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REVIEW

Design and construction of super-long span bridges in China: Review and future perspectives

Wei HUANG[a], Minshan PEI[b], Xiaodong LIU[b], Ya WEI[c*]

[a] *Intelligent Transportation System Research Center, Southeast University, Nanjing 211189, China*
[b] *China Communications Construction Company Ltd., Beijing 100088, China*
[c] *Department of Civil Engineering, Tsinghua University, Beijing 100084, China*
[*] *Corresponding author. E-mail: yawei@tsinghua.edu.cn*

ABSTRACT Super-long span bridges demand high design requirements and involve many difficulties when constructed, which is an important indicator to reflect the bridge technical level of a country. Over the past three decades, a large percentage of the new long-span bridges around the world were built in China, and thus, abundant technological innovations and experience have been accumulated during the design and construction. This paper aims to review and summarize the design and construction practices of the superstructure, the substructure, and the steel deck paving of the long-span bridges during the past decades as well as the current operation status of the existing long-span bridges in China. A future perspective was given on the developing trend of high-speed railway bridge, bridge over deep-sea, health monitoring and maintenance, intellectualization, standard system, and information technology, which is expected to guide the development direction for the construction of future super long-span bridges and promote China to become a strong bridge construction country.

KEYWORDS long-span bridges, steel box girder, design technology, construction technology, review and future perspectives

1 Introduction

Bridge is an important part of transportation infrastructure, which can provide a solid support for the country's economic and social development. China has been a big bridge construction country since the ancient times. In recent decades, it has maintained an average annual growth rate of 30000 bridges, which has greatly promoted the development of China's transportation industry. The super-long span bridge, an important indicator reflecting the technical level of building bridge of a country, requires high design criteria and is difficult to be constructed. The construction of the super-long span bridge started relatively late in China. Until the 1990s, with the urgent needs of China's economic development, various types of bridges across rivers, mountains, and trans-oceans were built. For example, Nanpu Bridge, which was built in 1991, has a main span of 423 m, creating a precedent for the construction of long-span cable-stayed bridges of more than 400 m in China. Yangpu Bridge, built in 1993, spans more than 600 m and became the longest cable-stayed bridge in the world at that time. Meanwhile, China's first modern suspension bridge-Shantou Bay Bridge (main span of 452 m) and the first steel box girder suspension bridge-Jiangyin Yangtze River Bridge (span of 1386 m), were completed and open to traffic in 1995 and 1999, respectively. Since then, the construction of super-long span bridges has begun to develop in a blowout style in China.

Since the 21st century, China has become the world center of the construction of long-span bridges. By the end of 2018, there were 140 cable-stayed bridges with a span of more than 400 m in the world, and 83 (3 from Hong Kong) of them were built in China. There were 106 suspension bridges with a span of more than 500 m in the world, and 42 (1 from Hong Kong) of them were built in China. There were 67 arch bridges with a span of more than 300m, and 37 of them were built in China. The above information is from Wikipedia up to the end of 2018. The different types

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of bridges in China that rank top ten in the world, including the cable-stayed bridges, the suspension bridges, the arch bridges, and the sea-crossing bridges, are summarized in Tables 1 to 4, respectively. After being inspired by and learning from the foreign experiences on design and construction of large-span bridge, China has gradually developed the design, construction, and maintenance technology of long-span bridges with independent innovation property rights, which has greatly promoted the development of bridge projects in China and around the world.

The construction of super-long span bridges not only helps to promote the development of the transportation industry, but also presents an important manifestation of a country's scientific and technological levels. The key technologies for the design and construction of China's super-long span bridges in the superstructure, substructure, and bridge deck pavement in the past few decades are summarized in this paper. Additionally, the operation status of China's super-long span bridges and the perspectives on the future super-long span bridges are illustrated.

Table 1 Cable-stayed bridges of China ranking Top 10 in the world

world ranking	bridge name	main span (m)	completed year	award won
2	Hutong Yangtze River Bridge	1092	under construction	First Prize of the 2017 National BIM Application Competition
3	Angchuanzhou Bridge	1018	2009	
4	Edong Yangtze River Bridge	926	2010	
7	Jiujiang Bridge	818	2013	
8	Jingyue Yangtze River Bridge	816	2010	
9	Wuhu Yangtze River No. 2 Bridge	806	2017	2018 George Richardson Award
10	Yachihe Bridge	800	2016	2018 Gustav Lindenthal Award

Table 2 Suspension bridges of China ranking Top 10 in the world

world ranking	bridge name	main span (m)	completed year	award won
2	Nansha Bridge	1688	2019	
3	Xihoumen Bridge	1650	2009	2010 Gustav Lindsall Award of International Bridge Conference, 2014–2015 China Construction Engineering Luban Award
7	Runyang Yangtze River Bridge	1490	2005	
8	Dongting Lake Bridge	1480	2018	
9	The Fourth Nanjing Yangtze River Bridge	1418	2012	

Table 3 Arch bridges of China ranking Top 10 in the world

world ranking	bridge name	main span (m)	completed year	award won
1	Chaotianmen Yangtze River Bridge	552	2009	
2	Lupu Bridge	550	2003	2008 International Bridge and Structural Engineering Association "Outstanding Structure Award"
3	Hejiang First Bridge	530	2013	
7	Wushan Yangtze River Bridge	492	2005	
8	Guantang Bridge	457	2018	
9	Mingzhou Bridge	450	2011	
9	Xijiang Bridge	450	2014	
10	The First Beipan River Bridge (Qinglong Railway Bridge)	445	2016	

Table 4 See-crossing bridges of China ranking Top 10 in the world.

world ranking	bridge name	total length (km)	completed year	award won
1	Hong Kong-Zhuhai-Macao Bridge	50	2018	
2	Hangzhou Bay Bridge	36	2008	
3	Jiaozhou Bay Bridge	35.4	2011	2013 George Richardson Award
4	East Sea Bridge	32.5	2005	
6	Zhoushan Peninsula Project	25	2009	

2 General information on super-long span bridge construction in China

Cable-stayed bridges, suspension bridges and arch bridges are the common structural forms of super-long span bridge structures. The structural forms of these three bridge types and the technological development in the construction of China's super-long span bridges are reviewed in this section.

2.1 Long-span cable-stayed bridge

Cable-stayed bridge is one of the most commonly-used types for long-span bridges. It is mainly composed of cable tower, main girder, and stayed cables. At present, there are more than 100 cable-stayed bridges built in China, and nearly half of them span more than 200 m. According to the different structural forms of the main girder of the cable-stayed bridge, three bridges including Sutong Yangtze River Bridge, Hutong Yangtze River Bridge, and Edong Yangtze River Bridge, were illustrated in details.

Sutong Yangtze River Bridge (Fig. 1(a)) [1] spans more than 1000 m and has been in service for more than 10 years, which is a double-tower steel box girder cable-stayed bridge with a seven-span continuous beam structure. The main span of Sutong Yangtze River Bridge is 1088 m. It is the second longest cable-stayed bridge in the world. The pylon is 300.4 m in height and the cable is 577 m in length, which used to be the first in the world. The technological innovations have successfully solved the problems of wind resistance, earthquake resistance, collision avoidance of the main structure, super large pile foundation construction, as well as ultra-high steel-concrete pylon design. It won the 2008 George Richardson Award and the 2010 American Society of Civil Engineers Outstanding Engineering Achievement Award.

Hutong Yangtze River Bridge (Fig. 1(b)) [2] will be the world's first highway and railway dual-purpose cable-stayed bridge with a span of more than 1000 m in the world when its construction is completed soon. It is also the world's largest highway and railway cable-stayed bridge with a main span of 1092 m. It has structural forms of two towers, three cable sections, and steel truss girder. The main tower is 325 m high and adopts an inverted "Y" shape. The main tower foundation adopts a rounded rectangular sinking foundation scheme with a plane area of 5100 m^2, which is the largest bridge caisson structure in the world. The main girder uses the newly developed Q500qE high-strength steel; the main channel bridge uses the bridge rail temperature regulator and telescopic device with the available deformation of 2000 mm, which is adopted for the first time in the world.

Edong Yangtze River Bridge [3] (Fig. 1(c)) is the second largest hybrid-girder cable-stayed bridge built in the world. The main span is 926 m. The middle span is made of steel box girder and the side span is made of concrete box girder of the same shape. The steel-concrete joint section is 8.5 m long, located in the mid-span close to the root of the tower. The mixed girder joint section is the transitional structure of the steel girder to the concrete girder. The joint section adopts the multi-grid force transmission structure of the PBL shear connector. The bridge also adopts the life design concept, both the reinforced concrete durability and the steel structure anti-corrosion design are carried out, and the

(a) (b) (c)

Fig. 1 (a) Sutong Yangtze River Bridge; (b) Hutong Yangtze River Bridge; (c) Edong Yangtze River Bridge.

inspection and maintenance passages of the main components of the bridge are set up. The life cycle cost design is realized for the first time in the construction of large-scale bridges in China.

2.2 Long-span suspension bridge

Suspension bridge is also one of the main structural forms of super-long span bridges. It is mainly composed of suspension cables, bridge towers, booms, anchors, and rigid girders (stiffening girders). Since its invention in the early 19th century, it has been widely used in the construction of super-long span bridge structures. It is mainly applied for the bridges that currently span more than 1000 m. In the mid-1990s, Guangdong Shantou Bay Bridge started the construction trend of China's modern long-span suspension bridge. After that, the spanning capacity of the Chinese suspension bridge was continuously improved. Jiangyin Yangtze River Bridge (Fig. 2(a)), which was completed in 1999, is the first suspension bridge with main span of over 1000 m in China. By the end of 2018, there were 31 suspension bridges with span of more than 1000 m under construction or completed in China, with the total number ranking first in the world.

Xihoumen Bridge, as an important part of the Zhoushan mainland island link project (Fig. 2(b)) [4], is the first suspension bridge with a split-type steel box girder in the world, which adopts a two-span continuous steel box girder structure, and the span layout is 578 + 1650 + 485 m. It has the second longest span and the first longest steel box girder length among suspension bridges built in the world. The split-type steel box stiffening girder scheme used in Xihoumen Bridge has significantly improved the performance of flutter stability, which can resist super typhoon with wind force scale of 17. It has successfully stood the attacks from the two typhoons during construction, created a precedent of long span steel box girder suspension bridge in the areas with powerful typhoon in China. This bridge won the International Association of Consulting Engineers Fidick 2015 Outstanding Engineering Project Award.

Haicang Bridge (Fig. 2(c)) [5] is a three-span continuous full-floating steel box girder suspension bridge. The main bridge is 1108 m long (230 + 648 + 230 m). It is the first large-scale bridge for landscape design in China. Based on a shape of curvature, the integration of the bridge and the natural environment in many aspects were considered.

Taizhou Yangtze River Bridge (Fig. 2(d)) [6] is the world's first three-tower double-span steel box girder suspension bridge with a main span of 2 × 1080 m. Compared to the traditional two-tower suspension bridge, the three-tower and two-span suspension bridges are connected by adding a middle tower to realize the continuous arrangement of the structure, and the middle tower is designed to bear the difference in the force of the two main cables caused by the live load. In addition, Taizhou Yangtze River Bridge set the first record in the world in four aspects: 1) the tower uses the "Y"-shape in the transverse direction, and "portal"-shape steel tower in the longitudinal direction; 2) the middle tower foundation is buried in a depth of 70 m, which is the first in the world, because of the W-shaped and soft riverbed section; 3) first

(a) (b) (c) (d)

Fig. 2 (a) Jiangyin Yangtze River Bridge; (b) Xihoumen Bridge; (c) Haicang Bridge; (d) Taizhou Yangtze River Bridge.

adopted the W-shaped main cable with an erection of 3117 m; 4) the construction of the two-span steel box girder is synchronously and symmetrically hoisted. In 2014, Taizhou Yangtze River Bridge won the Outstanding Structural Engineering Award by the International Federation of Consulting Engineers.

2.3 Long-span arch bridge

Arch bridge structure in China has a history of more than 1000 years. Zhaozhou bridge built in 605 and Lugou bridge built in 1192 are in the form of arch bridges. In recent years, arch bridges are mainly built to cross rivers and mountains. The world's largest steel arch bridge — Chaotianmen Yangtze River Bridge with the main span of 552 m, and the world's largest span concrete-filled steel tube arch bridge- the First Hejiang Bridge with main span of 530 m, have been successively built, which significantly improved the technical level of arch bridge in China.

Lupu Bridge (Fig. 3(a)) [7] spans 550 m and maintains the world record for the longest arch bridge over 6 years. Lupu Bridge is a steel box arch bridge that was completely connected by welding for the first time. They are ranked top in the world in terms of the length of the welding in the main bridge, the weight of the ribs to be hoisted, the amount of steel used, the length of the horizontal tie line, and the tonnage of the tension. Lupu Bridge won the 2008 Outstanding Structural Engineering Award by the International Federation of Consulting Engineers.

To the end of 2018, Chaotianmen Yangtze River Bridge (Fig. 3(b)) [8] is the completed arch bridge with the longest span in the world, and is also an important milestone in the application of steel truss structures in the super-long arch bridges. Chaotianmen Yangtze River Bridge is designed as three spans of 190, 552, and 190 m, respectively. It is a mid-supported steel truss tied arch bridge, and has double decks with the upper deck used for a two-way six-lane driveway and sidewalks on both sides, and with the lower deck equipped with two-way urban rail transit. The entire bridge is arranged with upper and lower tie rods. The upper layer adopts the "H" section steel tie rod, and the lower layer adopts the "王" section steel tie rod and the external prestressed cable. During the construction, it overcame eight problems such as severely broken water-bearing rock foundation construction, 552 m span steel arch cantilever assembly construction, high-strength bolt construction control in high temperature and high humidity environments, steel truss arch, and rigid tie rod geometric closure control.

Nanjing Dashengguan Yangtze River Bridge (Fig. 3(c)) [9] is a high-speed railway bridge, which can meet the railway design requirement of a speed of 350 km/h. It is the control project of Beijing-Shanghai high-speed railway, reaching the world-leading in its large volume, long span, heavy loads, and high speed. The total length of the bridge

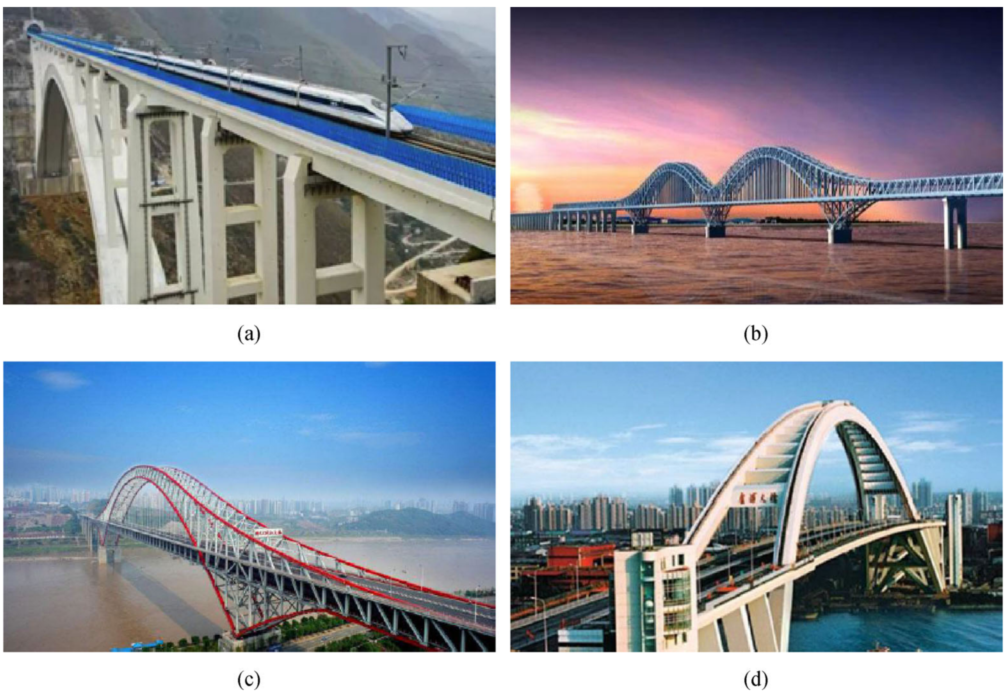


Fig. 3 (a) Lupu Bridge; (b) Chaotianmen Yangtze River Bridge; (c) Nanjing Dashengguan Yangtze River Bridge; (d) Shanghai-Kunming High-speed Railway Beipanjiang Bridge.

is 9.27 km, the main bridge is a 6-span continuous steel truss arch bridge with a main span of 2 × 336 m, and it is the longest high-speed railway bridge in the world. In 2015, Nanjing Dashengguan Yangtze River Bridge won the Outstanding Structural Engineering Award by the International Federation of Consulting Engineers.

