Comparison of construction methods of the Pingtang Bridge in China and the Millau Viaduct in France

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Abstract. The cable-stayed bridge is a kind of bridge deck system under pressure and a support system under tension. The Pingtang Bridge is 2135m long, with the main bridge being 249.5m + 550m + 550m + 249.5m three-tower, double cable-faced steel and hybrid combination girder cable-stayed bridge. Its highest cable-stayed tower is 320m, making it the third highest bridge structure in the world. The Millau Viaduct is 2460 m long, with two end spans of 204 m each and six central spans of 342 m each. Its tallest tower is 343 m, making it the second tallest bridge structure in the world. The two bridges suffer from similar climatic and geological factors, but the construction methods differ significantly. This paper summarizes the similarities between the construction methods of the two bridges and compares their differences. Results show that the construction methods of the Milo Viaduct are very creative, challenging and technically difficult, and the construction methods of the Pingtang Bridge are operational and imitative.

Keywords: Pingtang Bridge; The Millau Viaduct; Construction Methods.

1. Introduction

The cable-stayed bridge is a kind of bridge deck system under pressure and a support system under tension. The deck system is composed of stiffened girders and the support system consists of tension cables. The idea originated in the 19th century, limited by the level of materials, soon to be eliminated. 20th century, the emergence of high-strength steel wire, orthogonal anisotropic steel girders and electronic computers, such as this form of the cable-stayed bridge was reconsidered. Due to the overall stiffness, low cost, and soon spread worldwide, the span is getting bigger and bigger. With the development of new materials and computer technology, modern cable-stayed bridges occupy an important position in modern bridge structures with their large spanning capacity, good technical and economic indexes and aesthetic values. With the increase in the span and structure of cable-stayed bridges, the development of structural analysis and design theory are prompted, and construction methods become an important subject.

The Pingtang Bridge and the Millau Viaduct are typical cable-stayed bridges worldwide. The Pingtang Bridge is the cable-stayed bridge with the third highest structural height, and the Millau Viaduc is the second. The two bridges are of similar length and have similar construction cycles. Both bridges are located in areas with poor geology and often subject to high winds, storms and other adverse weather conditions Although the two bridges share many similarities, their construction methods are very different.

Taking the Pingtang Bridge and the Millau Viaduc as examples, this paper expounds and compares the construction methods of these two bridges, and discusses their advantages, disadvantages, and application scope.

2. Background of the Pingtang Bridge and the Millau Viaduct

2.1 Basic Background

The Pingtang Bridge is located in Pingli River Village, Tongzhou Town, Pingtang County. It is a high-speed channel in Qiannan Buyi Miao Autonomous Prefecture, Guizhou Province, located above the Grand Canyon of the Trough River, and is one of the important components of the Yuqing-Anlong Expressway. The bridge is 2135m long, the main bridge is 249.5m + 550m + 550m + 249.5m and the three-tower double cable-stayed steel-hybrid combination girder cable-stayed bridge (Figure 1). The construction of this bridge is of great significance to improve the overall layout of the Guizhou transportation network and promote the economic prosperity of the southern region of Guizhou Province.

Figure 1. Elevation of the Pingtang Bridge

On the A75 freeway that runs from Clermont-Ferrand in the center of southern France to Béziers on the Mediterranean coast, there is a significant bridge known as the Millau Viaduct. It is a part of a new transportation hub that will connect northern Europe and eastern Spain, and it will connect the Lévezou and Larzac plateaus on both sides of the Tarn River. The main span will cross the Tarn Valley at its lowest point. It is a multi-stilt structure that extends for a total of 2,460 meters, has a plan that is only slightly curved, has a radius of 20,000 meters, and has a constant upward slope of 3.025 percent from north to south (Figure 2). The construction is uninterrupted along each of its eight diagonal spans, which are as follows: two end spans with a length of 204 meters each, and six middle spans with a length of 342 meters each. The completion of the bridge not only alleviates the strain on north-south traffic in France during the summer months but also contributes to the resolution of France's traffic bottlenecks and makes it easier for large trucks and buses to travel to the Mediterranean coast and Spain.

