all of which are reinforced concrete arch bridges and were built in China. Three of them were completed in 2016, creating a miracle in the history of the world bridge development (see Figure 2 for some reinforced concrete arch bridge).

2 CONCRETE FILLED STEEL TUBE ARCH BRIDGE

2.1 *Overview*

In 1990, the first CFST arch bridge – Sichuan Wangcang East River Bridge was built in China, then this

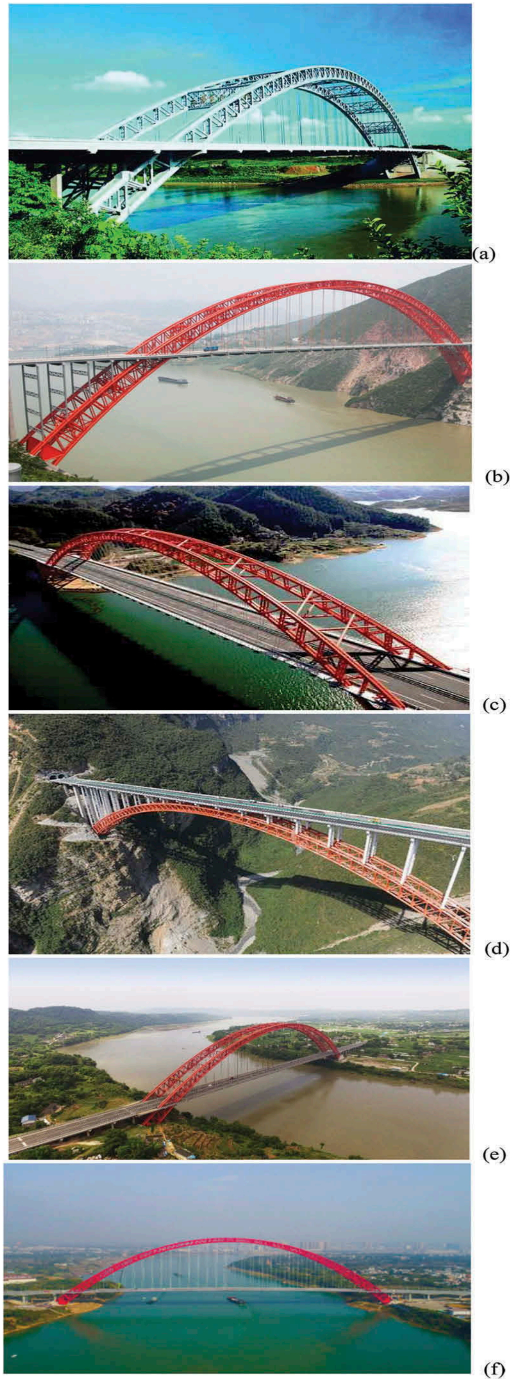


Figure 1. Several representative CFST arch bridges in China. (a) Guangxi San'an Yong River Bridge (main span of 270 m, completed in 1998); (b) Wushan Yangtze River Bridge (clear span of 460 m, completed in 2005); (c) Anhui Huangshan Taiping Lake Bridge (main span of 352 m, completed in 2007); (d) Hurongxi Expressway Zhijing River Bridge (main span of 430 m, completed in 2009); (e) Hejiang Yangtze River First Bridge (main span of 530 m, completed in 2013). (f) Pingnan Third Bridge (main span of 575 m, completed in 2020).

Figure 2. Several representative steel-reinforced concrete (SRC) arch bridges in China. (a) Beipan River Bridge on Shanghai–Kunming High-Speed Railway (main span of 445 m, completed in 2016); (b) Nanpan River Bridge on Yunnan–Guangxi Railway (main span of 416 m, completed in 2016); (c) Yelang River Bridge on Chongqing–Guizhou High-Speed Railway (main span of 370 m, completed in 2016); (d) Wanzhou Yangtze River Bridge (main span of 420 m, completed in 1997); (e) Guangxi Yongning Yong River Bridge (main span of 312 m, completed in 1996); (f) Zhaohua Jialing River Bridge (main span of 364 m, completed in 2012).

type of bridge experienced an explosive application in China, see Figure 3 (Chen & Wang 2009). According to statistics, by the end of 2018, China had built more than 400 CFST arch bridges, of which 70 were over 200 m in span, 19 were over 300 m (See Table 1), 8 were over 400 m, and 3 were over 500 m. Pingnan Third Bridge, which was open to traffic in 2020, is the largest CFST arch bridge in the world at present. Among the CFST arch bridges under construction, the Jinshajiang bridge on Sichuan-Tibet Railway has a span of more than 500m. The maximum span growth of the CFST arch bridge is shown in Figure 4.

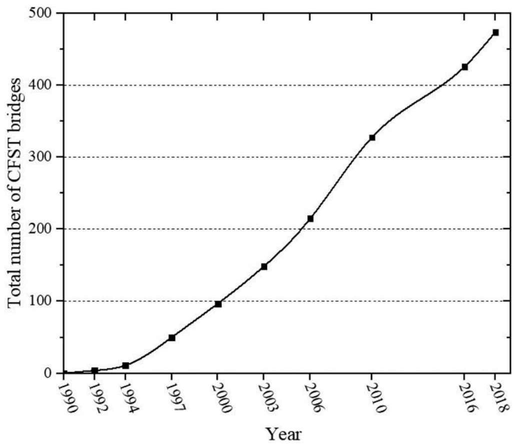


Figure 3. Increase in the total number of CFST arch bridges in China over the years.

2.2 *Installation of steel tube arch truss*

The erection of the steel tube arch truss is the most important stage in the construction of a CFST arch bridge (Afshan et al. 2019). Three methods, including cable-stayed fastening-hanging cantilever assembly, rotation construction, and large-segment lifting construction, have been widely used in China.

2.2.1 *Cable-stayed fastening-hanging cantilever assembly*

In 1968, a Chinese engineer, Jielian Zheng, developed an installation technique of arch bridges utilizing the cable-stayed fastening-hanging cantilever assembly method with closure after loosening the steel wire rope. This method made it possible to construct arch bridges without supporting frames for the first time, and ensured the safety and convenience of the cantilever assembly of the arch ring within five segments and with a span of around 100 m. Due to the simplicity of the fastening-hanging system and the low construction cost, the unit construction cost of a concrete arch bridge with a span of 100 m is equivalent to that of a simply-supported concrete

Table 1. List of Concrete Filled Steel Tubular Arch Bridges Built in China (Span L ≥ 300m).