Shanghai-Kunming high-speed railway Beipanjiang Bridge (Fig. 3(d)) [10] has the longest span both as reinforced concrete arch bridge in the world and high-speed railway bridge in China. It can meet the design requirement of high-speed railway operation with a speed of 350 km/h The bridge has a total length of 721 m and the main span is 445 m. The First Beipan River Bridge goes across the river with only one span. It has innovations in the structural form as well as construction process, which combines the characteristics of arch bridges, cable-stayed bridges, and continuous beam bridges. In addition, The First Beipan River Bridge has solved the technical problems of constructing ballastless track on long-span arch bridge, and controlling long-span bridge stiffness, especially the use of C80 concrete steel tube arch structure which is first created in China. In 2018, The First Beipan River Bridge won the Gustav Lindsal Award.

3 Design technology of super-long span bridges in China

3.1 Life-cycle design theory

In the early stage of the construction of large-span steel bridges, bridge design theories around the world often pay attention to construction technology and structural safety. Few designs related to the management, maintenance, component renewal and demolition of bridges, with the investment costs considered only during the construction period [11]. The second generation of bridge design theory adopts reliability theory to evaluate the service life of bridges to achieve structural durability design. However, there are still problems such as poor eco-friendliness and inability of material components to meet life cycle durability requirements. To improve the performance of the bridge, the United States, Japan, Finland, and other countries have begun to pay attention to the design of the full life cycle of long-span steel bridges, including life cycle cost, ecological friendliness, and structural safety, etc [11]. After summing up experiences from both China and other countries, the bridge design in China has stepped into the third-generation with the engineering service life design concept which is composed of the analysis of life cycle cost, green transportation, and structural performance [11].

The concept of life cycle design is the inevitable trend of bridge construction. Chinese scholars have carried out researches on such aspects as life-cycle design method based on structural details [12], life-cycle maintenance and risk assessment [13,14], life-cycle cost calculation, and life-cycle concept-based bridge management [15,16].

3.2 Superstructure design

For long-span steel bridges, their superstructures generally include stiffening girder (steel box girder or steel truss girder), bridge deck pavement, cable towers, cable systems, and ancillary facilities.

3.2.1 Design of steel box girder

Steel box girder, also known as steel plate box girder, is generally composed of top flange, bottom flange, web stiffener, and transverse and longitudinal diaphragms. The general connection method of these parts is through welding. Steel box girder is a common structural form of large-span steel bridge stiffening girders. Steel box girders span hundreds or even over one thousand meters, and are often divided into sections that are prefabricated and hoisted together. Since 1958, when George Stephenson first proposed the thin-walled closed section bridge and presided over the construction of the world's first metal structure box girder bridge, the steel box girder bridge has been developing rapidly worldwide. China began to build long-span steel box girder bridges sine 1990s.

3.2.1.1 Steel box girder overall design

The cross-section of steel box girder can be either single-box girder or double-box girder, as illustrated in Fig. 4. The Sutong Yangtze River Bridge and the Jiangyin Yangtze River Bridge both adopt the form of single-box steel box girder [17,18], and the Xihoumen Bridge adopts a double-box stiffening girder [19].

The flat steel box girder is composed of a top flange, inclined web, and bottom flange by welding to form a closed streamlined thin-walled box structure. Transverse diaphragms are arranged along the longitudinal direction of bridge inside the box body. Sometimes longitudinal diaphragms are used, which are arranged along the transverse direction of bridge. The top flange, the inclined web, and the bottom flange are all orthogonal plate structures. In general, flat steel box girders achieve their wind resistance through large flatness, wind deflecting angles on both sides, and wind-resistant splitter plates. The dimensional design of steel box girders of some bridges in China is shown in Table 5.

3.2.1.2 Orthotropic steel bridge deck design

The orthotropic steel bridge deck is composed of a top plate, transvers cross-beams and longitudinal stiffeners.

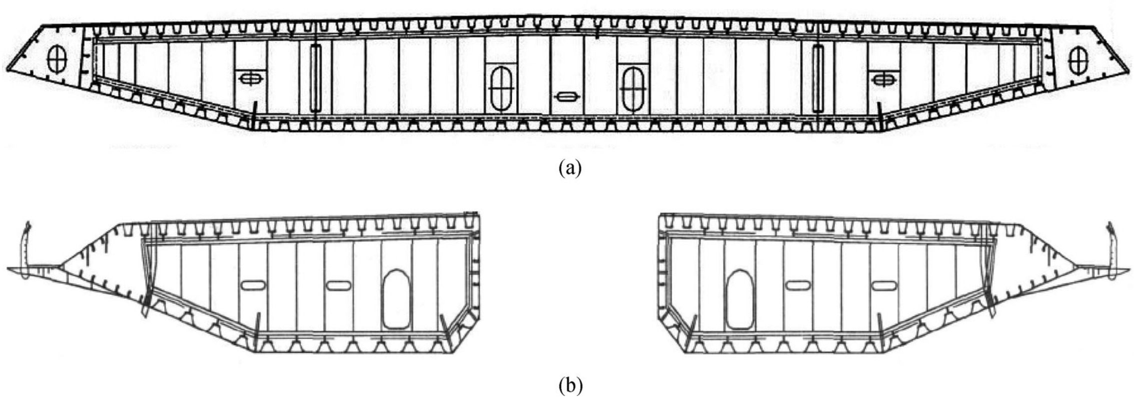


Fig. 4 Design of the steel box girder cross-section: (a) single-box girder and (b) double-box girder.

Table 5 Design parameters of steel box girders of the representative bridges in China [17–24]

bridge name (completed year)	bridge type	main span (m)	design parameters of stiffened steel box girder				
			height (m)	width (m)	deck thickness (mm)	longitudinal stiffener type	transverse diaphragm spacing (m)
Humen Bridge (1997)	suspension bridge	888	3.0	33.0	12	U	4.00
Jiangyin Yangtze River Bridge (1999)	suspension bridge	1385	3.0	36.9	12	U	3.20
Haicang Bridge (1999)	suspension bridge	648	3.0	36.6	12	U	3.00
The Second Nanjing Yangtze River Bridge (2001)	cable-stayed bridge	628	3.5	38.2	14	U	3.75
Junshan Yangtze River Bridge (2001)	cable-stayed bridge	460	3.0	38.8	12, 14, 16	U	3.00
South Branch Main Bridge of Runyang Bridge (2004)	suspension bridge	1490	3.0	38.7	14	U	3.22
Runyang Bridge (2005)	cable-stayed bridge	406	3.0	37.4	14	U	3.75
The Third Nanjing Yangtze River Bridge (2005)	cable-stayed bridge	648	3.2	37.5	14, 16	U	3.75
Yangluo Bridge (2007)	suspension bridge	1280	3.0	38.5	14	U	3.20
Hangzhou Bay Bridge (2008)	cable-stayed bridge	448	3.5	37.1	14, 16, 20	U	3.75
Xihoumen Bridge (2009)	suspension bridge	1650	3.5	36.0	14, 16	U	3.60
Sutong Yangtze River Bridge (2008)	cable-stayed bridge	1088	4.0	35.4	14-24	U	4.00
The Fourth Nanjing Yangtze River Bridge (2012)	suspension bridge	1418	3.5	38.8	14, 16	U	3.12
Yunnan Long Jiang Bridge (2016)	suspension bridge	1196	3.0	33.5	16	U	3.10

The cross-beams and the stiffeners are meshed in a vertical direction and bear the weight together with the upper plate. Generally, the longitudinal stiffeners are arranged more closely, and the transverse partitions are arranged at a larger pitch, which work together to improve the stability and torsion resistance of the girder. This special structural form makes the orthotropic plate have different stiffness in the horizontal and vertical directions, and the mechanical properties also exhibit orthogonal anisotropy. For long-span steel box girder bridges, orthotropic plates can participate in the bearing performance of the box girder as part of the top flange of girder, and can also function as a bridge deck to withstand the vehicle loads, which is a high-efficiency bridge deck form.

A paving layer of a certain thickness is laid on top of the orthogonal rigid plate of the long-span steel bridge, and the vehicle load spreads to the steel deck through the paving layer. Due to the need to ensure the smoothness for the moving vehicle and the fatigue resistance of the deck structure, the thickness of the steel deck is often designed by deflection control. Chinese "Code for Design of Highway Steel Structure Bridges (JTG D64-2015)" stipulates that the thickness of the deck at the roadway location should not be less than 14 mm. The local ratio of deflection to the span of the bare steel deck in the transverse direction should not be greater than 1/700, and the local ratio of deflection to the span of the paved orthotropic plates in the transverse direction should not be greater than 1/1000. The thickness of the bridge deck of China's long-span orthotropic steel bridges is generally in the range of 12 to 20 mm.

The longitudinal stiffeners are divided into open ribs and closed ribs, as shown in Fig. 5. The cross-section of the open rib could be flat steel plate, round angle steel, L-shaped, and inverted T-shaped. Its main feature is easy to process and install. However, its bending and torsional stiffnesses are small. The closed rib has V-shaped, Y-type, U-shaped, and semi-circular type cross sections, etc., and its main feature is high requirement in production precision and welding process, but with high bending and torsional rigidity, less steel consumption, and less work needed for welding and painting than that of the opening ribs. U-shaped stiffeners are used in the design of steel bridge decks for most highway bridges due to its comprehensive performance and construction convenience.

To ensure enough stiffness, the moment of inertia of the stiffener is generally increased by increasing the height of the stiffener. However, when the stiffener is too high, it is easy to develop local buckling of the bridge panel between the stiffeners, or cause buckling of the stiffener before the buckling of the bridge panel. To reduce stress concentration and enhance local stability, Chinese "Code for the Design of Highway Steel Bridges (JTG D64-2015)" recommends the arrangement of longitudinal stiffener with equal spacing, and it maintains continuous through the diaphragm or transverse stiffener. In terms of thickness of ribs, regulations of various countries stipulate that the thickness of U rib is no less than 6 mm. The U rib section parameters of some China's typical long-span steel bridges are shown in Table 6.

There are three types of steel box girder diaphragm: rib type, Vierendeel truss type, and solid web type. Chinese "Code for Design of Highway Steel Structure Bridges (JTG D64-2015)" recommends that the spacing of internal diaphragms of box girders with closed longitudinal stiffeners should not be more than 4 m, and diaphragms must be set at corresponding points of bridge fulcrum. In general, the spacing of diaphragms for long span steel bridges in China is 3–4 m, and the thickness is 8–14 mm. To reduce the fatigue stress at the curved opening of the diaphragm, different opening forms are given in various specifications, which are shown in Table 7.

3.2.2 Structure design of cable tower

The cable tower is an important part of cable-stayed bridge and suspension bridge, and the design of cable tower needs not only to satisfy the bearing capacity requirements, but also fulfill its aesthetic requirements. From transverse direction of bridge, the commonly used structural forms of pylons at present include single column shape, "A" shape, and inverted "Y" shape. From the longitudinal direction of bridge, the commonly used structural forms of pylons are column type, portal shape, "A" shape, and inverted "Y" shape. Column-style pylons have poor lateral load resistance, and are often used in bridges with large torsional stiffness. The structure of portal shape cable tower is complex, but has strong ability to resist lateral load. For long-span bridges with high wind and seismic

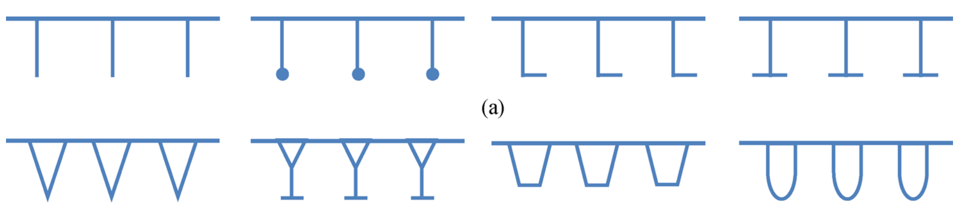
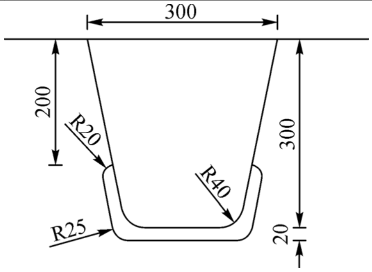
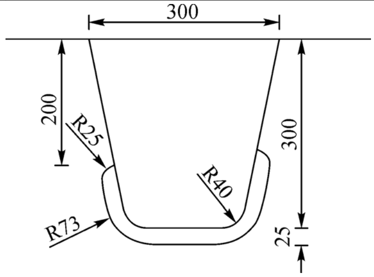
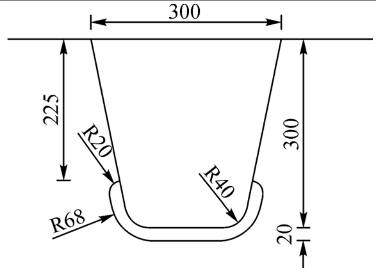


Fig. 5 Shapes of the (a) open ribs and (b) closed ribs.

Table 6 Information about stiffening rib of long-span steel bridges in China.

bridge name	year opened	main span (m)	bridge type	deck stiffener form (upper opening width × lower opening width × height × thickness) (mm)
Jiangyin Yangtze River Bridge	1999	1386.0	suspension	U-shape rib (300 × 170 × 280 × 6)
Haicang Bridge	1999	648.0	suspension	U-shape rib (300 × 170 × 280 × 6)
The Second Nanjing Yangtze River Bridge	2001	628.0	cable-stayed	U-shape rib (320 × unknown × 280 × 8)
Anqing Yangtze River Bridge	2004	510	cable-stayed	U-shape rib (300 × 170 × 280 × 8)
Yangluo Bridge	2007	1290	suspension	U-shape rib (300 × unknown × 280 × 6)
Sutong Yangtze River Highway Bridge	2008	1088	cable-stayed	U-shape rib (300 × 180 × 300 × 8)
The Fourth Nanjing Yangtze River Bridge	2012	1418	suspension	U-shape rib (300 × 170 × 280 × 8)
Hong Kong-Zhuhai-Macao Bridge	2018	1150	cable-stayed	U-shape rib (300 × 180 × 300 × 8)
Nansha Bridge	2019	1688	suspension	U-shape rib (300 × 170 × 280 × 8)

Table 7 Diagrammatic sketch of different openings in U-shape rib from different codes (mm).

item	AASHTO (US)	Eurocode 3 (Europe)	Japan road specifications
cross-section			

resistance requirements, "A" and "Y" shape cable-tower structures with high lateral stiffness are commonly used [25].

