Design and application of ultra-high performance concrete —— Case review of Changjiang Jiayu Bridge

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Abstract. Ultra-high performance concrete (UHPC), as a new type of cement-based material with ultra-high strength, excellent durability, and good workability, has shown significant application value in bridge engineering in recent years. This paper takes the Jia Yu Bridge on the Yangtze River as an example to explore the design and application of ultra-high performance concrete. The Jia Yu Yangtze River Bridge, a key project of the Wuhan Urban Circle Ring Expressway, adopts a cable-stayed bridge structure. By introducing ultra-high performance concrete, it addresses multiple technical challenges in large-span bridge design. The high strength and durability of ultra-high performance concrete effectively enhance the scour resistance of the bridge foundation, improve seismic performance, and significantly reduce main beam deformation. Additionally, the application of ultra-high performance concrete optimizes construction techniques and reduces maintenance costs throughout its lifecycle. Studies show that ultra-high performance concrete not only meets engineering requirements under complex hydrogeological conditions but also achieves structural lightweighting and aesthetics, providing crucial technical support for modern bridge engineering. The successful practice of the Jia Yu Bridge on the Yangtze River validates the technical advantages and application potential of ultra-high performance concrete in large-scale bridge projects, offering valuable experience and reference for future bridge construction in China.

Keywords: Ultra-high-performance concrete (UHPC), bridge engineering, technical advantages, Changjiang Jiayu Bridge.

1. Introduction

As China continues to update its urbanization and improve living standards, the demand for the aesthetics and safety of buildings is increasing, leading to higher requirements for the aesthetic and durability performance of concrete structures. This has spurred the development of ultra-high-performance concrete (UHPC). Ultra-high-performance concrete is a new type of cement-based material that differs from ordinary high-performance concrete in terms of material composition, mix design, and microstructure. It combines the characteristics of high-performance concrete and fiber-reinforced composites, offering exceptional mechanical and durability properties. Over the past 30 years, it has been one of the most innovative cement-based engineering materials, achieving a significant leap in material performance. Ultra-high-performance concrete increases density through the densest possible packing of particles, reduces water-to-binder ratio and enhances strength with high-performance water reducers, and improves internal structural homogeneity by incorporating ultra-fine active mineral admixtures. Therefore, ultra-high-performance concrete not only boasts high strength but also an extremely dense internal structure. Experimental evaluation results show that the compressive strength, tensile strength, and elastic modulus of ultra-high-performance concrete are all superior to those of ordinary concrete, validating its rationality and effectiveness in bridge design. Additionally, the bridge has achieved innovations in material selection, structural design, and construction techniques, showcasing technological advancements and aesthetic value in modern bridge engineering.

2. Ultra-high performance concrete

2.1. Development process and its characteristics

The history of Ultra-High-Performance Concrete (UHPC) can be traced back to the 1970s, initially studied and developed in Denmark. In 1973, Danish scholar Hans Henrik Bache (Hans Henrik Bach) proposed the DSP theory, which involves using highly efficient water reducers to fully disperse cement, ultra-fine particles, and aggregates, resulting in extremely dense mortar or concrete. In 1978, Danish company Albo Portland (Aalborg Portland) successfully experimentally prepared ultra-high strength concrete based on the DSP theory, achieving compressive strengths of 124-268 MPa.

The concept of ultra-high-performance concrete was first proposed in the 1990s by Bouyues (Bouygues) in France, initially referring to reactive powder concrete (RPC), a type of concrete with superior durability and excellent mechanical properties. In 1994, Larrard (Francois Delarre) and Sedran (Sedran) further refined the concept of ultra-high-performance concrete, and Richard reported on RPC, marking the entry of concrete into the era of ultra-high performance. Ultra-high-performance concrete saw extensive research and application from the late 20th century through the early 21st century. After entering the 21st century, as a new, future-oriented, or strategic engineering material, ultra-high-performance concrete has been extensively studied and developed in Europe, America, Japan, and South Korea. France and Japan have also established design guidelines that standardize the preparation, production, construction, and prefabrication techniques of ultra-high-performance concrete. Currently, the structural performance and design standards for ultra-high-performance concrete are continuously improving, and the application of engineering structures and products is steadily advancing, earning it the accolade of "the strongest concrete" in the industry [1]. Ultra-high-performance concrete is a modern advanced material, combining cement-based materials (concrete or mortar) with fibers and steel (reinforcing bars or high-strength prestressed bars), significantly enhancing the strength utilization efficiency of fibers and reinforcing bars within concrete, leading to a leap in the overall performance of cement-based structural materials. Using ultra-high-performance concrete can build lightweight, high-strength and high-toughness structures, changing the state of "fat beams and fat columns" of concrete structures; its durability and working life are far greater than steel, aluminum, plastic and other structural materials.

