Recent Development and Challenges of Long-Span Railway Cable- Stayed Bridges in China

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Recent development and challenges of long-span railway cable-stayed bridges in China

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Abstract

The main span of railway cable-stayed bridge in China has broken through from 312m in 2000 to 1092m in 2020, with rapid development in recent years. It comes from aspects of new material, new structural form, accelerated bridge construction method, and innovated construction facilities and equipment. New materials mainly include bridge structural steel with higher yield strength, stay cable with higher tensile strength and ultra-high-performance concrete (UHPC), etc. New structural forms refer to three-main truss with three-cable plane, cable-stayed bridge with ballastless track system, multi-pylon railway cable-stayed bridge, etc. Concept of accelerated bridge construction has been also applied in caisson construction, truss girder assembling, truss girder hoisting, etc. Several new facilities and equipment have also been created such as integral bridge expansion joint, hoisting crane, and smart torque wrench, and so on. Challenges have also been discussed.

Keywords: railway cable-stayed bridge, new material, structural system, structural devices, bridge expansion joint, hoisting crane, torque wrench, technological challenges

1 Introduction

Rapid development has been witnessed in construction of railway cable-stayed bridges in China since completion of Wuhu Yangtze River Bridge with main span of 312m in 2000, within only 20 years [1]. In aspects of material, structural system, construction and equipment, those bridges can be regarded as the milestone such as Wuhan Tianxingzhou Bridge, Tongling Bridge, Husutong Bridge, etc. with main span of 504m, 630m, 1092m, respectively [2]. Now, Changtai Bridge and Maanshan Bridge are under construction, with main span 1176m and 2×1120m, representing a breakthrough of much longer span.

Major innovations have been summarized for railway cable-stayed bridges in China in 21st Century. And main challenges of railway cable-stayed bridges have also been discussed.

2 New material

New material such as bridge structural steel, high performance stayed cable, and UHPC supports the construction of railway cable-stayed bridge with main span over 1000 meters.

2.1 Bridge structural steel

From 1950s, bridge structural steel had been consecutively studied in China to meet the development requirements of railway steel bridges, with different bridge types besides cable-stayed bridge. A3q steel (Q235) was early used in Wuhan Yangtze River Bridge built in 1957 with yield strength of 235MPa and rivet joint. The main span was only 128m. 16Mnq (Q345) steel was then developed and used in Nanjing Yangtze River Bridge in 1968. As an independent R&D steel, 16Mnq steel had a lower toughness, and the strength was sensitive obviously to plate thickness, thus the maximum plate thickness was only 32mm. Later, 15MnVNq steel was developed and used in Jiujiang Yangtze River Bridge in 1995. Such a steel type had yield strength of 412MPa when the plate thickness was less than 16mm, and the maximum thickness could be 56mm. However, poorer weldability and low temperature toughness made the bridge construction difficult. In early 1990s, micro-alloyed bridge structural steel named 14MnNbq was studied by series of scientific test and the influence of plate thickness effect was nearly eliminated. By decreasing element content of Carbon, Phosphorus and Sulphur on basis of 16Mnq steel, and adding content of Niobium, the steel strength was enhanced, and better low temperature toughness was also obtained, thus the steel plates with thickness 32~50mm could be supplied in batch. The new steel type was firstly and successfully adopted in Wuhu Bridge, the first steel railway cable-stayed bridge in China. Later, it was used in Wuhan Tianxingzhou Bridge, the world's first railway cable-stayed bridge with three main trusses and three cable planes. Q420q steel with higher yield strength of 420MPa was then applied in Nanjing Dashengguan Bridge, a steel truss arch bridge in Beijing-Shanghai HSR. The maximum plate thickness reached 68mm without obvious thickness effect, and this steel type was widely used in long-span railway cable-stayed bridges. Q500qE steel, which has high yield strength and lower yield ratio, was applied in part of the truss steel girder in Husutong Yangtze River Bridge opened in July 1st, 2020, the world's first railway cable-stayed bridge with main span over 1000m. In 2021, Q690qE steel had been used in Wuhan Jianghanwan municipal arch bridge and the fourth Macau-Taipa bridge in Macau. Overall, the bridge structural steel in China developed later than developed countries in Europe and Japan, etc. But the bridge construction requirements boosted the research achievements in performance of base metal, manufacturing performance and structural design with new structural steel, thus promoted development of railway cable-stayed bridges [4].