3.2.2.1 Design of concrete cable tower

Xinghai Bay Bridge [26] adopts a portal-shape structure (Fig. 6(a)), which consists of a tower column, upper and lower beams. The tower column is a reinforced concrete structure and the beams are prestressed reinforced concrete structure. To improve the stability and stiffness of the bridge tower, a total of five transverse diaphragms are arranged along the vertical direction of "D" shaped hollow-section column, and a solid section of 1 m high is arranged at the bottom of the tower column.

The Sutong Yangtze River Bridge [27,28] is equipped with an "A" shape cable tower (Fig. 6(b)), and the tower column adopts a hollow box section. The solid section is used within 10 m of the bottom of the lower tower column to resist the crash impact from the ships.

The Hutong Yangtze River Bridge (Fig. 6(c)) [29] has an inverted "Y" shape cable tower above the bridge deck. It is a reinforced concrete tower due to its foundation form and by considering wind stability and economy aspect. The tower part below the bridge deck is a diamond-shaped structure. With a height of 325 m, the main tower is divided into four parts: the lower tower column, the lower beam, the middle tower column and the upper tower column. All of them are made of C60 high-performance concrete.

3.2.2.2 Design of steel cable tower

Compared to the concrete cable tower, the steel cable tower requires higher construction precision, but with the advantages of light weight, seismic resistance, easy modeling, easy factory production, shortened construction period, and environmental friendliness [30].

Steel cable towers are most common in the form of inverted "Y" shape. The main cable tower of the Third Nanjing Yangtze River Bridge [31,32] used the inverted "Y" shaped steel structure tower for the first time in China. The tower is equipped with four beams, of which the lower tower column and the lower beam were reinforced concrete structures, and the rest were steel structures. The steel tower column has constant cross-section dimensions in the vertical direction. In addition to the sections of the steel-

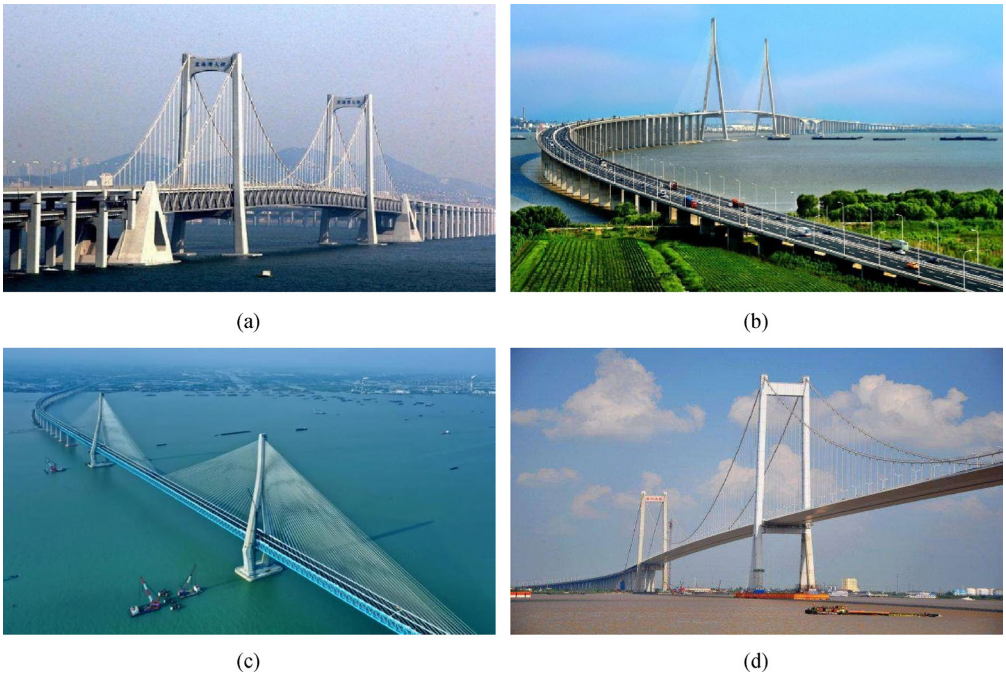


Fig. 6 (a) Xinghai Bay Bridge with portal shaped concrete tower; (b) Sutong Yangtze River Bridge with the “A” shaped concrete tower; (c) Hutong Yangtze River Bridge with inverted “Y” shaped steel pylon; (d) Taizhou Yangtze River Bridge.

concrete structure, each steel cable tower is divided into 21 sections, and the sections are connected by means of high-strength bolts as well as the cross-section surface contacts. Since the cable tower adopts prefabricated segments, precision lifting has become the key during the construction, which includes the process of “positioning-adjustment-measurement-positioning” to improve the construction accuracy.

The Taizhou Yangtze River Bridge [33,34] adopts a three-tower two-span suspension bridge structure. Since both sides of the middle tower are main spans, the top of the middle tower will have a large displacement if the stiffness of the tower is insufficient; on the other hand, there is a risk that the main cable will slip at the top of the tower if its stiffness is too large. Therefore, by using a steel tower with a certain degree of flexibility and an inverted “Y” shape to improve the rigidity, the optimum rigidity of the middle tower can be achieved. The middle tower is a “portal” frame structure from the transverse direction, as shown in Fig. 6(d). The tower legs on both sides of the steel tower are divided into 21 hoisting sections, including the first section, the lower tower column, the closing section, the lower transverse beam, the upper tower, and the upper transverse beam. The high-strength bolts are used for connections of these sections.

3.3 Substructure design

3.3.1 Anchorage foundation

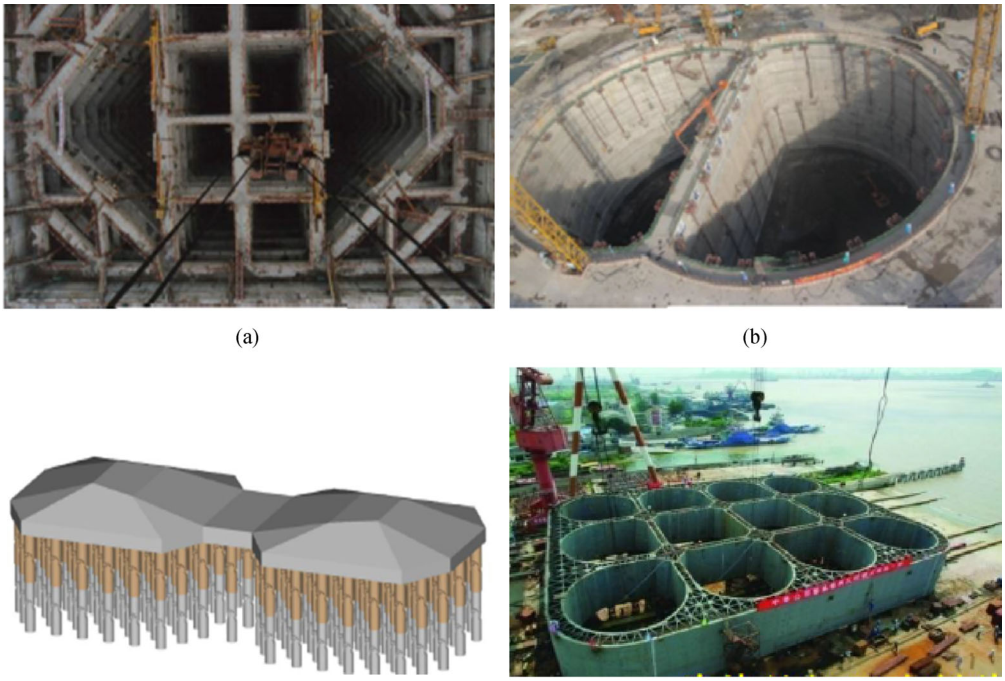
The anchorage foundation is an important structural component of the suspension bridge, which is divided into two types: gravity anchorage and tunnel anchorage. Since the gravity anchor foundation is applicable for various geological conditions, it is currently the most widely used one. Gravity anchors take the force component of the main cable in the vertical direction by gravity, and take the tensile force of the cable in the horizontal direction by the friction between the anchor block and the foundation [35,36].

Gravity anchor foundations have been used for Runyang Yangtze River Bridge, the Fourth Nanjing Yangtze River Bridge, Jiangyin Yangtze River Bridge, Yangluo Yangtze River Bridge, and Humen Bridge.

Runyang Yangtze River Highway Bridge [37] was the largest suspension bridge in China at that time. Its foundation was built with breeze bedrock as the bearing layer, and the rectangular underground diaphragm wall scheme was adopted (Fig. 7(a)). The foundation pit structure was formed by the combination of the underground diaphragm wall and the inner linings, and was finally completed by pouring and backfilling the reinforced concrete. The south anchorage foundation of the Fourth Nanjing Yangtze River Bridge [38] adopted the “∞” (infinity) shape underground diaphragm wall structure (Fig. 7(b)), which resists the lateral earth pressure from the arch effect through its shape advantage.

3.3.2 Group pile foundation

The group pile foundation has the advantage of large bearing capacity, small settlement, good stability, and



(a) (b) (c) (d)

Fig. 7 (a) Rectangular anchorage foundation of Runyang Yangtze River Bridge; (b) "∞" shaped anchorage foundation of the Forth Nanjing Yangtze River Bridge; (c) pile group foundation of Sutong Yangtze River Bridge; (d) caisson foundation of Taizhou Yangtze River Bridge.

seismic performance, which is one of the most common forms for cable-stayed and suspension bridges. This foundation type does not require extensive excavation and support, which speeds up construction process. It is generally applicable to the conditions of large loads applied, weak soil layer on the upper part of the foundation, and the deep bearing layer with difficulty to use the rigid expanded foundation, etc.

The foundation of the main tower of Sutong Yangtze River Bridge [39] is the largest group pile foundation in the world, and its structure is shown in Fig. 7(c). The group pile foundation is composed of 131 bored piles with a diameter of 2.8 or 2.5 m and length of 117 m, arranged in a plum shape. The bearing cap is in dumbbell shape, 113 m in length, and 48 m in width, and the thickness increases from 5 m at the edge to 13 m in the middle. To reduce the crash impact from ships and earthquakes, the design adopted the combination mode of the permanent steel shell and the reinforced concrete pile, which improves the bearing capacity of the pile as well as the engineering efficiency without pulling out the steel shell.

3.3.3 Caisson foundation

The caisson foundation can withstand both large vertical load and horizontal load, and thus has relatively low requirements for ground bearing capacity. This type of foundation is more suitable for deep water area applications. The caisson is multi-functional, which can be used as a foundation structure as well as a cofferdam structure for soil or water retaining during construction. If deviation occurs during the positioning and laying process of the foundation, evacuating the water inside the cavity of the segment can be conducted to make the foundation float for repositioning.

In the 1960s, when the Nanjing Yangtze River Bridge was built in China, heavy-duty concrete caisson, deep-water floating reinforced concrete caisson, and steel caisson were developed, which realized the application of caisson for the deep-water bridge foundation. The caisson foundation of the tower pier in the Taizhou Yangtze River Highway Bridge [1,40] is the foundation sank into the soil with the largest depth in the world. Its structure is shown in Fig. 7(d). The foundation adopts a rounded rectangular caisson with a section size of 58 m × 44 m and a total height of 76 m. The lower part is a steel shell concrete caisson, divided into 7 sections. The first section is prefabricated on the shore, and the rest 6 sections were jointed to a height of 38 m in the water, and finally concrete is poured into the compartment of the shell for caisson to sink. The upper part is reinforced concrete caisson with height of 38 m, which is divided into 5 sections for pouring. Another case is the Hutong Yangtze River Bridge [2,41] under construction currently, which also adopts a rounded rectangular sinking foundation with dimensions of 86.9 m × 58.7 m × 115 m, which is the largest caisson foundation in the world. The steel caisson adopts a double-walled compartment structure, which can fully utilize the buoyance of the water during the sinking and adjust the position of the caisson by changing the water level in the compartment.

3.4 Material and structure design of bridge deck pavement

3.4.1 Bridge deck pavement material

The paving layer on the steel box girder bridge deck has main function of providing vehicles with stable, smooth, and safe road surface. The surfacing layer needs to satisfy the requirements of high strength and durability, good abrasion and slip resistance, excellent high-temperature stability, low-temperature crack resistance, and waterproof ability. It also needs to have good deformation compatibility with the steel deck [42]. Orthotropic plate is not only used as the top flange of the steel box girder, but also as the bottom plate of the asphalt paving layer.

Because of the relatively small stiffness of the orthotropic plate structure, the paving layer is more complex than the asphalt mixture surface layer on ordinary highway, and is prone to be damaged by tensile force. After the re-compaction caused by the heavy vehicles, asphalt mixture will rut due to plastic deformation, and the bonding performance between the paving layer and the steel deck under high temperature and heavy load is very difficult to satisfy the engineering requirement. Therefore, the long-span steel bridge deck paving has become a worldwide challenge [43,44]. It is one of the research field that China has invested most in more than 20 years, and fruitful results have been achieved at the world leading position.

There are mainly three types of paving materials for steel bridge deck: epoxy asphalt mixture (EAM), Gussasphalt (GA) mixture, and stone matrix asphalt (SMA). According to the characteristics of the operating environment where the steel bridge is located, the types of asphalt and aggregate are selected, and the aggregate gradation is adjusted and optimized [45–47].

3.4.1.1 Epoxy asphalt (EA) concrete

EA is a type of irreversible curing substance formed by curing reaction of the epoxy resin and the hardener mixed in the base asphalt. This material fundamentally modifies the hot melt properties of asphalt and endows it with excellent physical and mechanical properties. EAM has excellent mechanical properties, good toughness at low temperature, resistance to melting at high temperature, water tightness, and crack resistance.

The Second Nanjing Yangtze River Bridge, which opened in 2001, is China's first long-span steel bridge paved with EA. With Tongyan Lin engineering consulting company as a technical consultant, South-east University team conducted a comprehensive study on EA material, and first successfully realized the goal of the design service life of more than 15 years. The first and the second lanes still keep good performance till now without any overhaul, and it becomes the long-span steel bridge deck pavement with the longest service life in China [48–50]. After that, based on the successful experience of the Second Nanjing Yangtze River Bridge, EAM was used in a large number of large-span steel bridges in China. The summary of the EA usage in China is listed in Table 8.

