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Research on PBL Shear Bonds in Steel UHPC Composite Structures

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Abstract: The steel UHPC (ultra-high-performance concrete) composite structure has become a widely used structural form in modern bridge engineering due to its excellent mechanical properties and durability. Through a detailed analysis of experimental research and numerical simulations, the main findings and shortcomings of existing studies on connectors in steel UHPC composite structures were summarized. The performance of current research under extreme environmental conditions, limitations in parameter selection, and challenges faced in practical engineering applications were pointed out. Finally, this article proposes future research directions, including the development of new connectors, improvement of overall structural performance, and refinement of design specifications, to promote the further application and development of steel UHPC bridge decks.

1. Introduction

With the development of bridge engineering, the limitations of traditional concrete bridge decks in terms of durability and fatigue resistance have gradually emerged, affecting the service life and safety of bridges. To address this issue, a steel UHPC composite structure combining ultra-high-performance concrete (UHPC) with steel has emerged. UHPC has become an ideal bridge deck material in modern bridge engineering due to its excellent mechanical properties and durability. The steel UHPC bridge deck structure can not only improve the bearing capacity of bridges, but also significantly extend the service life of bridges, so it has been widely studied and applied at home and abroad.

In steel UHPC composite structures, the design and performance of connectors directly affect the overall stress performance and long-term durability of the structure. As the connecting medium between the bridge deck and the steel main beam, the connectors not only need to bear the role of shear force transmission, but also have good fatigue resistance and durability. Traditional shear bolts are difficult to meet these requirements in certain situations, therefore, PBL (Perfobond Leiste) shear connects and other new types of connectors have gradually become a research hotspot. These connectors not only enhance structural performance, but also face many challenges in design and application.

This article aims to review the research progress of connectors in steel UHPC bridge decks, with a focus on exploring key indicators such as shear performance, shear stiffness, fatigue performance, etc. of shear bolts, PBL shear connects, and other new connectors. Through the analysis and summary of existing experimental research and numerical simulations, this article will reveal the main mechanical properties and application prospects of connectors in steel UHPC composite structures, and point out the shortcomings of current research and future development directions.

2. Types of connectors in steel UHPC bridge decks

The steel-concrete composite structure consists of steel components, concrete components, and shear connectors. This structure fully utilizes the advantages of two materials, namely steel tension and concrete compression, achieving the effect of "1+1>2". Since the beginning of the 21st century, highway bridges have been continuously developing towards large-span, multi lane, lightweight and high-strength directions. Steel concrete composite structures have been widely used in bridge engineering due to their excellent mechanical properties.

When steel-concrete composite structures were first applied in engineering, shear connects were not arranged, and the connection between the steel and concrete interface was only achieved through the bonding force between the two. Later, the engineering personnel found that this connection method was extremely unstable, and the steel-concrete interface would separate under small loads, which could not meet the requirements of common force and could not fully utilize the advantages of steel-concrete composite structures. Therefore, engineers design various components to ensure the connection between steel and concrete, and refer to these components as shear connectors or shear connects. At the same time, the main function of shear connects is further clarified, which is to transmit the shear force at the steel-concrete interface, limit the separation of the two, and ensure that they are subjected to the same force. Therefore, it is an important content of steel-concrete composite structure design and a hot topic in the research of this type of composite structure.

The commonly used shear connects are mainly steel bar connectors and section steel connectors, but with the continuous expansion of shear resistance requirements in engineering, the connection effect of these two types of shears connects is not ideal. In the mid-20th century, bolted shear connects gradually became the most widely used shear connects due to their four-way shear resistance characteristics and simple manufacturing methods [1]. However, the disadvantage of bolted shear connects is also prominent, that is, they are prone to fatigue failure under repeated loads [2,3]. In addition, due to the small shear force that a single bolt can withstand, a large number of bolts need to be arranged to meet the shear resistance requirements of the structure. Even with professional equipment, it still requires a lot of manpower and material resources. In addition, there are certain requirements for the size of the layout area.

In 1987, Leonhardt et al. [4] proposed Perfobond Leiste (PBL) to solve the fatigue problem of shear connects in the Coroni Third Bridge. The shear key construction form is shown in Fig.1. First, the steel plate is perforated and welded to the steel component, and then the concrete is poured. At this time, a concrete tenon is formed at the hole, which is located in the middle of the perforated steel plate and is integrated with the concrete slab. It can transmit the shear force between the two, effectively suppressing the horizontal sliding and vertical lifting between the steel and concrete. Compared with bolts, PBL shear connects have higher shear resistance and fatigue resistance, especially after adding through steel bars in the holes, their ductility is greatly improved. At present, PBL shear connects have become one of the most commonly used shears connects in steel UHPC composite structures. Therefore, it is particularly important to explore the shear performance of PBL shear connects in steel UHPC composite structures and propose corresponding design theories and methods.

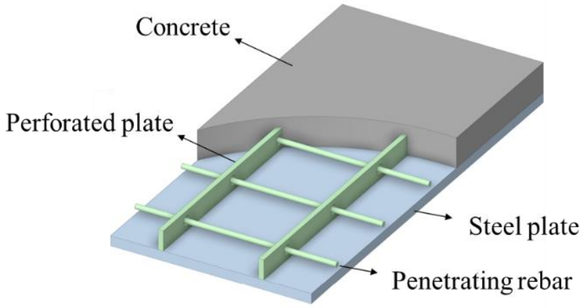

Figure 1: Configuration of PBL shear connector

3. Research progress on PBL shear connects in UHPC

In 2014, Kang et al. [5] conducted a series of push out tests to investigate the mechanical properties of PBL shear connects in concrete with compressive strength greater than 50MPa. The compressive strength of the specimens included two types: 80MPa and 180MPa. Research has shown that the shear resistance of PBL shear connects increases with the increase of concrete strength; After comparing the experimental results with the predicted results of existing calculation formulas, it was found that the existing PBL shear key bearing capacity calculation formula does not have universal applicability for UHPC with high compressive strength of concrete.

