Opinion Article

Overview of Research Progress on Innovative Approaches to Steel-Concrete Joint Interfaces for Enhanced Performance in Cable-Stayed Bridges

Abstract: The steel cable-stayed bridge has the characteristics of light weight, high construction precision, easy assembly, good seismic performance and clear force of cable tower anchorage structure. The concrete tower or pile cap has the advantages of high rigidity, low cost and low maintenance cost. Steel-concrete hybrid bridge tower combines the advantages of steel bridge tower and concrete bridge tower, and has been adopted by more and more bridge structures. This paper mainly introduces the structural form of steel-concrete composite bridge tower, and supplements the application of steel-concrete composite structure in main beam. The force borne by each part of the component is also different. In the process of excessive bearing capacity, shear keys, shear studs and other components play an important role. Future research can use computers to simplify the design process.

Keyword: cable-stayed bridge, steel-concrete composite section, steel-concrete composite beam

Introduction

Steel has excellent tensile properties, and concrete has excellent compressive properties. Steel-concrete hybrid structure refers to two or three forms of steel structure, concrete structure and composite structure in different parts of the structure, and connect different structural parts through the joint section. The steel-concrete hybrid structure can make the two materials work together and do their best to give full play to the respective advantages of steel and concrete. Compared with the traditional concrete structure and steel structure, steel-concrete hybrid structure has better technical advantages and economic benefits [1]. Since the 1970 s, the steel-concrete composite section was first applied to the main girder of the bridge, and then it was also applied to the bridge tower. The following is analyzed from two aspects: the application of the main girder and the application of the bridge tower.

1 steel-concrete joint section structure form

The steel-concrete joint section in the steel-concrete composite beam can be divided into a lattice joint section and a non-lattice joint section according to its force transmission mechanism. The connection mode of steel tower column and concrete cap can be divided into three types: pressure type, shear type and pressure shear type according to the different force transmission mechanism.

1.1 Non-cell pressure plate

Compared with the pressure plate joint section with lattice chamber, the pressure plate joint section without lattice chamber has simple structure and clear force transmission. According to whether the steel box girder is extended into the concrete box girder, the joint section of the non-cell bearing plate can be divided into the end bearing plate and the roof and floor bearing plate. The end bearing plate joint section connects the bearing plate at the end of the steel beam with the concrete box girder through the shear connector to transmit the internal force between the steel box girder and the concrete box girder. At the same time, to avoid the problems of stiffness mutation and stress concentration, stiffeners are set near the joint section of the steel box girder to balance the stiffness on both sides of the joint section. In addition to relying on the bearing plate at the end of the steel box girder to transfer the internal force, the top and bottom plates are extended for a certain distance, and the shear connectors are set to connect with the concrete box girder to form a steel-concrete mixed zone. The concrete box girder side of this kind of joint section is convenient to pour and the pouring quality is easy to guarantee, and the steel box girder side is also simple to make.

1.2 Pressure-bearing plate with cell

The pressure-bearing plate joint section with lattice room is to set a steel lattice room on one side of the steel box girder, and to fill the concrete inside to connect with the concrete box girder. At the same time, the shear connectors are set on the top and bottom plates of the steel lattice room, the pressure-bearing plate and the steel box girder to achieve the purpose of transmitting internal forces. According to the different positions of the bearing plate, the joint section of the bearing plate with lattice chamber can be divided into the following three forms : the bearing plate is set on the side of the concrete box girder of the steel lattice chamber as the front bearing plate ; when the bearing plate is set on the side of the steel box girder of the steel cell, it is the rear bearing plate ; when the pressure plate is set on both sides, the front and rear pressure plate joint section is set. Compared with the non-cell pressure-bearing plate joint section, the stiffness change of this type of joint section is relatively stable and the force transmission is smooth, but its structure is complex, and it is not easy to vibrate when pouring concrete in the lattice room, and the pouring quality cannot be guaranteed.