At present, there are three types of EA commonly used in China: ChemCo EAM from the United States, new EAM in China, and KD-BEP EAM from Japan. EA from United States consists of two parts: epoxy resin and a

Table 8 Parameters of EA pavement of the representative bridges in China [48–54]

bridge name	year opened	steel deck thickness (mm)	pavement layer thickness (mm)	current status
Jiangyin Yangtze River Bridge	1999	12	55	in 2010, the cast asphalt was replaced with double-layer EA, and it has been used until now
The Second Nanjing Yangtze River Bridge	2001	12	50	maintain good performance without overhaul
Runyang Yangtze River Bridge	2005	14	50	no overhaul, local maintenance
The Third Nanjing Yangtze River Bridge	2005	14	50	no overhaul, local maintenance
Yangluo Yangtze River Bridge	2007	14	60	no overhaul, still using the original pavement
Sutong Yangtze River Bridge	2008	14–22	55	no overhaul, local maintenance, still using the original pavement
Tianxingzhou Yangtze River Bridge	2009	14	60	massive repairs in 2015
Minpu Bridge	2009	16	55	no overhaul, local maintenance

homogeneous mixture of petroleum asphalt, curing agents, and other additives. Japan EA consists of three parts: matrix asphalt, epoxy resin (main agent) and curing agent (hardener) [55]. Since the EA produced from the United States has harsher construction requirement than that from Japan, China has widely adopted the EA from Japan in the paving and maintenance of bridge in recent years.

The researches on the mixture design and mechanism of EA in China began in the 1990s, and the team of South-east University made remarkable achievements [56]. More than one hundred doctoral students have successively carried out researches, and the related results have been applied in more than 30 large-span bridges [48,49,51]. The research team also invented a new type of EA and developed the related construction equipment. The domestic EA invented by the team was applied in the paving of Tianxingzhou Yangtze River Bridge in Wuhan, which effectively solved the problems caused by the traditional asphalt, such as high-temperature instability and low-temperature cracking. It broke the high price monopoly by the foreign products. The design theory and method of steel deck paving on long-span bridges [42,51,57] have been greatly promoted. The axle load conversion method based on fatigue equivalence [47] was established. And the dynamic analysis of pavement structure was conducted [58,59]. Relevant studies show that the domestic EAM has a good low-temperature construction performance and a wide range of reserved time, and the development of its strength mainly depends on the time and temperature during curing [60]. Compared to SMA-10, the domestic EAM has good high-temperature stability, fatigue resistance, water damage resistance, and low-temperature cracking resistance [61]. It has been successfully applied in dozens of bridges such as Tianxingzhou Yangtze River Bridge and Shanghai Yangtze River Bridge.

Though the early strength of EAM made in China is similar to that from the Unites States, its late strength growth period is longer and the strength is higher. In terms of cost and performance, EA in China is an excellent material for paving long-span steel bridge deck. The EAM in China has almost no deformation during the rutting test at 60°C, which has the same excellent high-temperature resistance as the EA from the United States. Meanwhile, the low temperature splitting residual strength ratio is about 80%, which is higher than that of the EAM made in the United States. In addition, the EAM in China has better water stability and oil corrosion resistance.

3.4.1.2 GA

GA paving materials originated in Germany are widely used in Europe and Japan. It can be paved by its own fluidity at a high temperature of 190°C–240°C, without rolling to achieve a dense mixture. Germany generally refers to this cast asphalt mixture as GA, which is termed as high-temperature mixed paving asphalt mixture in Japan, and is termed as asphalt mastic in Britain, France, and the Mediterranean. China usually translates it as an inlaid (rolled) or cast asphalt mixture. Jiangyin Yangtze River Bridge (1999) was the first bridge paved with GA mixture in China by referencing to British code and Tsing Ma Bridge technology. However, due to the insufficient consideration of the high-temperature stability and anti-rutting performance requirements, large-scale damage occurred shortly after the bridge was opened to traffic.

In 2000, German GA technology and the advanced production equipment were introduced in China and then have been applied to Shengli Yellow River Bridge in 2003. After that, the GA was popularized as a paving material [62]. GA is well adaptable to the complicated working environment and has been mainly used in the construction of the base course of steel deck pavement, due to its good water tightness, anti-fatigue performance, excellent deformation follow-up ability, and the bonding performance with steel bridge deck. At present, the proportion of GA mixture in domestic steel deck paving field is close to 50% [63]. A variety of paving schemes have been formed, such as GA + modified SMA, GA + EA, GA + open-graded asphalt friction course (OGFC).

In practice, a GA mixture is poured into place and requires no compaction. This is different from the traditional asphalt mixtures and the SMA mixtures. Therefore, the traditional Marshall and the volume design method cannot be applied to the GA mixture. According to the experiences in Germany and Japan [64], the engineering properties of a GA mixture could be evaluated by tests including Lueer fluidity, indentation, wheel tracking, and bending flexibility at low temperature [65,66].

3.4.2 Pavement structure design

The research on the long-span steel bridge deck paving in China began in the 1980s, however, these research results have rarely been successful in the applications to the long-span steel box girder bridges in the last century. Under normal circumstances, after 2–3 years, the bridge deck pavement has undergone large-scale deterioration.

The research team of South-east University invented the thin-layer pavement structure through systematic researches, which solved the problems of cracking, delamination, and deformation compatibility, proposed four typical pavement structures, and established the steel bridge deck pavement design parameters and indicators. A steel bridge deck pavement design method was established, which has been applied to dozens of bridges constructed afterwards.

It is found that the thickness and modulus of the paving layer have a great influence on the interior and interlayer stresses, based on which the paving structures was investigated [67–81]. At present, there are four main types of steel bridge deck pavements for long-span bridges in China: 1) “double-layer epoxy” structure, as shown in Fig. 8(a), has high strength, good durability, and excellent high-temperature stability; 2) “GA + SMA” structure, as shown in Fig. 8(b), has good low-temperature stability and good bridge deck deformation compatibility, however, rutting deterioration can occur in the continuous high temperature conditions; 3) “EA + SMA” structure, as shown in Fig. 8(c), has high strength, excellent high-temperature stability, good low-temperature stability, and easiness to maintain; 4) “GA + EA” structure, as shown in Fig. 8(d), has high composite strength, good deformation compatibility, and low-temperature stability. Based on China’s existing bridge deck paving experiences, the double-layer epoxy pavement structure performs best among the above four structures in adapting to overload and the high- and low- temperature stability. The pavement structures of some steel bridges in China are summarized in Table 9.

3.5 Wind resistance design

The large-span bridges that have been built and under construction in China are mainly concentrated in the Yangtze River Delta and the Pearl River Delta. These two regions are also the most frequent areas of typhoons in China. Bridge deck vibrations caused by strong winds may cause severe damage to bridges [82,83]. The light weight of the high-performance materials and the increasing span make the modern long-span bridges more sensitive to wind loads.

After years of design experience, Chinese scientific and technical personnel have explored the wind-resistant design theory and the wind-induced vibration control method in line with China’s geographical climate. The Humen Bridge (opened in 1997, suspension bridge with main span of 888 m) is China’s first bridge that was researched on its wind performance by wind tunnel test with the largest scale of air-elastic model to ensure its wind stability. The wind resistance design of the Lupu Bridge (opened in 2003, arch bridge with main span of 550 m) used the calculation method of vortex-equivalent wind load caused by the bridge structure interacting with the airflow. It was the first time in the world to adopt the longest cumulative time of vortex vibration and the vortex vibration probability as the two indexes to evaluate the vortex vibration of bridge, and the vortex vibration was controlled by membrane structure. In the study of the wind resistance performance of the Xihoumen Bridge (opened in 2009, suspension bridge with main span of 1650 m), China took the lead in research and developed a series of bridge flutter pneumatic control technology and bridge turbine vibration control to optimize the cross section of the steel box girder. A slotted double-box girder cross section with a spacing of 6 m was adopted [84]. Both the lateral windward control measures of the bridge deck and the software with wind-vehicle-bridge coupled vibration analysis function were developed.

At present, China has several achievements in the following aspects: 1) established a high-precision bridge aerodynamic model and wind vibration analysis method, developed and improved the bridge wind resistance design theory; 2) established aerodynamic shape design criteria for long-span cable-bearing bridges, and proposed a systematic wind-vibration pneumatic control technology [85]; 3) developed a new type of pneumatic control device with “bridge deck slot + aerodynamic wing” combination; 4) independently developed the world’s largest and advanced boundary layer wind tunnel, provided key technology for wind-resistant design of long-span cable-bearing bridges.

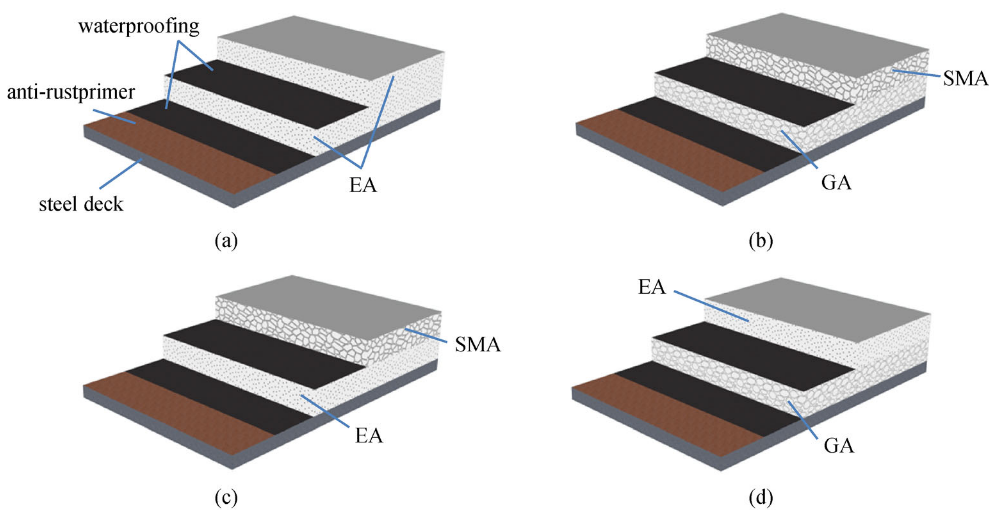


Fig. 8 Wearing surface of steel deck of some long-span bridges in China. (a) Double-layer EA; (b) GA + SMA; (c) EA + SMA; (d) GA + EA.

Table 9 Pavement structure on steel deck of long-span bridges in China [48]

bridge name	year opened	main span (m)	initial wearing surface system	maintenance record
Jiangyin Yangtze River Bridge	1999	1385	47 mm GA	re-paved in 2003 according to the original plan; in 2010, replaced with 55 mm double-layer EA
Haicang Bridge	1999	648	30 mm SMA13 (upper layer) 35 mm SMA10 (lower layer)	In 2002, 2005, and 2013, the original paving plan was used for overhaul
Junshan Yangtze River Bridge	2001	460	35 mm SMA (upper layer) 40 mm SMA (lower layer)	re-paved in 2010: 40 mm SMA (upper layer) + 30 mm SMA (lower layer) re-paved in 2018: 30 mm asphalt (upper layer) + 50 mm UHPC (lower layer)
The Second Nanjing Yangtze River Bridge	2001	628	50 mm double-layer EA	the first and second lanes are not overhauled; for the pre-conservation considerations, the pavement is replaced by using the original pavement plan in the heavy traffic lane (the third lane) in 2018 [49]
South Branch Main Bridge of Runyang Bridge	2005	1490	50 mm double-layer EA	local maintenance and repair, no overhaul
Yangluo Yangtze River Bridge	2007	1280	30 mm EA (upper layer) 30 mm EA (lower layer)	no major repair record, still using original pavement
Sutong Yangze River Highway Bridge	2008	1088	30 mm EA (upper layer) 25 mm EA (lower layer)	paving without overhaul
South Branch Bridge of Tianxingzhou Yangze River Bridge	2009	504	25 mm EA (upper layer) 35 mm EA (lower layer)	paving without overhaul
Hong Kong-Zhuhai-Macao Bridge	2018	1150	38 mm SMA13 (upper layer) 30 mm GMA10 (lower layer)	no overhaul record
Nansha Bridge	2019	1200 + 1688	35 mm EA (upper layer) 30 mm EA (lower layer)	no overhaul record

As China's long-span bridge projects gradually move toward the oversea and the span length continues to increase, the related wind-resistant design is facing new challenges. It is necessary to refine the current wind resistance theory and the test methods, and consider the wind-resistant measures in the bridge operation stage. However, due to the limitations of wind resistance theory, the design is still wind tunnel test-dependent, and there is a long way to achieve wind resistance design by computing.

3.6 Seismic design

China is located between the Eurasian seismic belt and the Pacific Rim seismic zone. Most of the areas belong to earthquake-prone areas. Therefore, China has always attached importance to the seismic design of long-span bridge structures. After years of theoretical research and engineering practice in China, great progress has been made in bridge design theory and seismic provisions, preparation and revision of bridge seismic design codes, as well as bridge damping and isolation technology.

The early seismic design mainly adopts static theory or response spectrum theory, these theories do not consider the ground motion and the dynamic characteristics of structure or the elastoplastic behaviors of the structure. With more understanding of bridge seismic damage, the performance-based seismic design concept came into being [86], which considers the structural characteristics and performance requirements of different bridges, and comprehensively applies the design parameters, structural system, structural requirements, and seismic isolation devices to ensure its seismic resistance under different earthquakes degrees. Currently, many countries such as the United States, Japan, New Zealand, and China have introduced performance-based seismic design theory into their national seismic design codes. The current seismic analysis of bridge structures generally uses the uniform excitation as the input parameter, that is, the amplitude and phase vibration at various locations of the bridge foundation are equal, and the spatial variation of the ground motion is not considered. However, for long-span bridges, the effects of the spatial difference of ground motion are very significant. At present, the design method is mainly improved by adopting multi-point excitation [11]. In general, research about the spatial difference characteristics of ground motion is still insufficient.

The existing engineering experience shows that bridge seismic isolation technology is an effective way to reduce bridge earthquake damage [87–93]. In recent decades, it has been focused on the development of seismic isolation bearings with stable performance and good isolation effect. Normal bridge isolation bearings include laminated steel rubber bearings and sliding friction type isolation bearings. The Hong Kong-Zhuhai-Macao Bridge adopts a new type of high-damping rubber bearing in which multiple layers of high-damping rubber and steel plate alternately superimposed. It is the largest rubber isolation bearing in the world with dimensions of 1.77 m × 1.77 m. With a bearing capacity of up to 3000 ton, it can assist the bridge to withstand earthquake with magnitude 8.0 [94]. The sliding friction type isolation bearing is less affected by the ground motion frequency, and has the advantages of large bearing capacity, good durability, and strong self-recovering ability [95]. This type of bearing is widely preferred, which has been adopted in the Sutong Yangtze River Bridge and the Shanghai Yangtze River Bridge [96].

At present, the bridge damping technology reduces the bridge vibration under the action of earthquake by adjusting the stiffness and damping characteristics of the bridge through active control, semi-active control, and passive control. Among them, passive control technology is widely used due to its high reliability, low maintenance cost, and valid theory. The active control technology mainly changes the vibration of the bridge by applying external energy, and has better control efficiency, however, its reliability is not guaranteed, and the application range is limited. Semi-active control technology is a type of shock absorption technology with good development prospects. It can combine the advantages of active control and passive control technology to achieve reliability and adaptability, which has been successfully used in many bridge structures.

In general, China's bridge seismic isolation technology has made remarkable progress in the past, but there are still many technical problems that need to be solved. For example, the design life of rubber-based isolation bearings (usually 50 years) does not match the design life of bridge structures (generally 100–120 years). In addition, the functional requirements such as stability and intelligence of the isolation bearing need to be further improved. Furthermore, the damping device may change the dynamic characteristics of the bridge structure, thereby affecting the accuracy of the seismic analysis of the bridge structure. In the future, further research is needed to clarify the interaction between the damping device and the bridge structure.