After decades of development, ultra-high-performance concrete has produced many characteristics in the contemporary era. Its characteristics are as follows:

(1) Ultra-high mechanical properties refer to the compressive strength, flexural strength and tensile strength can reach several times to more than ten times of ordinary concrete.

(2) Ultra-high durability refers to the extremely low porosity, almost no cracks in the interior, and corrosion resistance far exceeds ordinary concrete.

(3) Super high working performance means that it does not separate or seep water, has excellent pumping properties, self-compaction and no vibration, and can also reduce the amount of steel used and the weight of the structure.

2.2. Application scenarios and application types of ultra-high performance concrete

(1) Ultra-high-performance concrete (UHPC), due to its high strength, durability, stability, and crack resistance, has extensive engineering applications. As an excellent material, UHPC is primarily used in the following key areas: In bridge engineering, because of its high strength, UHPC can not only be used to construct longer-span bridges with greater clearances but also in bridge piers, continuous beams, main spans, deck slabs, and cantilever beams, replacing reinforced concrete to effectively enhance bridge strength and durability, extending service life. Steel-UHPC composite decks have achieved large-scale and sustainable development in China. In structural repair, UHPC is suitable for structural reinforcement and on-site emergency repairs, quickly restoring structural performance. In construction, it can be used for building facades and lightweight staircases, offering new design and performance options. In pipeline engineering, due to its high tensile strength and corrosion resistance, UHPC can serve as a conveying medium, ensuring safe and stable transportation.

In underground projects, its excellent water resistance makes it an ideal material for underground utility tunnels. Additionally, with its high compressive strength and toughness, UHPC can also be applied in high-impact environments, providing reliable safety assurance.

(2) Ultra-high-performance concrete is also commonly used in tunnel structures. Due to its excellent strength and stability, it can be used to manufacture tunnel lining, tunnel entrances, and other structural components, enhancing the structural integrity and extending the service life of tunnels. The reason ultra-high-performance concrete can be used for tunnel linings is that its high strength and durability effectively resist adverse environmental factors such as groundwater pressure, chemical erosion, and freeze-thaw cycles. For example, in some underground transportation tunnels, prefabricated lining panels made from ultra-high-performance concrete can reduce construction time and improve efficiency. In tunnel structures, joints and connectors are prone to problems. The high performance of ultra-high-performance concrete can be used to produce durable joint materials and connectors, enhancing the overall integrity and durability of the tunnel structure. The Federal Highway Administration conducted tests on ultra-high-performance concrete materials under cyclic live loads ranging from 1 to 8 t, with no leakage occurring over 9 million cycles, concluding that the superior water-tightness and resistance to penetration make ultra-high-performance concrete particularly suitable for reinforcing bridge and tunnel projects. It is evident that using ultra-high-performance concrete can repair and reinforce structures, with its strong compressive, flexural, and wear-resistant properties making it an ideal material for maintenance and reinforcement.

Ultra-high-performance concrete, with its outstanding mechanical properties and durability, has shown great potential in bridge, tunnel, construction, and repair projects. Its application in large-scale cable-stayed bridges further maximizes the advantages of ultra-high-performance concrete—high strength, lightweight, and long life. Practices such as the Dongting Lake Bridge and the Peisen Liujiang Special Bridge not only validate its technical feasibility but also drive innovation in bridge engineering.