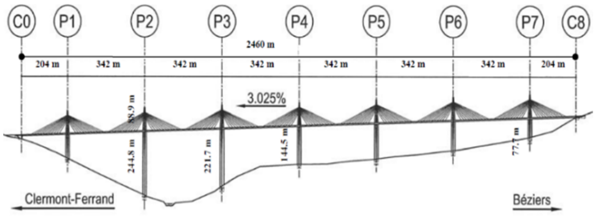

Figure 2. Elevation of the Millau Viaduct

2.2 Geological Setting

The Pingtang Bridge is located in the southern part of the Yunnan-Guizhou plateau, and the valley of the Trough River is a "V"-shaped valley with a width V-shaped trough valley with width of 800~1,500m, and the topography is undulating. The topography varies greatly, with an elevation of 595.0~1,185.0m and a relative height difference of 590.0m. The geomorphological type of the site belongs to dissolution - tectonic low mountain valley landform. The overall topography of Pingtang is a single steep slope (25°~45°), due to the effect of differential dissolution and denudation. The topography is steeply sloped near the bridge platform, with a slope of 30° to 40°, and a local topography of 60° to 80°, especially in the anchorage area, with a cliff shape.

There are many strata and complex rock associations in the bridge location area. Among them, the Quaternary soil layers are sporadically distributed with thin bed thickness, diverse genesis types, and a gently sloping section. The main soil is the residual slope (Qel + dl) clay. The bedrock is mainly the thin to medium-thick laminated mudstone and sandstone interbedded in the Triassic Feixianguan Formation (T2x). The thin to moderately thick laminated mudstone and sandstone interbeds of the Lower Feixianguan Formation (T1f) interbedded with siltstone, the moderately thick to thickly bedded mudstone and sandstone of the Lower Ditianmaokou Formation (P2m), the thin to moderately thick bedded mudstone of the Lower Feixianguan Formation (T1f), the thick laminated tuffs, and thin to medium-thick laminated tuffs of the Lower Qixia Formation (P2q). There are two faults in the bridge site area, both of which are inactive and thus, the site is stable as a whole.

The Millau Viaduct connects two limestone plateaus, separated by a deep valley eroded by the Tarn River. The sedimentary basin, which began to form in the middle of the Second Age, appears well preserved. Tarn River reveals the area's stratigraphy, showing Triassic stratigraphy at the base of the valley, and then showing the complete sequence up to the end of the Jurassic era. The rocks on site are entirely sedimentary, consisting partly of dolomitic limestone and partly of dense marl. 65 limestones and 53 marks are present at the Millau Viaduct site (Figure 3).

There are three different types of foundation stones along the viaduct. The first, the Bayeux dolomitic tuff, is a tough rock located on the northern abutment. With Rc = 110 MPa, an RMR value of 70-80 was determined. The compacted marl from pier P7 to pier P6 constitutes the second rock type. Sliding can be seen on the soil surface, as the 2 m thick gravel layer lies beneath the soft clay on top of the marl. Laboratory tests give: Rc = 10-15 MPa, E = 3-6 GPa, = 25 kN/m3. The Hertan order marl from pier P4 to the bridge platform (C0) on both sides of the Tarn constitutes the third rock type. Its laminae are subhorizontal on the south side. The laboratory test results are: RMR = 50 to 70 MPa, E = 8 to 15 GPa, = 25 kN/m3.

