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Research review on steel–concrete composite joint of railway hybrid girder cable-stayed bridges

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Abstract

Purpose – This study aims to research the development trend, research status, research results and existing problems of the steel–concrete composite joint of railway long-span hybrid girder cable-stayed bridge.

Design/methodology/approach – Based on the investigation and analysis of the development history, structure form, structural parameters, stress characteristics, shear connector stress state, force transmission mechanism, and fatigue performance, aiming at the steel–concrete composite joint of railway long-span hybrid girder cable-stayed bridge, the development trend, research status, research results and existing problems are expounded.

Findings – The shear-compression composite joint has become the main form in practice, featuring shortened length and simplified structure. The length of composite joints between 1.5 and 3.0 m has no significant effect on the stress and force transmission laws of the main girder. The reasonable thickness of the bearing plate is 40–70 mm. The calculation theory and simplified calculation formula of the overall bearing capacity, the nonuniformity and distribution laws of the shear connector, the force transferring ratio of steel and concrete components, the fatigue failure mechanism and structural parameters effects are the focus of the research study.

Originality/value – This study puts forward some suggestions and prospects for the structural design and theoretical research of the steel–concrete composite joint of railway long-span hybrid girder cable-stayed bridge.

Keywords Railway, Hybrid girder cable-stayed bridge, Steel-concrete composite joint, Structure, Stress characteristics, Review

Paper type Research paper

Hybrid girder cable-stayed bridge refers to the cable-stayed bridge with the mid-span mostly or completely adopting steel girders and two sides partially or completely adopting concrete girders, which makes reasonable use of the advantages of the two types of materials. Since the 1970s, the hybrid girder cable-stayed bridge has become one of the most competitive long-span highway bridges with good spanning capacity, the balance of stress in middle and side spans, and good economic performance. At present, hybrid girder cable-stayed bridge is widely applied in the construction of long-span highway bridges. However, the application of hybrid girder cable-stayed bridge on railway bridges started relatively late because a railway bridge has heavier loads and higher rigidity requirements, but it keeps developing at present.

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The steel–concrete composite joint is the connecting part between steel section and concrete section on the main girder and it receives much attention in terms of structure, mechanical property and durability. Highway hybrid girder cable-stayed bridges have been used early, so there are abundant research data on the stress, force transmission and deformation characteristics of the steel–concrete composite joint. Chen, Wang, and An (2006) verified the structural rationality of the steel–concrete composite joint of Taoyaomen Major Highway Bridge through model tests and analyzed the stress distribution and force transmission law of composite joints. Zhang, Li, Xiao, and Bao (2014) simulated the stress and stud slip behavior of composite joints in detail based on a nonlinear numerical analysis to provide a reference for the reasonable design of the composite joint. Huang, Huang, You, Yang, and Yang (2020) studied the stress characteristics and bearing capacity of shear connectors in composite joints based on the push-out test and put forward the "rubber–shear stud" combined connector and the formula of its bearing capacity. Relevant research results have provided references for the structure of steel–concrete composite joints of railway bridges. Aiming at the structure and performance under stress of the steel–concrete composite joint in the main girder of long-span railway cable-stayed bridge, Zhou, Pu, Shi, and Liu (2015) and Shi, Yang, Pu, and Zhang (2019) discussed in detail the reasonable structure and fatigue damage of the steel–concrete composite joint of railway cable-stayed bridge through model tests and finite element simulation analysis based on Yongjiang Super Major Bridge as the engineering background. Yang *et al.* (2020) explored the stress and deformation laws of the steel–concrete composite section of Tanjiang Super Major Bridge of Shenzhen–Maoming Railway and verified that the composite joint has sufficient rigidity and bearing capacity to meet the operation requirements of high speed trains. Shi, Gu, Gao, Yang, and Ning (2021a) analyzed in detail the influence of the length parameters of the steel–concrete composite joint of the railway cable-stayed bridge on the structural stress to provide a reference for the structure optimization of the composite joint.

Scholars from different countries have made abundant achievements in research studies related to reasonable structural construction, stress and force transmission and shear connector stress of steel–concrete composite joint in hybrid girder. However, with the increasing span of railway hybrid girder cable-stayed bridges and usage in high speed railway bridges, the steel–concrete composite joint still need further research on aspects of structural design and optimization, stress and force transmission characteristics, fatigue stress and parameter influence rules.

Aiming at the steel–concrete composite joint of railway long-span hybrid girder cable-stayed bridge, the development trend, research status, theoretical research findings as well as the existing problems of joints are expounded from the aspects of the development history, structure form, structural stress characteristics, shear connector stress state, force transmission mechanism, fatigue performance and structural parameter influence rules. This paper puts forward relevant suggestions and expectations for subsequent structural design and theoretical research of the steel–concrete composite joint of the long-span hybrid girder cable-stayed bridge.

1. Development history of railway hybrid girder cable-stayed bridge

In 1963, the conceptual scheme of hybrid girder cable-stayed bridge was first put forward in Germany. It is a bold innovation to the structural system of traditional cable-stayed bridge. In 1972, the world's first highway hybrid girder cable-stayed bridge (Kurt Schumacher Bridge) was completed. Later, in less than half a century, the span of highway hybrid girder cable-stayed bridge developed from 287 m to kilometer-class (The main span of Russki Island Bridge reaches 1,104 m). However, for a long time, due to heavy live load and high rigidity requirements, hybrid girder cable-stayed bridges are rarely applied on railway bridges both in China and in other countries. Few railway hybrid girder cable-stayed bridges have been reported in other countries. In China, Yongjiang Super Major Bridge of Ningbo Railway Hub represents the first application of hybrid girder cable-stayed bridge on long-span railway bridges. It changes the pattern where long-span railway cable-stayed bridges only employ steel truss girders. Later, for Tanjiang Super Major Bridge of Shenzhen–Maoming Railway, the hybrid girder cable-stayed bridge was first applied to 200 km/h high speed railway. Bianyuzhou Yangtze River Bridge of Anqing–Jiujiang Railway is the hybrid girder cable-stayed bridge of four-track high speed railway with a main span of 672 m. In this case, the hybrid girder cable-stayed bridge has been successfully applied to the Yangtze River Bridge of four-track heavy-haul high speed railway. The Baihe Yujiang Super Major Bridge of Nanning–Yulin Intercity Railway under construction is the case where the hybrid girder cable-stayed bridge is applied to 350 km/h high speed railway with ballastless track. Through literature investigation, systematic analysis statistics were made for domestic and foreign railway hybrid girder cable-stayed bridges. Some representative railway hybrid girder cable-stayed bridges are listed in Table 1. Throughout the development history of railway hybrid girder cable-stayed bridge, it was first applied in ordinary railway bridges, and then applied from high-speed railways with ballasted tracks to those with ballastless tracks. Along the way of development, the span of the main girder is also increasing.