Number	Bridge name	Type	Built-up Year	Span/m	cross-section	construction method
1	Pingnan Third Bridge	Half through	2020	575	Four - tube truss	Cable swing, cable-stayed fastening
2	Hejiang Yangtze River First Bridge	Half through	2013	530	Four - tube truss	Cable swing, cable-stayed fastening
3	Hejiang Yangtze River Highway Bridge	Flying swallow	2021	507	Four - tube truss	Cable swing, cable-stayed fastening
4	Wushan Yangtze River Bridge	Half through	2005	460	Four - tube truss	Cable swing, cable-stayed fastening
5	Guizhou Daxiao well Super Bridge	Deck arch	2019	450	Four - tube truss	Cable swing, cable-stayed fastening
6	Tibet Yarlung Zangbo River Bridge,	Half through	2020	430	Four - tube truss	Cable swing, cable-stayed fastening
7	Hurongxi Expressway Zhijing River Bridge	Deck arch	2009	430	Four - tube truss	Cable swing, cable-stayed fastening
8	Liangshuigou Bridge	Deck arch	2009	430	Four - tube truss	Cable swing, cable-stayed fastening
9	Xiangtan Liancheng Bridge	Cable-stayed-fly-bird-type	2007	388	Six - tube truss	Cable swing, cable-stayed fastening
10	Zhunshuo Railway Yellow River Bridge	Deck arch	2015	380	Four - tube truss	Cable swing, cable-stayed fastening
11	Yiyang Maocao Street Bridge	fly-bird-type	2005	368	Four - tube truss	Cable swing, cable-stayed fastening
12	Guizhou Zongxi River Bridge	Deck arch	2014	360	Four - tube truss	Cable swing, cable-stayed fastening
13	Guangzhou Yajisha Bridge	fly-bird-type	2000	360	Six - tube truss	Cable swing, cable-stayed fastening
14	Hurongxi Expressway Xiao River Bridge	Deck arch	2009	338	Six - tube truss	Cable swing, cable-stayed fastening
15	Matan Red River Bridge	Half through	2018	336	Four - tube truss	Cable swing, cable-stayed fastening
16	Anhui Huangshan Taiping Lake Bridge	Half through inner basket handle	2007	336	Horizontal dumbbell truss	Cable swing, cable-stayed fastening
17	Nanning Yonghe Bridge	Half through	2004	335	Horizontal dumbbell truss	Cable swing, cable-stayed fastening
18	Chun'an Nanpu Bridge	Half through	2003	308	Four - tube truss	Cable swing, cable-stayed fastening
19	Guizhou Xianghuoyan Super Bridge	Deck arch	2017	300	Heightened six - tube truss	Cable swing, cable-stayed fastening

beam bridge with a span of 30 m. This method has been applied to the erection of the arch rings of over 1000 arch bridges. A good representative of the application of this technology is Changsha Juzizhou Bridge, which is a double-curvature arch bridge over the Xiang River, and was completed in 1972 with a total length of 1250 m and a maximum span of 76 m.

In 1994, another closure technique was developed by Zheng Jielian that utilizes the cable-stayed fastening-hanging cantilever assembly method with closure before loosening the steel strand. This method was used to complete the cantilever assembly of a steel tube arch skeleton with a span of 312 m for the first time. The method uses a lifting jack to deploy and retract the cable-stayed steel strand, thereby achieving millimetre-level precision. The arch is fastened and consolidated segmentally. Closure can be completed in a static state with only three segments, regardless of the number of segments assembled together, making this method suitable for the cantilever assembly of arch bridges with a span of over 100 m. This method has been used to complete the erection of hundreds of the arch rings of arch bridges, including Shanghai Lupu Bridge (main span of 550 m), Hejiang Yangtze River First Bridge (main span of 530 m), the Wanzhou Yangtze River Bridge (main span of 420 m), and the Beipan River Bridge (main span of 445 m) on the Shanghai–Kunming High-Speed Railway.

The two abovementioned methods were simultaneously applied to the Hangzhou Fuxing Bridge (Figure 5), thereby allowing the achievement of a high finishing speed (the closure of one span

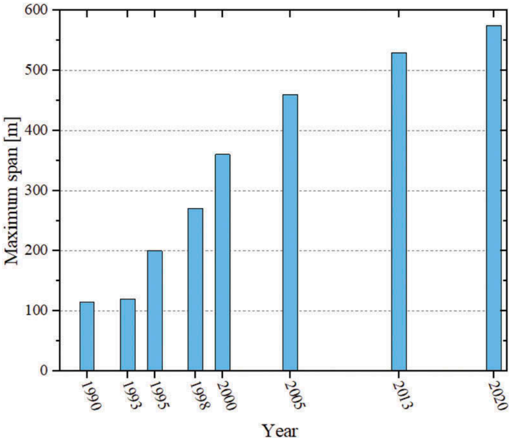


Figure 4. Increase in the maximum span of CFST arch bridges in China over the years.

within two days). These methods also contributed to the accomplishment of erecting a 1376 m long, double-deck bridge with a total area of 70 000 m^2 within two years.

Chen and Yang collected available information on the construction methods of 103 CFST arch bridges and found that 67% of these bridges were constructed with the cable-shifting and cable-stayed fastening-hanging method. Among the 11 CFST arch bridges that have a span of over 300 m, 10 were constructed with this method.

2.2.2 *Rotation construction*

The rotation construction method for arch bridges was developed by Chinese engineer Zhang Lianyan in 1977 and includes horizontal rotation, vertical rotation, and a combination method of horizontal and vertical rotations. To date, the rotation construction method has been used in the construction of more than 70 arch bridges. A typical project using the horizontal rotation construction method is the Beipan River Bridge on the Guizhou-Shuibai Railway, which is a deck-arch type of CFST arch bridge with a main span of 236 m. A typical project using the vertical rotation construction method is the Gui River Third Bridge in Wuzhou, Guangxi, China which has a main span of 175 m. A typical project using the combination method of horizontal and vertical rotations is Guangzhou Yajisha Bridge (Figure 6), which is a half-through rigid-frame CFST arch bridge with a tie. This bridge has a span layout of (76 + 360 + 76) m, a rotation mass of 13850 t, and a horizontal rotation distance of 180 m, all of which still hold the world record. Rotation construction interferes the least with the space under the bridge, does not change the mechanical behavior of the structure in the process of rotation, and has a good safety performance. However, the construction of the rotary system, such as the rotary table, requires a great deal of investment, which hinders the application of the rotation construction method to arch bridges with longer spans (Hu et al. 2014).

2.2.3 *Large-segment lifting construction*

Two steel arch bridges have been constructed with the large-segment lifting construction method. One is Guangzhou Xinguang Bridge, which crosses the Pearl River. This bridge was completed in 2007 and is a three-span continuous steel trussed arch bridge with a span layout of (177 + 428 + 177) m. The two side-spans of the bridge were assembled at the support in situ and then lifted together. The mid-span was divided into three parts, with a mass of 2850 t for the largest piece, and fabricated in the prefabrication field. These parts were then shipped to the bridge site and lifted to the support in order to complete bridge closure using the synchronous hydraulic-lifting technology. The whole process caused only 56 h of navigation delay.

The other bridge constructed using this method is the Third Fenghuang Bridge in Nansha District in Guangzhou, which was completed in 2017. This three-span steel trussed arch bridge with a tie has a total length of 510 m (Figure 7) and a span layout of (61 + 308 + 61) m. The lifting segment has a length of 249.5 m and a total mass of 4690 t, and

Figure 5. Cable-stayed fastening-hanging cantilever assembly of Hangzhou Fuxing Bridge.

was shipped to the bridge site and then lifted in order to complete bridge closure using the synchronous hydraulic-lifting technology.

The large-segment lifting construction method minimizes high-altitude operations, and the stress of the arch truss can be reduced with temporary bracings during the construction, making it possible to increase the length of the lifted segment. In addition, the weight increase in the lifted segment can be solved using more lifting jacks. Therefore, the span of steel arch bridges can be increased further with the large-segment lifting construction method, making it a feasible construction method for super-long-span CFST arch bridges (Zeng & Yang 2013).

Figure 6. Rotation construction of Guangzhou Yajisha Bridge.

(a)

(b)

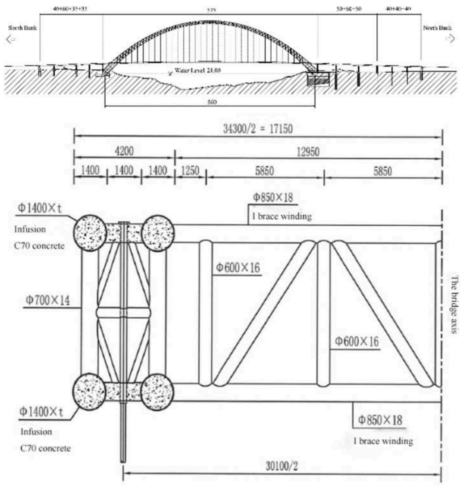
Figure 7. Third Fenghuang Bridge. (a) bridge after completion; (b) large-segment lifting of the main arch rib.