2.3. Advantages of ultra-high performance concrete in large (tensioned) Bridges

However, there are many cases of ultra-high-performance concrete being used in large cable-stayed bridges, such as the Dongting Lake Bridge and the Haoji Railway Dongting Lake Bridge. These are the first railway steel bridge deck projects worldwide to use a steel-ultra-high-performance concrete composite deck. Compared with the original design paving scheme, the ultra-high-performance concrete paving system offers numerous advantages: (1) The ultra-high-performance concrete paving layer serves as a waterproofing layer, significantly simplifying construction procedures and eliminating the need for additional waterproofing and gravel layers; (2) The total thickness of the paving layer is reduced by 20%, thereby lowering the overall weight of the paving system; (3) Ultra-high-performance concrete materials possess exceptional density and durability, greatly enhancing the waterproofing and anti-corrosion capabilities of the paving layer, allowing it to have the same lifespan as the main structure, thus significantly reducing maintenance costs over its entire lifecycle; (4) Key parameters such as the thickness, slope, and smoothness of the ultra-high-performance concrete meet requirements, ensuring good surface quality with a dense and crack-free appearance. By controlling key paving parameters, the construction quality of the ultra-high-performance concrete paving layer can be well guaranteed. Additionally, the world's largest span highway prestressed concrete cable-stayed bridge—the Pei Sen Liujiang Special Bridge—is another significant case of ultra-high-performance concrete application.

From the steel-Ultra-High Performance Concrete composite deck of Dongting Lake Bridge to the prestressed structure of Peisen Liujiang Special Bridge, the successful application of Ultra-High-Performance Concrete in cable-stayed bridges has laid the foundation for its promotion in more complex projects. The Jiayu Yangtze River Bridge, located in the middle reaches of the Yangtze River and serving as a key project on the Wuhan Urban Circle Ring Expressway, further challenges the performance limits of Ultra-High-Performance Concrete under ultra-long spans and high hydrogeological requirements, marking another milestone in the integrated innovation of Ultra-High Performance Concrete technology.

3. Design review of Changjiang Jiayu Bridge

3.1. Background

The Jiayu Yangtze River Bridge is a key project of the Wuhan Urban Circle Ring Expressway's western section, spanning the Yangtze River from Xiaogan to Xiantao and Xianning. The bridge site is in the middle reaches of the Yangtze River between Jiayu and Yanwohe, with Unity Village in Yanwo Town, Honghu City on the north bank and Xinjie Town in Jiayu County on the south bank. The river width is approximately 1,300 meters. The upper reaches of the river segment are characterized by mainstream oscillation and island cutting, while the engineering section is generally straight and stable. The riverbed at the bridge site has a V-shaped double-section profile, with deeper channels slightly offset to the left. Over the years, the cross-section has alternated between erosion and deposition, with deep channels oscillating but showing little overall change, maintaining a basically stable form. Factors such as the clearance above the bridge, the clear space for the road on top of the dike, and the ongoing construction of connecting roads on both banks control the alignment. The longitudinal profile of the main bridge is designed with an asymmetrical herringbone slope ranging from 1.9% to 1.1%, with the steepest point located at the centerline of the main span. The convex vertical curve has a radius of 30,000 meters. The maximum longitudinal gradient is 1.9%, with the shortest gradient length being 1,330 meters. The minimum radius of the vertical curve is 30,000 meters for the convex shape and 40,000 meters for the concave shape, accounting for 40.2% of the total route length. The overall alignment is smooth, with good combination of plan and profile, ensuring harmonious operation speed.

The basic wind speed for the bridge design is 27.2m/s. The 100-year flood level at the bridge site is +30.64m (national elevation in 1985, same below), with a 20-year maximum navigable water level of +30.1m and a minimum navigable water level of 14.5m. The navigable clearance height in the bridge area should not be less than 18m, the single-span one-way navigable width should not be less than 220m, and the single-span two-way navigable width should not be less than 410m. The engineering geological conditions of the bridge site are stable, with weak neotectonic movements [2]. The thickness of the overburden on the north bank side of Honghu Lake is approximately 40-59m, while on the south bank side of Jiayu it is about 41-65m, with the thickest part of the riverbed cover being around 15m. Above the overburden are layers of clay, silty soil, saturated fine sand, medium sand, and old clay, with the underlying bedrock consisting of Cretaceous-Tertiary clayey siltstone and siltstone mudstone. The basic seismic intensity at the bridge site is VI, with a defense standard of VII.