2. Location and structure of steel–concrete composite joint

The structural form, location and transition section information of the steel–concrete composite joint of some domestic railway hybrid girder cable-stayed bridges are listed in Table 2.

Name	Country	Year of completion	Main span/m	Speed/ (km/h)	Type of track
Dnieper river bridge in Kiev	Ukraine	1993	271	160	Ballasted
Hong Kong Jishuimen super major bridge	China	1997	430	160	Ballasted
Suiyan road cable-stayed bridge of Guiyang–Guangzhou high-speed railway	China	2012	175	200	Ballasted
Yongjiang super major bridge of Ningbo railway hub	China	2014	468	120	Ballasted
Tanjiang super major bridge of Shenzhen–Maoming railway	China	2017	256	200	Ballasted
Yuekou Hanjiang super major bridge of Qianjiang railway	China	2018	260	100	Ballasted
Ganjiang super major bridge of Nanchang–Ganzhou high-speed railway	China	2018	300	350	Ballasted
Longxue South super major bridge of Nansha port railway	China	2020	448	120	Ballasted
Wulongjiang super major bridge of Fuzhou–Xiamen high-speed railway	China	2021	432	200	Ballasted
Bianyuzhou Yangtze river bridge of Anqing–Jiujiang railway	China	2021	672	300	Ballasted
Jialingjiang super major bridge of Hanzhong–Bazhong–Nanchong high-speed railway	China	Under construction	335	250	Ballasted
Baihe Yujiang super major bridge of Nanning–Yulin intercity railway	China	Under construction	330	350	Ballastless

Table 1.
Some representative railway hybrid girder cable-stayed bridges

Table 2.
Structural form, location and transition section information of steel-concrete composite joint of some railway hybrid girder cable-stayed bridges in China

Name	Year of completion	Main span/m	Ratio of side span to midspan	Location of composite joint	Form of composite joint	Steel transition section/m	Composite joint/m	PC transition section/m	Total length/m
Suiyan road cable-stayed bridge of Guiyang–Guangzhou high-speed railway	2012	175	0.19	Pylon-beam anchorage area	Front and rear bearing plates with cells	2.00	4.00	1.20	7.20
Yongjiang super major bridge of Ningbo railway hub	2014	468	0.47	Extension into midspan by 24.5 m	Front and rear bearing plates with steel cells	5.00	7.35	1.70	14.05
Tanjiang super major bridge of Shenzhen–Maoming railway	2017	256	0.25 and 0.86	Location of auxiliary pier of side span	Front and rear bearing plates with cells	1.50	7.00	4.00	12.50
Yuekou Hanjiang super major bridge of Qianjiang railway	2018	260	0.15 and 0.68	Extension into midspan by 27 m	Front and rear bearing plates with cells	4.00	7.35	1.70	13.05
Ganjiang super major bridge of Nanchang–Ganzhou high-speed railway	2018	300	0.45	Extension into midspan by 20 m	Embedded rear bearing plate	5.00	5.00	3.50	13.50
Longxue South super major bridge of Nansha port railway	2020	448	0.42	Extension into secondary side span by 9.2 m	Front and rear bearing plates with cells	6.30	3.20	1.80	11.30
Wulongjiang super major bridge of Fuzhou–Xiamen high-speed railway	2021	432	0.26 and 0.42	Extension into midspan by 22 m	Front and rear bearing plates with cells	4.40	4.70	2.90	12.00
Bianyuzhou Yangtze river bridge of Anqing–Jiujiang railway	2021	672	0.48	Near the auxiliary pier of side span	Embedded rear bearing plate	6.00	2.00	6.00	14.00
Jialingjiang super major bridge of Hanzhong–Bazhong–Nanchong high-speed railway	Under construction	335	0.47 and 0.32	Extension into midspan by 20 m	Front and rear bearing plates with steel cells	5.00	7.35	2.00	14.35
Baihe Yujiang super major bridge of Nanning–Yulin intercity railway	Under construction	330	0.42		Front and rear bearing plates with steel cells	5.00	6.00	2.00	13.00

2.1 Location of steel–concrete composite joint

The anchoring and weighing effects on the midspan are mainly considered for using concrete materials on the side span of the hybrid girder cable-stayed bridge. And the location of the steel–concrete composite joint interacts with the ratio of side span to midspan of the hybrid girder cable-stayed bridge. Professor Xu (2002) analyzed the reasonable span of Sutong Major Bridge based on the assumption that the hybrid girder cable-stayed bridge is under ideal dead load, and pointed out that the ratio of steel girder weight to concrete girder weight and the ratio of steel girder length to concrete girder length in the side span determine the reasonable ratio of side span to midspan of the hybrid girder cable-stayed bridge, and believed that the minimum reasonable ratio of side span to midspan shall be 0.24 for no negative reaction in the side span. Such ratio can be used to determine the preliminary location of the steel–concrete composite joint. As listed in Table 2, the ratio of side span to midspan of railway hybrid girder cable-stayed bridges is mainly from 0.24 to 0.35, and the relatively short side span can be more economical. The location of the steel–concrete composite joint is mainly arranged in three areas: pylon-beam anchorage area, midspan near the main pier and near the auxiliary pier of side span.

When the composite joint is arranged in the midspan, the obvious weighing effect of concrete and the significant improvement of overall rigidity are conducive to enhancing the wind resistance of the bridge and improving stable train operation. When the composite joint is arranged near the auxiliary pier of the side span, its internal force and deformation are relatively small, and its structure can be appropriately simplified. With the improvement of the stress performance of the steel–concrete composite joint, its location can be arranged more flexibly. However, in engineering practice, many factors such as the environment of bridge site, construction condition and cost still need to be considered. Generally, the following requirements shall be met:

1. Relatively balanced stress on the bridge.
2. Relatively small internal force and deformation of the composite joint.
3. Convenient site conditions for main girder steel and concrete construction.