2.2 High performance stay cable

Due to heavier self-weight and train live load compared to highway bridge, railway cable-stayed bridges have higher requirements for cables on tensile and fatigue strength. Meanwhile, improving the tensile strength with smaller total diameter of cable could decrease the transverse deformation under wind load, which benefits the running train on the bridge. Parallel cable wire with diameter 7mm is widely used. The tensile strength of cable wire is often 1670MPa for many railway bridges such as Wuhu Bridge, Wuhan Tianxingzhou Bridge, Anqing Bridge, Gongan Bridge, Ningbo Yongjiang Bridge, Ganzhou Ganjiang Bridge, etc. Cable wire with higher strength was also used in several bridges such as Huanggang Bridge (1770MPa), Pingtan strait bridge (1860MPa) and Yibin Lingang Bridge (1860MPa), etc. Steel strand stay cable was seldomly used in railway bridge. Tongling Bridge adopted this type with diameter of single steel strand 15.2mm and tensile strength 1860MPa [5].

Parallel cable wire with tensile strength of 2000MPa was used in New Wuhu Bridge and Husutong Bridge, which's the highest level of strength in built railway bridge. During the study, R&D of wire rod and cable wire, anti-corrosion technique by the coating of zinc-aluminium alloy, compatible anchorage, anchoring reliability, and fatigue of stay cable are key aspects. Micro-alloyed hot rolled wire rod with higher content of sorbite was suggested to produce cable wire, using proper wire drawing technology, hot-dip-galvanized technology, and stabilizing treatment. Test results showed that tensile strength was 2032~2060MPa, yield strength was 1832~1856MPa, and 6~8 times of reverse bending, more than 8 times of torsions. Mechanical properties were proved to satisfy the requirements. Now higher performance stay cable was used in Changtai Bridge with strength of 2000MPa and 2100MPa, and Maanshan Bridge with strength 2100MPa [6].

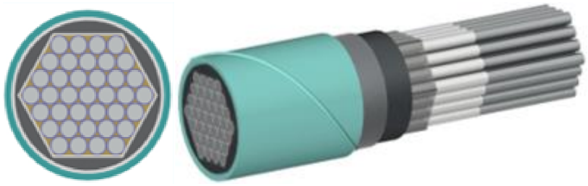


Figure 1 Stay cable with parallel steel wire

2.3 Ultra-high-performance concrete

The mechanical properties of UHPC such as tensile, bending and shear strength, etc. are much higher than normal concrete, and durability can be enhanced obviously after adding steel fibre. And resistance in frost and corrosion is better than normal. In recent years, Steel-UHPC composite bridge deck was adopted in several railway cable-stayed bridges such as Husutong Bridge and Dongtinghu Bridge in Haoji Railway. Its construction process was as follows: bridge deck derusting by sand-blast→anti-corrosion coating→ Stud welding→reinforcement positioning →UHPC layer construction and curing [7].

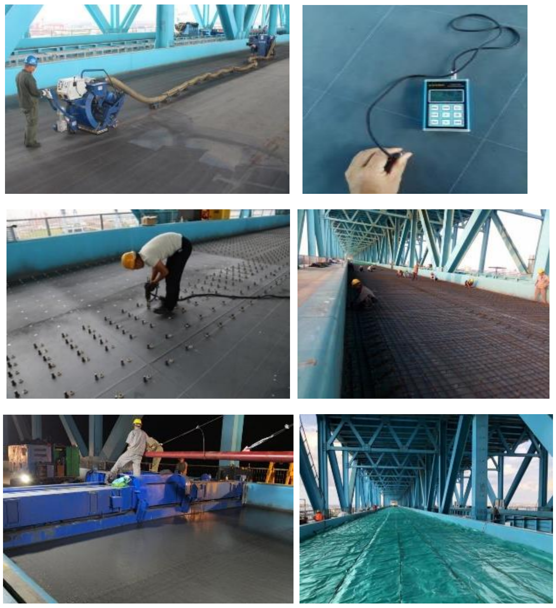


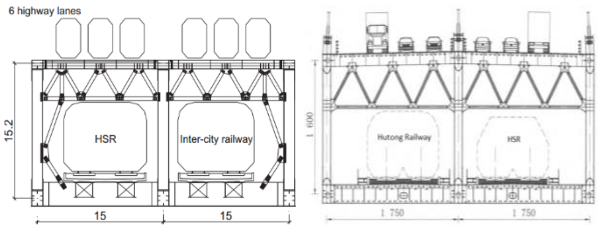
Figure 2 Construction of Steel-UHPC composite bridge deck

3 Innovations of Structural system

Some key innovations of structural system were introduced in this section, including three main trusses and three cable planes, ballastless track in railway cable-stayed steel bridge, and multi-pylon railway cable-stayed bridge.