4 Construction technology of super-long span bridge in China

4.1 Construction technology of foundation

4.1.1 Anchorage foundation

Anchorage foundation is a common form of foundation for suspension bridges, which is generally constructed by open-cut method, blasting method, and freezing method [97]. It is important to choose the appropriate pit shape considering the actual construction conditions of bridges. The common pit shape of anchorage foundation includes rectangular shape, circular shape, and "∞" shape. Gravity anchorage foundation can be used when the bridge foundation has a good bearing capacity. Many long-span bridges built in China, including Runyang Yangtze River Bridge, Yangluo Bridge, and the Fourth Nanjing Yangtze River Bridge, adopted gravity anchorage foundation. In the construction practice of anchorage foundation of large-span bridges, China has made many innovative achievements, including the development of anti-segregation device to drop concrete mixtures, invention of cutoff wall made by self-setting mortar with low strength, low elastic modulus and low permeability, and the establishment of foundation pit structural analysis model based on the spatial elastic-plastic finite element theory, etc. The relevant construction technologies have led the world, for example, the North Anchorage of Jiangyin Yangtze River Bridge was 69 m in length, 51 m in width, 58 m in depth, and 210000 m^3 in volume, which was the largest land caisson in the world at that time.

Tunnel-type anchorage foundation is also a common anchorage foundation. China has accumulated a lot of successful experiences in the construction of tunnel-type anchorage foundation. For example, during the construction process of tunnel-type anchorage foundation of Balinghe Bridge that faces the complicated construction conditions such as large dip angle, large cross section, small distance between caverns, karst cave development, and rock fragmentation, China creatively put forward the key construction technology of large dip-angle (45°C) anchorage plug. At the same time, the highway tunnel was excavated on the upper part of the tunnel-type anchorage. The tunnel-type anchorage foundation of the Balinghe Bridge was known as the world first tunnel anchor at that time [98], which provides important guidance for the foundation construction of similar long-span bridges in China

4.1.2 Pile group foundation

Pile group foundation is the most commonly-used foundation for bridges, more than 40% of bridges adopt the pile group foundation [11]. In recent years, new green concrete materials such as superfluid concrete, fiber reinforced concrete and the expansive concrete have been widely used for the construction of pile group foundation, which has greatly improved the construction efficiency and quality of the pile group foundation. Large-scale steel pipe pile foundation has become a common form of pile foundation for deep-water bridges, because it can overcome complicated geological, hydrological and climatic conditions and difficulties in construction positioning. Many bridges in China including Hangzhou Bay Bridge, Hong Kong-Zhuhai-Macao Bridge, and East China Sea Bridge have adopted the large-scale steel pipe pile foundation. The diameter of steel pipe piles has reached 2 m and the length of pile body is more than 100 m. However, theoretical researches on the large-diameter steel pipe piles are relatively limited. The bearing capacity of the large-diameter steel pipe piles is mainly determined by the static load test.

For the construction of bored grouting piles for bridges, the maximum length of bored grouting piles in China has exceeded 150 m, the diameter of dig-pouring piles has reached 9 m, the diameter of bored grouting piles has reached 5 m. The related construction technologies have taken the lead in the world. A lot of engineering experiences in China have shown that the grouting technology is an effective way to improve the construction quality of bored piles [11]. For example, China creatively developed the U-tube grouting technique in the construction of super-large bored grouting piles of Sutong Yangtze River Bridge, which increased the bearing capacity of pile group foundation by 48%–100%. This technology has contributed greatly to the successful construction of pile group foundation of super-long span bridges in China [99].

4.1.3 Caisson foundation

Caisson foundation is also widely used in the construction of long-span bridges because of its advantages of good integrity, large stiffness and large sinking depth. China has built a series of super-caisson foundations for bridges such as Jiangyin Yangtze River Bridge, the Fourth Nanjing Yangtze River Bridge, and Taizhou Yangtze River Bridge. Currently, hundreds of caisson foundations have been built in China. In terms of construction technology of caisson foundation, China is in the forefront of the world. For example, the large reinforced concrete circular caisson built on land in China is 68 m in diameter and 3600 m^2 in cross-section area, the maximum sinking depth reaches 57 m. For deep-water caisson foundation, the sinking depth by floating caisson sinking method is more than 50 m and the cross-section area reaches thousands of square meters [100]. The dimensions of the foundation of the main tower of Hutong Yangtze River Bridge under construction in China are 86.9 m × 58.7 m × 115 m, which will become the largest caisson foundation in the world after its completion. Facing the complicated deep-water construction conditions of river-crossing or sea-crossing bridges in the future, the composite foundation formed by the combination of traditional foundations such as caisson foundation and pile foundation, will become promising and popular for constructing the long-span bridges.

4.2 Construction technology of cable tower

The cable tower can be divided by the structural materials used into reinforced concrete cable towers, steel cable towers, steel tube concrete cable towers, and the steel-concrete composite cable towers. Currently, steel cable towers and reinforced concrete cable towers are widely used due to their easiness in construction.

4.2.1 Construction technology of steel cable tower

With the rapid development of anti-corrosion technology for steel structures, steel cable towers are favored again for long-span bridge because of their advantages of small section, light weight, high strength, toughness, seismic performance, short construction period, easy control of construction quality, and adaptability to deformation of long-span bridges [101]. At present, the long-span bridges built in China including Taizhou Yangtze River Bridge, Ma'anshan Yangtze River Highway Bridge, the Third Nanjing Yangtze River Bridge, and Zhijiang Bridge were constructed by adopting steel cable tower. Compared to concrete cable towers, the installation process of steel cable tower is more complicated [101]. It is necessary to select the appropriate construction method according to the shape, the height, the cross-section, and the weight of cable tower, and the geological and climatic conditions of the construction site, etc.

After many years of engineering practice and theoretical research, the construction technology of steel cable towers in China has reached the international advanced level. For example, China has developed the three-dimensional tracing measurement and marking method for the cross-section of steel cable tower section and the curve control method for steel cable tower column with curve-line shape, which have been successfully applied to the construction of steel cable tower of the Third Nanjing Yangtze River Bridge. The steel cable tower of the Third Nanjing Yangtze

River Bridge was the first steel cable tower in China and the first curved steel cable tower in the world at that time. The Third Nanjing Yangtze River Bridge won the Gustav Lindenthal award due to its technological innovations. During the construction of Taizhou Yangtze River Bridge where the middle tower column is 12000 tons in weight, the maximum segment is 530 tons in weight, and the maximum segment is 15 m in length, China successfully solved the technical problems such as welding, precision control of assembling, and horizontal pre-assembling. Figure 9 displays construction procedures of the cable tower of Taizhou Yangtze River Bridge by the entire process error controlling system that integrates segment manufacturing, assembling and hoisting [33]. The vertical error in the longitudinal and the transverse directions of bridge after the completion of the cable tower can be controlled within 1/19591 and 1/150065, respectively, which meet the construction requirements at high quality. The steel tower of Taizhou Yangtze River Bridge was the heaviest cable tower in China at that time.

4.2.2 Construction technology of concrete cable tower

Concrete cable tower is the main cable tower form for long-span bridge in China. For long-span bridge with high and large-volume cable, hydraulic climbing formwork is the most commonly-used construction method for concrete cable tower due to its fast construction speed, simple operation, good engineering quality and low cost [102,103]. The concrete cable towers in Jiashao Yangtze River Bridge, Tongling Yangtze River Bridge, and Yangsigang Yangtze River Bridge are all constructed by the hydraulic climbing formwork method, which are shown in Fig. 10.

The concrete used for cable tower will not only affect the performance, but also the construction quality and efficiency of the cable tower structure. With the development of bridge structures toward super long span and deep water in China, high-performance concrete with high strength, high fluidity, low viscosity and excellent durability will contribute greatly to the construction of concrete cable tower under more complicated conditions in the future.

The construction of concrete cable tower is very vulnerable to sunshine, rainfall, strong wind and other factors due to its high-altitude and harsh operation conditions, the concrete cable tower is prone to crack. Moreover, the cable tower of sea-crossing or river-crossing bridges is tall and far from the shore, so it is not easy to ensure the survey accuracy during the construction, which will no doubt affect the overall construction quality [104]. In view of the technical difficulties, China has successfully developed hydraulic climbing formwork technology, concrete super-high pumping technology, and other supporting technology. Currently, the maximum segment length of concrete reaches 6 m, and the construction of such segment can be completed within 12 d. The tilt error of the top of cable tower can be controlled within 1/42000, which is far less than the requirement of 1/3000 stipulated by the construction code.

4.3 Construction technology of superstructure

4.3.1 Manufacturing technology of steel box girder

With the development of long-span bridges in China, the

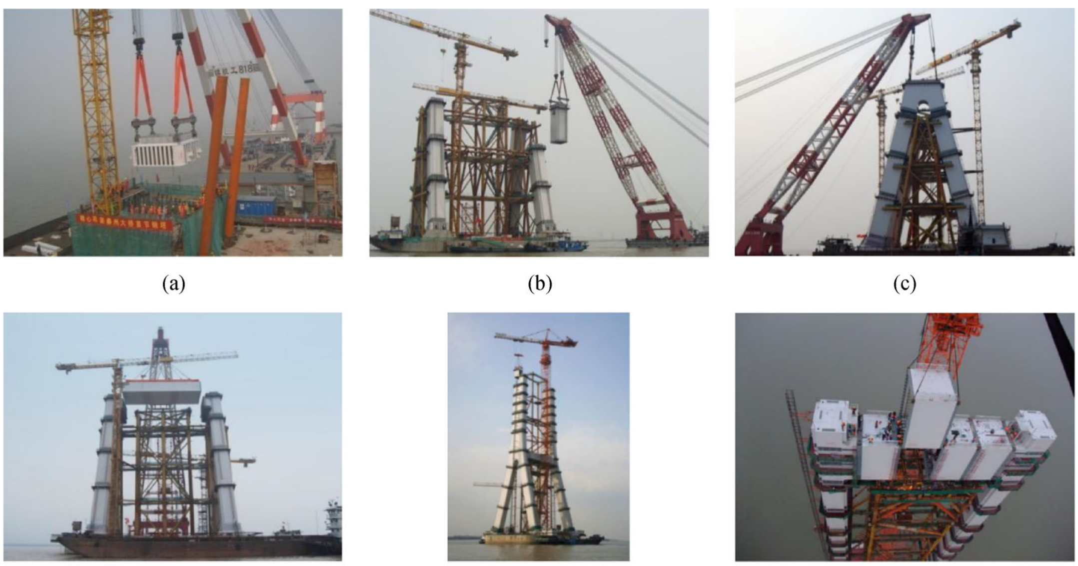
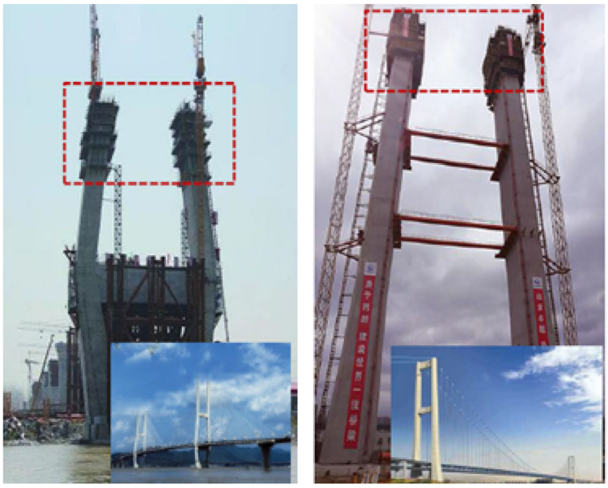


Fig. 9 Construction procedure of steel pylon of Taizhou Yangtze River Bridge: (a) the first section; (b) the bottom cable tower; (c) the joint section; (d) the lower cross beam; (e) the upper tower column; (f) the upper cross beam.



(a) (b)

Fig. 10 The use of hydraulic climbing formwork technology in concrete pylon of (a) Tongling Yangtze River Bridge and (b) Yangsigang Yangtze River Bridge.

width and span of steel box girders are increasing. Therefore, the total number of related elements is increasing, which will lead to the increase of the processing error of the entire steel box girder [105]. To control the overall quality and the processing error of steel box girder, it is necessary to improve the quality and accuracy of manufacturing and assembling for girder elements. After the splicing of the steel box girder is completed, the processing quality of the steel box girder can be evaluated through the geometric indices that include cross-section dimension, longitudinal alignment, and the relative dislocation and distortion of cross section. The key to the manufacture of steel box girder lies in the accurate control of these three indices. The progress of manufacturing technology of steel box girder in China is mainly reflected in the manufacture of steel box girder of Hong Kong-Zhuhai-Macao Bridge.

Hong Kong-Zhuhai-Macao Bridge is the first one that uses hot-rolled flat plates for the manufacture of steel box girder in the world, which is quite different from the formerly-constructed bridges where cold-formed U ribs were often used in the orthotropic slabs. The traditional cold-formed U ribs are formed by flattening the hot rolled coil, cutting the edges, and then bending when cold. Due to different cooling speeds inside and outside the coil, the residual stress on both sides and the middle of the steel plate is not uniform, a large side bend usually occurs after the cutting process, and the flatness of the steel plate cannot be effectively guaranteed. Therefore, the cold-formed U rib has shortcomings such as high production cost, low efficiency, and being prone to fatigue damage during the service life [106,107]. The hot-rolled U ribs used in Hong Kong-Zhuhai-Macao Bridge are formed by a universal rolling machine, which can ensure the uniform distribution of the residual stress in the steel plates. Therefore, the quality and accuracy of the U ribs can satisfy the design requirements. In addition, the dimension, stiffness, strength, stability, and fatigue resistance of the hot-rolled U ribs are consistent with the calculated ones, which is conducive to the formulation of relevant standards and specifications of hot-rolled U ribs.

In terms of element assembly, the steel box girder of Hong Kong-Zhuhai-Macao Bridge was the first one around the world to be assembled automatically with machine tool to position and assemble the U rib and the plate stiffener [107] (see Fig. 11). In the past, the assembly of orthotropic plates was completely artificial, and the assembly gap between U rib and panel, the quality of positioning weld, the center distance and straightness of U rib were greatly affected by manual factors. By using automatic positioning technology, Hong Kong-Zhuhai-Macao Bridge effectively ensures the position accuracy of each element during the assembly, which reduces the welding defects caused by the large assembly gap [108], and improves the overall quality of the steel box girder.

For the first time in the field of steel box girder manufacturing in China, the Hong Kong-Zhuhai-Macao Bridge has adopted robotic welding. During the initial period of bridge construction in China, the welding of orthotropic plate elements usually adopted the manual welding method, therefore, the welding quality is greatly

(a) (b)

Fig. 11 (a) Automatic assembly positioning machine for U-shaped rib unit; (b) automatic assembly positioning machine for plate type stiffener.

influenced by the man-made factors. The manual welding method has been gradually replaced by the welding carriage or gantry multi-head combined welding carriage. However, manually adjusting the welding wire position was still required. Influenced by the processing deviation and straightness of U rib, the welding wire often deviates from the groove root due to the tracking deviation, which leads to the deviation of welding pool and makes it difficult to ensure the stability of the welding penetration [107,108]. Based on the ARCMAN-MP welding robot system made by KOBELCO Japan, China has developed a special multi-end welding machine for manufacturing orthotropic plates during the construction of Hong Kong-Zhuhai-Macao Bridge (see Fig. 12). The robot system adopted advanced arc tracking technology to track the zero position of the welding pool in real time. Based on the real-time and accurate tracking of the groove root, the fusion and penetration depth of welding at groove root are effectively guaranteed. And thus, the welding quality is guaranteed.