3.2. Design concept

3.2.1. Origin of the concept of cable-stayed bridge structure

Since the mid-20th century, cable-stayed bridge technology has made breakthrough progress on a global scale. With the application of high-strength materials, the refinement of computational theories, and innovations in construction techniques, cable-stayed bridges have gradually become the preferred solution for spans ranging from 300 to 1000 meters. China's technical accumulation in major projects such as the Sutong Bridge and the Angchuanzhou Bridge has provided mature technological support for the adoption of cable-stayed bridge solutions on the Jiayu Yangtze River Bridge. The specific considerations are as follows: (Figure 1)

(1) Span Adaptation: The river surface at the bridge site is wide, requiring a large-span bridge to cross. Cable-stayed bridges, with their unique load-bearing system, transmit the main girder load through inclined cables to the piers, which then distribute it to the foundation [3]. This allows for achieving a larger span with a relatively lighter structure, effectively meeting the requirements of the

Jiayu Yangtze River Bridge for crossing capacity. Compared to suspension bridges, cable-stayed bridges have greater structural stiffness and less deformation in the main girder over medium and large spans, making them more suitable for the high traffic volume and heavy vehicle traffic demands of this bridge.

(2) Structural economy: In the comparison of various bridge types that meet the design requirements, cable-stayed bridge shows comprehensive advantages in terms of material consumption, construction difficulty and maintenance cost in the later period. Its structure is relatively simple, the construction period is controllable, and the long-term capital occupation cost is reduced. From the perspective of the whole life cycle, the economic benefit is significant.

(3) Landscape and Regional Integration: The geometric shapes formed by the piers and cables of cable-stayed bridges are diverse and varied [4]. Through design optimization, they can harmonize with the surrounding natural landscape and regional culture. In the design of the Jiayu Yangtze River Bridge, the pier shapes incorporate local cultural elements, featuring smooth and graceful lines. While meeting traffic functions, it has become a landmark building in the area, enhancing the city's image and cultural depth.

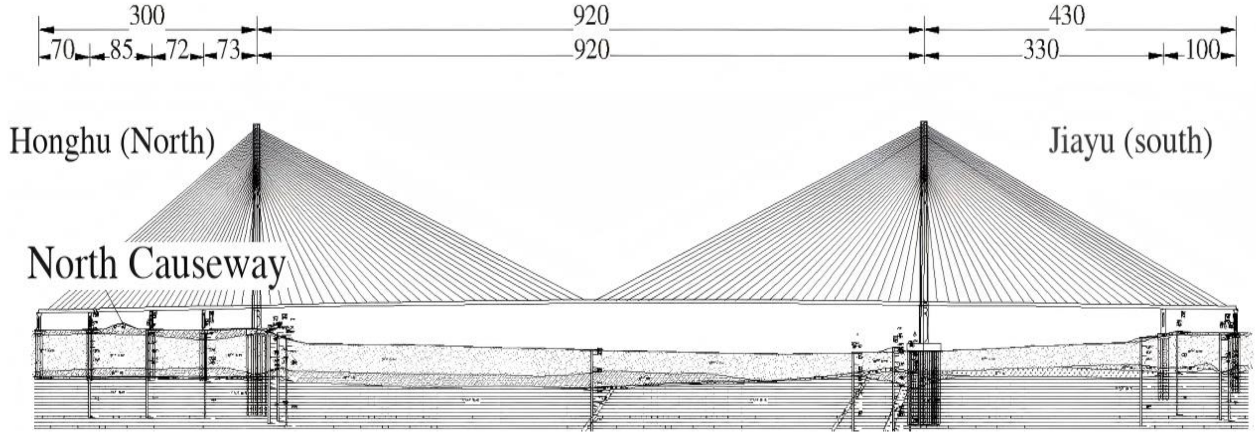

Figure 1. Main bridge facade layout of Jiayu Yangtze River Highway Bridge (unit: m)

(Photo credit: Zhang Bin, Zuo Wei, Wang Changxi, Xu Dongsheng, Li Likun, "Key Design Technologies of the Main Bridge of Jiayu Yangtze River Highway Bridge" [J] China & Foreign Highways, 2021 (03).)

3.2.2. Key problems in the design process

Complex Hydrogeological Challenges: The Yangtze River at the bridge site has swift currents and intense erosion, coupled with complex geological conditions, including various rock formations and weak interlayers. This places extremely high demands on the stability of the bridge foundation. [5] Ensuring the foundation's safety and reliability under long-term water erosion and complex geological conditions is the primary challenge in design.

Seismic performance guarantee: The area where the bridge is located is at the edge of the seismic activity zone, so the influence of earthquake on the bridge structure should be fully considered. How to optimize the cable-stayed bridge structural system and improve its overall seismic performance under the seismic load, to avoid structural damage and collapse, is a key technical problem in the design process.