1.3 Pressurized steel-concrete joint section

The bearing steel-concrete joint section is to connect the bottom of the steel tower with the concrete pier by high-strength bolts or prestressed bolts embedded in the concrete cap. When high-strength bolts are used, the axial force at the bottom of the steel tower structure is transmitted to the top of the concrete pier through the thicker bearing steel plate, the bending moment is transmitted by the high-strength bolts, and the shear force is overcome by the friction between the bearing plate and the concrete foundation ; when the prestressed anchor is used, the axial force at the bottom of the steel tower structure is still transmitted by the pressure-bearing steel plate. The tension caused by the bending moment is overcome by the pre-pressure of the prestressed anchor, and the shear force is resisted by the friction between the bottom of the pressure-bearing steel plate and the top of the concrete cap. To transfer the pressure at the bottom of the main tower evenly, the bearing plate needs to adopt a thicker steel plate and maintain close contact with the concrete cap. To ensure the close and effective contact between the bearing plate and the concrete cap, the following two methods are currently used: First, the surface of the concrete cap is polished and polished, and the bearing steel plate is cut at the same time. This method is strict with the process requirements and the workload is large; the second is to carry out cement grouting between the surface of the pile cap and the bearing steel plate. This method has a small workload, but it is not suitable for large-scale steel towers. The pressure-bearing steel-concrete joint section has a clear force transmission mechanism and is convenient for construction. Most steel towers are connected with the foundation cap by this structure. At present, Zhijiang Bridge and Taizhou Bridge, which have been built, adopt this kind of joint section. Taizhou Bridge is the first three-tower suspension bridge with a main span of more than one thousand meters in the world.

1.4 Shear-type steel-concrete joint section

The shear-type steel-concrete joint section is to embed a part of the bottom of the steel tower column into the concrete pier, so it is also called the embedded steel-concrete joint section. To ensure that the bottom of the steel tower and the concrete pier can be fully combined with the common force and the load is uniformly transmitted, the shear studs or perforated plate shear connectors are generally used on the wall of the steel tower. This method avoids the polishing operation of the concrete cap surface in the pressure-bearing joint section and reduces the workload. However, the axial force is transmitted to the foundation through the shear force, which is a splitting force for the foundation concrete itself, and the force transmission length is long. At the same time, the steel plate and shear connectors are embedded in the construction process of the shear-type joint section, which may affect the arrangement of steel bars in the concrete pile cap. In addition, due to the shrinkage deformation of concrete and the great influence of temperature on the steel tower, the force transmission mechanism of this kind of steel-concrete joint section will become more complicated than that of the pressure-bearing steel-concrete joint section. Therefore, appropriate construction technology and other measures should be adopted to ensure the construction quality. Before installing the bottom section of the main tower, it is necessary to install the positioning base in advance, and then fix the bottom section of the tower on the positioning base. Because the installation accuracy of the positioning base has a great influence on the verticality of the main tower, the installation must be as accurate as possible.

1.5 Steel-concrete composite joint section with pressure-bearing and shear-transferring

The combined steel-concrete joint section of pressure transmission and shear is a combination of the above two methods. This type of joint section uses the steel tower web, wall plate and stiffening plate to form a steel lattice room. The connectors are arranged on the side of the lattice room, the pressure-bearing steel plate is arranged at the end, and the concrete is poured in the lattice room to transfer the internal force at the bottom of the steel tower to the concrete cap, which is also called the lattice pressure plate. The force transmission mechanism of the combined section is as follows: The axial force at the bottom of the steel tower is transmitted to the concrete in the form of shear force by some of the tower columns embedded in the concrete, while the tensile stress caused by the bending moment is transmitted to the concrete cap by high-strength bolts. Therefore, the combined section can avoid the disadvantage that the tensile stress may be generated when the combined section is used.

Table 1 Comparison of structural forms

configuration	Force transmission components	Advantage	Disadvantage
cell-front pressure plate	Bearing plate, prestressed tendons, shear connectors, steel grille webs	The axial force is borne by the bearing plate and prestress. Steel cell shoulders the role of force transmission, the cell stress is uniform and the stiffness change is small.	The position welding of steel cell is complex, there are many welds, and the construction quality is difficult to control. It is difficult to reinforce concrete at the joint section position. The room needs to be filled with mortar, which is difficult to ensure the quality of concrete pouring, and it is easy to cause voids in indoor concrete.
cell-rear pressure plate			
cell-front and rear pressure plate			
no cell-front pressure plate	Pressure plate, prestressed steel beam, front pressure plate shear connectors	The construction is convenient, the steel beam is easy to make, the concrete is easy to pour, and the pouring quality is easy to guarantee.	The roof and floor do not transmit force, and the stiffness of the bearing plate changes from ancient to modern, which is prone to stress concentration.
no cell-rear pressure plate	Pressure plate, prestressed steel beam, rear pressure plate shear connector, combined section roof and floor connector	While containing the advantages of the front bearing plate structure, the top and bottom plates of the steel beam jointly bear the force transmission function, reducing the sudden change of the stiffness of the joint section, so that the stiffness change and stress concentration near the bearing plate are relatively reduced.	The position stiffness diagram of the bearing plate is less unchanged, but there is still a problem of stress concentration.