2.3 *Typical engineering examples*

The Pingnan Third Bridge is located in Pingnan County, Guangxi Zhuang Autonomous Region, China. The bridge deck is arranged with 4 motor lanes and 2 non-motor lanes and sidewalks. The span of the main bridge is 575 m, which ranks first among all kinds of arch bridges in the world, as shown in Figure 8(a). Construction began on August 7, 2018, and the bridge was completed and opened to traffic on December 28, 2020. It has achieved zero safety accidents, excellent quality, and lower cost than the approved estimates of the Ministry of Communications of China. During the construction, Guangxi University successfully held a world conference on long-span arch bridge construction technology, where the bridge was highly praised by domestic and foreign counterparts (Chen et al. 2019).

2.3.1 *Design, manufacture and installation of steel tube arch truss*

The main bridge of the Pingnan Third Bridge is a half-through concrete-filled steel tube arch bridge. The effective span is 560 m, the rise-span ratio is 1/4, and the arch axis coefficient is 1.5. The unilateral arch rib adopts a four-tube truss section. The radial height of the vault section is 8.5 m, the radial height of the arch foot section is 17.0 m, the rib width is 4.2 m, the diameter of the main pipe is 1.4 m, and C70 concrete is poured into the tube. The upper chord ‘K’ type transverse brace and the lower chord ‘I’ type transverse brace are used to connect the two ribs to form the main arch ring with a full width of 34.3 m, as shown in Figure 8(b). The main arch-truss and bridge girder are suspended by cable and adopt cable-stayed fastening-hanging cantilever assembly.



(a)

(b)

Figure 8. Main dimensions of Third Pingnan Bridge (a) overall layout (m); (b) arch ring section (mm).

The total mass of the steel structure of the main bridge of Pingnan Third Bridge is 14558 t, which is divided into 44 steel pipe arch-truss segments and 37 bridge deck segments. To take into account the construction efficiency and installation accuracy, the general construction idea of factory manufacturing, water transportation and site installation was adopted. The large-scale, assembly and factory construction are realized. The factory manufacturing proportion of the upper structure reaches 85% (Zheng et al. 2021), as shown in Figure 9.

After the fabrication of the arch truss segments was completed, the segments were shipped along the Xijiang River to the site, and then the cable crane and the cable-stayed fastening-hanging cantilever assembly method is used for installation, as shown in Figure 10. Only the high-altitude connection joints are set in the upper and lower chord pipes, and the internal flange technology of bolting first and then welding is used for the connection (Yu et al. 2020).

Figure 9. Horizontal assemblies of arch ribs.

Figure 10. Suspended assemblies of arch ribs.

2.3.2 *The adjustment and control of rheology performance of in-tube concrete and whole process compensation shrinkage technology*

The total volume of concrete in the main arch tubes of the Pingnan Third Bridge is 7657 m^3, and C70 high-strength concrete is used. Under the conditions of long-distance and large elevation difference, it is a great challenge to the preparation of high-performance concrete in the tube and the short-term and long-term performance control. In this regard, on the basis of vacuum-assisted pressure perfusion technology, we developed the control of rheological properties of concrete in the tube and the whole-process shrinkage compensation technology.

In the aspect of rheological property regulation, slow controlled release and thixotropic robust chemical admixture technology of self-compacting concrete is developed, as shown in Figure 11. On the one hand, the slump loss of concrete in the pipe under high temperature (30 ~ 40 °C) within 3h was controlled within 20%. On the other hand, the segregation rate and bleeding rate ratio were reduced by more than 50%. Combined with the above technology, the continuous perfusion and high density and uniformity of concrete in pipe are guaranteed.

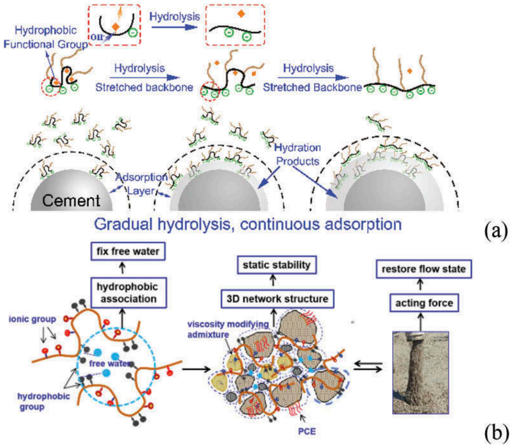


Figure 11. Technology of slow release and thixotropic stable chemical admixtures for self-compacting concrete in tube. (a) Dynamic adsorption dispersion; (b) Hydrophobic association thickening.

In the aspects of whole-process shrinkage compensation, a composite expansion agent which can flexibly compensate different types and sizes of shrinkage was developed. (Li et al. 2018, Liu et al. 2019, Liu et al. 2012a, Liu et al. 2012b, Guo et al. 2013). Specifically, the plastic stage shrinkage is compensated by modified azodicarbonamide, while the surface-coated calcareous expansive material, high-activity MgO and medium to low-activity MgO are used to compensate for the early, middle and late shrinkage of the hardening stage, respectively. The type, occurrence time and magnitude of the shrinkage of the concrete in tube are accurately matched. The expansion time is extended by more than twice, realizing the non-shrinkage of the concrete in the tube at the whole age, see Figure 12.

Thanks to the above rheological property control and the whole-process shrinkage compensation

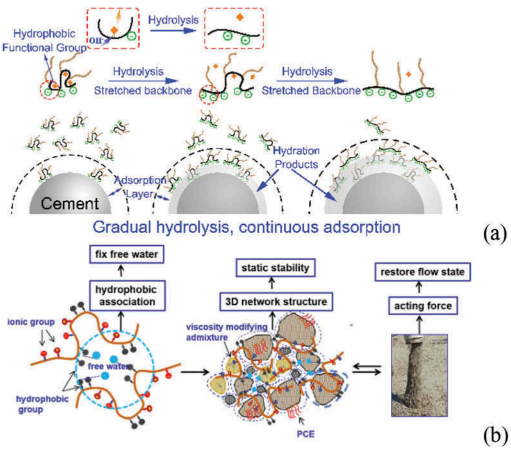


Figure 12. Time-controlled shrinkage compensation technology of concrete in tube. (a) process-controllable composite expansion functional components; (b) volume deformation process of concrete in tube.

technology, the C70 self-compacting concrete without shrinkage tube of Pingnan Third Bridge was successfully prepared. The excellent and good rate of ultrasonic compactness detection of the main tube reached 100%, and the ultrasonic velocities in all directions of all eight main tubes at 270 days were above 4500 m/s, indicating that no debonding and void occurred in the steel tube, and the synergistic force between steel tube and concrete was realized.

2.3.3 *New scheme of thrust arch bridge foundation on plain soft soil foundation*

The Pingnan Third Bridge is located in a mild rolling terrain. The north bank stands over a thick clay and pebble layers. If the bedrock is selected as the foundation bearing layer, it is necessary to spend a large cost for foundation pit excavation. If the pebble layer is selected as the foundation bearing layer, the horizontal thrust at the arch foot is only supported by the base friction and the limited soil behind the foundation, which cannot meet the design requirements. Therefore, in the design process of the Pingnan Third Bridge, the superstructure was optimized and the foundation was innovated.