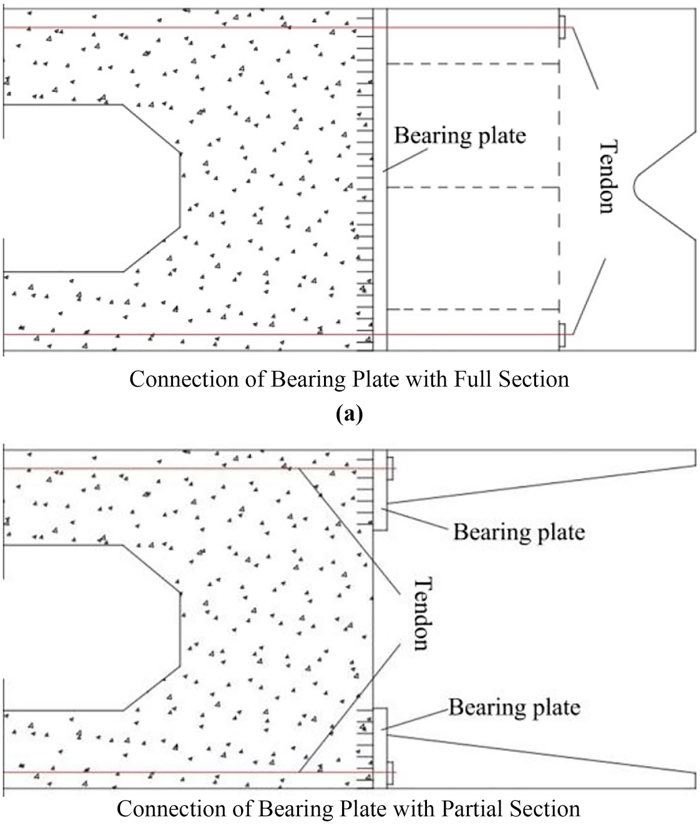
2.2 Structure of steel–concrete composite joint

The steel–concrete composite joint of the hybrid girder mainly works to smoothly and evenly transmit the huge internal force of the main-span steel girder to the concrete girder. It is generally composed of bearing plates, shear connectors, tendons and other major structural members. Generally, reinforcement members such as stiffeners and steel cells are also provided to strengthen the steel–concrete interface. Research studies on steel–concrete composite joints of highway hybrid girder cable-stayed bridges have revealed continuous development of structural form. The force transmission transformed from initial force transmission by direct contact between the bearing plate and concrete to joint force transmission by the steel roof plate, floor plate and shear connector, which can lower the ratio of force transmitted by the bearing plates while adding more force transmission paths. The steel roof and floor plates inserted into the concrete side are configured with diaphragms to form cells, which further increase the rigidity of the composite joint and reduce the risk of detachment of the steel–concrete interface in long-term operation. An increasing number of steel–concrete composite joints adopt cell structure (Morgenthal, Sham, & West, 2010; Tuo & Zhao, 2017; Zhang & Wu, 2013; Liu, 2005; Xu, Zhang, & Liu, 2013). In addition, the diaphragms forming the cells are usually perforated and threaded with steel bars to form perfobond leiste (PBL) shear connectors to further strengthen the steel–concrete bonding.

Compared with the highway steel–concrete composite joint, due to higher density of the load from railway trains (compared with highway bridges with the same span, the density of the load of railway double-track trains is equivalent to more than four times that of six-lane highway vehicles), higher requirements are imposed on the stress, force transmission, deformation and fatigue properties of components of the steel–concrete composite joint. In addition, for railway operation and maintenance, stricter requirements are made for the durability of the steel–concrete composite joint. Therefore, the railway steel–concrete composite joint is usually longer for the purpose of more reliably and evenly transmitting greater internal force of the main girder and meeting the requirements of track smoothness for railway operation. The statistics listed in Table 2 also show that except for a few bridges in the early stage, all the steel–concrete composite joints of railway bridges adopted the structure of inserting the steel girder into concrete to strengthen the steel–concrete force transmission.

According to different force transmission mechanisms, the steel–concrete composite joint can be divided into the pressure-bearing type and pressure-bearing shear transfer type.

For the pressure-bearing composite joint, the axial force and bending moment are transmitted by direct contact between the bearing plate and concrete, and the vertical shear force is only transmitted by the shear stud on the bearing plate and the bond force of the steel–concrete interface. According to the contact between the bearing plate and concrete, the pressure-bearing composite joint is divided into the connection of bearing plate with the full section and that with the partial section, as shown in Figure 1. The pressure-bearing



Connection of Bearing Plate with Full Section
(a)

Connection of Bearing Plate with Partial Section
(b)

Figure 1.
Structure of pressure-bearing steel-concrete composite joint

composite joint has a simple structure and meets the basic strength and rigidity transition requirements of actual engineering. It is mostly applied to the early highway steel–concrete composite joint. However, due to weak connection of its steel–concrete interface, it is vulnerable to cracking and detachment of the steel–concrete interface in operation, thus causing durability problems. At present, the use of a single type of pressure-bearing steel-concrete composite joint is rare in engineering practice.

The pressure-bearing shear transfer steel–concrete composite joint is also known as the shear-compression steel–concrete composite joint, where the bearing plate, steel top and bottom plates and shear connector are used to transmit the internal force of the main girder. The insertion of the steel roof and floor plates into the concrete section significantly strengthens the integrity and vertical shear transfer capacity of the composite joint. The shear-compression composite joint is usually also provided with cells to form a multi-directional constraint to the concrete inside, further strengthen the steel–concrete connection and improve steel–concrete force transmission. The 7.35 m long steel–concrete composite joint of Yongjiang Super Major Bridge of Ningbo Railway Hub is of a typical shear-compression structure with cells. Long rigid transition sections are provided on both sides, and tendons are anchored on the front and rear bearing plates in a distributed manner. The 2 m long steel–concrete composite joint of Bianyuzhou Yangtze River Bridge of Anqing–Jiujiang Railway is of a shear-compression structure without cells. A 6 m rigidity transition section is provided on each side. Shear studs and conical PBL shear connectors on the concrete side of steel roof and floor plates are inserted into concrete to strengthen connection, and many tendons are used to strengthen the joint surface connection. The structure of the shear-compression steel–concrete composite joint is shown in Figure 2.