In the same year, Wirojjanapirom et al. [6] designed and fabricated 12 UHPC-PC hybrid beams using PBL shear connects, with PBL thickness, hole diameter, and steel bar diameter as research parameters. After conducting experimental research, it was found that compared with ordinary concrete, the use of UHPC improved the shear efficiency of PBL shear connects, and its shear bearing capacity was positively correlated with thickness and opening diameter; In addition, applying prestress can increase friction, thereby enhancing the shear resistance of the shear key.

In 2017, He et al. [7] conducted a push out test of PBL shear connects in UHPC based on ordinary concrete. The results showed that steel fibers in UHPC can improve the ductility of concrete joints and the bonding effect between steel and concrete, thus significantly increasing the shear bearing capacity of PBL shear connects; Based on the research results, the calculation formula for the bearing capacity of PBL shear connects in ordinary concrete was revised, and reinforcement factors were added to the concrete tenon and bonding effects. Comparative verification showed that the revised formula has high accuracy in predicting the shear bearing capacity of PBL in UHPC.

In 2019, Duan et al. [8] conducted experiments and numerical simulations to investigate the stress and failure mechanism of PBL shear connects in UHPC. Research has found that the shear performance of PBL shear connects is influenced by the diameter of the steel bars, the number of holes, and the spacing between them. The optimal spacing between holes is about 2.25 times their diameter, which is the same as in ordinary concrete; Unlike the previous calculation of shear stiffness using Euler beam theory, this article considers concrete tenons as deep beams with small span to height ratios, takes into account the shear deformation caused by shear forces, and then uses elastic foundation beam theory to calculate the initial stiffness, thereby obtaining the formula for calculating the load slip curve.

In 2021, Tan et al. [9] conducted push out tests on 26 PBL specimens, studying parameters such as concrete type, number of holes, and spacing. The experimental results show that the average shear bearing capacity of a single hole with multiple rows of PBL shear connects is relatively small, mainly due to the uneven distribution of relative slip along the load direction, decreasing from the near load end to the far load end; The reduction of hole spacing will make the stress distribution more uniform, but it will lead to local stress concentration in concrete, resulting in a decrease in bearing capacity. Therefore, in the proposed formula for calculating shear bearing capacity, the influence of the number and spacing of holes was considered, and the calculated results were in good agreement with the experimental results.

In 2023, Liu et al. [10,11] used a combination of experimental research and numerical simulation to investigate the shear behavior and failure mode of PBL shear connects embedded in UHPC. Based on this, they replaced the steel of PBL shear connects with high-strength steel and analyzed the mechanical properties of PBL shear connects using two high-performance materials. The research results indicate that the failure modes of the test specimens can be classified into perforated plate failure, through steel bar fracture accompanied by hole wall yielding, and through steel bar fracture without hole wall yielding. The shear strength corresponding to these three failure modes increases sequentially; When the thickness or strength of the perforated plate is sufficient, the shear bearing capacity increases with the increase of the perforated diameter. When the thickness or strength of the perforated plate is small, increasing the perforated diameter will make the perforated steel plate more prone to damage, resulting in a decrease in its shear capacity.

In the same year, Cao et al. [12] conducted push out experiments using concrete type, PBL shear key burial depth, and transverse steel bar diameter as parameters, with a focus on exploring the influence of burial depth changes on PBL shear connects. The research results indicate that the shear bearing capacity and initial shear stiffness of PBL shear connects with lower burial depth are higher than those of specimens with deeper burial depth; The failure mode of PBL shear connects with excessive diameter of steel bars is manifested as the failure of perforated plates, resulting in premature failure of the entire specimen; Taking into account the influence of burial depth and failure mode, the formula for calculating shear bearing capacity has been revised, and the revised formula has a certain level of calculation accuracy.

4. Shortcomings and challenges of existing research

It can be found that there are currently abundant research results on PBL shear connects in ordinary concrete, clarifying their stress mechanism and the influence of some factors on their mechanical properties, and establishing representative formulas for calculating shear bearing capacity. However, research results on their application in UHPC are relatively limited. In terms of experimental research, most of the research parameters focus on a few common parameters, and there is relatively little analysis on parameters such as steel fiber content and hole distance; In terms of establishing calculation models for shear bearing capacity and shear stiffness, most formulas are based on ordinary concrete calculation formulas and then fitted based on experimental results, lacking theoretical derivation, so their applicability is relatively small.

5. Conclusion

In summary, the design specifications for PBL shear connects in steel UHPC composite structures have not yet been promulgated, and their design theories and methods are not perfect. Therefore, it is necessary to conduct systematic research on PBL shear connects in UHPC, reveal the force transmission mechanism and shear resistance mechanism of PBL shear connects in steel UHPC composite structures, clarify the key influencing parameters of their shear mechanical performance, and propose practical design theories and methods to provide theoretical basis for the design of shear connects in steel UHPC composite structures.

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