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Research on the Application of UHPC in Steel-Concrete Composite Bridge Decks

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Abstract. The high strength and toughness of ultra-high performance concrete (UHPC) show excellent performance in the steel-concrete composite bridge deck. This paper mainly discusses the application of UHPC in steel-concrete composite bridge deck. Firstly, the structural form of steel-UHPC composite bridge deck is introduced. It is emphasized that the combination of UHPC and steel plate not only reduces the dead weight of the bridge, but also improves the bearing capacity and durability of the structure. Then the mechanical properties of steel-UHPC composite bridge deck are analyzed in detail, and the advantages of UHPC in compressive strength, tensile strength and durability are emphasized. Research results have shown that the high performance of UHPC significantly improves the flexural, shear and fatigue resistance of the bridge deck, while maintaining excellent performance under harsh environmental conditions. Finally, the application of UHPC in bridge deck reinforcement is discussed, including joint reinforcement during construction and bridge deck reinforcement after construction. It is found that ultra-high performance concrete shows excellent performance in joint and bridge deck reinforcement. In summary, as a high-performance material, UHPC has a broad application prospect in steel-concrete composite bridge deck, which is helpful to solve many technical bottlenecks in traditional bridge engineering.

Keywords: UHPC; Steel-concrete composite bridge deck; Joints; Reinforcement.

1. Introduction

In recent years, the technology of steel-concrete composite bridge has made great progress and has broad application prospects. These composite bridges effectively reduce the height of the structure, while increasing the stiffness of the structure, both reducing the deflection under live load and improving the ductility of the structure. This kind of bridge is cost-effective, supports factory production, and ensures high quality when on-site installation. However, the traditional steel-concrete composite beam has the limitation of large slab thickness and high dead weight, so it is not suitable for large span bridge structure. In addition, the concrete of steel-concrete composite bridges is prone to cracking under temperature changes and repeated vehicle loads. The rigid connection between the composite bridge deck and the steel beam limits the free deformation of the bridge deck, and the concrete bridge deck is easy to crack under external load, which further reduces the stiffness of the main beam structure. Problems such as the corrosion of internal steel bars and the deterioration of the underlying steel structure also endanger the durability and safety of the bridge.

Ultra-high performance concrete (UHPC) is a high-performance, new cement-based composite material characterized by high compressive strength, high elastic modulus, and high tensile strength. Compared to ordinary concrete, the application of UHPC can significantly improve the strength and quality of construction projects and reduce road and bridge diseases . To address the technical bottlenecks in existing steel-concrete composite bridge structures, such as limited spanning capability and poor durability, researchers have proposed solutions involving steel-UHPC composite bridge decks by leveraging the performance advantages of UHPC [1]. Significant achievements have been made in the areas of flexural performance, crack resistance, fatigue performance, shear performance of studs, joint performance influencing factors, and prefabricated structural systems and assembly methods.

2. Steel-UHPC Composite Bridge Decks

2.1. Structural Style

Steel-UHPC composite bridge decks typically consist of a steel deck and a UHPC deck. As shown in Fig. 1, the steel deck and UHPC layer of the composite bridge deck are usually connected by segmental shear studs and steel mesh [2]. Common structural style includes stud shear connections, composite deck system, and prefabricated bridge deck. Stud shear connection is one of the most common forms of steel-UHPC composite bridge decks. In this structure, UHPC bridge deck is closely integrated with steel decks by setting shear studs on the steel beams, forming a unified force-bearing system. This connection method not only enhances the overall stiffness of the bridge deck but also improves the structure's shear and flexural performance. The composite deck system utilizes the high strength and toughness of UHPC, combining it with steel beams to create a bridge deck system with higher load-bearing capacity and durability. This system has been applied in many real-world engineering projects, demonstrating good performance and durability. Some bridge projects have replaced traditional concrete bridge decks with UHPC, significantly extending the service life of the bridges. Prefabricated bridge decks offer an efficient construction method, with UHPC bridge decks being prefabricated in factories and then transported to the construction site for assembly, significantly improving construction efficiency and quality. Prefabricated bridge decks not only reduce the self-weight of the bridge but also optimize the structural dimensions. This method is widely used in large-span bridges, offering convenient construction and easy quality control [3]. In summary, steel-UHPC composite bridge decks demonstrate good economic viability and feasibility.