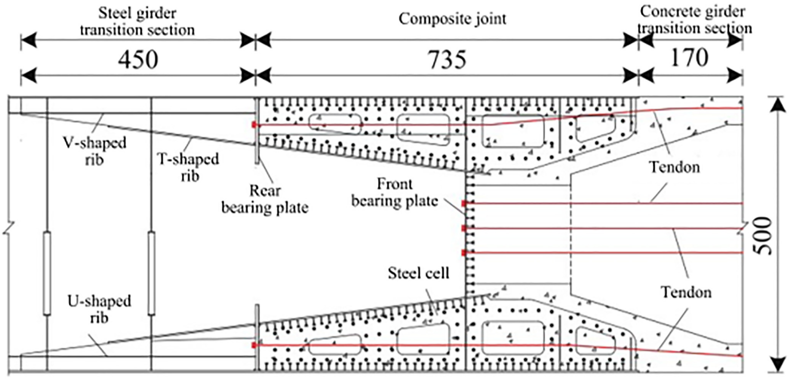
Analyzing from the perspective of stress and force transmission, the shear-compression composite joint has a stronger steel–concrete connection and more force transmission paths (Zhou, Ding, & Zhang, 2019) compared with the traditional pressure-bearing composite joint, and is more suitable for force transmission requirements of long-span railway bridges. For the application of hybrid girder cable-stayed bridges in railway bridges with a heavier load, especially high-speed railway bridges, on the premise of meeting structural safety and durability, many factors such as construction convenience and economy shall still be considered for the steel–concrete composite joint. It can be further optimized on the basis of the existing shear-compression composite joint, specifically as follows (Liu, Pei, Zhang, Ding, & Fang, 2019; Zhang, 2012; Zhang, Liu, Ju, & Liu, 2016):

(1) The length of the steel–concrete composite joint and the structural form of the steel–concrete connection are optimized according to girder height and width to realize balanced transmission of the axial force, shear force and bending moment of the main girder section;

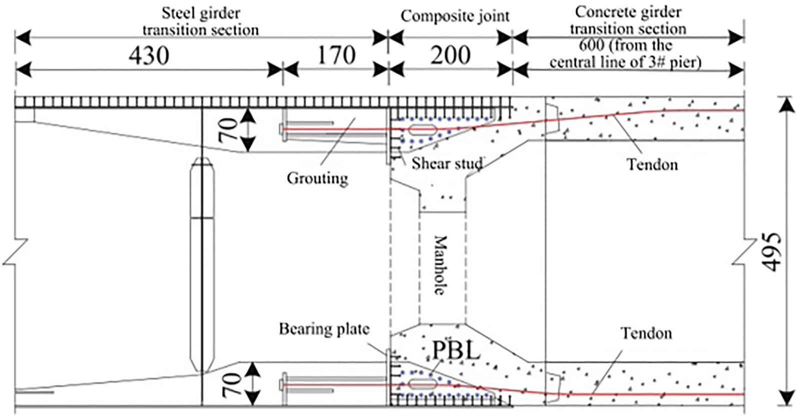
(2) The configuration and anchorage position of prestressed tendons are optimized to ensure that the steel and concrete are still effectively connected in the composite joint under the most unfavorable load and concrete is under a stressed state.

(3) The overall rigidity of the composite joint is optimized to reserve a certain safety factor for internal force transmission and nonuniform force transmission of the main girder and keep complex structures with excessive local rigidity from causing inconvenience in construction.

(4) The steel and concrete girder transition sections are optimized to ensure smooth force transmission of the composite joint, avoid the concentration of local stress and realize smooth rigidity transition.



Cells Adopted (Yongjiang Super Major Bridge)
(a)



No Cells Adopted (Bianyuzhou Yangtze River Bridge)
(b)

Figure 2.
Structure of shear-compression steel-concrete composite joint (unit: cm)

2.3 Main parameters of steel–concrete composite joint

2.3.1 Length of composite joint. The length of the steel–concrete composite joint is of great significance to the smooth transmission of the internal force of the main girder. Generally speaking, longer composite joint brings more uniform rigidity transition, smoother force transmission, and higher safety reserve shorter composite joint brings shorter force transmission path and more concentrated force transmission, but higher requirements are imposed on the quality of structures such as steel structural members and tendons in the composite joint and the construction of concrete pouring (Shi *et al.*, 2021a). It can be seen from the lengths of the steel–concrete composite joints of existing railway hybrid girder cable-stayed bridges in Table 2 that the length of the steel–concrete composite joint of the railway hybrid girder cable-stayed bridge is about 4.0 m, and the overall length, including the transition sections on both sides, is generally more than 12.0 m, which is longer than the length of the steel–concrete composite joint of highway bridge (about 2.0 m) and the total length including the transition sections (generally shorter than 8.0 m). With the gradual maturity of hybrid girder technology, the length of the steel–concrete composite joint of the railway tends to decrease. For example, short composite joint with a length of 2.0 m is first applied to Bianyuzhou Yangtze River Bridge. In view of the influence of the length of the composite joint on its performance under stress, Li (2018) conducted a finite element simulation analysis on 1.25–2.25 m composite joint and pointed out that 1.5 m is the critical length of the composite joint. When it is less than 1.5 m, the bearing plate and shear connector in the composite joint suffer large stress locally, which is unfavorable to structural stress. Literature (Shi, Jiang, Gao, Ning, & Yu, 2021b) research shows that under the most unfavorable positive and negative bending moment loads, the change in the length of the composite joint only affects the stress in the composite joint area and the rigidity transition section within 1.0 m, and the longitudinal and transverse stress distribution laws have no great correlation with the length of the composite joint.

It can be seen that when the steel–concrete connection length of the composite joint is more than 3.0 m, length increase has no significant impact on the stress of the main girder, but the excessively long steel–concrete composite joint easily causes inconvenience in construction. Considering that the actual bridge structure is not under a single stress, the length of the composite joint shall be optimized between 1.5 and 3.0 m according to the actual stress characteristics of different bridge structures.