4.3.2 Construction technology of cable structure

Cable structure is the lifeline of suspension bridge. From the current construction technology, once the bridge is built, it is not easy to replace the cable. Therefore, the construction quality of the cable is very important.

During the construction of long-span suspension bridges, the cables may exhibit excessive deflection, which would lead to the torsion of strands, relaxation of steel wire, and the fracture of bandage, etc. [109]. Therefore, it is necessary to strictly control the quality and efficiency of the cable erection during the construction of cable structure. In China, the prefabricated parallel strand method is widely used for the cable construction of suspension bridges. During the cable construction, two hoisters are set at the anchorage end of the suspension bridge, the traction rope can move to the other side of the bridge via the catwalk roller, and then it can return to the original position via the other roller of the same catwalk. To ensure the continuous and smooth alignment of the traction cables and to avoid bending or sagging of puller, it is necessary to keep the traction system in proper tension [109]. Shantou Bay Bridge is the first bridge in China to erect the cables with track carriage traction system. The construction technology was improved subsequently by the overhead cableway traction system adopted in the construction of Jiangyin Yangtze River Bridge. After the successful application of the gantry puller traction system to Haicang Bridge and Humen Bridge, this construction method was widely used in China. For example, Yichang Yangtze River Bridge and Zhongxian Yangtze River Bridge have also adopted this construction method. During the construction process of Runyang Yangtze River Bridge, the traction system was improved to a double-track reciprocating system, which improves the efficiency of cable erection and construction progress.

In terms of construction of main girder, China has developed erection technique for precast concrete beam, short-line match prefabricated technique for segmental girder, and integral hoisting technique for steel box girder, etc. In addition, China has independently developed many key devices such as floating crane, bridge erecting machine, bridge deck crane, cable-borne crane, large gantry crane and sliding form. For example, both the lifting capacity of the cable-borne crane (740 tons per segment) and the swivel construction technique (swivel length is up to 198 m and the swivel weight is up to 22400 tons) reach the international leading level. Currently, incremental launching method is the most commonly-used method for the erection of steel box girder in China. It is usually divided into single-point and multi-point incremental launching methods according to the number of power devices. Hongshanmiao Bridge, the first steel box girder cable-stayed bridge constructed by incremental launching method, was built in 2005 in China. After that, the incremental launching method has developed rapidly in China, and it can be applied not only to the straight bridges

Fig. 12 Robot anti-deformation ship position welding system.

but also to the curved bridges. The maximum launching span has been continuously improved, and the cross section of girders can be changed from constant to variable type [110].

Since load will transmit between the main girder and the cable, it is necessary to take the erection of girder and the cable as a whole during the construction. For suspension bridges, a large prefabricated strand of 127 wires per share has been successfully designed, manufactured, and erected for Humen Bridge for the first time in China, and a complete set of advanced construction technologies and special devices for suspension bridges has been developed. Hydraulic cable-borne crane was also developed to hoist all steel box girder in place [111]. In addition, full welded method for the joint connection between different segments was invented to eliminate the welding gap and improve the welding quality. For cable-stayed bridges, the side span and the larger girder segment at the cable tower of Sutong Yangtze River Bridge were hoisted by the integrated floating crane. The standard girder segment was hoisted by a double crane system and the closure of the midspan was constructed by the launching-assisted closure method [112]. In addition, Sutong Yangtze River Bridge has systematically proposed the adaptive geometric control method for the entire construction process of the cable-stayed bridge with length of multiple kilometers in the world for the first time, and established an integrated manufacturing and installation program. It has created the key technology of digital installation control for cable and steel box girder. Constructed by using this method, the manufacturing accuracy of long cables can be controlled to 1/20000, and the elevation error of the main girder is less than $L/4000$, and the bridge axis is less than $L/45000$. This method overcomes the difficulties during construction of cable-stayed bridge with length of one kilometer.

4.3.3 Construction technology of concrete arch bridge

The construction method of concrete arch bridges can be divided into two types: the bracketed method and the non-bracketed method, which depends on whether the completed structures of arch bridge serve as the support system during the construction of the main arch. The span breakthrough of arch bridges is closely related to the construction techniques, which have developed from the bracketed method to the non-bracketed method. Currently, the cable hoisting method, the swivel method, the cable-stayed suspension method, and the stiff skeleton method have also employed in the construction of concrete arch bridges, which have significantly improved the efficiency and quality of concrete arch bridge construction [113].

The cable-stayed suspension method is one non-bracketed method that has been mostly used in the construction of concrete arch bridges previously. When the cable-stayed suspension method is used, temporary towers should be set at the arch foot and the arch abutment. One end of the cable is used to hold the arch ring segment, and the other end is anchored on the rock plate through the arch abutment. Then, the arch ring segments are constructed one by one through the cantilever method until the arch crown is closed [114]. Since cables are needed in the cable-stayed suspension method, the sagging problems caused by the self-weight of the steel lock should be solved carefully when the span of the main arch is large. For this case, carbon fiber composite cable with light weight and high strength can be used, which can also ease the construction procedure.

The stiff skeleton method is mainly used in cast *in situ* construction of long-span arch bridges with non-bracketed suspension formwork, which can greatly improve the spanning capacity of the concrete arch bridges. The reason lies in that the erection of heavy concrete arch can be transformed into that of lighter steel skeleton arch [115]. The development of stiff skeleton from section steel to concrete filled steel tube has made further breakthroughs in the span of concrete arch bridges. Wanzhou Yangtze River Bridge is the first reinforced concrete arch bridge with a span of more than 400 m in the world [115,116]. The concrete-filled steel tube served as the stiff skeleton, and high-strength concrete (C60 grade) was used as the arch ring material. Large tonnage and multi-segment cable hoisting and assembling anchor were used for the installation of concrete-filled steel tubes [117,118]. A symmetric two-stage pumping and pouring technology for long distance and large drop was adopted for the construction of concrete arch [119]. Hejiang Yangtze River Bridge, built in 2013, is the first concrete filled steel tube arch bridge with a span of more than 500 m in the world. During the construction, a vacuum-assisted pouring method and the corresponding construction equipment were developed, which achieved the three-stage vacuum-assisted continuous pumping construction for super-long span concrete arch bridges [120]. The successful application of concrete filled steel tube arch bridge in China, especially the hydraulic hoisting technique, computer-controlling technique, and the testing technique, has greatly promoted the construction safety of steel arch with large cross section. During the construction of concrete filled steel tube arch bridge, it should pay more attention to the construction accuracy and stability of arch ribs during the erection and closure construction. The instability of arch ribs during the construction can be analyzed by finite element method, when the span of arch bridge is large or concrete filled steel tube is used as the construction stiffness skeleton, it should take the large deformation effect into consideration since the structure stiffness is weak.

The swivel method is very applicable to the construction of long-span arch bridge across valleys and rivers. The sphere hinge is the key to conduct the swiveling construction, which is commonly made by steel or concrete. At present, the swiveling weight by steel sphere hinge in the construction of Shanghai-Hangzhou High-speed Railway Bridge is the heaviest in China, which reaches 16800 tons [121]. To increase the span of concrete arch bridge, the stiff skeleton is usually used in the swiveling construction. However, it should be noted that the stability of the bridge structure will inevitably decrease, which may lead to the instability problem. Therefore, one should evaluate the weight, unbalanced moment, friction moment and eccentricity of the swiveling segments carefully before the swiveling operation.

4.4 Bridge deck paving technology

The bridge deck paving technology takes the synthetical consideration of the engineering properties of materials, the structural combination, and the construction techniques and equipment. Some pavement materials show excellent performance in the indoor tests, but the application of them outdoor brings a lot of difficulties due to the unstrictly controlled construction quality of the factors such as mix proportion, paving temperature and construction time. Therefore, the reasonable arrangement of construction scheme and the establishment of quality control system are the two keys to guarantee the quality.

4.4.1 Paving technology of EA concrete

The EAM for long-span bridge deck paving needs strict organization and management in construction, and many demands of control indexes must be meet. The reason lies in that the construction of EAM pavement is accompanied by rapid curing reaction of epoxy resin, and thus is very sensitive to the pavement structures and environment situations. According to the typical paving schemes of long-span steel bridge, the main procedures include: material preparation, mix design, waterproof layer construction, mixture production and transportation, bottom layer paving and compacting, joint treatment, bonding layer construction, upper layer paving and compacting, and maintenance. With high energy consumption and pollution, hot-mixed asphalt mixture does not comply with the trend of global energy saving and environmental protection. In recent years, the domestic EAM preparation technology has been developed from hot-mixing to warm-mixing and cold-mixing methods, and a new process of low-temperature mixing was proposed [122]. At present, several technical codes and specifications have been issued in China to guide the design and construction of EAM pavement [123], such as Technical Specifications for Design and Construction of Highway Steel Box Girder Bridge Deck Pavement.

The key paving procedures of warm-mixed EAM are summarized as follows. 1) Mixing and transportation: before mixing, the temperature of epoxy resin should be controlled at 80°C±5°C, the temperature of curing agent and asphalt mixture should be controlled at 150°C±5°C, the temperature of the outlet EAM should be controlled at 110°C–120°C. 2) The pavement quality depends on the performance of the paver used. The screed should be preheated to guarantee that the mixture may not be caking due to the lower temperature at the start stage of paving. 3) The procedures of paving, preliminary roller compacting and final roller compacting must be under strict management. The temperature after preliminary compacting should be higher than 85°C, and the temperature after final compacting should be higher than 65°C. The criteria of Marshall stability (⩾40 kN) and the air voids (⩽3%) are applied to determine the permissible reserved time [60]. 4) The strength formation of EAM needs definite temperature and time, and thermal insulation materials are recommended to be laid on the surface of the paving layer. The Marshall stability (⩾40 kN) can be taken as the strength control index to meet the requirement of traffic opening.

Unlike warm-mixed EAM, the viscosity of the hot-mixed EA decreases gradually with the increase of temperature. This feature prolongs the allowable construction time of the mixture and has higher adaptability to condition of site [124]. The early strength of the hot-mixed EAM increases rapidly, and thus the traffic can be opened only after several days of curing. The domestic EAM (N-EA) developed by Huang et al. possesses the characteristic of a wide range of construction temperature and long operation time: the allowable construction time could reach 3 h under the reserved temperature of 165°C–185°C, and the Marshall stability is higher than 50 kN after 4 d of curing at 40°C [125].

In general, the EAMs have strict technical requirements in terms of compacting temperature, allowable construction time, and rolling craft. The detecting indexes for compactibility and porosity are the most basic guarantee of the construction quality of EAM pavement [126].

4.4.2 Paving technology of GA and Mastic asphalt (MA)

Two different types of poured asphalt mixtures are known as GA and MA. GA was originally developed in Germany. In UK, based on the material's characteristic, the steel bridge deck asphalt concrete was termed as MA. Both GA and MA have high asphalt content, high fine aggregate content and less coarse aggregate content. At a high temperature, GA was sufficiently fluid to be poured into place without compaction, forming a voidless pavement and providing resistance to moisture penetration from the top paving surface and fatigue cracking resulting from the flexural bending of the deck. In UK, MA had its own system of design and production processes. GA and MA are commonly used in the construction of the base course due to their high impermeability and compliance. The primary difference between GA and MA is the different production and evaluation processes used in these two mixtures (shown in Table 10).

Table 10 Different production processes in producing GA and MA [127]

mixtures	mixing temperature	asphalt binders	production processes
GA	200°C–250°C	PMB + TLA + hard asphalt	The production of GA is a one-step process: All ingredients are fed into the batch plant and the mixing of GA only took 2 min. The GA mixtures are then dumped into the cooker for secondary mixing and transportation
MA	210°C–240°C	TLA + AH	The production of MA consists of a two-step process: The filler (at ambient temperature), bitumen and fine aggregate are mixed to produce ME. ME is then fed into a cooker, mixed with coarse aggregates to produce the final MA

Due to high traffic volume, overloading problem and harsh climate conditions, the performance of single layer MA or GA structure was unsatisfactory. In recent years, the trend has moved toward to the use of the 2-layer system because of its advantages in functional properties and lower construction cost, and the 2-layer system with the SMA on top of the GA (GA + SMA) or the MA (MA + SMA) has been widely adopted [128].

The Hong Kong-Zhuhai-Macao bridge, is a project that has the largest bride deck paving area in China at present, and the paving is consisted of GA + MA. In the course of paving, the applied large-scale vehicle-mounted shot blasting machine and the developed full-face automatic spraying system have solved the problem of low efficiency of steel plate sandblasting and rust removal. To implement the optimized MA asphalt pavement scheme, a new manufacturing technology called GMA was proposed, and a specific processing technology for fine aggregate was proposed to ensure the stability of raw materials [129]. The GMA process combines the characteristics of GA and MA, but the evaluations for the two mixes are different: the indentation test was adopted to investigate the high temperature stability of the GA mixture, fluidity test was used to assess the workability of the GA mixture; while the Marshall stability and the Lueer fluidity were used to evaluate the high temperature stability of the MA mixture. In the practical evaluation for GMA, the rutting test was used to evaluate the high temperature stability, and the impact toughness was used to evaluate its fatigue properties. The quality evaluation specifications are shown in Tables 11–12.

5 Service status of super-long span bridges in China

There are hundreds of long-span bridges with various types in China. After a long service time, the performances of

Table 11 Measuring items of GMA mixture for bottom layer [130]

inspection terms	standardized requirements
Lueer fluidity, 240°C (s)	⩽20
hardness, 35°C (mm)	0.5–2.0
impact toughnes, 15°C (N·mm)	⩾400
dynamic stability, 60°C (time/mm)	300–800
planeness (mm)	± 3
transversal slope (%)	± 0.3
bonding force with waterproof layer (MPa)	⩾0.9

Table 12 Technical requirements for GMA + SMA composite structure [130]

technical performances	test indicators	requirements	test method
high temperature stability	dynamic stability, 60°C (time/mm)	⩾4000	JTGE20-2011 (T 0719)
	dynamic stability, 70°C (time/mm)	⩾2000	
low-temperature anti-cracking	maximum bending strain, −10°C	⩾8000	JTGE20-2011 (T 0715)
structural integrity	bond strength, 25°C (MPa)	⩾1.0	
	shear strength, 25°C (MPa)	⩾1.5	
water tightness	water permeability coefficient (mL/min)	⩽50	JTGE20-2011 (T 0730)
skid resistance	texture depth (mm)	⩽0.7	JTGE20-2011 (T 0731)

Note: JTGE20-2011 is the Chinese Standard "Specifications and Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering".

many bridges are affected by construction, climate, traffic, and maintenance, and their damage is becoming more and more severe. Taking the steel box girder bridge as an example, the defects mainly include structural cracks in the steel box girder, cracks in the bridge deck pavement, aging of the cable, damage of the wind fairing, support component, and the tower. These defects significantly degrade the performance and reduce the safety of the bridge. Among these defects, the structural cracks of steel box girder are the most severe one.

In 2018, the authors conducted a survey of several representative bridges in China aiming to inspect the service status of these bridges, and especially the service status of the steel box girder. The survey results are summarized in the following sections.