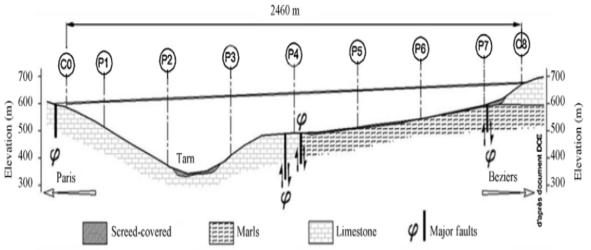

Figure 3. Simplified geotechnical cross-section of the viaduct

2.3 Climatic Conditions

The field in Pingtang is a subtropical humid monsoon climate zone, mild climate, heat rich, abundant rainfall, long frost-free period, no summer heat, no winter cold, and four seasons are relatively clear. The average annual temperature in the region is 17°C～20°C, with the extreme lowest temperature of -7.7°C, the highest extreme temperature of 40.6°C, and the annual average relative humidity is 77%-83%. The annual relative humidity ranges from 77% to 83%.

Millau has a Mediterranean climate with mountainous features, with hot, dry summers and mild, rainy winters. The cold season in Millau lasts 3.9 months, with an average daily maximum temperature below 49 degrees Fahrenheit (F) from November 16 to March 12. The coldest month of the year in Millau is January, with an average low of 29°F and a high of 42°F. Temperatures usually vary between 28 F and 77 F throughout the year and rarely fall below 18 F or above 86 F. Millau receives rainfall throughout the year. The month with the most rainfall in Millau is October, with an average of 3.1 inches of rainfall. The month with the least amount of rainfall in Millau is July, with an average of 1.1 inches. The snowiest period of the year lasts 2.5 months, from 9 December to 24 February, with the snowiest month in Millau being January. The windiest period of the year lasts for 6.7 months and the windiest month of the year in Milo is March with an average wind speed of 9.6 miles per hour.

2.4 Description Of Materials And Structures

Both the Pingtang Bridge and the Millau Viaduct are cable-stayed bridges. The material of the piers and towers are concrete, and the suspension cables are made of steel wires.

3. Construction methods and designs of the Pingtang Bridge

3.1 Piers

3.1.1. Structure of piers

The Pingtang Bridge has three towers, all of which are reinforced concrete towers (Figure 4). Towers 15 and 17 above the deck are 145.2m, tower 16 is 149.2m, and towers 15 to 17 below the lower crossbeam are 174.8m, 182.8m and 152.8m, giving a total height of 320m, 332m and 298m respectively. Each tower has a rectangular hollow section with rounded chamfers at all corners. The towers are equipped with two upper and lower crossbeams with rectangular cross sections. A single box and three-chamber section vase-shaped pier is provided between the towers and the bearing platform.

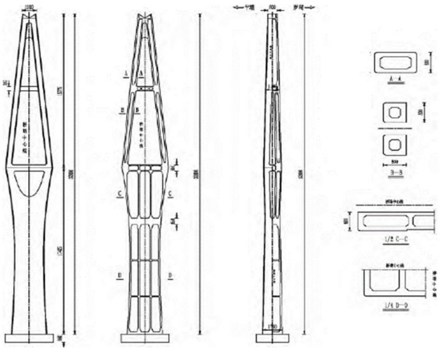

Figure 4. Elevation of a pier

3.1.2. Hydraulic mould climbing technology

In order to achieve the construction of the ultra-high towers, the towers are built using hydraulic mould climbing technology (Figure 5), allowing the moulds to be attached to the towers through brackets. As the towers continue to be built, the moulds are continuously climbed up through the hydraulic tracks carried by themselves, avoiding the safety risks caused by dismantling and lifting the moulds at height. At the same time, the mould is an operating platform on which the workers can easily work to ensure their safety.

Figure 5. Demonstration of mould climbing techniques

3.1.3. Concrete pumping methods

During construction, traditional concrete pumping methods could only deliver concrete to a height of 180 metres. This was because the builder had to use machine-made sand to make the concrete due to a shortage of local sand, which has a more angular surface and increases the friction with the pipe wall. The concrete was pumped twice on this project, first to a height of 180m and then to the required height from height of 180m.