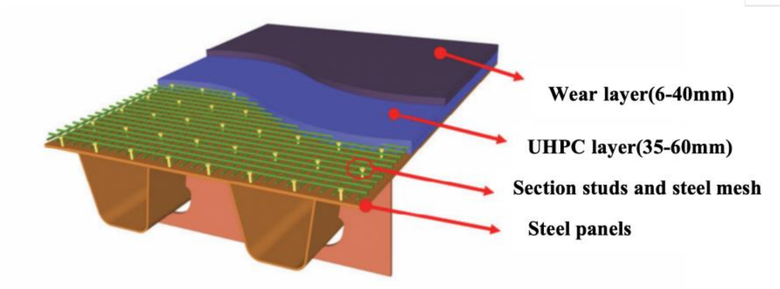


Figure 1. Closed ribbed light composite deck [2]

2.2. Mechanical Property

UHPC has extremely high compressive and tensile strength, making it particularly outstanding in flexural and shear performance. Its compressive strength typically exceeds 150 MPa, and its tensile strength reaches 8-15 Mpa [4]. UHPC maintains excellent performance even in high-temperature, high-humidity environments, making it suitable for bridge engineering under various harsh climate conditions. Moreover, UHPC has excellent durability, resisting freeze-thaw cycles, chemical corrosion, and fatigue loads. The high strength and toughness of UHPC give it excellent fatigue performance, effectively extending the service life of bridges. By optimizing the reinforcement design of UHPC, its flexural and shear performance can be further enhanced [5].

In addition, researchers have conducted in-depth studies on the fatigue performance, seismic performance, and durability of steel-UHPC composite bridge decks. Researchs indicate that UHPC bridge decks can effectively share the load of steel beams, reduce structural deformation, and improve the overall stiffness and stability of the bridge, with durability under repeated loads significantly superior to traditional concrete bridge decks [6]. Steel-UHPC composite bridge decks exhibit good durability during long-term use, reducing the need for maintenance and repair. This further verifies the superior performance of UHPC in these aspects. Besides experimental research, many scholars have also conducted theoretical analysis on the mechanical behavior of steel-UHPC composite bridge decks [7]. One study established a finite element model of a steel-UHPC composite bridge deck to analyze its stress distribution and deformation characteristics under different load conditions. The result showed that the application of UHPC significantly improved the mechanical properties of the bridge deck, enhancing its flexural and shear capacity [7].

2.3. Application Research

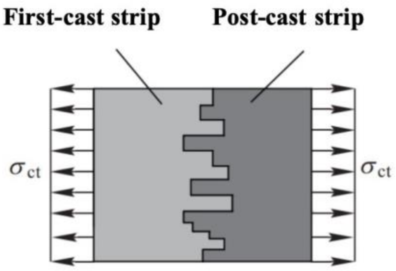
In recent years, steel-UHPC composite bridge decks have been widely applied and studied in real-world engineering projects. Many bridge engineering cases indicate that steel-UHPC composite bridge decks not only improve the load-bearing capacity and durability of bridges but also significantly shorten construction periods and reduce maintenance costs. In some large-scale bridge projects, UHPC has been used to replace traditional concrete bridge decks with good results. The steel-UHPC composite structure bridges effectively combine the excellent performance of steel and UHPC, breaking the limits of multiple materials and application fields, increasing the span of the structure, and reducing the risk of cracking [8]. The Korea Institute of Civil Engineering and Building Technology conducted a UHPC research project-SUPER BRIDGE 200-focusing on the structural system of cable-stayed bridges. They proposed a ribbed UHPC bridge deck and a UHPC girder system with prestressed side beams, which were applied in actual engineering projects [9].