For the optimization of the superstructure, the weight of the superstructure was reduced as much as possible, and a relative large rise-span ratio was adopted to reduce the horizontal thrust and vertical force generated by the dead load of the superstructure on the foundation, and the action point of the vertical resultant force was adjusted to make the bottom moment of the foundation generated by the horizontal force and the vertical force close to the balance.

In terms of foundation innovation, the new foundation of ‘diaphragm wall encapsulating grouting-reinforced pebble layer’ is proposed, as shown in Figure 13. That is to say, the diaphragm wall is used to penetrate into the foundation rock, and the pebble layer in the diaphragm wall is reinforced by grouting. The overall concrete foundation is placed on the pebble layer so that it can meet the requirements of the foundation of a long-span arch bridge (Zheng et al. 2018).

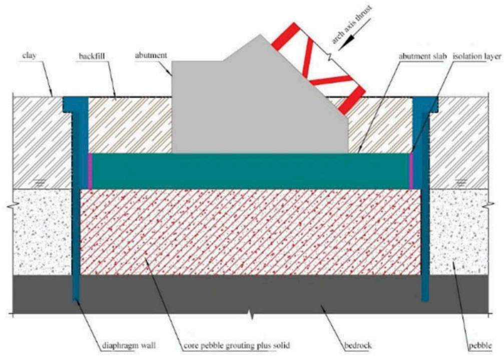


Figure 13. The new composite foundation of ‘circular diaphragm wall + grouting reinforcement pebble layer’.

The composite formation of the new foundation enables three functions of diaphragm wall, including: (1) imposing the hoop effect to the pebble layer and putting it in a triaxial stress state, which can significantly improve the strength, stiffness, and stability of the pebble layer; (2) enlarging the soil bearing area at the foundation back and then increasing the ability of foundation to resist the arch thrust; and (3) acting as earth retaining and water sealing structure in construction and preventing the pebble layer from scouring during the long-term use period.

During the excavation of the diaphragm wall, five pebble layer samples at different elevations are acquired first while excavating the diaphragm wall for laboratory testing on grouting properties. Then 2400 tons of cement is estimated for grouting the 35000 cubic-meters pebbles under the north abutment of Pingnan Third Bridge based on the test results, which is quite consistent with the actual cement consumption of 2300 tons, indicating perfect grouting compactness of the bridge abutment, as shown in Figure 14.

The composite foundation of ‘diaphragm wall encapsulating grouting-reinforced pebble layer’ has many advantages, such as clear load transfer path, high bearing capacity, good integrity and large stiffness. Compared with the excavation of bedrock in the diaphragm wall, the investment is saved by RMB 20 million yuan, the construction period is shortened by 60 days, and the seismic isolation ability is improved by retaining the pebble layer. The basic allowable bearing capacity of the reinforced sandy cobble layer is increased by 0.53 times compared with that before reinforcement, and the deformation modulus is also significantly improved. The calculated settlement of the natural cobble layer is 60 mm, and the measured settlement of 20 months after grouting is only 5.2 mm. The successful

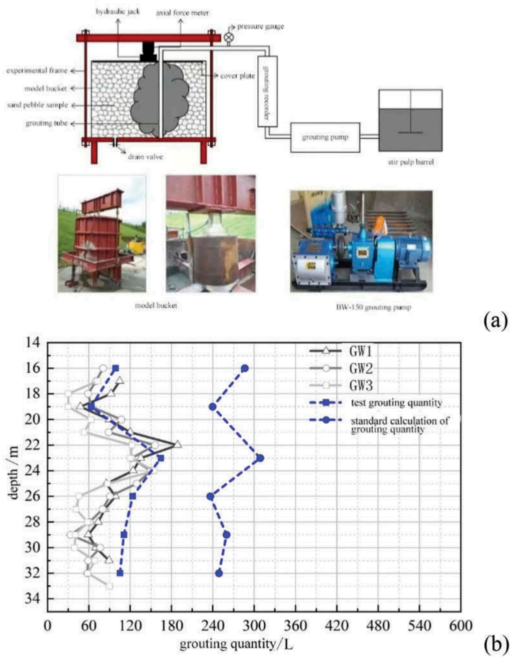


Figure 14. Grouting model test of cobble layer (a) testing apparatus; (b) test results of single pebble grouting amount.

construction of the Pingnan Third Bridge provides a competitive abutment foundation design scheme for long-span thrust arch bridges crossing rivers in hilly areas.

2.3.4 *Active force control and displacement adjustment technology of construction-tower*

In the process of arch rib segment lifting, the horizontal displacement of the construction-tower top is caused by the horizontal force transmitted by the main cable, which leads to the deviation of the arch rib that buckled on it. The traditional countermeasure is to separate the hoisting tower and the buckle tower, or to joint the hoisting tower and the buckle tower to set hinges between them, which can eliminate the influence of the hoisting tower on the buckle tower, but the cost is high. In this regard, we invented the active force control method of tower displacement. The top displacement of the tower is controlled within a centimeter level, which realizes the tower structure slimming and saves the cost. The 200 m-high tower of Pingnan Third Bridge is only 12 m wide along the bridge direction. During the lifting of 200 tons steel pipe arch-truss, the horizontal displacement of the tower top is controlled within ±2 cm.

The system uses the Beidou satellite positioning system to measure the displacement of the tower top. The intelligent jack tension control cable is timely tensioned, without human operation, and a working sequence can be completed in 6 seconds, as shown in Figure 15.

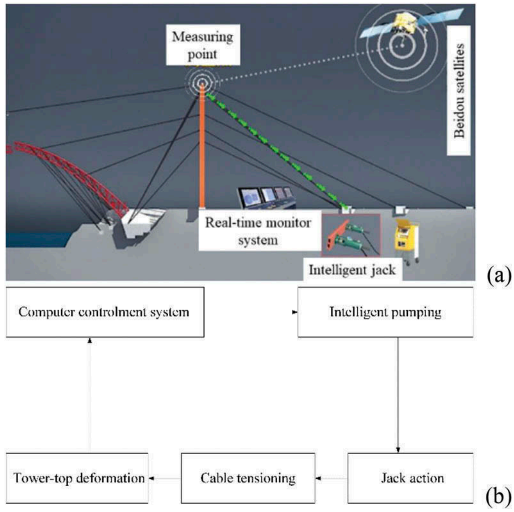


Figure 15. Active control system of tower displacement (a) control principle; (b) workflow.

2.3.5 *Fast one-time tensioning and loosening of buckle cables*

In a cable-stayed installing system, appropriate tensioning and loosening of buckle cables are essential. The urgency grew as a large number of buckle cables are used during the construction of large bridges. Since the traditional cable tension method generally requires multiple cable tensions, the cable force is uneven and varies greatly, a cable force optimization calculation method based on the principle of influence matrix and optimal process and controllable results is proposed. Specifically, taking the displacement difference between the closure pine and the target line shape after the closure of the cable as the constraint condition, and taking the minimum deviation between the line shape and the target line shape in each suspension construction stage as the optimization goal, the optimization model of the cable tension in the one-time suspension construction is established and solved. The solution results are the initial cable force of each group of buckles and the initial elevation of the suspension section to guide the suspension construction (Qin et al. 2020).

For the button rope demolition after closure, the button rope demolition method of gradual loosening and repeated circulation loosening is usually used at this stage, and the buckles demolition of long-span arch bridges is time-consuming. Based on this, according to the analysis of the influence of removing a single buckle cable at different positions on the stress and deformation of the structure, a rapid method of removing buckle cable alternately from the arch foot to l/4 and l/4 to the vault is proposed.