3.1.4. Tower cranes

In order to be able to transport various engineering materials to high altitudes, on both sides of the bridge towers, tower cranes were set up so that they increased in height with the towers. The tower cranes consist of single 6m high sections. The tallest crane in this project has 53 sections and weighs 750 tonnes to resist the effects of wind and increase the crane's stability. The sections were structurally reinforced and provided with auxiliary supports. The structural strengthening was achieved by reinforcing the sections' thickness and weight to increase their strength. The auxiliary support strengthens the connection between the tower crane and the knockers, ensuring the stability of the bridge tower. In addition, to ensure that the operator can accurately lift and transport the material, the crane control room is equipped with a monitor to display the position of the hook, the height, the range and the wind force in real-time.

3.2 Decks

3.2.1. Structure of prefabricated decks

The bridge deck is joined from both sides of the bridge tower, extending forward and eventually coming together. The main girders are double “H” shaped steel girders and concrete slabs with a steel-hybrid combination (Figure 6). On top of the steel framework that is formed by the "H" shaped longitudinal steel girders, cross girders, and small longitudinal girders being joined by nodal plates and high-strength bolts, prefabricated bridge deck slabs are assembled, and wet joints in micro-expansion concrete are cast in situ.The main girders are 30.2m wide and 3.36m high, with two “H” shaped steel longitudinal girder ribs spaced 25.7m apart and the main steel girders 2.92m high, using Q370qD. The standard length of the steel longitudinal girder sections is 12m, manufactured in sections at the factory. The “H” shaped steel longitudinal beam and “H” shaped steel longitudinal beam, crossbeam and “H” shaped steel longitudinal beam, crossbeam and small longitudinal beam are connected by friction type high strength bolts. The deck plates are bonded to the beams through shear nails arranged at the top of the “H” shaped longitudinal steel beams, the steel crossbeams and the small longitudinal beams. The shear nails are 22 round head welded nails, 250 (220) mm long and are arranged on the main steel girders so they do not conflict with the normal and prestressing reinforcement of the deck slab. The standard deck slab is 28cm thick, with the side spans partially thickened to 44cm, with a full width of 26.7m, using C55 concrete [3,7].

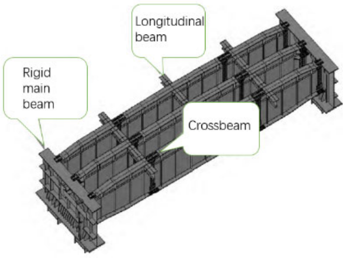

Figure 6. Diagram of the steel beam section structure

The bridge deck members are lifted by crane from the ground piece by piece to the overhead bridge deck, assembled into large parts of the section girders (after, installed to the front of the bridge deck, so that the bridge deck diffraction. There are 95 section girders, each weighing 149 tonnes and over 3m in height, and in order to maintain the balance and stability of the bridge, the installation of the section girders on both sides of the bridge tower had to be carried out simultaneously.

3.2.2. Innovative load-bearing structure

The bridge deck crane was equipped with an innovative load-bearing structure (Figure 7), changing from a single pivot point to a frame structure. Moreover, the track is laid so that it can travel freely. The load-bearing capacity is 5 times higher than the original slewing crane. Rear anchors are added to the crane's rear side to strengthen the bridge deck's connection. In order to minimise the effects of thermal expansion and contraction on the steel elements, the lifting time for the segmental girders was set at 8pm, when the temperature was most stable. The assembly before erection method and the improvement of the bridge deck lifting equipment effectively reduced the risk factor of working at height and reduced the erection time of the segmental girders from 3 days to 6 hours.