The Jura Bridge in Franceis a bridge that uses a steel-UHPC composite structure. During construction, a steel-UHPC composite bridge deck was used to reduce self-weight and improve fatigue resistance. This structure effectively extended the bridge's service life and reduced maintenance costs. The Ludwig Bridge in Germany is an important transportation node in Germany. During the renovation of the bridge, engineers adopted a steel-UHPC composite bridge deck to address fatigue issues. The use of UHPC improved the bridge's crack resistance and durability, while also reducing self-weight to meet load requirements. The Fifth Nanjing Yangtze River Bridge in China used a steel-UHPC composite bridge deck during construction to improve the bridge's durability and fatigue resistance. The application of UHPC material at the joints significantly reduced crack formation and improved the overall performance of the bridge. The La Vanelle Bridge in Switzerland is a highway bridge that uses a steel-UHPC composite bridge deck. By introducing UHPC material into the bridge deck, the goals of reducing self-weight and improving fatigue resistance were achieved, while also enhancing the bridge's durability. The Wuhan Junshan Yangtze River Bridge in China is a typical case of using UHPC material to reinforce a steel bridge deck. After 17 years of service, the bridge deck experienced severe fatigue cracking issues. To address this, engineers proposed a solution to reinforce the bridge deck with UHPC material, achieving significant results by greatly reducing fatigue stress and extending the service life of the bridge. These cases demonstrate the wide application of steel-UHPC composite bridge decks in bridge engineering and their significant technical advantages, particularly in improving fatigue performance, extending service life, and reducing self-weight.

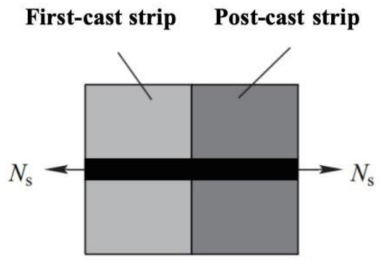
3. The Application of UHPC in the Reinforcement of Steel-Concrete Composite Bridge Deck

3.1. Joint Reinforcement during Construction

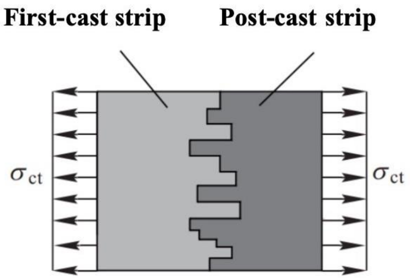
Joints are the weakest positions in composite bridge decks, and their strength and performance are critical to ensuring the overall quality of the structure. The application of UHPC at bridge connections is a key research direction in steel-UHPC composite bridge decks. During bridge construction, joints are weak points of the structure. Traditional concrete joints are prone to cracks and leakage, which can compromise the overall performance of the bridge. Compared to traditional concrete materials, UHPC has significant advantages in joint treatment during bridge construction. UHPC not only has excellent impact resistance and high fracture toughness, but also offers long service life and durability, which suits the stress environment of post-cast strip concrete at expansion joints. Experimental research on joints of steel-UHPC composite bridge decks reveals that UHPC joints have significantly better tensile performance than traditional concrete joints. This demonstrates that UHPC thin-layer reinforcement can effectively improve the stress condition of the bridge deck, enhance its stiffness, and reduce its deflection [10]. When applied to continuous sections of the bridge, this approach can comprehensively improve the overall structural performance of the bridge, reduce issues related to bridge deterioration, and effectively prevent or mitigate problems in the post-cast concrete sections. This, in turn, allows full utilization of the material's performance, extends the service life of the bridge, reduces the frequency and number of repairs, and enhances the overall operational efficiency of the project. UHPC has good anchoring performance with reinforcement, making it a common material for joint casting. The cracking of joints originates at the intersection of the transverse and longitudinal edges of the joint and then develops transversely. The crack resistance of the transverse edge depends on the bond strength at the interface between the new and old UHPC, provided by the chemical bond and the mechanical interlock due to the interface roughness. The limited number of steel fibers at this location does not significantly contribute to tensile strength. Additionally, the collaborative tension of the longitudinal reinforcement passing through the transverse joint interface can significantly reduce the tensile stress on the transverse edge. No longitudinal detachment has been observed at the longitudinal edges of the joints between the new and old UHPC. The mechanisms of crack resistance at the transverse edge and detachment resistance at the longitudinal edge are illustrated in Fig. 2 [11].