2 Application of steel-concrete composite structure in main girder

With the continuous breakthrough of the span of cable-stayed bridge, concrete structure has been rarely used in the main span girder of long-span cable-stayed bridge due to its shortcomings such as self-weight and weak spanning ability. Steel beam has strong spanning ability, but it has the limitations of high cost and poor stability. Based on the consideration of span requirements and economy, the current long-span bridges mainly adopt the following structural system forms: he main span adopts steel structure, the side span adopts concrete structure, and the steel-concrete hybrid girder bridge structure system with a joint section between the steel beam and the concrete beam [2-3]. This new type of structural system can give full play to the spanning capacity of steel structure and the self-weight characteristics of concrete structure. The mechanical performance, spanning capacity and economic benefit of hybrid beam are better than those of steel structure bridge or concrete bridge with single material. Whether the steel-concrete hybrid girder bridge can give full play to its own mechanical properties depends largely on whether the steel and concrete can be well connected. In other words, the design and construction of the steel-concrete joint section play a vital role in this structural system bridge.

In the 1970s, the Kurt-Schumacher Bridge, the first hybrid girder cable-stayed bridge in the world, was built in West Germany[4]. The bridge is a double-plane cable-stayed bridge with a main span of 287.04 m and a side span of 146.61 m. The combined section is set at the bridge tower. However, due to the immature construction technology of the joint section at that time, the development of the steel-concrete hybrid girder bridge stagnated for decades. Until the 1990 s, the structural design of the steel-concrete joint section continued to develop, and the connection technology between steel and concrete continued to improve. The steel-concrete hybrid girder bridge was gradually restored to life. In view of the greater spanning capacity of such bridges, it has been promoted and applied in bridge engineering in Europe and even around the world. Since the 1980s, a series of hybrid girder cable-stayed bridges have been built in Japan. Among them, the most famous one is the Dodoro Bridge.This bridge adopts a double-tower hybrid girder cable-stayed bridge with a span of 890 m, which is the largest cable-stayed bridge in the world at the end of the 20 th century. Although the research and construction of hybrid girder cable-stayed bridges in China started late compared with other developed countries, they have developed rapidly in recent years. Typical representative hybrid girder cable-stayed bridges such as Shanghai Xupu Bridge, Shantou Queshi Bridge and Zhoushan Taoyaomen Bridge have been built one after another.

2.1 Research status of steel-concrete composite section of main girder

In order to study the stress and theoretical calculation formula of the steel-concrete composite section of the railway hybrid beam, Shi et al.[5] proposed the calculation formula of the section stress, the shear connector of the top and bottom plate and the force transmission of the bearing plate of the steel-concrete composite section of the railway hybrid beam on the basis of the calculation formula of the steel-concrete composite section of the existing highway bridge. Taking the Jialing River Bridge of Hanbanan Railway as the research background, the finite element analysis is carried out to explore the longitudinal and transverse distribution of stress and stress in the joint section, and then the calculation and analysis of the joint section are carried out. The results show that there is a certain inhomogeneity in the transverse distribution of steel and mixed stress at different cross-section positions.

Pu Qianhui[6]studied the mechanical properties and force transfer mechanism of the steel-concrete joint section of the railway based on the Yongtaiwen Bridge across the Yongjia right line of the Hangzhou-Wenzhou Railway with a main span of 216 m, and discussed the reasonable structural parameters of the steel-concrete joint section of the bridge. The finite element software was used to establish the local finite element model of the steel-concrete joint section. The distribution of internal forces between steel and concrete in the joint section was analyzed, and the structural parameters affecting the distribution of force transmission were discussed. The results show that the longitudinal stress plate of the structure is in a compressive state, and the stress of the steel beam decreases gradually along the joint section. The proportion of axial force shared by the bearing plate is about 56.2 %. With the increase of the thickness of the bearing plate, the proportion of load shared by the bearing plate also increases. When the thickness of the bearing plate is between 40 mm and 60 mm, the increase is faster, and the increase is not obvious when the thickness of the bearing plate is greater than 60 mm. When the length of the embedded section of the steel beam is greater than 2.5 m, it has little effect on the force transmission effect. The increase of the stiffness of the shear studs will significantly increase the shear force along the bridge and increase the uneven distribution of the shear force along the transverse bridge.

In order to guide the design of this kind of steel-concrete composite section, Zou[7]made a large-scale steel-concrete composite section model based on a hybrid girder cable-stayed bridge (the steel-concrete composite section is in the form of a lattice back bearing plate structure). Considering the creep effect of concrete, the static load test was carried out to analyze the stress distribution of the model under 9 working conditions, and the force transmission characteristics of the combined section were studied based on the test results and theoretical analysis. The results show that under various working conditions, all steel members and concrete are under compression, and the creep effect of concrete causes the structural stress to increase generally, and its influence on the stress of steel members is greater than that of concrete. Under the most unfavorable conditions, all parts of the test model are in the elastic stage, and the load and strain of steel beam and concrete show a good linear relationship. The bearing plate bears 55 % ~ 60 % of the load transferred from the mid-span composite beam to the steel-concrete composite section. The composite beam bridge deck can be an effective way to reduce the load of the bearing plate.

