Orthotropic Steel–UHPC Composite Deck

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Although orthotropic steel decks (OSDs) have been widely used in the construction of long-span bridges, there are frequently reported fatigue cracks after years of operation, and the bridge deck overlay also presents severe damage due to OSD crack-induced stiffness reduction. Ultra-high performance concrete (UHPC), recognized as the most innovative cementitious composites and the next generation of high-performance materials, shows high strength, ductility, toughness, and good performance on durability. After its first application to the OSD bridge in the early 2000s, the orthotropic steel–UHPC composite deck has been comprehensively studied worldwide.

composite deck OSD UHPC stress behavior fatigue

1. Introduction

For bridge engineering applications, the fundamental function of the bridge deck is to directly bear, distribute, and transfer the wheel loads. The bridge deck may also react as part of the main girder to bear force acting on the bridge superstructure. Highway bridges normally adopt three types of bridge decks, namely the concrete deck, steel deck, and steel–concrete composite deck [1]. It is well known that under the action of wheel loads, the concrete decks produce small deformation due to the high stiffness of the deck system. However, its heavy dead load and low tensile strength of concrete limit its application in bridge engineering. The steel bridge deck is usually made of an orthotropic steel deck (OSD), which has light weight, high bearing capacity, and significant overloading capacity. However, this type of deck system can produce large deformation under wheel load due to its low structural stiffness. As a result, fatigue cracking and pavement damage are frequently reported after years of operation. The steel–concrete composite deck includes several types of structures, such as the orthotropic steel–concrete composite deck, the orthotropic steel–steel fiber reinforced concrete composite deck, and the orthotropic steel ultra-high performance concrete (steel–UHPC) composite deck. The first two can only be applicable to medium and small-span bridges because of the large thickness overlay and its significantly increased dead loads. They may also be prone to cracks under concentrated wheel loading due to the low tensile strength of concrete. With the development of the UHPC, the orthotropic steel–UHPC composite deck is widely used in various types of bridge structures with different span lengths, especially in long-span bridges.

The OSD, consisting of the deck plate, respectively, stiffened by the floorbeam and the ribs in bridge transverse and longitudinal directions, presents different structural properties in two orthogonal directions. The OSD was first used in Germany as the bridge deck to build the steel bridge. After the Second World War, the growing demand for post-war traffic recovery made OSDs widely used in bridge engineering [2]. Since the Severn Bridge in the UK adopted the OSD steel box girder for the first time, the OSD has become the most popular deck system for long-span bridges. **Figure 1** shows two structural forms consisting of open ribs or closed ribs, with the traditional pavement on the deck plate.

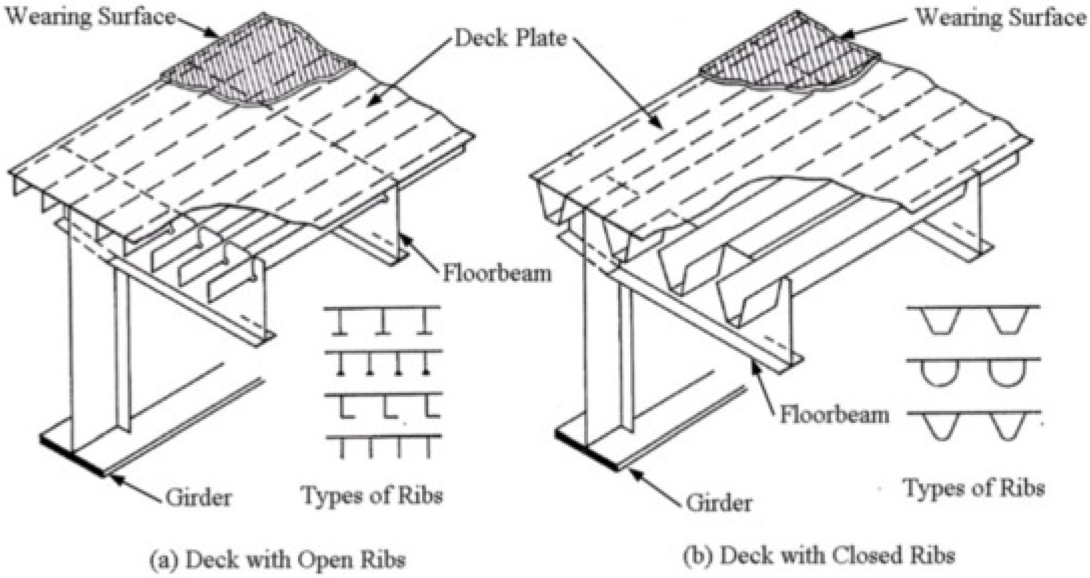

Figure 1. Typical structural layout of OSD.