3.1 Three main trusses and three cable planes

To improve the integral and local stiffness of railway bridge deck with multi-line , three main trusses and three cable planes are proposed early in the design of Wuhan Tianxingzhou Bridge in 2009. Later, such a structural system was adopted in Tongling Bridge, Husutong Bridge, and Maanshan Bridge. Plate-truss composite railway bridge deck was used in Tianxingzhou Bridge. Then the box-truss composite structure was applied in Tongling Bridge's railway bridge deck at the position of pylon and counterweight section while the orthotropic bridge deck at the mid-span subject to less internal force. For kilometer-scale cable-stayed bridge in Husutong and Maanshan Bridge, box-truss composite bridge deck was applied in all the segments [2].



(a) Tianxingzhou Bridge (b) Husutong Bridge

Figure 3. Diagram of three main trusses and three cable planes

3.2 High-speed railway cable-stayed bridge with ballastless track

Ballast track is widely adopted in high-speed railway cable-stayed bridge in China. However, due to riding comfort, durability, and less maintenance work, ballastless track has its advantage especially for the line with design train speed over 300km/h. Some experience has been obtained from Japan and Germany. A PC continuous cable-stayed bridge in Japan adopted slab ballastless track, which had main span arrangement 2×133.9m and a single pylon, was open to traffic in 1997 with design speed 260km/h. Froschgrundsee Viaduct in HSR line Ebensfeld–Erfurt in Germany, was a concrete arch bridge with main span 270m, with design speed 300km/h and actual operation speed 250km/h, adopting OBB/PORR slab ballastless track [8].

Due to the advantage in rigidity, concrete bridges were used widely in HSR line with ballastless track. In recent years, several long span HSR bridges with ballastless track had been built, such as Tingsihe Bridge in Wuhan-Guangzhou HSR line in 2009 with CRTS I double-block ballastless track on 140m steel tied-arch simple supported bridge, Ronggui waterway bridge in Guangzhou-Zhuhai intercity railway with CRTS I frame-slab ballastless track on (108+2×185+115)m continuous rigid frame bridge, and Zhenjiang Jinghang canal bridge in Beijing-Shanghai HSR line with CRTS Ⅱ slab ballastless track on (90+180+90)m continuous girder-arch combined bridge. Cable-stayed bridge with ballastless track has also been considered when the main span increases. Ganjiang River bridge in Nanchang-Ganzhou HSR line open in 2019 with train speed 350km/h, is a steel-concrete hybrid girder cable-stayed bridge, which the side and auxiliary span adopt concrete box girder. Its span arrangement is (35+40+60+300+60+40+35)m with CRTSⅢ slab track. During static acceptance of the bridge and track, the long-wave longitudinally vertical irregularity 7mm and lateral alignment irregularity 6mm under midpoint chord measurement method with a 60 m chord length were proposed [9]. Later, Yuxihe Bridge in Shangqiu-Hefei-Hangzhou HSR line with span arrangement (60+120+324+120+60) adopted steel box-truss girder to improve the rigidity of cable-stayed bridge. It’s the longest cable-stayed bridge with ballastless track which had been built in 2020 and the value of 60 m chord length was also used to track alignment acceptance [10]. Now, a ballastless track cable-stayed bridge named Maanshan auxiliary branch bridge in 350km/h Chaohu-Maanshan intercity railway line is under construction, with steel truss girder and span arrangement (56+168+392+168+56) [11]. Cable-stayed bridge has become an important type of HSR ballastless track bridge with steady increase of the main span.

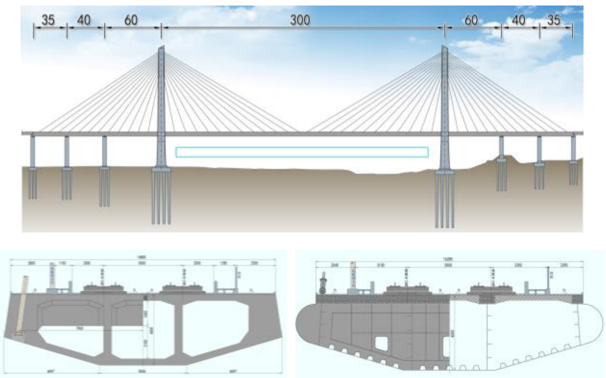


Figure 4. Representative HSR cable-stayed bridge with ballastless track (photo from China Railway Siyuan Survey and Design Group CO., LTD.)