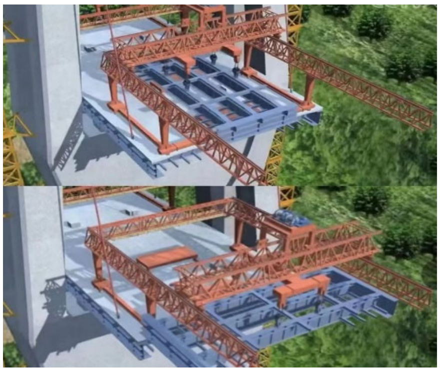

Figure 7. The innovative load-bearing structure

3.2.3. Friction type high strength bolts

The steel girders were all connected with M30 and M27 friction type high strength bolts, constructed by the torque method and checked by the loose buckle reset method. The key to quality control of high-strength bolts' construction is ensuring that the friction surface has a sufficient slip resistance factor and the design torque factor. The construction process is as follows: spanner calibration → bolt torque coefficient determination → positioning of the four corners of the connection plate → 25% punching nail 25% common bolt → 50% high strength bolt perforation → initial screwing → high strength bolt replacement punching nail and common bolt and initial screwing → final screwing → inspection → connection plate sealing. The technician indicates the specification, length and number of bolts near the friction surface (forbidden within the friction surface) after the steel beam has been delivered to the site (Figure 8).

Figure 8. Workers on site tighten high-strength bolts

3.3 Cables

In order to facilitate the construction of the bridge cables, connection points between the bridge deck and the bridge tower have been reserved. Once installed, the cables, deck and towers form a stable triangle of forces. There are 264 steel cables with a diameter of 16cm, each weighing just under 20 tonnes and with angles ranging from 27.4 to 79.8 degrees. To ensure construction safety, the connection of the section girders to the steel cables needed to be completed within 24 hours of the section girders being lifted. The steel cables had to undergo three tensioning to gradually release the steel cable tension as the weight due to the bridge construction increased. The first tensioning took place after the deck girders were connected, the second tensioning took place after the deck slabs were laid and the third tensioning took place after the section girders were finished with the concrete pouring [3,9].

4. Construction methods and designs of the Millau Viaduct

4.1 Piers

4.1.1. Structure of piers

The Millau Viaduct has seven piers, the tallest of which is 245m. Each pier is assembled from several sections, which themselves are assembled on site from reinforced concrete slabs of 4m x 17m weighing approximately 120t, which are fabricated in Eifel's prefabrication yards in Lauterburne and Voss-Maritime before being delivered to the site for assembly. The piers will be based on four 4-5m diameter, 9-16m deep sunken shafts, and an 87m high tower will be erected directly above each pier. The internal four faces of the piers are fixed in size, while the external four faces vary slowly in each section of construction along the pier height, including their orientation [2,10].

4.1.2. Self-lifting cranes

The assembly is carried out through an external self-lifting crane modified by Peri, while the internal restriction formwork is moved using a tower crane which, due to the height of the piers, has to be gradually fixed to the corresponding section of the pier (Figure 9). Thus, although the cross-sectional shape of the piers was variable, the construction of the piers was not difficult, thanks to the close cooperation between the architects and the engineers. To ensure the accuracy of the construction, CKI used the world's most advanced satellite positioning system, including more than 300 small precision reflectors (sensing devices), some of which were cast and anchored into the concrete piers and some fixed to the surrounding rock. For every 4m rise in the pier during construction, the satellite positioning system receives information from the sensors to correct any small deviations in the pier that may be caused by temperature or wind. When the bridge was completed, the piers were vertically within 5 mm of each other.