The OSD has been widely used in long-span suspension bridges and cable-stayed bridges due to its remarkable advantages, but the OSD is not a perfect structure since there are many welds in the orthotropic steel bridge deck, which have small defects. Under the cyclic loading of the vehicle, the defects lead to the emergence of fatigue cracks. With the extent of the fatigue cracks, the cross-section weakens significantly and the stress concentration is severe [3][4][5]. Fatigue cracking is frequently reported on bridges, particularly for those with large traffic volumes and serious overloading trucks, the typical locations of fatigue cracking are shown in **Figure 2** [6]. The fatigue cracking may also lead to frequent maintenance and replacement of bridge deck pavement, which presents a great impact on local traffic. Therefore, avoiding fatigue cracking and pavement damage is one of the major long-term considerations in the bridge engineering community.

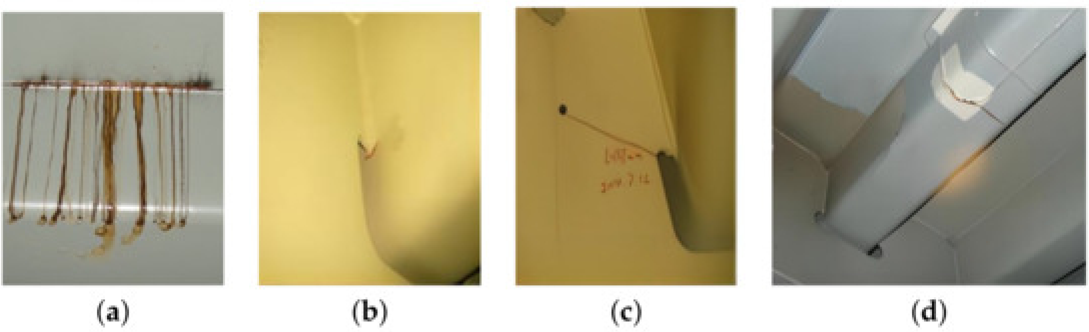

Figure 2. The typical locations of fatigue cracking: (**a**) Rib-to-deck crack; (**b**) Rib-to-floorbeam crack; (**c**) Cutout crack; (**d**) Rib splice crack.

With the growing increase in bridge main span and the rapid increase in traffic volume, fatigue cracking of the OSD becomes a severe challenge in bridge engineering. Hence, many scholars have conducted extensive research on this topic, including laboratory model tests, FEM analyses, and field tests. Wang [7] conducted full-scale fatigue tests on the OSD of a cable-stayed bridge, and found that the impact of welding residual stress on the fatigue life of structural details in the compressive stress zone cannot be ignored. Zhang's [8] research shows that there are significant differences in the fatigue of vulnerable parts of OSDs, and the stress distribution in the vicinity of fatigue cracks constantly changes as the cracks propagate. Zweraeman [9] believes that the small stress amplitude generated by high-order vibration of steel bridges under random traffic flow, which is lower than the fatigue cutoff limit, can also cause fatigue damage to the steel bridge. Connor [10][11] conducted controlled loading tests and random vehicle flow tests on two different bridges, and studied the effect of out-of-plane deformation on the fatigue life of the diaphragm based on on-site test data.

The deck of a steel bridge faces the challenges of orthotropic deck cracking and easy damage to the pavement layer, which conventional techniques cannot fundamentally solve [12]. Only by relying on breakthroughs in materials and developing corresponding new structural systems can researchers find effective solutions to the difficult problems in traditional steel bridges and steel–concrete composite bridges. Compared with traditional orthotropic bridge decks, the steel–UPHC composite bridge structure has the following two characteristics: Firstly, it can significantly improve the stiffness of the bridge deck. Secondly, the synergistic effect of the UHPC layer and orthotropic steel plate can significantly reduce the fatigue stress amplitude in the orthotropic plate under local wheel loads. The steel–UHPC composite bridge structure is in its initial stage of practical application, and its superior performance needs to be known and accepted through a process. Therefore, summarizing existing literature and analyzing the characteristics of static, shear, and fatigue performance of composite structures under different conditions have important guiding significance for subsequent theoretical research, experimental development, and engineering applications of this structure.