3.3 Multi-pylon railway cable-stayed bridge

Multi-pylon cable-stayed bridge has been widely used in highway bridges at home and abroad. Due to lack of anchorage cable at the mid-pylon, the rigidity of such a structure system is smaller and thus the number of cases in railway is not many. Zhengzhou Yellow River Bridge in Beijing-Guangzhou HSR line built in 2012 was an extradosed cable-stayed bridge with span arrangement (120+5×168+120) m and steel-concrete composite main girder, which had six pylons with single cable plane and the pylon had only the effect of stiffening. Dongting Lake Bridge in Haoji heavy haul railway, was a three-pylon cable-stayed bridge with span arrangement (98+140+406+406+140+98) m and box-truss composite girder [12]. The bridge supported two-track railway designed by 1.2 times China-Live load times, and the stabilizing cable was set at the mid-pylon to increase the vertical rigidity. Moreover, there are several multi-pylon cable-stayed bridges under construction such as Jinhai Bridge in Zhuhai-Zhuhai Airport Intercity Railway with a span arrangement (58.5+116+3×340+116+58.5) m and four-pylon steel box girder, supporting two-track railway and 6-lane highway with train speed 160km/h [13].Taiping Lake Bridge in Chizhou-Huangshan railway line is an extradosed concrete cable-stayed bridge with a span arrangement (48+118+2×228+118+48), supporting two-track railway with design speed 350km/h [14].

Maanshan Rail-cum-Road Yangtze River Bridge is the longest three-pylon steel truss girder cable-stayed bridge under construction. It supports four-track railway and 6-lane highway, with a span arrangement (112+392+2×1120+392+112) m and design speed 250km/h. To improve the vertical rigidity, the mid-pylon is higher than side-pylon, adopting 3D triangle pylon with height 345m. And the side pylon is 308m and 306m respectively, with A-shape in the transverse direction and I-shape in the longitudinal direction, as shown in Figure 5. Steel-concrete hybrid structure are adopted in three pylons, in which steel structure is used in cable anchorage region with 112.5m for mid-pylon, 87.5m for side-pylon, and concrete structure is used in lower part with 229.5m for mid-pylon and

217.5m (215.5m) for side-pylon. UHPC is adopted in the transition region of all three pylons with 3m height. The longitudinal expansion amount of the bridge is restricted to ±800mm by setting elastic cable at mid-pylon. And wind-resistant bearings are arranged at side piers, auxiliary piers, and pylons to decrease the lateral displacement.

Figure 5. Maanshan Rail-cum-Road Yangtze River Bridge (Photo from BRDI)

Q370qE、Q420qE、Q500qE are used in truss girder and three types of segment, i.e. 28m, 21m and 14m divide the truss girder into 121 segments. The maximum weight of segment is about 1620t and ordinary segment 1400t. Integral steel-box railway bridge deck is used and rolled stainless compound steel plate is adopted for bridge deck under the ballast bed. ϕ7mm 2100MPa parallel cable wire is used for stay cable with the longest 650.55m and the heaviest 79.6t, which has totally 642 cables and maximum specification 379-ϕ7mm.

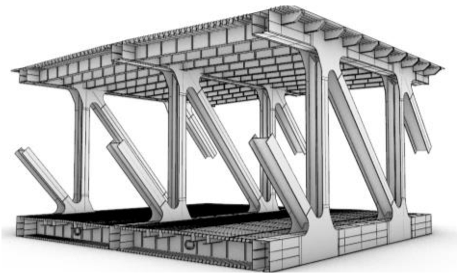


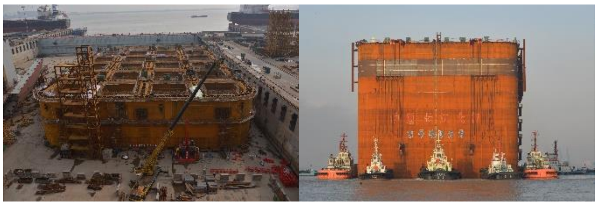
Figure 6. 3D diagram of 2-segment truss girder of Maanshan Bridge (Photo from BRDI)

4 Accelerated bridge construction

Accelerated bridge construction is a hot topic in recent years [15]. During the construction of railway cable-stayed bridge, series of accelerated construction method is developed.