2.3.2 Thickness of bearing plate. The bearing plate, the main structural member for internal force transmission of the steel–concrete composite joint, bears and transmits about 30%–50% of the internal force of the main girder. Its thickness determines its rigidity, which directly affects the internal force distribution of the main girder, and then affects the overall stress and smooth force transmission of the structure. Tang, Wu, Liu, and Xu (2010) found that the bearing plate mainly bears the longitudinal shear force of the main girder, and there is concrete support near the weld with the roof and floor plates. He (2017) gave the calculation formula of the minimum thickness $t_{\mathrm{b,min}}$ of the bearing plate based on the assumption of rigid bearing plate:

$$t_{\mathrm{b,min}} \geq \frac{F_{\mathrm{h}}}{L_{\mathrm{h}}[\tau_{\mathrm{s}}]} \tag{1}$$

where: L_{h} is the length between the edge of the bearing plate and the weld; $[\tau_{\mathrm{s}}]$ is the design allowable shear stress; F_{h} is the axial force borne by concrete in the composite joint.

F_{h} can be calculated with reference to the *Specifications for Design and Construction of Highway Steel-Concrete Composite Bridge*. For railway bridges, the thickness of the bearing plate needs further study.

In order to study the influence of changes in the thickness of the bearing plate on the stress of the composite joint, Kim and Nguyen (2010) analyzed the stress change of the steel–concrete composite joint when the thickness of the bearing plate changes from 50 mm to 70 mm. The results show that the ultimate bearing capacity of the composite joint is proportional to the thickness of the bearing plate, but when the thickness of the bearing plate exceeds 75 mm, the ultimate bearing capacity of the composite joint no longer increases; Hu, Wan, and Lu (2014) pointed out through research that the internal force borne by 40–80 mm thick bearing plate varies obviously as the plate thickness changes; He (2017) made parameter discussions for the thickness of the bearing plate of the steel–concrete composite joint made of high-performance concrete, but obtained similar pattern with that of ordinary steel–concrete composite joint. However, the application of high-performance concrete greatly reduces the thickness of the bearing plate, and the emergence of novel materials is continuously providing ideas for the optimal design of traditional structures.

To sum up, within a certain range, thickness increase of the bearing plate can effectively improve its rigidity and enable the bearing plate to bear and transmit more internal force, but excessive increase in the thickness of the plate will cause obvious stress concentration and large difference in rigidity, which will hamper the smooth force transmission of the composite joint. On the premise of ensuring good force transmission performance of the steel–concrete composite joint, the bearing plate should be 40–70 mm in thickness, but should not be too thick. It is optional to add stiffeners connected with steel roof and floor plates on both sides of the bearing plate to improve the rigidity and increase force transmission. Stiffeners (also used as PBL perforated plate) can be added on the concrete side to strengthen the steel–concrete connection.

2.3.3 Parameters of shear connector. The shear connector is a key structural member for coordinated operation of steel and concrete and also one of the main structural members for internal force transmission of the main girder. Its structural form has a significant impact on the mechanical performance of the composite joint. In order to study the influence of structural parameters of shear studs on the mechanical performance of the composite joint, Hu *et al.* (2014), Lin and Liu (2015) and Pu, Zhou, and Shi (2016) discussed the diameter of and spacing between shear studs and the failure of shear studs. The results show that the shear strength and rigidity of shear studs with a relative diameter of 22 mm can be increased by about 42% and 35% respectively when the diameter is increased by 8 mm; when the spacing between shear studs is 150 mm, the internal force of the composite joint is reasonably distributed among force transmission members; but when the spacing between shear studs is further increased, the number of shear studs arranged and the proportion of force transmission gradually decrease. Once yielding failure occurs on shear studs near the loading end, they are prone to “domino effect” damage.

Unlike shear studs, PBL shear connectors realize the steel–concrete connection and force transmission through interaction between steel plates, transverse steel bars and concrete tendons in the holes. The hole diameter, spacing between holes, the number of holes and the configuration of transverse steel bar of PBL plates will not only affect the bearing capacity of PBL shear connector itself (Hu, Ye, & Huang, 2006), but also affect the overall mechanical performance of the composite joint. In view of the influence of structural parameters of PBL shear connector on the stress of the composite joint, Zhang *et al.* (2016) discussed the structure, diameter and position of hole and welding shape of the perforated plate. The analysis shows that thicker and longer perforated plate with larger hole diameter makes the PBL shear connector stronger in the bearing and force transmission capacities, but it also brings obvious stress concentration. Larger distance between the position of the hole and the end contributes to a greater stress value. The research studies on the existing bridges show that the reasonable structure of PBL shear connector is as follows: the perforated plate shall be 12–30 mm thick, the ratio of the hole diameter to the plate thickness shall not be greater than 0.4, the spacing between holes shall not be less than two times the diameter of the hole and the PBL steel bar shall be 12–25 mm. Parameter values shall be coordinated with each other. In addition, in order to reduce the stress concentration in the composite joint and improve its bearing capacity and performance, the optimal layout scheme of “strengthening both ends, simplifying the middle, and refining the corners”, the combined use of shear studs and PBL shear connectors, and trapezoidal, U-shaped and other new PBL shear connectors with perforated plates are worth further study.

3. Mechanical performance of steel–concrete composite joint

3.1 Performance under stress of steel–concrete composite joint

In order to explore the mechanical characteristics of steel and concrete members in the composite joint and verify the rationality of the structural form of the existing steel–concrete composite joint, many scholars simulated the stress state of the composite joint in construction and operation based on model tests and finite element analysis to further explore its stress distribution pattern and bearing capacity under the most unfavorable combined load conditions, overload conditions and failure conditions.

The research results of steel–concrete composite joints of highway bridges (Li, Xiao, Huang, & Wei, 2013; Zhang, Huang, & Xu, 2010) show that under the most unfavorable combined overload conditions, the composite joint in elastic stress stage can realize overall compression without yield trend on the steel plate and the steel–concrete interface is free from cracks and voids and well bonded, which meets the basic requirements of composite joint design; but transverse stress of steel and concrete members in the composite joint has an obvious shear lag effect. Therefore, structural measures such as reasonable addition of transverse diaphragms, beams and transverse stiffeners of roof plates shall be taken to deal with the adverse impact of the shear lag effect. Zhang *et al.* (2014) and Liu *et al.* (2019) conducted a refined simulation on the mechanical characteristics of the steel–concrete composite joint by using the finite element software and believed that pure steel cells can effectively reduce stress concentration on the bearing plate. They also believed that the rigidity of concrete girder should be 2.0–3.0 times that of the standard steel girder to prevent concrete from cracking in the operation stage. Relevant research studies have provided references for steel–concrete composite joints to be used on railway bridges.