5.1 Service status of steel box girder

5.1.1 Defects in steel box girder

Based on the survey in steel box girder of long-span bridges, it is found that the defects include cracks, corrosion, and coating scaling. Among them, the crack defect is the most severe one, which accounts for more than 80% of the total defects. The common crack types in steel box girder are shown in Fig. 13. The statistics of cracks in the box girder of long-span bridges in China are summarized in Table 13. It is found that the number of new cracks developed in 2017 increases by about 85% compared to those in 2015, and the repaired region that used to have old cracks will crack again under the environment and traffic loads.

Table 13 Cracking survey in steel box girder of long-span bridges.

crack type	number of cracks in 2015	number of new cracks in 2017	ratio of new cracks (%)[a)]	number of cracks in repaired welding	ratio of cracks in repaired welding (%)[b)]
crack at U rib	4026	3597	89	429	11
crack at cross-diaphragm plate	1476	1393	94	83	6
crack at the welded joint between U rib and cross-diaphragm plate	1034	908	88	126	12
crack at U rib around the cable bracket	988	432	44	556	56
crack at top plate	218	205	94	13	6
crack at U rib joint	8	7	88	1	13
other cracks	154	152	99	2	1
total	7904	6694	85	1210	15

Note: a) number of new cracks in 2017/number of cracks in 2015; b) number of cracks in repaired welding/number of cracks in 2015.

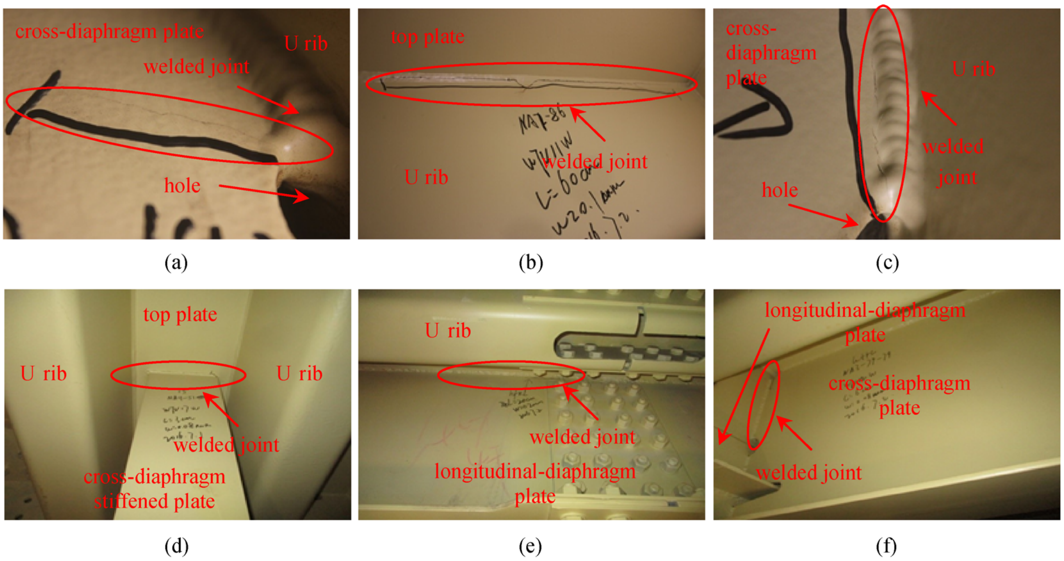


Fig. 13 Cracks in steel box girder of long-span bridge: (a) crack at cross-diaphragm plate around the hole; (b) crack at welded joint between top plate and U rib; (c) crack at welded joint between cross-diaphragm plate and U rib; (d) crack at welded joint between cross-diaphragm stiffened plate and top plate; (e) crack at welded joint between top plate and longitudinal-diaphragm plate; (f) rack at welded joint between cross-diaphragm plate and longitudinal-diaphragm plate.

The causes of box girder defects can be divided into internal and external. The internal causes include poor design, improper construction, defects of base materials, etc. The external causes include heavy vehicle load, large traffic volume, environment, and untimely maintenance, etc. Based on the survey of box girder defects of several bridges in China, it is found that the distribution and development of cracks in box girders have the following characteristics.

1) Most cracks occur at welding joints of components such as joints between U rib and the top plate, joints between U rib and the cross-diaphragm plate, etc. In addition, a few cracks will occur in base material. The cracks inside the U rib are the most difficult one to be detected.

2) Most cracks in box girders occur beneath the heavy traffic lanes.

3) Cracks are mostly concentrated in the mid-span, side-span, and uphill section, and they are along the longitudinal direction of bridges.

4) The location of cracks in steel box girder corresponds to the location of defects in the bridge paving layer.

5) Cracks in the box girder are generally begin to be observed at about 10 years after opening to traffic. Then the cracks may exhibit an explosive growth, which depends on the bridge structure and the maintenance quality.

5.1.2 Repair of steel box girder

Due to the different forming mechanisms of cracks in steel box girder, the repair should be determined based on the causes. The crack defect cannot be solved simply by the welding method.

1) For the bridge deck cracks, the paving layer on the deck should be removed first, then the cracks are repaired by the welding method with ceramic pad at the bottom. The ultrasonic method or drilling method can be used to first detect the location, length, and the propagation direction of the hidden cracks.

2) For the cracks at the welding joint between U rib and the top plate, drilling method can be used to determine the start and end positions of cracks, then the welding repair starts from the crack tip after removing the old cracked welds.

3) For the cracks at U rib, when the crack length is less than 60 mm, bolt holes should be drilled at the crack tip, and then M16 high-strength bolt is used to tighten the cracks. When the crack length is more than 60 mm, strengthened steel plates should be applied at the crack and clamped with high-strength bolts along the cracks.

4) For the cracks at the cross-diaphragm plate that is located around the arc-shaped opening, it should be repaired by means of the punching stop-crack holes method or the bolted reinforcing plate method.

5.2 Service status of stayed cable and wind fairing

5.2.1 Defects in stayed cable and wind fairing

The causes of damage of the stayed cable can be mainly divided into two categories: anthropic factors and environmental factors. The anthropic factors are those occurring during the construction of stayed cable. Since the construction process of stayed cable is quite complicated, the sheath protective layer of the stayed cable, which is made of flexible polymer, will inevitably be damaged to a certain extent during the construction of stayed cable. The environmental factors mainly refer to the combined actions of the live loads including traffic load, wind load, and snow load. Since the cable stress will change greatly under the action of live loads, the repeated length change of the stayed cable will result in fatigue cracks in the stayed cables or the sheaths, which will weaken the integrity of the protection system of the stayed cables. The typical defects in stayed cables are presented in Fig. 14, which include corrosion of cable cap, corrosion of sleeve, oil leakage of damper, and the scratch of sheath.

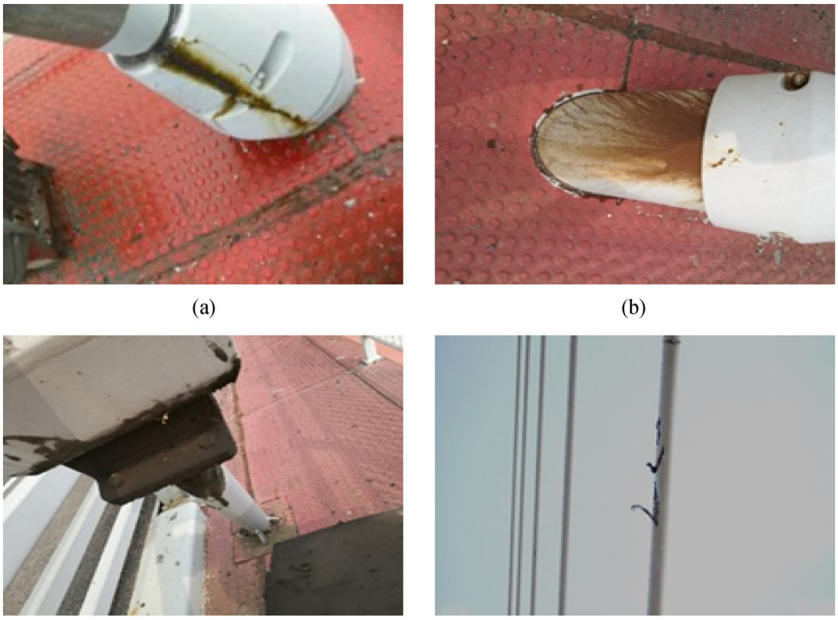
Defects of the wind fairing include corrosion of steel plates, coating scaling, seepage, oil contamination, sludge, etc., which are summarized in Table 14. It can be found from Table 14 that corrosion and seepage are the two main defects during the service life of wind fairing.

5.2.2 Repair of stayed cable and wind fairing

For minor surface damage of stayed cable such as scratches, the damage region should be cleaned by water with pH value of 7 and then grinded. For the deep damage with obvious cracking, the contamination around the damaged sheath should be removed, and the sheath should be cut along the periphery of the damaged region with a knife to allow the damaged steel wire to be exposed. The same material should be welded at the cut opening of the

Table 14 Damage of wind fairing of long-span bridges.

defect type	area of defect (cm^2)	number of defects	ratio of defect area (%)	ratio of defect number (%)
corrosion	315384	239	56.26	66.20
seepage	180900	101	32.27	27.98
coating scaling	2465	10	0.44	2.77
oil contamination and sludge	61800	11	11.03	3.05
total	560549	361	100	100.00



(a) (b) (c) (d)

Fig. 14 Cable defects of long-span bridge: (a) corrosion of cable cap; (b) corrosion of sleeve; (c) oil leakage of damper; (d) scratch of sheath.

sheath with an extrusion plastic welding gun, as shown in Fig. 15(a). Then the damaged region should be grinded by a polishing machine to obtain a plain surface as the original one, as shown in Fig. 15(b). For the severe damage of cable sheath with exposure of steel wire, the repair procedures are summarized as follows: the waterproof system at both ends of the cable should be checked. The accumulated water at the anchor end should be drained first, and the inside space of the cable needs to be dried fully. The rust on the corroded steel wire needs to be grinded or removed with a brush or a sandpaper, then preservative (e.g., zinc-rich primer + epoxy mica-iron sealing paint) should be applied at the polished surface of steel wire. Finally, the steel wire should be wrapped by two layers of polyester belt, as shown in Fig. 15(c). After these repair processes, the sheath is sealed by the same welding material as the previous one, and the welded region is smoothed by the polishing machine.

The joint of the cable cap is often corroded by water accumulation. Measures of removing the rust of the internal structure after opening the cable cap can be applied. The accumulated water should be drained through a drilled hole at the lower anchor of the stayed cable, and the old cable cap and the fillers should be replaced with new ones.

5.3 Service status of tower and support

5.3.1 Defects in tower and support

As the main load-bearing structure, the common defects of towers include vertical and transverse cracks, segment cracks, and concrete damage. Take one bridge in the survey as an example, the bridge inspection report releases that there are 124 vertical cracks, 77 transverse cracks, and 9 network cracks on the No. 5 tower. Additionally, 121 vertical cracks, 26 transverse cracks, and 7 network cracks are found on the No. 6 tower.

The main defects of support include corrosion of coating, cracking of steel plate of the restricting support

(a) (b) (c)

Fig. 15 Restoration procedure of cable of long-span bridges: (a) welding by plastic welding gun; (b) grinding; (c) wrapping by polyester tape.

due to large deformation, severe wear of vertical support, and extrusion of filler. Cracking of steel plate of the restricting support may be caused by the corrosion of support or the aging of rubber, which will degrade the performance of the support. Defects in the vertical support are mainly caused by two aspects: 1) the aging or corrosion of the rubber support, poor maintenance, and insufficient rust-removing measures; 2) uneven pressure on the support, fatigue damage, wear of the tetrafluoro plate, and extrusion of fillers under the repeated traffic loads.

5.3.2 Repair of tower and support

For the damaged support with serious corrosion or wear, it is not recommended to use manual control of the hydraulic jack to conduct the replacement for the long-span bridges. In one of the surveyed bridges, the replacement of the damaged support was done by a computer synchronized jack-up control system. During the replacement, the left and right supports were lifted at the same time to ensure the synchronization of the lifting. The height of jacking-up should be strictly controlled. After the box girder was elevated by 20 mm, auxiliary support should be erected immediately to ensure that each temporary support is evenly loaded. Then all the connection bolts of the old support were removed by cold cutting method, followed by the removing of the old support. After cleaning the surface of the installation location, the new support was placed and connected to the cleaned surface. The box girder should be lifted up at about 1 mm to take out the temporary support, then the box girder was slowly lowered down to complete the support replacement.

5.4 Service status of bridge deck pavement

5.4.1 Defects in bridge deck pavement

Heavy traffic and harsh high and low temperature conditions are the main causes for the damage of steel deck pavement in China. From the perspective of fracture mechanics, many minor defects will always be left on the surface of the steel bridge deck pavement during its construction. With the increasing number of axle loads, the pavement performance will be degraded at various degrees. The design volume of average daily traffic of one bridge is 80000 vehicles, however, the actual daily traffic volume has exceeded 100000 which even reaches 142400 during a busy day. Furthermore, different damages will be caused at different service ages even under the same traffic load.

The locations of bridge pavement defects mainly concentrate on the heavy lanes and the mid-span areas. Influenced by paving materials and traffic loads, the plastic deformation of the bridge deck pavement made by GA in one bridge occurred within one year after its opening to traffic. The deformed area was about 5–8 mm in depth and 200 m in length with a trend to develop into rutting. After two years of opening to traffic, cracks of 0.5–2 m in length and 1–3 mm in width were found at the rutting area.

In general, the sub-tropical monsoon climate area is a serious defect-prone area of steel deck pavement. The high temperature in this area will last for a long time, with the average maximum temperature during May to October of 33°C–37°C. The surface temperature of steel deck pavement can reach up to 70°C in summer, and the maximum temperature difference between day and night exceeds 30°C, which further aggravates the damage of pavement materials.

According to the summary of pavement defects of many bridges, it is found that: 1) most of defects occur along the wheel path and at heavy traffic lanes; 2) longitudinal cracks are easily formed at the joints between different lanes; 3) the defects are mostly concentrated in mid-span, side-span, and uphill section along the longitudinal direction of bridges, however, there are fewer defects near the bridge supports; 4) the defect-prone area of the bridge deck pavement corresponds to that of steel box girder; 5) the defects of bridge deck pavement will exhibit an explosive growth after 7 to 10 years of opening to traffic.

5.4.2 Repair of bridge deck pavement

The bridge deck pavement will inevitably be damaged to various degrees after a period of service. According to the different damage degree and traffic conditions, the bridge deck pavement can be repaired by preventive maintenance, repairing maintenance or refurbishment.

Preventive maintenance is an active maintenance measure taken before obvious defects occur in bridge deck pavement with the goal to delay the damage and extend its service life. Common preventive maintenance measures include crack filling, fog sealing, and micro-surfacing [131]. Engineering experiences show that preventive maintenance is the most important one among the three repair methods due to its high efficiency and low cost, which is the key to ensure the service life of bridge deck pavement.

Repairable maintenance mainly refers to the repair of local pits, cracks, and other defects of bridge deck pavement. According to the expected service life of the repaired bridge pavement, repair methods can be divided into emergency repair, semi-permanent repair, and permanent repair. Common repairable maintenance technologies include in situ hot regeneration technology, plant mixing hot regeneration technology, in situ cold regeneration technology, and the fog seal technology [132].