Deformation control of large span main beam: With the increase of span, the deformation of the main beam of cable-stayed bridge under the action of self-weight, vehicle load and wind load increases significantly. How to effectively control the deformation of the main beam and ensure the driving comfort and structural safety is another major challenge faced by the design.

3.2.3. Ultra-high performance concrete solutions

Outstanding Mechanical Properties Address Fundamental Challenges: Ultra-high-performance concrete boasts ultra-high strength, high durability, and excellent water resistance. In bridge foundation design [6], using ultra-high-performance concrete can reduce the size of the foundation, enhance its load-bearing capacity, and improve its resistance to erosion. Its high-strength characteristics effectively resist the erosion and scouring forces of water on the foundation, ensuring long-term stability under complex hydrological conditions. Additionally, the excellent durability of ultra-high-performance concrete can reduce foundation maintenance costs and extend the service life of bridges.

Enhancing Structural Seismic Performance: The high toughness and energy absorption capacity of ultra-high-performance concrete enable it to effectively dissipate energy under seismic loads, reducing the structural response to earthquakes. Using ultra-high-performance concrete in critical areas such as bridge piers and main beams can enhance the overall ductility and seismic performance of the structure, improving the survival capability of bridges during earthquakes and reducing post-earthquake repair difficulties and costs.

Supporting Beam Deformation Control: Due to the low density and high strength of ultra-high-performance concrete, using it for the main beam of cable-stayed bridges can reduce the structural self-weight [7]. Under the same load, the deformation of the main beam is significantly reduced. This not only enhances driving comfort but also strengthens the stability and safety of the structure, providing strong technical support for the design and construction of large-span cable-stayed bridges.

3.3. Design presentation and its advantages

Ultra-high-performance concrete (UHPC) demonstrates significant technical advantages in road and bridge engineering thanks to its superior material properties and innovative design presentation. Its high density, low porosity microstructure, and fiber-reinforced composite design not only break through the performance limitations of traditional concrete but also achieve a leap in structural performance through optimized construction techniques. The following systematically discusses the design characteristics and engineering value of ultra-high-performance concrete from three dimensions: structural strength, durability, and economy.

3.3.1. High structural strength

Due to its unique structure and excellent application effects, ultra-high-performance concrete has extremely high construction strength, providing strong assurance for the safety and integrity of road and bridge projects, effectively reducing the possibility of structural instability [8]. Practical experience has shown that in the construction of concrete interface structures, using ultra-high-performance concrete can not only significantly improve the interface structure but also provide more reliable assurance for the stability of roads and bridges. As the load on road and bridge structures continues to increase, the bearing pressure on the foundation also intensifies. If the tensile strength of the foundation is insufficient, it may lead to structural instability. However, with the application of ultra-high-performance concrete, this issue can be effectively alleviated, enhancing the overall strength of the structure while reducing deformation in roads and bridges, thus ensuring traffic safety and normal travel for people.

3.3.2. Excellent durability

Through practical experience, ultra-high-performance concrete has demonstrated excellent strength and durability [9], effectively resisting external environmental challenges to ensure the stability of projects. If concrete fails to withstand severe weather conditions, it can severely damage bridge and road structures [10], significantly impacting their lifespan and safety. By introducing ultra-high-performance concrete, construction and maintenance work for bridges and roads can be greatly improved. It not only significantly enhances the earthquake resistance and durability of bridges and roads but also reduces construction costs, saves labor and resources, further improving the efficiency and quality of bridge and road construction. (Figure 2)