In 2014, the completion of Yongjiang Super Major Bridge of Ningbo Railway Hub denoted the first application of hybrid girder cable-stayed bridge and steel–concrete composite joint in railways. Theoretical and experimental studies on mechanical properties, key structural parameters, fatigue performance and key connection structure of long-span railway hybrid girder steel–concrete composite joint were carried out based on the bridge, and a series of research results were obtained (Pu *et al.*, 2016; Yao, Yang, Liu, Shi, & Pu, 2015): under up to 2.0 times of the most unfavorable load of the full-section model of the composite joint, the load-strain curve of each measuring point is basically linear, there is no obvious slippage on the steel–concrete interface and the structure is in the elastic working stage; during the failure test of the model, the concrete of the transition section fails in tension before the composite joint. As there are many supporting plates and stiffeners in the composite joint of Yongjiang Super Major Bridge of Ningbo Railway Hub, the stress is uniformly distributed at transverse measuring points of the model, and there is no obvious shear lag effect. After that, Yang *et al.* (2020) verified the structural rationality of Tanjiang Super Major Bridge of Shenzhen–Maoming Railway through scale model tests and pointed out the nonuniformity of stress on the shear connectors. The test results of the model of Bianyuzhou Yangtze River Bridge of Anqing–Jiujiang Railway with 2.0 m short composite joint show that under 1.6 times of the most unfavorable load, the composite joint is still elastically stressed, only the concrete transition section shows microcracks and force transmission is stable and efficient. The research data of steel–concrete composite joints shows that their force transmission is significantly different and their structural optimization and theoretical research on force still need further development.

The existing research results show that the stress distribution and force transmission characteristics of structural members in the composite joint are mostly explored based on model tests and finite element simulation analysis to verify the bearing capacity of the existing steel–concrete composite joint. The calculation of and theoretical research on the overall bearing capacity of the composite joint are still scarce. Due to its complex structure, it is difficult to simplify the entire composite joint into a single calculation model. Existing research studies are mostly the exploration of the simplified calculation and parameter discussion of main members in the composite joint. The literature (Ministry of Transport of the People's Republic of China, 2015) specifies the methods for estimating the minimum thickness of the bearing plate and the maximum shear force of the shear stud and PBL shear connector in the composite joint to provide a reference for detailed structural design of the composite joint. He (2017) explored the simplified calculation formula for force transmission of the bearing plate in the composite joint based on two assumptions, namely rigid bearing plate and bearing plate deformation. It can be used for the preliminary design of the steel-concrete composite joint of highway bridge, but whether it is suitable for the more complex steel–concrete composite joint of railway bridge needs further study.

For the calculation of the overall bearing capacity of the steel–concrete composite joint, the calculation of ultimate flexural bearing capacity of truss composite beam (Pan, Nie, & Yu, 2013) and the section bearing capacity of steel and concrete girders (Ministry of Construction of the People's Republic of China, 2002) can be referred to, assuming that the bearing capacity of the steel–concrete composite joint can be jointly borne by the steel structure, the concrete in the compression area and the prestress. In addition, considering the difference of steel and concrete in terms of rigidity and the nonuniform stress due to force transmission, the calculation results of each part shall also be multiplied by the nonuniformity coefficient of force transmission respectively for safety estimation. In addition, it is particularly urgent to consider force distribution characteristics among steel and concrete members based on the stress law of the steel–concrete composite joint, discuss the value law of the nonuniformity coefficient of each part and study more scientific theoretical calculating methods for the bearing capacity.

3.2 Performance under stress of shear connector of steel–concrete composite joint

The shear connector is mainly used to strengthen the steel–concrete connection and transmit the shear force of the main girder. The most common shear connectors are shear studs and PBL shear connectors. The former has been widely used since early stages because of its mature technology and high reliability. The latter is also widely used in engineering practice and has many advantages such as large shear rigidity, high bearing capacity, large pre-failure deformation and good fatigue resistance.

3.2.1 Performance under stress of shear stud. The mechanical performance of shear studs features a nondirectional characteristic, convenience in construction and good separation resistance. Their ultimate shear capacity is related to their tensile strength and sectional dimension. Generally, their performance under stress and the bearing capacity of a single shear stud are explored through push-out tests. The research results have been applied to the codes of various countries. However, the calculation formula of the bearing capacity fitted based on the push-out test is too conservative, and the excessive number of shear studs designed accordingly affects convenience in construction (Nie, Shen, Yuan, Lin, & Wang, 1996). Therefore, Zhang, Li, and Tang (2007) simulated the real stress state by using small test pieces other than push-out test, and based on the failure mechanism of shear connectors. Their study put forward a unified calculation formula of ultimate shear bearing capacity F_{u} with certain physical significance:

$$F_{\mathrm{u}} = \alpha_1\beta_1\mu_1F_{\mathrm{cu}} + \alpha_2\beta_2\mu_2F_{\mathrm{su}} \tag{2}$$

where: α_1 and α_2 are influence coefficients of concrete and transverse steel bar respectively; β_1 and β_2 are regression coefficients; μ_1 and $\mu 2$ are failure type coefficients of the concrete tendon and penetrating steel bar respectively; and F_{cu} and F_{su} are bearing capacities provided by concrete and steel members respectively.

For the calculation of the bearing capacity of shear studs, their failure mode is generally brittle failure of a single shear surface, in which $F_{\mathrm{cu}} = 0, F_{\mathrm{su}} = (\pi d_{\mathrm{s}}^2/4)f_{\mathrm{y}}$ (d_{s} is the diameter of shear studs, and f_{y} is the yield strength of shear stud steel).