The above optimized construction technologies of buckle cables were applied to the Pingnan Third Bridge to achieve one-time rapid demolition after closure. The maximum deviation of the arch axis of the main arch ring is 10 mm, and the maximum elevation error is 30 mm, which is far below the specification limit of 50 mm. The elevation difference between the two ends of the closure mouth is within 5 mm, and the main arch ring achieves high-precision closure. This not only speeds up the construction and reduces the risk, but also reduces the amount of buckle cable controlled by the maximum buckle cable force in the construction process due to the small change of buckle cable force. Compared with the conventional setting of inclined buckle cable, the amount of buckle cable is reduced by 17.6%.

3 STEEL REINFORCED CONCRETE ARCH BRIDGE

3.1 *Overview*

The steel-reinforced concrete (SRC) arch bridge, also known as the Melan arch bridge, was invented by the Austrian engineer Josef Melan in 1898. To construct this type of arch ring, the stiff steel skeleton is set up first; next, the formwork for casting the outer concrete are fastened onto it. Along with the casted concrete, the steel and concrete form the arch. In the 1990s, Chinese engineers first proposed using the CFST arch to replace the steel arch truss as the stiff skeleton in this type of bridge; the use of a CFST arch in this way reduces the amount of steel used in the stiff skeleton by about half. Among the stiff skeleton concrete arch bridges that have spans larger than 300 m, only the Yachi River Bridge adopted structural steel as the stiff skeleton; all other eight bridges are stiffened with CFST.

The mass of the steel arch truss is only about 1/14 that of the concrete arch ring. Although in-tube concrete improves the load-carrying capacity and rigidity of bridges, a CFST stiff arch skeleton must bear the self-weight of the concrete wrapping the arch ring, which is much greater than the sum of the secondary static load and the live load of the arch ring. Moreover, as the reserve of the initial compressive stress of the concrete in the steel tubular skeleton is small, it is very likely that the instantaneous tensile stress will exceed the allowable stress, making the load adjustment necessary. Chinese engineers have developed a construction method that adjusts the load using stayed cables and that divides concrete in the arch ring by ring and then casts concrete on multi-working platforms in the ring. To be specific, in this method, the concrete in the arch ring is divided into a number of rings, and the concrete is cast ring by ring. After the concrete in one ring has gained sufficient strength and forms a composite structure with a stiff skeleton, the concrete in the next ring is cast. In this way, the load-carrying capacity of the arch ring is increased step by step and the load that is carried by the stiff arch skeleton is reduced. The depth of each ring is calculated to ensure that the structure remains secure after a load of cast concrete is added for each ring or each time. Since it is impossible to finish casting the concrete in one ring at the same time, the instantaneous stress and deformation of the arch during the casting process may be much larger than those that occur after casting is finished. Therefore, casting on multi-working platforms is done to reduce the instantaneous stress and deformation of the stiff skeleton. Load adjustment by means of stayed cables is adopted to maintain the instantaneous stress and deformation within the safe range and to reduce the permanent stress of the CFST stiff skeleton. It has been demonstrated that the construction method for concrete arch bridges that uses a CFST stiff skeleton, as proposed by Chinese engineers, has less risk, a shorter construction period, and a lower cost than the popular construction method that is used in many other countries, which involves suspended-basket grouting on both ends and a stiff skeleton in between.

In 2016, the longest concrete arch bridge in the world, the 445 m Beipan River Bridge on Shanghai–Kunming High-Speed Railway (Qin & Gao 2017), was built in China. Both this bridge and Nanpan River Bridge on the Yunnan–Guangxi Railway, which has a span of 416 m, were originally designed to be built using the construction method of suspended-basket grouting on both ends and a stiff skeleton in between. However, that design was eventually abandoned, after thorough consideration, and was replaced by a construction method that adopted an all-span CFST stiff skeleton, adjusted the load using stayed cables, divided the arch ring into five rings, and simultaneously cast concrete on six working platforms in each ring. This method was eventually shown to be successful. Over the past 30 years, four SRC arch bridges with a span greater than 400 m and nine such bridges with spans greater than 300 m have been built in China. In contrast, the greatest span of SRC arch bridge built in other countries is only 260 m over the past 100 years. This difference in the span is mainly due to the different construction methods adopted.

Chinese engineers developed the cable-stayed fastening-hanging cantilever assembly technology in 1968, the rotation construction method for arch bridges in 1977, and the suspended-basket grouting technology for arch bridges in 2008. Although all three of these methods can be used to construct concrete arch bridges with spans under 400 m, the longest concrete arch bridge that has been constructed using these technologies is only 210 m. The existing concrete arch bridges with spans larger than 300 m are all SRC arch bridges (Table 2). There is a total of four concrete arch bridges with spans longer than 300 m in other countries (Table 3), all of which were constructed with the cantilever assembly or suspended-basket grouting construction technology. In Table 4, the weight of steel tube stiff skeleton in Zhaohua Jialing River Bridge is 1866t, which is 1/14.9 of the concrete weight of the arch ring. The construction period of the bridge is 2 years less than that of the Mike O'Callaghan-Pat Tillman Memorial Bridge in U.S. that using hanging basket casting construction method, and the cost is only 1/8. This is the main reason why the concrete arch bridge with a span of more than 300 m in China does not use hanging casting and hanging assembly.

Table 2. Steel-reinforced concrete arch bridges with spans longer than 300 m in China.

Serial	Bridge Name	Span/m	Weight of steel for Steel Reinforced /t	Volume of concrete /m^3	Weight ratio of concrete to Steel Reinforced	Built year	Cost or bid/billion RMB
1	Shanghai–Kunming High-Speed Railway Beipan River Bridge	445	4 709	26 500	14.2	2016	4.5
2	Chengdu–Guiyang High-Speed Railway Yachi River Bridge	436	11 580	17 140	–	under construction	5.2
3	Yunnan–Guangxi Railway Nanpan River Bridge	416	4 011	24 000	15.0	2016	4.00
4	Chongqing–Guizhou High-Speed Railway Yelang River Bridge	370	5 531	29 370	13.2	2016	—
5	Dali–Ruili Railway Lancang River Bridge	342	5 520	16 800	7.6	Under construction	—
6	Zhengzhou–Wanzhou High-Speed Railway Meixi River Bridge	340	2 545	14 210	13.9	Under construction	—
7	Zhaohua Jialing River Bridge	364	1 866	11 130	14.9	2012	2.08
8	Wanzhou Yangtze River Bridge	420	2 091	11 000	13.2	1997	1.33
9	Guangxi Yongning Yong River Bridge	312	851	4 702	13.8	1996	0.45

Table 3. Concrete arch bridges with spans longer than 300 m in other countries.

Bridge name	Country	span /m	construction technics	Built year
Gladesville Bridge	Australia	305	Precast cantilever assembly	1964
Krk Bridge	Croatia	390	Precast cantilever assembly	1980
Mike O'Callaghan–Pat Tillman Memorial Bridge	United States	323	Suspended-basket grouting	2010
Almonte Viaduct	Spain	384	Suspended-basket grouting	2016

Table 4. Comparison of a steel-reinforced concrete arch bridge and a suspended-basket-grouting concrete arch bridge.

bridge name	span /m	structural style	Construction method	Year of completion	Construction period	Cost/million yuan
Zhaohua Jialing River Bridge	364	CFST stiff-skeleton arch bridge	Stiff-skeleton-based method	2012	3 years	208
Mike O'Callaghan–Pat Tillman Memorial Bridge	323	CFST arch bridge	Suspended-basket grouting	2010	5 years	1670

3.2 *Adjusting the load using stayed cables*

The formula for adjusting the load by means of stayed cables is as follows

$$\Delta\sigma_K = \sum_{i=1}^{n} F_i \cdot \sigma_{Ki} \quad (1)$$

where F_i is the tension force applied to a pair of stay cables originally numbered as i; σ_{Ki} is the stress at section K induced by a unit load applied to the ith pair of stayed cables, which can be obtained with sufficient accuracy using the finite element method or direct field measurement; and $\Delta\sigma_K$ is the stress at section K of the stayed cable.