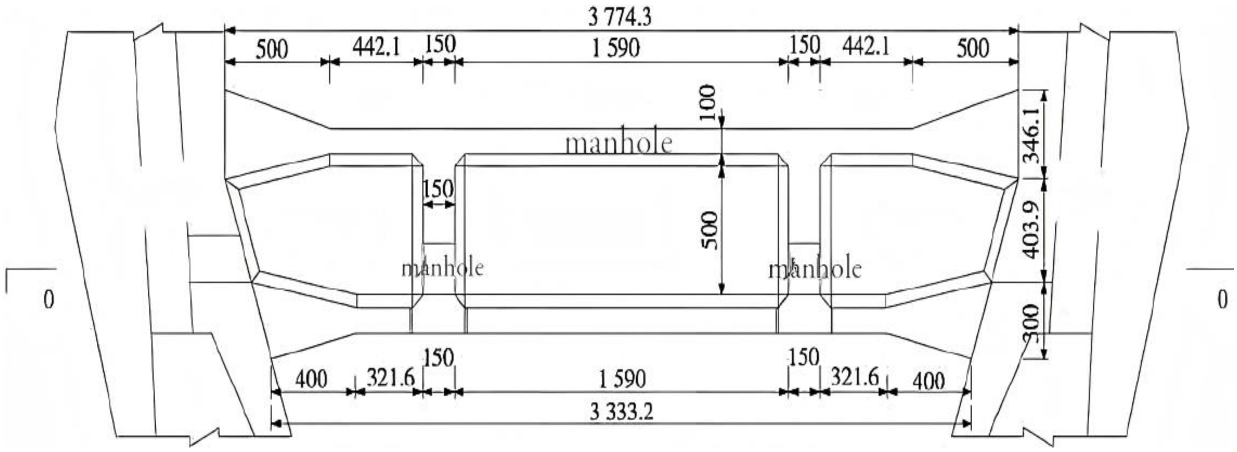

Figure 2. Zhu Xiaoming, Wang Changxi. Construction technology of main tower and crossbeam of kilometer-scale cable-stayed bridge [J], Highway and Automobile Transport, 2018 (03).

3.3.3. Strong energy saving effect

Compared to traditional construction projects, bridge and road construction is on a larger scale, thus requiring a longer construction period. If workers do not adopt innovative methods but instead follow traditional techniques, it will lead to significant resource wastage, making it impossible for the construction to meet its intended goals. Concrete with excellent performance characteristics can not only significantly shorten the construction period but also meet the basic requirements of an energy-saving society [11], thereby providing strong support for the sustainable development of bridge and road construction. Due to the structural features of ultra-high-performance concrete, its slump is extremely low, so if this material is used correctly, it can greatly reduce the likelihood of cracks in concrete structures and allow for more precise control over the construction process, thus better realizing its application value.

3.3.4. Good stability

Due to the heavy loads on roads and bridges, using ultra-high-performance concrete as the foundation can significantly enhance their overall load-bearing capacity, effectively resisting damage caused by changes in the external environment. This high-quality concrete can effectively resist adverse environmental impacts [12], ensuring the safety and reliability of roads and bridges. Using ultra-high-performance concrete can significantly improve structural stability, thereby achieving the expected application effects.

4. Conclusion

This paper, through a detailed discussion and comprehensive review of the design of the Changjiang Jiayu Bridge, further confirms its outstanding achievements and technological innovations in the field of bridge engineering. The bridge not only demonstrates foresight and innovation in its design philosophy but also showcases excellent structural performance and construction efficiency in practical applications.

In terms of structural design, the Yangtze River Jiayu Bridge has achieved a perfect combination of span and bearing capacity with its unique hybrid girder cable-stayed bridge structure [13].

Its kilometer-long main bridge not only demonstrates China's robust strength in bridge construction but also provides a solid guarantee for smooth regional traffic. The steel-concrete composite structure used in the main girder achieves a tight bond between steel and concrete through ingenious design solutions [14]. This innovative design not only enhances the load-bearing capacity of the main girder but also excels in crack resistance.

In terms of material application, the Yangtze River Jiayu Bridge extensively uses ultra-high-performance concrete. The introduction of this new material has significantly enhanced the durability and safety of the bridge. Ultra-high-performance concrete, with its high strength, toughness, and excellent crack resistance, notably improves the overall performance of the bridge, extending its service life. At the same time, the construction properties of ultra-high-performance concrete are excellent, meeting the high standards required for bridge construction materials, thus ensuring efficient and high-quality construction.

The construction of the Yangtze River Jiayu Bridge has also achieved significant breakthroughs in construction techniques. By adopting advanced construction technologies such as steel caisson lowering and skip construction, not only has the efficiency of construction been improved, but quality control has also reached new heights. The application of these technological innovations undoubtedly provides valuable experience and insights for future bridge construction.

The innovative practices of the Yangtze River Jiayu Bridge in bridge design and the application of ultra-high-performance concrete have not only enhanced the technical level of bridge engineering but also injected new vitality into the development of China's bridge construction industry. Its rational structural design, superior material properties, and efficient construction techniques collectively form this landmark bridge project. In the future, the successful experience of the Yangtze River Jiayu Bridge will be applied and promoted in more bridge projects, driving China's bridge construction industry to new heights.

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