However, in the actual steel–concrete composite joint, shear studs are provided in groups and greatly nonuniform in stress (Zhou, Pu, Shi, & Liu, 2017). That is, the stresses of the shear stud nearest the loading end are largest, the stresses of studs decrease with the increasing distance from the loading end, and then tend to be stable. In order to improve the force of shear stud groups, many scholars proposed the idea of combined connectors. Huang *et al.* (2020) based on push-out tests, identified that in the case of failure of the "rubber-shear stud" combined connector, it shows longer bending length and greater ductility compared with ordinary shear studs; verified the assumption that the combined connector can help improve the bearing capacity and nonuniform stress; comprehensively considered the material characteristics of the shear stud and concrete and the structural characteristics of the combined connector in combination with the calculation formula of the ultimate bearing capacity of a single ordinary shear stud; and derived the calculation formula of the ultimate bearing capacity $F_{\mathrm{u,r}}$ of a single shear stud in the combined shear connector, as follows:

$$F_{\mathrm{u,r}} = \varphi(\mu) A_{\mathrm{s}} f_{\mathrm{u}} \left(\frac{E_{\mathrm{c}}}{E_{\mathrm{s}}}\right)^{0.4} \left(\frac{f_{\mathrm{c}}}{f_{\mathrm{u}}}\right)^{0.35} \tag{3}$$

where: A_{s} is the sectional area of shear stud; E_{c} and E_{s} are the elastic modulus of concrete and shear stud respectively; f_{c} and f_{u} are the compressive strength of concrete cube and the ultimate tensile strength of shear stud respectively; $\varphi(\mu)$ is the correlation function, $\varphi(\mu) = 3.14 - 2.5\mu^2 + 2.3\mu$, which is obtained by nonlinear regression analysis; and μ is the ratio of rubber length to shear stud length.

In addition, in the nonlinear calculation analysis of the shear capacity of shear studs, the shear rigidity as a main parameter is mainly obtained based on the fitting of test data and is generally the secant modulus (Lin *et al.*, 2014) corresponding to a 0.2 mm slippage, which is of no clear physical significance. The value of nonuniform stress of shear stud groups and their longitudinal and transverse distribution laws still need further study. At the same time, the shear studs in the actual steel–concrete composite joint mostly bear the bend–shear force, but their shear capacity is also different from the bearing capacity obtained by direct shear of the push-out test. The difference also needs further study.

3.2.2 Performance under stress of PBL shear connector. The number of holes and the spacing between holes of the perforated plate, concrete strength and the distribution of transverse steel bars are the key factors affecting the bearing capacity of PBL shear connector. At present, three parts, including the pressure-bearing effect of concrete below the steel plate, the anti-sliding effect of transverse steel bars and the shear resistance effect of the concrete tendon in the hole, are mainly considered for the calculation of the bearing capacity of PBL shear connector. Based on this, Oguejiofor and Hosain (1997) derived the calculation formula of the bearing capacity of the PBL shear connector; on this basis, Medberry and Shahrooz (2002) derived the new calculation formula of the bearing capacity through linear regression considering the bonding effect of the steel–concrete interface; Al-darzi *et al.* (2007) and Verissimo, Paes, Valente, and Cruz (2006) made further improvement; however, test pieces differ greatly in the actual fabrication and loading processes and the fitted formula derived only through the push-out test is still of no significance for widespread use. Yang and Chen (2018) studied the contribution of the perforated plate, PBL steel bar, concrete tendon and other parts to the bearing capacity of the PBL shear connector under different working conditions, thus deriving a calculation formula with clear physical significance and high accuracy. A summary of calculation formulas of the bearing capacity of the PBL shear connector is listed in Table 3.

The influence of concrete strength on the bearing capacity is considered in all existing calculation formulas of the bearing capacity of the PBL shear connector, and these formulas show that the concrete with higher strength has a higher bearing capacity. Therefore, high-strength concrete can be poured to improve the bearing capacity of the PBL shear connector. In addition, in the existing research studies of calculation formulas of the bearing capacity of the PBL shear connector, the bearing capacity of a single row of PBL shear connectors is predicted mostly based on linear regression, which is difficult to reflect the actual bearing capacity and nonuniform stress of the connector group in engineering practice (When the

Table 3. Calculation formulas of bearing capacity of PBL shear connector

Responsible person	Calculation formula
Oguejiofor *et al.*	$F_{\mathrm{u,b}} = 4.50ht_{\mathrm{s}}f_{\mathrm{ck}} + 0.91A_{\mathrm{tr}}f'_{\mathrm{y}} + 3.31nD^2\sqrt{f_{\mathrm{ck}}}$
Medberry *et al.*	$F_{\mathrm{u,b}} = 0.747t_{\mathrm{c}}h\sqrt{f_{\mathrm{ck}}} + 0.413F_{\mathrm{N}} + 0.9A_{\mathrm{tr}}f'_{\mathrm{y}} + 1.66n\pi\left(\frac{D}{2}\right)^2\sqrt{f_{\mathrm{ck}}}$
Al-Darzi	$F_{\mathrm{u,b}} = 7.62\times10^{-4}ht_{\mathrm{s}}f_{\mathrm{ck}} - 7.59\times10^{-7}A_{\mathrm{tr}}f'_{\mathrm{y}} + 5.53\times10^{-3}A_{\mathrm{sc}}\sqrt{f_{\mathrm{ck}}} + 255.31$
Veríssimo	$F_{\mathrm{u,b}} = 4.04\frac{h}{t_{\mathrm{c}}}ht_{\mathrm{s}}f_{\mathrm{ck}} + 2.37nD^2\sqrt{f_{\mathrm{ck}}} + 0.16A_{\mathrm{cc}}\sqrt{f_{\mathrm{ck}}} + 31.85\times10^6\frac{A_{\mathrm{tr}}}{A_{\mathrm{cc}}}$
Yang Yong	$F_{\mathrm{u,b}} = 5.15A_{\mathrm{e}}f_{\mathrm{ck}} + 5.41n\lambda A_{\mathrm{sc}}f_{\mathrm{ck}}^{0.57} + 2.24n\lambda A_{\mathrm{tr}}f'_{\mathrm{y}}$

Note(s): $F_{\mathrm{u,b}}$ is the shear capacity of the PBL shear connector; h is the height of the perforated plate; t_{s} is the thickness of the perforated plate; t_{c} is the thickness of the concrete slab; n is the number of holes; D is the hole diameter; F_{N} is the steel–concrete bonding effect; λ is the hole influence coefficient; A_{tr} is the area of transverse steel bar; A_{sc} is the concrete tendon area; A_{cc} is the shear concrete area; A_{e} is the sectional area of the perforated plate; f'_{y} is the yield strength of PBL steel bar; f_{ck} is the standard value of concrete compressive strength

external load is small, the nonuniformity coefficient of PBL shear connectors reaches more than 5.0, but with the increase of the load, this coefficient decreases rapidly and is close to 1.4 (Zhang, Li, & Bu, 2011)). Related problems are still worth further exploration. At present, the co-arrangement of PBL shear connectors and shear studs is becoming more and more common, but there is no systematic research data on the joint stress characteristics of the two. The model test, theoretical research, and simulation analysis and calculation of the joint shear resistance of PBL shear connectors and shear studs need further study.