When there is a large damaged area occurring in the bridge deck pavement or the development of defects cannot be curbed by the repairing maintenance, it is necessary to take refurbishment measures for the bridge deck pavement. The refurbishment of bridge deck pavement includes removing the old deck pavement, followed by anti-rust and waterproofing treatments, and casting the new pavement structure. The refurbishment plan of bridge deck pavement is generally determined according to the traffic volume, environmental conditions, construction conditions as well as the economic and social benefits.

6 Progress and prospects of super-long span bridge technology in China

6.1 Standard system for long-span bridge

The standard system for the long-span bridge is an important index that reflects the design and construction level of one country, which summarizes the mature design and construction technologies of bridges. Due to the complexities of constructing long-span bridges, it is often necessary to adopt breakthrough technologies in the actual design and construction. Based on the large-scale construction of bridges in recent decades, China's bridge standards system has been improved significantly. In 2002, the Ministry of Transport of China revised and issued a new version of Standard System for Highway Engineering (JTG A01-2002), which contains 80 books of JTG standard codes for bridges, pavements, and tunnels. To meet the actual requirement of development of long-span bridge structures, China has formulated the Specifications for Design of Highway Suspension Bridge (JTG-T D65-05-2015), Guidelines for Design of Highway Cable-stayed Bridge (JTG D65-01-2007), and Specifications for Design of Highway Concrete-filled Steel Tubular Arch Bridges (JTG-T D65-06-2015). This provides an important guide for the design and construction of bridges in China. However, these standards are formulated mainly for the common highway bridges, while the design and construction of long-span railway bridges and high-speed railway bridges, etc., are not particularly specified in these standards. Currently, China has not yet established a national standard system for the design and construction of long-span bridges.

Compared to the developed countries, the standard system of long-span bridge structure in China lags behind the practice, and the national standard system is still insufficient, impeding the development of long-span bridge construction in China. During designing and constructing long-span bridges, China often refers to the existing codes worldwide (e.g., the European codes and Japan codes). Therefore, it is an urgent task to speed up the formulation of standard system for the design, construction, and maintenance of long-span bridges in China. More attention should be paid to improve the standard system by introducing the advanced design theory and those successful construction experiences obtained worldwide in recent decades, and removing the incorrect or immature design concepts from the current standard system. The future standard system should serve the national "Going Global" strategy in China.

6.2 High-performance materials

6.2.1 High-performance steel

The development of super-long span bridges largely depends on the development of steel materials used in bridge structures. The bridge steel in China has roughly experienced the developing stages of carbon-manganese steel → low-alloy steel → high-strength steel → high-performance steel [133]. Since the service condition of long-span bridges in China becomes more and more complex, bridge steel should not only meet the strength requirements, but also satisfy the higher requirements for toughness, weldability, and corrosion resistance. Currently, high-performance steel has undergone a rapid development with excellent mechanical properties, durability, and weldability, which not only improves the durability of bridge structure, but also reduces the construction and maintenance cost [134].

Researches on high-performance steel for bridges in China can date back to 1960. However, it was not until 1992 that the high-performance steel was really applied in bridge project in China. At present, high-performance steel with grade of Q420qE and Q500qE has been used in Nanjing Dashengguan Yangtze River Bridge, Hutong Yangtze River Bridge, and other bridges. However, high-performance steel has not been widely used in China, and researches on high-performance steel should be speeded up to meet the growing needs of long-span bridges in China.

At present, the technical specifications of Q345qNH–Q550qNH grade high-performance steel have been specified in Chinese Standard for Bridge Structural Steel. However, the formulation of specifications for high-performance steel lags behind the growing needs of bridge design and construction. In addition, with the development of new high-performance steel for bridges, the selection of welding materials and the quality index requirements of bridge components need to be updated and adjusted in time. In recent years, more and more attention has been paid to the concepts of green and safety during the construction of long-span bridges in China. Therefore, it can be concluded that the high-performance steel of long-span bridges will have a promising development in the future.

6.2.2 High-strength steel wire

The quality of cables is directly related to the safety and durability of bridges. As an important load bearing component of bridges, cables are mainly composed of steel wires. The use of high-strength steel wire brings many benefits to the design and construction of super-long span bridges. After years of research and construction, high-strength steel wire and high-strength steel strand with strength of 1860 MPa have been widely used in the construction of super-long span bridges in China. The newly developed high-strength steel wire with strength of 1960–2000 MPa [135] is also considered to be used for the cables of cable-stayed bridges and suspension bridges under construction. In addition, China's high-strength steel wire has formed a production process system with independent property rights, and the performance of high-strength steel wire is superior to that of the similar products abroad [136].

However, the existing bridge maintenance codes have not yet established for evaluating the service life of steel cables, and the maintenance plan for the cable is unsubstantiated [137]. At present, the bridge maintenance department in China usually replaces the steel cables when they are found corroded, which may cause an unnecessary waste. On the other hand, high strength steel wire is a corrosion sensitive material, and the corrosion of steel wire will lead to a significant attenuation of mechanical properties and threaten the safety of bridge in service. Currently, only limited researches have been carried out on the corrosion of high-strength steel wire [138–140]. In the future, it is necessary to conduct in-depth studies on the corrosion and degradation mechanism of high-strength steel wire to develop a method to evaluate the service life of steel cable.

6.2.3 (Super) High-performance paving materials

At present, the deck pavements of most long-span bridges in China are constructed by EA concrete, GA, and MA with gravel. Among them, EA concrete is the most successful deck paving material for long-span bridges in China, because of its excellent mechanical and road properties, high and low temperature stability, waterproofing property, and crack resistance. It has gained successful experiences in many long-span bridges, which provide a contribution to the performance and service life of the bridges.

However, due to the vast terrain in China, the service environment and traffic conditions of long-span bridges in different regions are quite different. To meet the requirements of more complex traffic conditions (such as overloading) and longer-span bridge construction, it is necessary to develop new (super) high-performance paving materials to further improve its strength, deformation ability, temperature stability, and durability in the future. Thinner paving structures (such as less than 5 cm) can be very beneficial to reduce the self-weight of the long-span bridge structures, and thus promote the innovation of structure design and significantly increase the span of bridges.

6.3 Information technology

The construction efficiency and performance of super-long span bridges depend largely on the information technology, which has become an important part of the next technological development of long-span bridges.

In terms of the design software, after more than 30 years of development and application, China has made great progress on the self-developed computer-aided design and analysis software for bridge structures. The widely-used software for structural design and construction control include Bridge Doctor, QJX, GQJS, PRBP, and BINAS. The calculation accuracy and efficiency of these software are in general comparable to the similar software abroad. The domestic bridge design-aid software includes Bridge Master and Program Designer, which cooperates well with the domestic standard and the practical projects.

China has realized the intelligent manufacturing of steel box girder in the Hong Kong-Zhuhai-Macao Bridge project [107], including U rib processing, component assembly, component welding, phased array detection of U rib fillet weld, by using the developed devices with independent property rights, such as the numeric control processing machine for U rib groove, the automatic assembly machine, and the welding robot, etc.

At present, BIM technology has been applied in the design, construction and maintenance of bridges in China [141–145]. The current BIM technology pilot work is underway, including the preparation of bridge BIM standards, the development of bridge BIM software, and the demonstration of related engineering applications. Meanwhile, China's long-span steel bridges have been freed from traditional manual monitoring. Information technology such as self-designed artificial intelligence (AI) health monitoring systems, sensor for internet connection [146], cloud computing [147], big data processing [141], etc. has begun to be adopted to improve monitoring efficiency and ensure the safety of bridge.

In general, China has begun to apply intelligent construction, AI monitoring, and other information technology in long-span bridges, but is still in the initial stage, and the technical level has not met the various needs of the actual project during the life cycle. In addition, the development of design software for China's long-span bridge construction is insufficient. In the future, it is necessary to focus on the development of domestic core software suitable for the analysis of complex mechanical behavior of long-span bridges. Meanwhile, China needs to develop practical domestic BIM software, and establish a BIM standard system for long-span bridges, considering the entire life cycle of the bridge's planning, design, construction, maintenance, management, etc., to realize the informational management during the bridge's life cycle.

6.4 Construction equipment for long-span bridges

China has made great breakthroughs in developing construction equipment for bridge foundation, tower, cable, and box girder, etc [135,148]. Chinese construction enterprises have developed equipment for various requirements of bridge foundation constructions, including piling boat, hydraulic piling hammer, drilling rig, concrete mixer, and double-wheel grooving machine. In particular, the piling boat can complete the piling operation for pile foundation with diameter of 5 m and length of 90 m, which reaches the world leading level.

For constructing super-high bridge towers, Chinese enterprises have developed the D5200 tower crane, the largest tower crane for the horizontal arm hoisting in the world, which provides strong support for constructing suspension bridges and cable-stayed bridges. The construction efficiency and casting length of the climbing formwork for bridge towers in China have reached the world leading level.

China has achieved innovative construction methods in erecting cables of long-span bridges. According to different bridge construction environments, various methods including rocket, helicopter, unmanned aerial vehicle, airship, and other equipment have been developed to complete the erection of cables. By replacing the wind-resisting cable with the brake device, the wind-resistant stability of catwalk during the construction can be greatly improved.

In terms of assembly and construction of box girder, China independently developed a set of assembly equipment including numerically-controlled machine tool for U rib groove, automatic assembly machine tool, and the welding robot, which greatly improve the efficiency and quality of assembling the box girders. In addition, China has independently developed key construction equipment for box girder. These devices include floating crane, bridge erector, bridge deck crane, cable-borne crane, large gantry crane, and sliding form, which can provide solid support for the accurate hoisting and installation of the box girders. In particularly, the lifting capacity of cable-borne crane made in China has reached the world leading level.

For steel wire winding, China has developed an advanced S-shaped wire winding machine, which can provide a good sealing for steel wire and ensure that the bridge deck pavement is paved after the winding of the steel wire. Furthermore, the S-shaped wire winding machine can greatly improve the construction efficiency and reduce the time of the wire being exposed to environment, which can thus increase the service life of steel wire.

In summary, China has been able to independently develop large-scale construction equipment, which helps significantly reduce rental costs of large-scale equipment. However, the reliability and service life of these equipment still need improvements compared to the similar equipment made in the developed countries. Currently, China is still not able to producing some key components of the equipment, and heavily relies on imports. In the future, it is necessary to enhance the reliability of construction equipment and improve the manufacturing capability of the key components of the construction equipment for the long-span bridge construction. In addition, the intellectualization and automation of the equipment for long-span bridge construction in China are far from being well developed, which is also the key research direction in the future.

6.5 Health monitoring and assessment

Since the wind-damage accident of the Tacoma Bridge in 1940, health monitoring of long-span bridges under operation has attracted a wide attention. The health monitoring system of long-span bridges can generally be divided into five subsystems: sensor system, data acquisition and transmission system, data processing and control system, structural health assessment system, and inspection and maintenance system. The main functions of the health monitoring system include structural monitoring, environment monitoring, traffic monitoring, equipment monitoring, damage identification, overall performance assessment, integrated alarming, information analysis and processing, and maintenance and management of bridges [149]. The research on bridge health monitoring in China started relatively late. Since the 1990s, China has established health monitoring systems on dozens of long-span bridges such as Tsing Ma Bridge, Jiangyin Yangtze River Bridge, and East Sea Bridge. Based on the original data collected by the monitoring system, the theoretical methods to analyze and evaluate the performance of bridge structures have been developed [150,151].

Many parameters need to be monitored for long span bridges, and the collected huge amount of raw data bring great challenges to the storage as well as the methods for analyzing. In addition, the working stability of some types of sensors is insufficient, and their service life does not match the life of long-span bridges. It is difficult to replace some failed sensors during the operation stage of bridges, which will weaken the expected functions of the health monitoring system. Therefore, in the future, in-depth researches are needed on the following aspects: 1) development of durable, reliable, and stable sensor system; 2) efficient method to store and analyze the collected original data; 3) establishment of the relationship between monitoring indicators and bridge service performance; 4) and formulation of the national standard for health monitoring and assessment of long-span bridges.

6.6 Super-long span sea-crossing bridge

Due to many coastal islands in eastern China, China still has a great need to build super-long span sea-crossing bridges in the future. However, the current bridge design standard in China is only applicable to suspension bridges with span of less than 2000 m [152] and cable-stayed bridges with span of less than 800–1000 m [153], which is not suitable for the construction of super-long span sea-crossing bridges. Although researches have been carried out in Europe, Japan and Korea for the structure design of cable-stayed bridges with span of 1200–1600 m and suspension bridges with span of 2700–3300 m currently [148], the span of either the existing long-span bridges or the bridges under construction in the world is less than 2000 m. There is no construction experience of super-long span sea-cross bridges worldwide. The marine environment is very complex and harsh. For example, a variety of static and dynamic loads caused by wind, waves, tides and other uncertainties may threaten the construction safety of super-long span sea-cross bridges. Therefore, in the future, it is necessary to develop high-strength, light-weight, and durable bridge construction materials to optimize the bridge structure to achieve a super-long span (e.g., more than 3000 m, or even longer). It is also promising to explore the design and construction of submerged floating tunnel.

6.7 High-speed railway bridge

At present, the construction of high-speed railway bridges in China is developing rapidly. Unlike highway bridges, there exists a strong dynamic effect on the railway bridges caused by the high speed and heavy live load of the trains, which has a higher requirement for the stiffness of railway bridges. In addition, the long-span high-speed railway bridges need not only to satisfy the safety requirement of rail vehicles, but also to meet the comfort requirement of driving [154]. In China, several studies have been conducted on the structural dynamic response [155,156], the mechanical response of deck pavement [157], earthquake resistance and shock absorption [158–160], and vehicle-bridge coupling vibration [161,162] for long-span cable-stayed railway bridges, and the relevant results have been applied in practical projects. Recently, China has made breakthroughs in the construction of long-span cable-stayed railway bridges. For example, Tongling Bridge with main span of 630 m is the largest cable-stayed railway bridge in the world. Hutong Yangtze River Bridge with main span of 1092 m under construction will become the world's first cable-stayed railway bridge with main span exceeding 1000 m. However, the construction experiences of long-span suspension railway bridges are very limited due to its flexible structure, which will exhibit a large deformation subject to the heavy train loads and is difficult to meet the safety and comfort requirements for the train vehicles. The long-span suspension railway bridges under construction now in China include Yangsigang Yangtze River Bridge, Zhenjiang Yangtze River Bridge, and Wufengshan Yangtze River Bridge. Presently, the theoretical researches on long-span suspension railway bridges have also been conducted, which mainly focus on the wind resistance and earthquake resistance [163,164].

In general, the development of high-speed railway bridges in China is still in its beginning stage, and the relevant design theories are far from being well developed. In the future, it is still necessary to carry out fundamental researches on load distribution characteristics, stiffness and stability of bridge structures, and optimization of the bridge structures to develop design standard system to guide the construction of high-speed railway bridges.

7 Conclusions

Upon the coming of the third decade of the 21st century, China's long-span bridge construction has entered a golden age. While facing great opportunities for development, China's long-span bridge construction also faces great challenges. In addition to structure safety and construction scale, the long-span bridges should also satisfy the requirements for aesthetics, comfort, and innovation. Moreover, the economic indicator is also important to be considered during the construction of long-span bridges. To construct economic, high-quality, durable, and beautiful bridges, China should not only pursue the technology innovation for "large" span, but also improve the design standard and control the construction cost. In the future, China will face challenges of new theories, new materials, new equipment, new processes, and new technologies for long-span bridges, and contribute to the technological advancement of long-span bridge construction in the world.

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