Mechanical properties and fatigue problems have always been difficult and hot issues that must be faced in the development of orthotropic bridge deck structures and even the entire steel structure field.

2. The Orthotropic Steel–UHPC Composite Deck

The UHPC is an innovative cement-based composite material, which was first developed by French scholars in 1993. The material consists of cement, silica fume, fine aggregate, fiber, water reducer and other materials, as shown in **Figure 3** and is constructed according to the principle of maximum compactness [13][14]. The goal is to minimize the internal pores and micro-cracks of the material, so as to obtain excellent mechanical properties and durability.


(a) (b) (c) (d) (e) (f)

Figure 3. Material used to form UHPC: (**a**) Cement; (**b**) Silica fume; (**c**) Quartz sand; (**d**) Fly ash; (**e**) Water reducer; (**f**) Fiber.

Due to the use of fiber inside the UHPC, the tensile and deformation properties of concrete have greatly improved, and the compressive and flexural strength of UHPC can reach 3 times and 10 times that of normal concrete (NC), respectively, with its creep coefficient only about 5% of the NC. It is reported that its durability performance is significantly better than the NC. The mechanical properties and durability index of UHPC are greatly enhanced compared to NC, as shown in **Table 1**.

The emergence of UHPC materials has led to the development of structures towards economy and environmental protection. Firstly, the superior mechanical properties of UHPC have greatly reduced the weight of the structure while meeting the usage conditions. Secondly, UHPC can be prepared by replacing part of cement with Industrial waste fly ash and mineral powder. Thirdly, UHPC can be used for combining structures and repairing and strengthening existing structures. Zhao [15] compared and analyzed the steel UHPC composite beam and conventional steel plate composite beam schemes based on a certain overpass bridge project. The results showed that they had significant advantages in construction and durability, and the unit price of the main materials decreased by about 4.3% compared to conventional steel–concrete composite beams.

With the use of UHPC, it is expected to develop a more economical, environmentally friendly, stronger, and more durable high-performance structure. Based on the above advantages, UHPC became more and more popular worldwide, and its preparation, production, construction, and prefabrication technology have become mature in bridge engineering.

Table 1. UHPC and NC main mechanics and durability index.

Material Type	UHPC	NC	References
Compressive strength/MPa	120~230	30~60	[16][17][18][19][20]
Flexural Strength/MPa	15~60	2~5	[16][17][18][19][20]
Elasticity modulus/GPa	40~60	30~40	[18][19][20]
Creep coefficient	0.2–0.3 (High temperature steam curing)	1.4~2.5	[18][19]
Diffusion coefficient of chloride ion/(m22/s)	<0.02 × 10−11−11	>1 × 10−11−11	[16][18][20]
Electrical resistivity/(kΩ·�·cm)	1133	96 (C80)	[18]

The traditional OSD uses asphalt, resin, or composite paving materials, such as stone mastic asphalt (SMA), epoxy asphalt concrete (EAC), and epoxy resin asphalt. The elastic modulus of these pavements, formed by organic glue, is significantly lower compared to steel or concrete and decreases notably with the increase in temperature. When the temperature of the pavement is high or the sunshine is strong, the elastic modulus of the pavement decreases obviously. For example, in China's southern area, like Guangdong Province, the weather is hot and solar radiation is strong. The observed highest temperature of the pavement can reach about 65 °C [21], and the elastic modulus of the pavement may only be a few hundred MPa, as shown in **Figure 4**. Therefore, the contribution of pavement to bridge deck stiffness is very small; thus, the stress at OSD details will be significantly increased under wheel loads, which may lead to fatigue cracking.