In a process of continuous concrete casting, σ_{Ki} remains unchanged while the section stress varies with time. When the stress at the critical section exceeds the allowable value, F_i should be adjusted to maintain the combined value of $\Delta\sigma_K$ and the stress of the critical section within the allowable range, and to keep the stresses of the other sections from exceeding the standard value. Based on having the σ_{Ki} decrease with increased stiffness of the arch, the permanent stress at the critical section can be reduced by applying cable force when the stiffness is small, and by removing the force when the stiffness is large. The extent of the reduction in the permanent stress depends on whether the adverse effect on the stresses in the other sections is within the acceptable range.

The effectiveness of adjusting the load by means of stay cables relies on the acting positions of the cables, the magnitude of the cable force, and the timing of the application and removal of the cable force (Zhang et al. 2021). By taking advantage of stayed cables for the cantilever assembly of the stiff skeleton, the load can be adjusted with almost no cost. The concept of adjusting the load by means of stayed cables originated in the construction of the Guangxi Yongning Yong River Bridge and was further developed in the construction of the Nanpan River Bridge on Yunnan–Guangxi Railway.

3.3 *Engineering practices*

3.3.1 *Nanpan River Bridge on the Yunnan–Guangxi Railway*

The Nanpan River Bridge on Yunnan–Guangxi Railway is an SRC arch bridge with a span of 416 m (as shown in Figure 16.), which carries passenger and freight double-track railways. Figure 17 shows the variation in the stress of the concrete in the upper and lower chord tubes of the CFST skeleton during the process of continuously casting the 6795 m^3 concrete of the bottom slab, from the arch foot to the arch crown. It can be seen from Figure 18 that the transient nominal tensile and compressive stresses were 24 MPa and 42 MPa, respectively, and that both occurred at the arch foot; these stresses are much larger than the stresses at the end of casting rings, while the stresses of the other sections were relatively small. The transient stress appeared to be large enough to cause the failure of the arch foot unless some countermeasures were taken. As can be seen from Figure 17, the transient stress can be reduced by simultaneously casting concrete in multiple sections. In addition, installing stayed cables that are inclined upward around the arch foot can effectively reduce the transient stress of the stiff skeleton at the arch foot, without having a significantly unfavorable influence on other sections.

The arch ring of the Nanpan River Bridge on Yunnan–Guangxi Railway, which is encased by a concrete volume of 24 000 m^3, is divided into five sub-rings that were cast by six working platforms. As illustrated in Figure 18, each sub-ring was cast following the given sequence, which included three separate castings. Two groups of stayed cables with a total force of 4000 kN were applied to the arch ring when the bottom slab was cast for the first time, and were later removed after the casting of the three sub-rings (i.e., the bottom slab, web, and top slab of the side box) was completed and the cast concrete had gained sufficient strength. The application of stayed cables increased the compressive stress reserve of the concrete in the upper chord tube by 5.51 MPa, and decreased the permanent stress of the concrete in the lower chord tube by 5.40 MPa.

(a)

(b)

Figure 16. The (a) stiff skeleton and (b) concrete arch ring of the Yunnan–Guangxi Railway Nanpan River Bridge.

Moreover, the allowable tensile stress was never exceeded during the casting.

Without the stayed cables, the maximum tensile stress of the concrete in the upper chord tube would have reached 7.39 MPa during the 35 casting stages, and the compressive stress of the concrete in the lower chord tube would exceed the allowable stress. In practice, due to the limited capability of producing and casting concrete at the construction site, each of the first three sub-rings (i.e., the bottom slab, web, and top slab of the side box) was completed in six castings, whereas each of the two remaining sub-rings (i.e., the top and bottom slab of the middle box) was completed in three castings. The 24 000 m^3 of encased concrete was cast a total of 24 times on the 4000 t CFST arch truss. Table 5 and Figure 19 show the measured and calculated cumulative deformations of the arch truss during the casting of the five segments. It can be seen that the measured deformations of the arch truss were very close to the calculated values.

Figure 20 compares the deflections at the arch top using the proposed casting scheme, which adjusts the load by stayed cables and uses three-time castings and six working platforms with one-time continuous casting from the arch foot to the arch top. It can easily be seen that the proposed casting scheme is much better than the one-time continuous casting scheme.

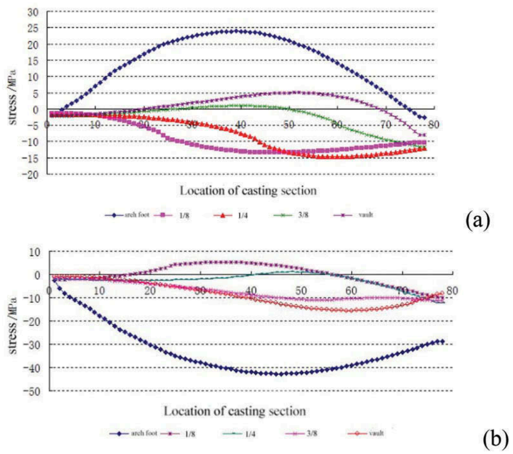


Figure 17. Transient stress of the concrete in the (a) upper and (b) lower chord tubes of the CFST skeleton during the concrete casting of the bottom slab.

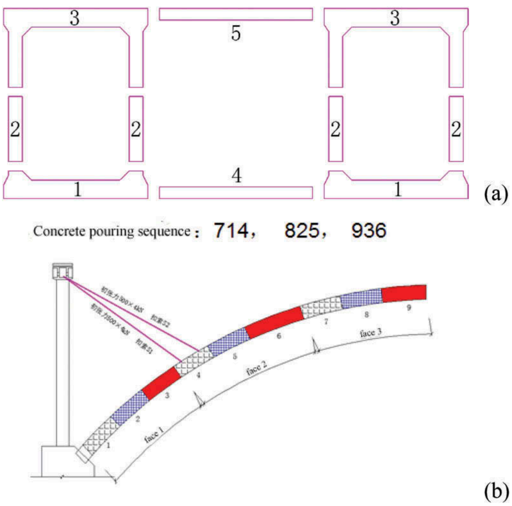


Figure 18. Illustration of the proposed concrete casting scheme for the Yunnan–Guangxi Railway Nanpan River Bridge. (a) illustration of the five sub-rings of the arch ring; (b) illustration of the six working platforms (half).

3.3.2 *The Guangxi Tian'e Longtan Bridge*

Tian'e Longtan bridge, which is the key project of the Nandan-Tian'e local expressway, is a super-long arch bridge under construction in Guangxi, China. The main bridge is an upper-supported steel-reinforced concrete (SRC) arch bridge with an effective span of 600 m, which ranks first among all types of arch bridges in the world. The main arch is composed of two parallel arch ribs, and each arch rib adopts a box-shaped section of equal width and varying height along the length. Specifically, the width of a single rib is 6.5m, and the height of the arch foot section and vault section are 12 m and 8 m, respectively. The traffic beam adopts T-shaped prestressed concrete (PSC) girder with a calculated span of 40 m. Being the longest arch bridge in terms of the main span, a series of technical innovations and breakthroughs have been conducted during the design of Tian'e Longtan bridge, among which the most dominant is the innovation in the method of in-plane bearing capacity calculation and the corresponding longitudinal reinforcement design principle.