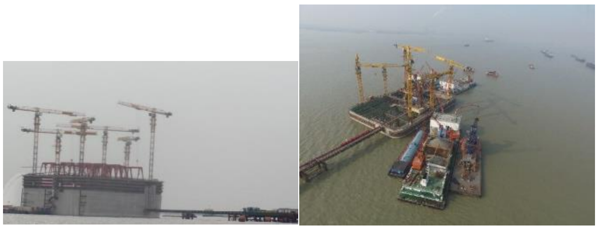
4.1 Caisson construction and inspection

Pile and caisson are two major foundation types for railway cable-stayed bridge, the latter is usually used in deep fine sand which the bedrock is hard to reach. Construction safety and efficiency are both two key factors for caisson. Steel-concrete composite caisson structure was applied in Husutong Bridge with the plane dimension 86.9m×58.7m, and the height 105m and 115m for two pylons (steel parts are 50m and 56m respectively). The scale can be regarded as caisson foundation with the biggest volume. Construction procedure in Husutong Bridge mainly includes integral fabrication of steel part in factory, launching and floating, mooring and positioning, steel caisson sinking and implantation, riverbed scour protection, concrete casting in steel wall, heightening and sinking, caisson bed sealing, etc. Integral fabrication improved the efficiency of caisson construction obviously. Since the positioning of huge caisson in complex reversing current was difficult, comprehensive measures were adopted by using large-diameter anchorage pile plus concrete gravity anchor as the mooring system, with technology of hydraulic jack for quick and simultaneous positioning in multi-direction. The precision was satisfying，with maximum plane position error 29cm, maximum torsion angle 5.02”, far less than the requirement of 1/150 of the caisson height and 1° of the plane torsion angle [16].When the caisson had been positioned, sonar equipment, under-water robot equipped with high-qualified video recorder, ultrasonic hole detector, and seabed static sounding system, etc. were used for inspecting the bed topography, buried depth of cutting shoe of caisson, thickness of floating soil, and soil properties, etc.



(a) Integral fabrication (b)Floating transportation

(c) positioning and implantation (d) concrete casting



(e) heightening and sinking (f) caisson bed sealing

Figure 7 Caisson construction in deep water

4.2 Integral hoisting construction

With the development of construction technique and equipment, the tonnage of integral hoisting has increased obviously in China which accelerates bridge construction. Compared to the hoisting of scattered member, hoisting of integral segment improved efficiency which was adopted in Wuhan Tianxingzhou Bridge and Husutong Bridge, with the maximum hoisting weight 1740t [17]. While under the help of crane ship SEAGULL with maximum hoisting ability 3600t, the maximum hoisting weight reached 3400t in Pingtan Strait Bridge to lift the girder at side and auxiliary span. And the steel pylon of Jinhai Bridge, with the total weight of 2800t, was also lifted integrally and positioned by the same crane ship as shown in Figure 8.