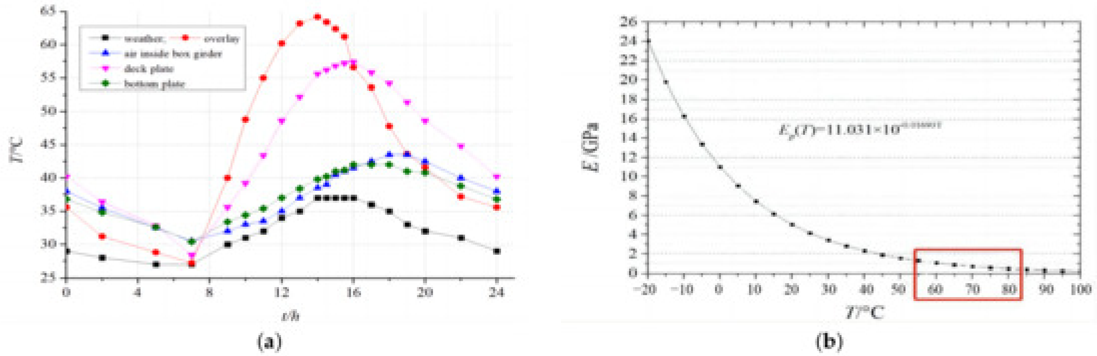

Figure 4. Measured temperature of deck overlay and its elastic modulus of EAC against temperature: (**a**) Measured temperature of steel girder and its overlay; (**b**) Elastic modulus of EAC against temperature.

The orthotropic steel–UHPC composite deck consists of the shear connectors welded on the OSD deck plate, and the casted UHPC layer, as shown in **Figure 5**. In order to reduce the dead loads, the thickness of the UHPC layer is generally 35 mm to 60 mm. While in order to reduce the tensile stress in the thin UHPC layer, double-layer bidirectional (longitudinal and transverse) steel bars are arranged in the UHPC. Steam curing is usually used to reduce shrinkage in the process of curing. In addition, in order to improve the driving conditions on the bridge deck, the traditional 20–40 mm asphalt overlay will be paved on the UHPC. **Figure 5** is the major construction process of orthotropic steel–UHPC composite deck.

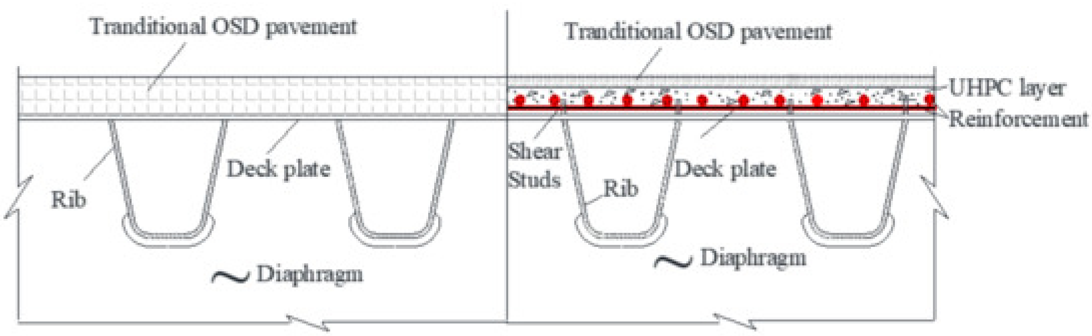

Figure 5. UHPC construction process.

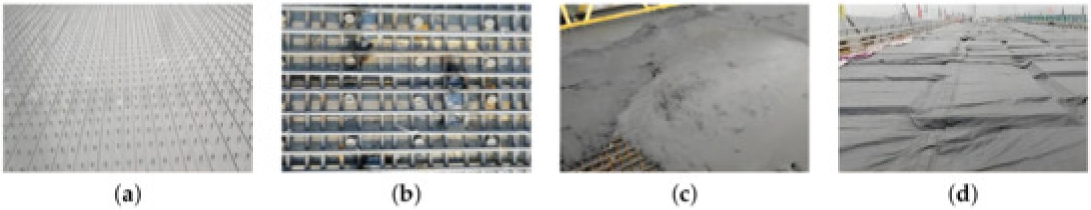

Figure 5. UHPC construction process: (**a**) Welded shear stud; (**b**) Steel mesh; (**c**) Pouring UHPC; (**d**) Steam curing.

Engineering application has recognized many advantages of the orthotropic steel–UHPC composite deck. The UHPC layer is cement-based material, which improves the performance of the upper asphalt pavement and can effectively reduce the debonding, cracking, and rutting of the asphalt pavement. Meanwhile, the steel–UHPC composite structure can improve the bridge deck stiffness and reduce the stress at details of the OSD under wheel load, hence greatly increasing the fatigue life of the bridge deck. The UHPC layer presents high tensile strength and high ductility, which can satisfy the demands of stress and deformation under wheel loads. In addition, the thin UHPC is light-weighted, which is helpful to reduce the seismic inertia force acting on the bridges and to facilitate larger-span crossing [22]. It is also found that the UHPC layer can be prefabricated together with the OSD, which is applicable for assembly construction to improve its quality control.