At present, the calculation of in-plane bearing capacity of long-span reinforced concrete (RC) arch mainly includes two aspects, i.e., the finite element (FE) analysis of the whole failure process of the integral structure considering the material and geometric nonlinearities (Figure 22), and the approximate calculation of sectional strength based on the equivalent beam-column methodology (Figure 23). Among them, the nonlinear analysis of the integral structure is direct and clear, and the nonlinear stability safety factor is used as the evaluation criterion. In comparison, the sectional strength calculation is consistent with the sectional (or component) strength-based limit state design (LSD) method that is generally adopted in current structural design methodology, thus it can directly guide the reinforcement determination. Moreover, since the threshold of the nonlinear stability safety factor (i.e, 1.75) of the arch in current standards comprehensively considers the load safety factor, material safety factor and working condition factor, it is generally deemed that the above two algorithms should have similar reliability level. However, in the design process

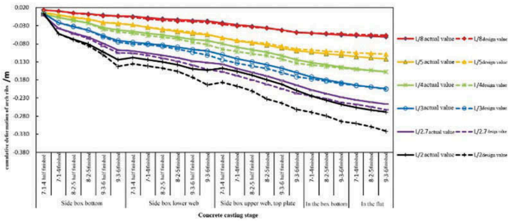


Figure 19. Cumulative deformation of the arch truss during the concrete casting of the Yunnan–Guangxi Railway Nanpan River Bridge.

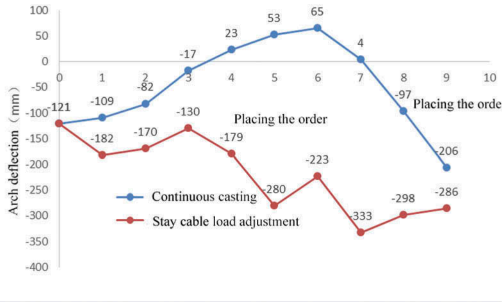


Figure 20. Comparison of the deflection of the arch top between the two casting schemes.

Figure 21. Rendering of Tian'e Longtan Bridge.

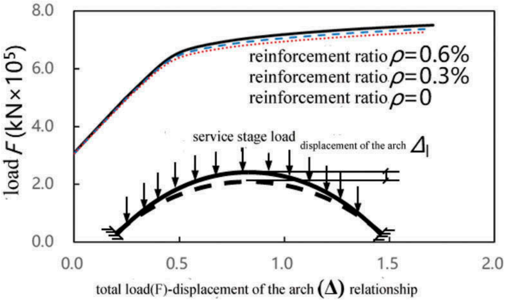


Figure 22. Partial results of dual nonlinear analysis for the bridge.

of Tian'e Longtan bridge and many previous long-span RC arch bridges, it is found that there is generally a great discrepancy between the calculation results of the aforementioned two algorithms. For Tian'e Longtan Bridge, if the bending moment increasing factor calculated by the formula suggested in the current Chinese highway bridge (GB 50923–2013) and culvert design specification is used, the sectional strength checking is difficult to pass, while the whole nonlinear stability safety factor of the structure under the same reinforcement is greater than 2.35, which is much larger than the defined threshold. Considering the reasonability of nonlinear FE analysis (Li 2012), it is preliminarily inferred that the current sectional strength calculation formula needs to be modified.

The calculation method of sectional strength of arch structure based on equivalent beam-column method mainly involves three basic theories and/or methods: the calculated length of arch rib, sectional moment increasing coefficient and sectional strength calculation. Through comprehensive investigation, it is concluded that the methods about the calculate length and sectional strength of arch rib are relatively reasonable. Therefore, the error of this method should be mainly due to calculation deviation of sectional moment increasing coefficient. The existing theories associated with sectional moment increasing the coefficient of RC structures are mostly focused on straight columns. The specific theories mainly include the critical force method and limit curvature method. However, due to the complexity of the problem, the sectional moment increasing coefficient of eccentrically compressed columns given in various standards around the world varies greatly (the maximum is tens of times) (Wei 2005). It shows that even for the relatively simple structure of straight RC column, the calculation theory of moment increasing coefficient is immature.

For RC arches, the secondary effect is much more complex, and it is essentially different from straight columns. Specifically, for the eccentrically compressed straight columns, the moment increasing coefficient is equal to the increased coefficient of lateral deformation, while the bending moment in the arch section is caused by both the horizontal thrust and vertical reaction force at the arch foot. Therefore, its secondary bending moment is affected by both the vertical deformation (corresponding to the lateral deformation of the straight column) and the horizontal deformation. In most cases, the two effects are reversed, i.e, they counteract each other. Therefore, the sectional moment increasing the coefficient of the RC arch is generally small and is significantly smaller than that of the straight column with the same equivalent length. This has also been confirmed by many previous investigations, especially experimental studies. For example, Li carried

Table 5. Measured and calculated cumulative deformations of the arch truss and concrete volume during the concrete casting of the Yunnan–Guangxi Railway Nanpan River Bridge.

Stage of concrete casting		Cumulative deformation of each point /m												Cumulative Concrete volume /m³
		L/8 Measured	Calculated	L/5 Measured	Calculated	L/4 Measured	Calculated	L/3 Measured	Calculated	L/2.7 Measured	Calculated	L/2 Measured	Calculated	
Bottom slab of side box	7-1-4 Half completed	0.013	0.013	0.006	0.006	0.002	0.002	0.004	0.004	-0.001	-0.001	0.003	0.003	1400
	7-1-4 completed	0.010	0.010	0.000	0.000	-0.007	-0.007	-0.021	-0.021	-0.037	-0.037	-0.052	-0.052	2681
	8-2-5 Half completed	0.005	0.004	-0.008	-0.007	-0.016	-0.015	-0.033	-0.031	-0.050	-0.052	-0.067	-0.069	3845
	8-2-5 completed	0.002	0.001	-0.012	-0.011	-0.023	-0.023	-0.042	-0.042	-0.061	-0.065	-0.080	-0.085	4870
	9-3-6 Half completed	-0.001	-0.003	-0.021	-0.022	-0.036	-0.041	-0.058	-0.061	-0.079	-0.086	-0.103	-0.110	5872
	9-3-6 completed	-0.004	-0.004	-0.025	-0.023	-0.042	-0.047	-0.071	-0.075	-0.098	-0.105	-0.124	-0.142	6759
Lower web of side box	7-1-4 Half completed	-0.005	-0.007	-0.028	-0.028	-0.046	-0.052	-0.076	-0.080	-0.100	-0.106	-0.118	-0.135	7446
	7-1-4 completed	-0.008	-0.012	-0.034	-0.034	-0.051	-0.058	-0.080	-0.082	-0.106	-0.112	-0.124	-0.141	8107
	8-2-5 Half completed	-0.011	-0.015	-0.041	-0.039	-0.056	-0.062	-0.084	-0.087	-0.112	-0.120	-0.130	-0.147	8701
	8-2-5 completed	-0.014	-0.018	-0.046	-0.044	-0.062	-0.067	-0.089	-0.094	-0.119	-0.128	-0.138	-0.156	9262
	9-3-6 Half completed	-0.016	-0.019	-0.052	-0.048	-0.068	-0.076	-0.096	-0.103	-0.128	-0.139	-0.149	-0.172	9873
	9-3-6 completed	-0.017	-0.021	-0.054	-0.054	-0.071	-0.083	-0.100	-0.111	-0.132	-0.151	-0.153	-0.193	10428
Bottom slab of middle box	7-1-4 Half completed	-0.023	-0.026	-0.063	-0.064	-0.080	-0.095	-0.110	-0.124	-0.137	-0.157	-0.148	-0.186	11747
	7-1-4 completed	-0.028	-0.031	-0.072	-0.071	-0.090	-0.102	-0.121	-0.133	-0.149	-0.168	-0.156	-0.197	13040
	8-2-5 Half completed	-0.032	-0.034	-0.077	-0.076	-0.097	-0.108	-0.130	-0.141	-0.159	-0.180	-0.166	-0.210	14873
	8-2-5 completed	-0.036	-0.037	-0.083	-0.079	-0.104	-0.113	-0.138	-0.148	-0.169	-0.192	-0.180	-0.232	16362
	9-3-6 Half completed	-0.042	-0.043	-0.092	-0.087	-0.113	-0.123	-0.148	-0.159	-0.181	-0.204	-0.192	-0.244	17966
	9-3-6 completed	-0.049	-0.049	-0.099	-0.095	-0.124	-0.134	-0.160	-0.171	-0.194	-0.217	-0.209	-0.261	19080
Bottom slab of middle box	7-1-4 completed	-0.051	-0.051	-0.103	-0.098	-0.132	-0.139	-0.172	-0.177	-0.208	-0.224	-0.224	-0.269	19818
	8-2-5 completed	-0.053	-0.052	-0.108	-0.101	-0.139	-0.143	-0.180	-0.183	-0.218	-0.232	-0.236	-0.279	20530
	9-3-6 completed	-0.056	-0.053	-0.112	-0.103	-0.144	-0.147	-0.188	-0.190	-0.227	-0.242	-0.247	-0.294	21332
Top slab of middle box	7-1-4 completed	-0.058	-0.055	-0.116	-0.105	-0.150	-0.151	-0.195	-0.195	-0.235	-0.247	-0.256	-0.300	22064
	8-2-5 completed	-0.060	-0.056	-0.119	-0.107	-0.154	-0.154	-0.199	-0.199	-0.241	-0.254	-0.263	-0.309	22703
	9-3-6 completed	-0.061	-0.057	-0.122	-0.109	-0.157	-0.158	-0.204	-0.205	-0.246	-0.262	-0.269	-0.321	23385
Final deviation /cm		-0.4		-1.3		-0.1		0.1		1.6		5.2		