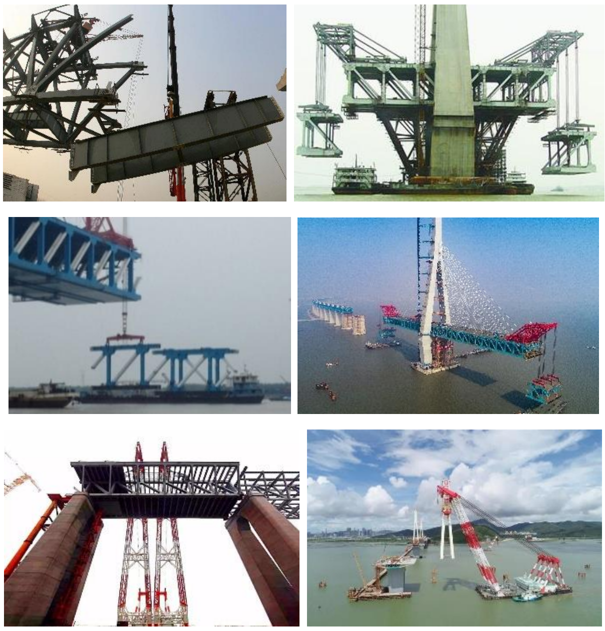


Figure 8 Development of integral hoisting construction and equipment

4.3 Synchronous construction of pylon and girder

Synchronous construction of pylon and girder has also become a popular method to accelerate the construction. Representative bridges using this technique include Wuhan Tianxingzhou Bridge, New Wuhu Bridge, Husutong Bridge, etc. Due to different workspace at the pylon and girder, the safety measures and organization are vital to deal with the complicated construction. Generally, the safety guard platform shall be erected to isolate the workspace. And the climbing formwork shall also be closed to prevent the falling of objects. To guarantee the safety of the whole process, detailed computation is necessary to provide scheme for temporary cross brace arrangement, unbalanced weight allowed at both sides of the cantilever, cable force error, and measurement time to avoid the influence of wind and temperature, etc. Taking New Wuhu Bridge as an example (shown in Figure 9), four temporary cross braces were suggested to optimize the behaviour of pylon. Unbalanced weight shall be not more than 25t, cable force error shall be within 2% and not more than 10t [18].

Figure 9 Synchronous construction of pylon and girder

4.4 Computer-aided virtual construction

Computer-aided virtual bridge construction has become a hot research and engineering topic in recent years, creating many scenarios for different bridge types and application stages. Computer-aided pre-assembly of steel girder is important to check the fabrication error and realize the precise assembly from engineering practice, which has been applied nearly mature. The flow chart of steel girder virtual pre-assembly is shown in Figure 10. Firstly, the 3D coordinate points are obtained by measuring the steel girder member using acquisition device with high accuracy. Secondly, the measured point and corresponding design point were fitted based on the theoretical assembly model, then the precision analysis was carried out to verify if the fabrication accuracy could be satisfied. Thirdly, all the steel girder members were then transformed into the same coordinate system to fit the axis and plane of measured points to check the accuracy [19].

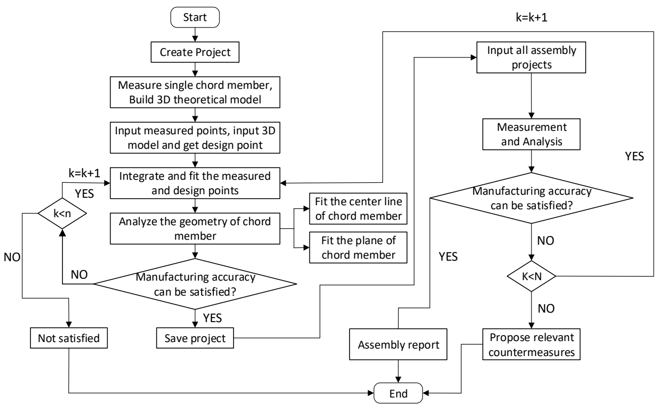


Figure 10 Flow chart of steel girder virtual pre - assembly

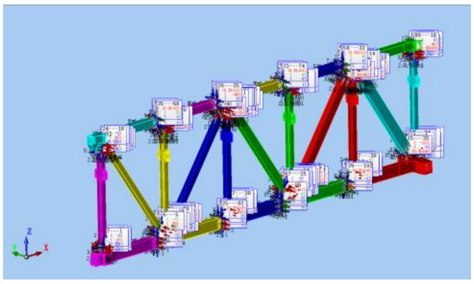


Figure 11 Assembly management of group chord members

Besides the virtual pre-assembly of steel girder, the virtual construction in field based on BIM has also been applied in many railway bridges, which includes construction procedure simulation and information management, etc. In recent years, the concept of digital twin has been discussed in mega bridge construction but the real value needs to be explored continually.

5 New equipment and devices

5.1 Bridge expansion joint with expansion amount of ±800mm

It has become a common sense that the performance of bridge expansion joint (BEJ) is vital to long span railway bridges since the safety of running train is more vulnerable at the girder end. According to relevant research, the longitudinal displacement of cable-stayed bridge at girder end is mainly caused by temperature, vertical live load, braking force, longitudinal wind, and total displacement of the approach bridge [20]. A lot of research achievements have been obtained which mainly deal with the operational performance of the device especially the relationship between displacement and temperature. However, it's more important to design, fabricate and install the railway bridge expansion joint, and consider its coordination with the rail expansion joint (REJ). An integral design method has been proposed for BEJ and REJ of long span railway bridges [21]. Deck-type expansion joint has been suggested which the longitudinal beam is on top of the movable steel sleeper, as shown in Figure 12. Several indexes have been suggested including frictional resistance, vertical rigidity, and fatigue, etc. And the frictional resistance is among the most important factor which influences the normal function of the devices. Its limit value is closely related to the number of movable steel sleepers and longitudinal beam, to obtain a relatively smooth sliding condition. The frictional value shall be lower than 12kN, 25kN, 30kN, and 40kN when the number of movable steel sleepers is 1, 2, 3 and 4 respectively.