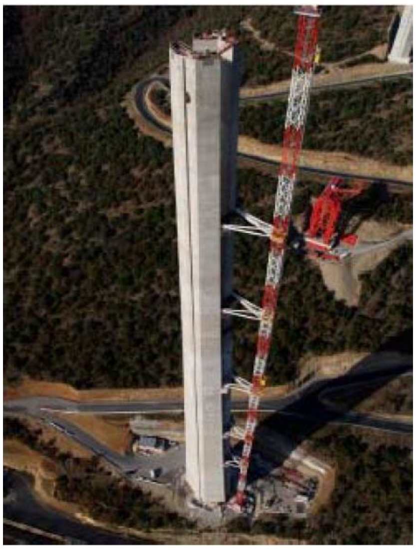

Figure 9. Pier 2

4.2 Decks

4.2.1. Structure of prefabricated decks

The main girder of the Millau Viaduct is an orthogonal anisotropic streamlined steel box girder section (Figure 10) with two vertical webs inside the steel box girder due to the construction process and a further triangular cross partition at 4.17m intervals along the longitudinal side of the bridge.Eiffel developed the deck's cross-sectional profile to take into account the potential of assembly and launching at the factory, as well as when it was being transported and once it had arrived at its final destination. Therefore, the primary component of the deck is sent to the construction site in the form of a "kit." On-site manufacturing was accomplished by constructing two factories on platforms located behind each abutment. These factories were outfitted with all of the essential machinery, such as cranes, material handling gantries with a capacity of 90 tons, welding shops, and paint shops .

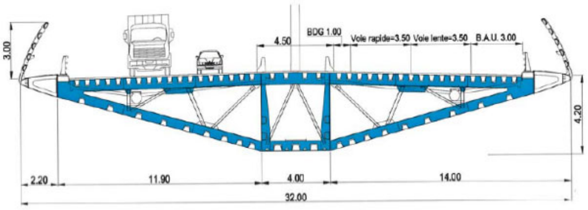

Figure 10. Cross-section of deck

4.2.2. Launching

The 2,000 deck plates were pre-welded into 32m wide plates at the Alsace factory, transported to the valley at each end of the bridge, welded together with the other elements and then slowly lifted onto the installation platforms for assembly and then the steel box girders were pushed into place (Figure 11).

The jacking process is as follows: firstly, the deck is supported by supports in its initial static position. Secondly, the lifting jacks lift the deck from the supports and rest it on the chute by making the wedge slide. The rails carrying the deck then move forward under the action of the horizontal launching jacks. After a final movement of 600 mm, the wedge resumes its initial position, leaving the deck on the supports.

The span between Piers P2 and P3 of the Mio viaduct was used as a span for the closure, where the steel box girders were jacked directly from both ends to the closure. In order to reduce the jacking distance of the middle span to about 150m, a set of temporary supports with a cross-section of 12m x 12m and two sets of steel pipe trusses with jacking equipment were erected in each middle span (Figure 12). The temporary supports for the side spans are much smaller and simpler than those for the middle span and are equipped with only one set of jacking equipment. Both jacking structures were fitted with a tower at the forefront of the girder section (the height of the tower was limited to 70-87m to minimise the effect of wind during jacking) and six pairs of diagonal cables were tensioned to reduce the bending moment at the cantilever end during the jacking process. Each jacking stroke was 171m, and each jacking span took 5d, with the first jacking operation being the most complex, taking about 3d even in good weather conditions. During the jacking process, the jacking operation had to be temporarily suspended when the average wind speed exceeded 37km/h. Due to the height of the piers, frictional forces had to be balanced directly on the individual supports, so all of them were equipped with movable thrust bearings (two sets of bearings per thrusting unit). The thrust control commands come from computers and sensors, and it is through these control commands that the horizontally oriented hydraulic jacks on the bearings can achieve the same horizontal displacement on all the supports at all times.

Figure 11. Construction of the deck and the pylons

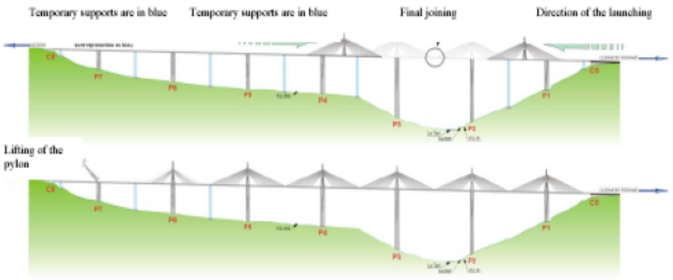

Figure 12. Diagram of launching process

To prevent the leading section's overhang from falling, the launching of the deck from each abutment is accomplished using a cable-stayed pylon. This leading section's length (171 m) relates to the distance between one support (pier or temporary pier) and the next.