3. Engineering Application of Orthotropic Steel–UHPC Composite Deck

De Jong and Kolstein first proposed the combination of the UHPC and the OSD to repair existing steel bridge cracks [23]. They first removed the bridge deck pavement of the Dutch Garland Bridge (Caland Bridge) and replaced it with RHPC (reinforced high-performance concrete), as shown in **Figure 6**. Then, they carried out FEM and laboratory tests and found that the local bending stress was reduced by 80% on the deck plate side. Although they proposed the idea to reduce the fatigue stress of OSD, the steel and UHPC are not treated as a composite structure since the UHPC layer and steel panels worked together through a thin bonding layer between them, in which the composite action is weak and only the load distribution function of the UHPC layer could be considered.

Figure 6. Deck replacement of Galand Bridge using glued UHPC layer.

In the subsequent years, the composite deck formed by steel and UHPC attracted many researchers and engineers. In 2007, the world's first steel–UHPC composite bridge, the Gärtnerplatz Bridge, was built over the Fulda River in Germany [24]. In 2011, the overlay of a traditional OSD bridge built in 1970 was replaced in France by using UHPC material. A similar replacement on the Illzach Bridge in France [25] was carried out using precasted UHPC plates and wet connection joints.

The application of UHPC in bridge engineering in Asia was relatively late, but it developed rapidly over the past decade. Currently, more than one hundred UHPC bridges have been built in Asia, some of which are steel–UHPC composite structures. In China, Shao Xudong [26] first practiced the deck replacement of the Zhaoqing Mafang Bridge, by using the UHPC layer, as shown in **Figure 7**. The thickness of the cast-in-place UHPC layer was 50 mm and the thickness of the surface asphalt pavement was 30 mm. The UHPC layer and the steel panel are connected by way of "stud + epoxy resin adhesive". Compared with the traditional epoxy pavement on other spans of the bridge, over 12 years of operation demonstrated that the composite deck system has obvious advantages.

Figure 7. Mafang Bridge using steel–UHPC composite deck: (**a**) Under construction; (**b**) After 12 years in service.

In the following years, the steel–UHPC composite deck, in which the steel and UHPC layers work together through shear connections has been comprehensively studied, including its bending and shear behaviors and its fatigue performance. In the meantime, the steel–UHPC composite deck has been widely used as a new deck system in the construction of steel bridges. **Table 2** shows newly built bridges using steel–UHPC composite deck in China, and **Table 3** shows deck replacement using the steel–UHPC composite structure. It is clear that the orthotropic steel–UHPC composite deck is increasingly popular and is used by different types of bridge structures, i.e., not limited to long-span bridges. **Figure 8** shows the orthotropic steel–UHPC composite decks under construction for four bridges.

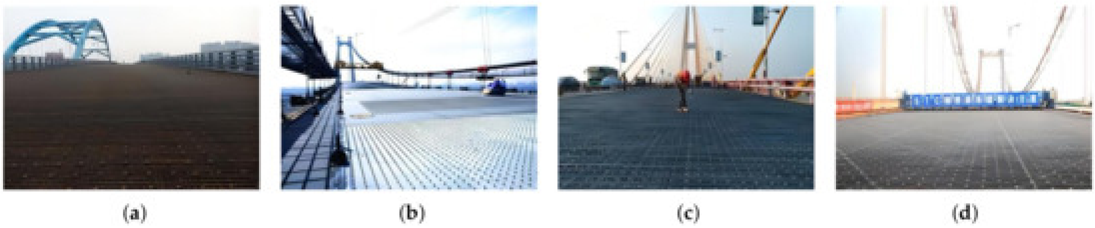

Figure 8. Bridge deck under construction: (**a**) Fochen New Bridge; (**b**) Hangrui Dongting Lake Bridge; (**c**) Queshi Bridge; (**d**) Fengxi Bridge.

Table 2. Newly built bridge using orthotropic steel–UHPC composite deck in China.