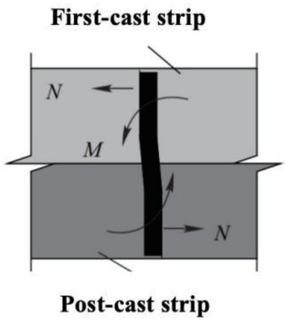
(a) Interlocking effect on the transverse boundary surface



(b) The longitudinal bar passing through the transverse edge



(c) Longitudinal boundary surface



(d) Cross-bar pin action across the longitudinal edge

Figure 2. Crack resistance mechanism of joint [11]

3.2. Post-reinforcement of Bridge Decks with UHPC

In addition, UHPC is widely used in the post-reinforcement of bridges. During operation, steel-concrete composite bridge decks are prone to cracking. To repair the cracks in the bridge deck and improve the structural performance of the bridge, a method of UHPC thin-layer reinforcement has been proposed. This involves pouring a layer of UHPC at the bottom of the lower structure, forming an integrated stress-bearing structure with the original concrete. During the UHPC pouring process, the original structure bears the load independently. Once UHPC has undergone early setting and the formwork is removed, UHPC and ordinary concrete bear the load together. Research has shown that reinforcing bridge decks with a thin layer of UHPC can effectively reduce the transverse tensile stress in the precast slabs. The UHPC thin-layer reinforcement method can enhance the connection between the main girders and bridge deck, reduce the transverse stress on the bridge deck, and improve its stiffness while reducing deflection. This indicates that UHPC thin-layer reinforcement of the bridge deck is a reliable approach that can enhance the load-bearing capacity and durability of the bridge [12].

4. Conclusion

This paper focuses on the application of UHPC in steel-concrete composite bridge decks, aiming to address the issues of high self-weight, poor durability, and susceptibility to cracking in traditional steel-concrete composite bridges. Through discussions on the structural style, mechanical properties, practical applications of steel-UHPC composite bridge decks, and the application of UHPC in the reinforcement of steel-concrete composite bridge deck, the following conclusions are drawn:

(1) Through the combination of UHPC and steel plate, the bridge deck can effectively reduce the dead weight of the bridge and significantly improve the overall bearing capacity and durability of the bridge. The high strength and toughness of UHPC make it excellent in practical engineering applications, especially in improving structural stiffness and shear properties. Precast modular bridge deck has a broad application prospect in large-scale bridge engineering because of its efficient construction method and excellent engineering performance.

(2) UHPC has significant advantages in compressive strength, tensile strength and durability, especially in bending, shearing and fatigue resistance. In addition, UHPC can still maintain excellent performance in harsh environments such as high temperature and humidity, and is suitable for bridge projects under various complex climatic conditions. Practical engineering cases show that steel-UHPC composite bridge deck significantly increases the service life of the bridge and reduces the maintenance cost.

(3) Although the application of UHPC in steel-concrete composite bridge deck has many advantages, there are still some areas to be further studied. First, the construction technology and materials of UHPC are costly and require further optimization and control before they can be applied on a large scale. Secondly, the long-term performance of steel-UHPC composite bridge deck is insufficient, especially under extreme climate and complex load conditions, which requires further long-term monitoring and research. In addition, the interface bonding properties of UHPC and steel, the formation mechanism of cracks on bridge floor and durability factors need to be further discussed. In the future, with the continuous development of UHPC technology and the accumulation of engineering practice, steel-UHPC composite bridge deck is expected to be more widely used and promoted in bridge engineering, and provide a more economical and feasible solution for bridge structural design.

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