Figure 12 Bridge expansion joint with expansion amount ±800mm designed and made by China

5.2 Hoisting crane with high capacity

With the help of heavy-duty hoisting crane, the erection of integral girder and pylon become possible. Figure 13 shows the girder hoisting crane with 1800t capacity, the crane ship with 3600t capacity [22].

Figure 13 Hoisting crane and crane ship

5.3 Torque wrench and management system

High-strength bolt and its connection construction have been always the key parts during the railway bridge construction. The study of this technology has been started since 1957 in China. In 1960s to 1970s, the torsion angle method was mainly used, matched with the pneumatic impact wrench which was hard to guarantee the construction quality of high strength bolt. In 1990s, the constant torque wrench of second generation was developed to make the torque method possible and successfully used in Jiujiang Yangtze River Bridge. It was proved that such a screwing tool could improve the construction precision, reduce labour intensity, and decrease the pollution. However, due to the complexity of operation, error existed inevitably which might cause overtightening. New generation of torque wrench named CNC servo electric wrench has been developed, together with relevant information management system. This tool could pre-set the threshold value of bolt tightening and pre-alarm the error during the construction [23].

Figure 14 CNC servo electric wrench and APP

6 Technological challenges

6.1 Deep-water foundation construction technology and relevant equipment

Experience on deep-water foundation construction has obtained with the development of long-span railway cable-stayed bridges. The maximum water depth is about 40m and 45m for Tongling Bridge and Guyumen Waterway Bridge in Pingtan Strait respectively, with the pile diameter 2.8m and 4.5m. KTY5000 drilling machine was created for the latter foundation construction under large wave current force and super typhoon. The maximum water depth is nearly 50m for the caisson construction of Husutong Bridge's pylon foundation. Xihoumen rail-cum-road sea-crossing bridge with span arrangement (70+112+406+1488+406+112+70) m is under construction, which is a combined cable-stayed suspension bridge. The foundation of No.5 pylon is 18 ϕ6.3m bored piles with length 88m. The challenges of deep-water foundation construction come from the uncertainties of rock and soil properties, the temporal variation of foundation scour during construction, complexity of wave-current forces, and structural response of large-scale foundation.

6.2 Static acceptance criteria and control for geometric alignment

HSR long-span railway bridges have strict requirements for geometric alignment of main girder and track. However, there is no special regulations on static acceptance criteria. Through correlation analysis between acceleration of train body and chord measurement value, midpoint chord measurement method and its value with a 60 m chord length were initially proposed as the static acceptance criteria for track geometric alignment of HSR long-span railway bridges under different design speed. While the limit value of geometry alignment of main girder is not yet clearly specified. Since the main span of HSR railway cable-stayed bridge has broken through 1176m, proper management and control of the geometric alignment of the bridge main girder and track need to study in detail and verified by field test.

6.3 Operational monitoring and status evaluation

Different from highway cable-stayed bridges, stricter requirement shall be considered for railway bridges since the status of track on the bridge has direct and obvious influence on the safety of running train with high speed. According to the maintenance experience of long-span railway bridges, the overall performance of bridge main structure has little change in earlier service stage, hence the key attention shall be paid to structural components such as bearings, dampers, expansion joints and stay cables. Some methods on how to evaluate the status of above components have been proposed but the effectiveness and accuracy still need to improve. On the other hand, considering the big data from track by regular inspection and bridge from health monitoring system, it's necessary to incorporate the data and analyse at the same time. And it becomes a big challenge on how to deal with these massive data effectively and maintain bridges by above data.

7 Conclusions

Due to space limitations, this paper summarizes major recent developments of railway cable-stayed bridges in China from new material, new structural system, accelerated construction method, and new equipment and devices. Technological challenges have also been proposed and discussed. In future, optimal design and construction in lifecycle view, track-bridge integral design method, performance-based static and dynamic design and smart maintenance of complicated bridges will emerge.

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