Huang Tiangui[8]based on the Chongqing Yongchuan Yangtze River Bridge project, through the means of test and finite element analysis, the steel-concrete composite section of steel-concrete hybrid girder bridge is studied in depth and systematically. By intercepting the steel-concrete composite section of the bridge and the adjacent beam section to make model specimens, the section model test was carried out to understand the mechanical performance, force transmission mode, stress and strain distribution of the composite section, and used as the basis and test standard for numerical calculation and analysis. In addition, the manufacturing and forming process of the segment model specimen can simulate the construction process of the actual original bridge joint section, and then put forward measures to improve the construction quantity. Through the actual loading, the stress and strain distribution of the steel-concrete composite section and its adjacent beam section under the design load is tested, and it is verified that the bridge section can be kept safe and reliable under the condition of 1.7 times overload of non-prestressed load.

Jiang Xianglin[9] designed a test model with a scale ratio of 1 : 2, and studied the stress distribution, failure mode and bearing capacity of the stiffening transition section of steel beams with different structural forms through static load tests. The results show that the transition section of the specimen enters the plastic stage before other parts of the specimen, that is, the transition section is the weakest part of the steel beam transition section. Setting a diaphragm at the end of the transition section can not only significantly reduce its stress concentration, but also limit the out-of-plane deformation of the nearby floor.

Clemence Lepourry et al.[10]proposed a U-shaped steel-concrete hybrid beam based on engineering practice, in which L-shaped shear connectors were used, and push-out tests were carried out to verify the performance of the structure. The results show that the structure can meet the needs of large-span rapid construction. The test of YaoYadong et al.[11]shows that the failure mode of the steel-concrete joint section is the tensile failure of the roof concrete, and the concrete transition section is destroyed before the steel-concrete joint section. The bearing plate plays a role of collection and redistribution in the process of structural force transmission.

Zhenxuan Yu et al.[12]carried out finite element analysis and experimental verification on the stress and force transmission performance of PBL shear connector in recycled aggregate concrete. The results show that the PBL shear connector with recycled aggregate concrete has sufficient ductility. The shear strength of PBL shear connector increases with the increase of steel plate strength. The study of Nguyen Minh Hai[13]shows that the use of steel fiber mortar can effectively improve the shear strength of steel-concrete joint section.

Bruno Briseghella[14]presents and discusses the dynamic response of a curved cable-stayed bridge in Venice (Italy). Specifically, the authors developed fourteen FE models of the bridge distinguished by the lack and different arrangement of the stay cables, the increasing value of the deck curvature and the tower cross-section inertia. The analysis intends to quantify the impact of the design choices of cable-stayed bridges on the modal parameters.

Nanjing Jiangxinzhou Yangtze River Bridge[15] innovatively develops a steel shell–concrete composite structure tower, deploys coarse aggregate reactive powder concrete (CA-RPC), and applies it to the main girder of the bridge to form a lightweight and high-performance steel–concrete composite beam. Numerous innovative technologies have been achieved with new materials, new structures, new processes, and many other aspects. The unique structural concept has significantly increased the factory manufacturing speed of bridge components, which not only reduces the work and labour cost at the bridge site above the bearing platform to less than 25% but also effectively reduces the amount and loss of engineering materials during bridge construction, all of which have made outstanding contributions to the development of cable-stayed bridges.

3 Conclusion and prospect

This paper summarizes the current research status of steel-concrete joint section, and introduces the common forms of steel-concrete joint section, including : non-cell pressure-bearing plate, cell pressure-bearing plate, pressure-bearing steel-concrete joint section, shear-type steel-concrete joint section, pressure-bearing shear-combined steel-concrete joint section, and introduces their respective characteristics. Through theoretical calculation, finite element analysis, model test and other methods, scholars have carried out in-depth discussions on the mechanical performance, failure mechanism and optimization measures of the steel-concrete composite section. Summarizing the research of scholars, it is found that the force transmission mechanism of steel-concrete composite section is different due to different structural forms. In the process of excessive bearing capacity, shear keys, shear studs and other components play an important role.

With the continuous progress of bridge engineering technology and the wide application of cable-stayed bridge structure, the research of steel-concrete composite section, as a key component of bridge structure, is also facing new challenges and opportunities. With the rapid development of computer technology and artificial intelligence technology, bridge engineering should also integrate intelligent technology to keep pace with the times. It is feasible to use the neural network model to optimize the key design parameters in the design optimization stage of the steel-concrete composite section. By making full use of the advantages of artificial intelligence technology, it can provide a strong guarantee for the safety and reliability of bridge engineering.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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