Bridge Name	Location	Span Arrangement/m	Type	Year
Fochen	Foshan, Guangdong	58.51 + 112.8 + 58.51	①	2014
Hexi Trans. Hub	Changsha, Hunan	54	①	
Beiguan Tonghuihe	Tongzhou, Beijing	11.5 + 60 + 18.5	②	2015
Haihe	Tianjin	310 + 4 × 48	③	
Longxi Interchange Ramp	Jiangmen, Guangdong	28 + 50 + 28	①	2016
Shendang	Jiaxing, Zhejiang	72	①	

Bridge Name	Location	Span Arrangement/m	Type	Year
Jiaoshanmen	Jiaxing, Zhejiang	36.5	①	2017
Beiguan Street	Tongzhou, Beijing	30 + 40 + 70 + 40 + 30	②	
Lichuan	Dongguan, Guangdong	138	③	
Fengxi	Zhuzhou, Hunan	300	④	
Chetian River	Guiyang, Guizhou	32 + 56 + 32	①	
Tongguan	Changsha, Hunan	50 + 50	①	
Wuyi	Huzhou, Zhejiang	60 + 128 + 60	①	
Gangxia North Trans. Hub	Shenzhen, Guangdong	30 + 2 × 46 + 34 + 32	①	
Shele	Taiyuan, Shanxi	30 + 150 + 150 + 30	③	
Hangrui Dongting Lake	Yueyang, Hunan	1480	④	
Zhaohua	Xiangtan, Hunan	168 + 228	④	
Fute Bay	Foshan, Guangdong	112 + 2 × 200 + 112	①	2018
Jinan Guodian Interchang	Jinan, Shandong	21.5 + 22 + 26 + 22 + 20	①	
Beiyuan Expressway West	Jinan, Shandong	30 + 47 + 30	①	
Da’an North Interchange	Baicheng, Jilin	31.2	①	
Tiansheng Harbour and Ferry	Nantong, Jiangsu	141.5 + 336 + 141.8	②	
Beijiang River Fourth	Qingyuan, Guangdong	100 + 218 + 100	③	
Maogang River	Shanghai	110 + 225 + 110	③	
Tianbaowan	Chengdu, Sichuan	230	①	2019
Hongfenglu	Changsha, Hunan	30 + 70 + 30	①	
Longsheng	Huizhou, Guangdong	40 + 185 + 40	②	
Haiwen	Haikou, Hainan	230 + 230	③	
Zhongxing	Ningbo, Zhejiang	64 + 86 + 400 + 86 + 64	③	
Jingzhou Yangtze River	Jingzhou, Hubei	98 + 182 + 518 + 182 + 98	③	
Yunlongwan	Chengdu, Sichuan	30 + 80 + 205 + 80 + 30	④	

Bridge Name	Location	Span Arrangement/m	Type	Year
Qinglongzhou	Yiyang, Hunan	60 + 110 + 260 + 110 + 60	④	
Dashahe 1st Road Crossing	Shenzhen, Guangdong	75	②	
Hutong Yangtze River	Suzhou, Jiangsu	140 + 462 + 1092 + 462 + 140	③	
Jiangxinzhou Yangtze River	Nanjing, Jiangsu	80 + 218 + 2 × 600 + 218 + 80	③	
Rongjiang	Jieyang, Guangdong	400	③	2020
Xinglinbao	Zhangjiakou, Hebei	217	③	
Taizicheng No.1	Zhangjiakou, Hebei	50 + 100 + 100 + 50	③	
Honghe	Yuanyang, Yunnan	700	④	
Qiushi Road Steel	Urumqi, Xinjiang	42 + 68 + 68 + 42	①	
Shennong Lake	Changzhi, Shanxi	130 + 130	③	2021
Qipanzhou	Huangshi, Hubei	340 + 1038 + 340	④	
Shachong	Dongguan, Guangdong	9 + 88 + 9	②	
Binhai Bay	Dongguan, Guangdong	60 + 200 + 200 + 60	③	

Bridge Name	Location	Span Arrangement/m	Type	Year
Mafang	Zhaoqing, Guangdong	14 × 64	①	2011
Queshi	Shantou, Guangdong	518	③	2016
Riyue-Chengwen Road Expressway	Chengdu, Sichuan	37 + 46 + 46 (Left) 46 + 46 + 42 (Right)	①	2018
Junshan	Wuhan, Hubei	48 + 204 + 460 + 204 + 48	③	
Lanzhou Donggang Interchange	Lanzhou, Gansu	595	①	2019
Songpu	JShanghai	419.6	①	2020
Shengli Yellow River	Dongying, Shandong	682	③	
Hongtang	Fuzhou, Fujian	50 + 150 + 150 + 50	④	2021
Yichang Yangtze River	Yichang, Hubei	960	④	

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① girder bridge; ② arch bridge; ③ cable-stayed bridge; ④ suspension bridge.

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