out an arch rib test with a span of 4.5m. According to the measured results, the eccentricity increasing coefficient of the arch foot section calculated by three methods is within 1.05 (Li 2012).

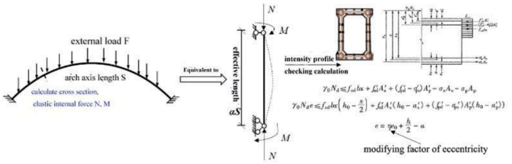


Figure 23. The equivalent beam-column method for RC arch.

In addition, the service conditions of several large-span RC arch bridges built in China could also serve as proof of the above conclusions. Taking Chongqing Wanxian Yangtze River Bridge with a span of 420m and Nanning Yongning Yongjiang bridge with a span of 312m as examples, the longitudinal ordinary reinforcement of the two bridges is significantly less than the calculation results according to the section strength. However, after more than 20 years of operation, the two bridges are in good condition. The few cracks at arch ribs are longitudinal cracks rather than transverse cracks, indicating adequate in-plane bearing capacity of these two arches.

In summary, it is concluded that the calculation methodology of the sectional moment increasing coefficient of an RC structure, especially that of arch structure is still in its infancy. In the meantime, a large number of previous experimental results confirm that the sectional moment increasing coefficient of RC arch should significantly less than the calculation results of the recommended formula in current bridge design standards. The formulas suggested by Li 1992, which is more rational in theory, are finally adopted for Tian'e Longtan Bridge, see equation (2). The calculated sectional longitudinal reinforcement ratio is only 1/16 of the initial design result according to the formula of China highway bridge design specification (GB 50923–2013), the engineering economy and construction feasibility are therefore greatly improved.

$$\text{Section–Arch foot: } \Delta\sigma_K = \sum_{i=1}^{n} F_i \cdot \sigma_{Ki}$$

$$\text{Section–Quarter point: } \psi = \frac{1 - 0.014\gamma}{1 - \gamma} \qquad (2)$$

$$\text{Section–Maximumbendingpoint: } \left(\frac{3l}{16}\right):$$

$$\psi = \frac{1 + 0.121\gamma}{1 - \gamma}$$

Where Ψ signifies an increased coefficient of bias distance. The term γ equals to N/Ncr, where N represents the axial force of the quarter-point section of the arch calculated by the first-order theory, and Ncr denotes the Euler critical force of equivalent beam-column of the arch.

4 CONCLUSION

Although both the CFST arch bridge and the concrete arch bridge with a stiff skeleton can be categorized as steel-reinforced concrete arch bridges, the concrete of the CFST arch bridge is cast into the chord tube without using formwork. For this reason, the CFST arch bridge has the advantage of relatively easy construction, shortened time to construct the arch ring, lower construction cost, and faster increase in the span length. As the largest span arch bridge in the world, the steel tube arch-truss and bridge girder of the main arch of Pingnan Third Bridge are all constructed in large scale, assembly and factory. The concrete in the tube is poured by four-stage vacuum-assisted pressure method, and the formwork-free construction is realized. The proposed new main arch structure and main arch manufacturing, installation and control technology accelerate the construction progress, reduce the construction risk and improve the installation accuracy. Timed shrinkage compensation technology and ultrasonic quantitative analysis method of perfusion density of concrete in chord tubes solved the technical problems of voiding and debonding risk of concrete-filled steel tube in the main arch and the difficulty in non-destructive quantitative analysis of void and debonding degree, and ensured the perfusion quality of concrete in the chords. The abutment foundation design and the construction of 'diaphragm wall encapsulating grouting-reinforced pebble layer' provides a new foundation alterative for a long-span thrust arch bridge on the thick over-burdened foundation in the plain area, and expands the application range of long-span thrust arch bridge. The new mode of informatization and intelligent construction management of long-span arch bridges greatly improves the level of bridge construction management.

The series of innovative technologies have solved many vital technical problems of super-long-span CFST arch bridges, which have good reference significance and value for the construction of similar bridges in the future. It is conducive to promoting the development of CFST arch bridges to a larger span, and also greatly improving the competitiveness of long-span arch bridges with suspension bridges and cable-stayed bridges. Moreover, the increase of the span of CFST arch bridge will inevitably promote the span of concrete arch bridge with concrete-filled steel tube as the rigid skeleton continues to increase. CFST arch bridges with light components and construction without large machinery and SRC arch bridge are more suitable to be built in mountainous areas, and their economic advantages are more prominent when replacing cable-stayed bridges and suspension bridges with much larger spans to cross valleys.

Even though Chinese engineers have achieved success in the design and construction of CFST arch bridges and SRC arch bridges, the existing technologies still cannot meet the needs of the Silk Road Economic Belt and the 21st-Century Maritime Silk Road (Belt and Road Initiative), or those of the fast development of the highways and railways in China. Technology innovations are still needed, for example, for CFST arch bridge, welding robot for improving the fatigue resistance of welded joints; more convenient connection between hanging sections. The inter-ring force transmission mechanism of rigid frame concrete arch bridge, the new calculation method of section bearing capacity and the rapid construction method are also studied. Further, reduce the weight of the stiff skeleton, reduce construction costs and risks, shorten the construction period, improve competitiveness. Both the aforementioned arch bridge types are necessary and may continue to increase the span. At present, we have demonstrated the feasibility of the CFST arch bridge with a net span of 700 m, and look forward to the concrete arch bridge with a span of more than 700 m as soon as possible to obtain greater economic benefits, create a new world record, and continue to lead the development of arch bridges.

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