4.2.3.Temporary piers

The installation of the deck through continuous launching operations required the erection of seven temporary piers (Figure 12). The highest temporary pier was 173 metres high. These piers consist of a K-shaped metal frame with a square cross-section of 12 m x 12 m, made up of 1,016 mm diameter tubes. The temporary piers are positioned using telescopic devices, except for two end spans, which are lifted directly into place by a crane due to their small dimensions (less than 30 metres high). A metal trimmer is mounted on top of each temporary pier to receive the launching brackets, known as translators, and the working platform.

4.3 Pylons

The towers were fabricated in various factories and brought together behind the abutments (Figure 13). On 18 May 2004, after the closure of the Mio viaduct, the five remaining towers, each weighing 650 tonnes, which had not been installed, were transported on two trailers (with tracks laid on the bridge deck) to their corresponding positions on the bridge deck - directly above the abutments. Sarens tensioned the temporary support towers for the diagonal cables, reversed the tilt of the towers upwards and installed them directly above the abutments. Finally, all launch fittings were removed, including the temporary piers, the trimmers on top of the piers and the launch rails.

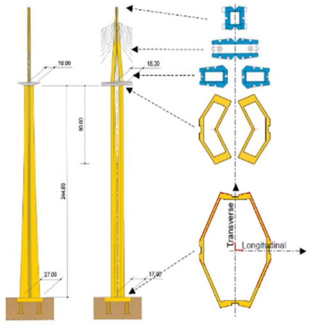

Figure 13. Elevation of a pier

4.4 Cables

The eleven different cable pairs that are used to support each span are laid out in a semi-fan pattern on a single plane. They are secured in place at intervals of 12.51 meters at regular intervals along the arc of the structure as well as along the axis of the central reservation. The cables are made up of T15 strands that are super galvanized, sheathed, and waxed. The grade of the cables is 1,860 MPa. Each cable has a non-injected PEHD sheath that is white and aerodynamic that is integrally wrapped around it to provide protection. This protects against ultraviolet rays and has a spiral pattern on its surface that breaks up the monotony to dampen vibrations brought on by the interaction of wind and precipitation.

5. Characteristics and comparison of construction methods of two bridges

5.1 Comparison

In summary, the construction method of the Pingtang Bridge is extensive, operable and imitable compared to the construction method of the Millau Viaduct, in terms of the installation of the bridge deck, the closing and the installation of the bridge towers.

5.2 Features of the Pingtang Bridge construction method and its application prospects

By comparing the construction methods of the various parts of the two bridges, two characteristics of the construction method of the Pingtang Bridge can be obtained in general.

(1) Operability: The lifting of the deck girders of the Pingtang Bridge is simple, with relatively few influencing factors and a high degree of safety.

(2) Imitatable: The Pingtang Bridge construction method turns the whole into a piecemeal one, with easy operation and high safety, and can be applied in various environments.

The simplicity and safety of the construction method of the Pingtang Bridge, such as the innovative rotating lifting of the main girders of the bridge deck and the closing of the bridge, are of great significance and reference value to the construction of cable-stayed bridges.

6. Conclusion

The Pingtang Bridge and the Millau Viaduct are architectural masterpieces full of human ingenuity. The construction methods used for these two bridges are important for constructing cable-stayed bridges.

The construction method of the Milo Viaduct, especially the way the bridge deck was closed, was very creative, challenging and technically difficult. The construction method of the Pingtang Special Bridge, which reduces the whole bridge into pieces and gradually assembles and constructs it, reduces the influence of each part on each other during construction and is easy to operate and imitable.

Compared to the creative construction method of the Milo Viaduct, the construction methods of the Pingtang Bridge are more suitable for a variety of challenging construction environments.

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