3.3 Force transmission mechanism of steel–concrete composite joint

The steel–concrete composite joint mainly works to ensure smooth internal force transmission from the steel girder to the concrete girder without local stress concentration, thus ensuring the durability of the overall structure of the bridge. According to the study of domestic and foreign research studies (Xiao, Ye, Wei, & Qiang, 2014; Zhang *et al.*, 2010) on the force transmission mechanism of the steel–concrete composite joint of hybrid girder cable-stayed bridge, it is concluded that the internal force of the main girder of the composite joint is mainly transmitted to the concrete girder by means of pressure bearing of the bearing plate, shear transfer by the shear connector and shear transfer by the bond force of the steel–concrete interface and there are four main force transmission paths, as shown in Figure 3. Direct pressure on the bearing plate is the prime force transmission path, through which about 30%–50% of the internal force is generally transmitted; shear studs and PBL shear

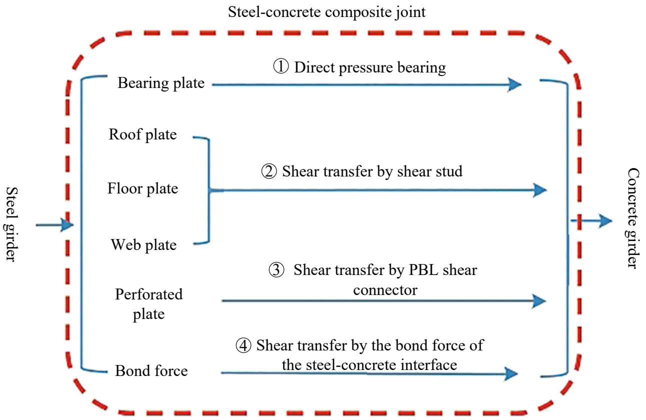


Figure 3. Force transmission path of steel-concrete composite joint

connectors, which are arranged in the steel roof and floor plates in the concrete girder, transmit part of the internal force to the concrete girder in the form of shear transfer; a small amount of internal force is transmitted through bonding of the steel–concrete interface, which is usually seen as a reserve for safety consideration. However, a compact steel–concrete connection is the key to affecting the mechanical performance of the composite joint. Therefore, it is necessary to ensure concrete construction and pouring quality in the composite joint. If necessary, shrinkage-compensating concrete or micro-expansive concrete can be used to strengthen steel–concrete bonding.

In order to further explore the force transmission characteristics of different members in the steel–concrete composite joint, the axial force borne by different members is obtained by integrating the longitudinal bridge stress of each member in each cross section, and then the force transmission ratio of different members in the same cross section is obtained. Figure 4 shows force transmission analysis results of steel members in the steel–concrete composite joint of Bianyuzhou Yangtze River Bridge of Anqing–Jiujiang Railway. It can be seen from Figure 4 that at the starting section of the steel girder transition section, the roof and floor plates, stiffeners, web plates and web ribs transmit about 49.1%, 20.7%, 17.0% and 6.5% of the internal force, respectively; the force transmission ratio of the steel members at the section of the bearing plate significantly decreases because the force is mostly transmitted through the bearing plate to the concrete, and in the steel–concrete composite joint the force transmission ratio further decreases; for different steel members, the change in force transmission in longitudinal direction of the bridge is also different, representing obvious nonuniformity of force transmission.

Through the analysis of force transmission characteristics of steel–concrete composite joint, it can be seen that the bearing plate and shear connector are major structural members for internal force transmission in the composite joint. The exploration of the internal force ratio borne by various structural members in the process of internal force transmission in the composite joint can provide a scientific basis for optimization design of the composite joint. Some scholars have respectively derived the bending moment and axial force borne by steel and concrete in the composite joint based on the assumption of rigid bearing plate and considering the deformation of bearing plate. However, the actual force transmission of the composite joint is a process coordinating the rigidity and deformation of the steel members, concrete and shear connectors under external load, which jointly determine the overall force transmission characteristics of the composite joint. Therefore, the actual force transmission

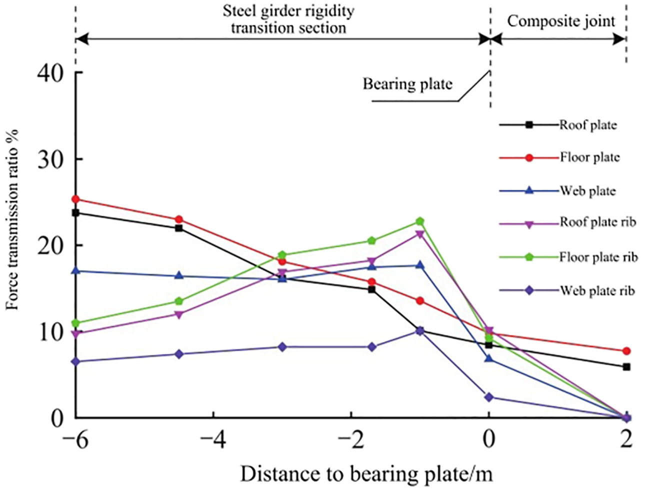


Figure 4.
Force transmission of steel members in composite joint of Bianyuzhou Yangtze river bridge of Anqing–Jiujiang railway

of the composite joint can be further explored through refined simulation analysis and model test to provide a basis for structural optimization of the composite joint.

3.4 Fatigue performance of steel–concrete composite joint

The fatigue of railway long-span steel–concrete composite joint under repeated external load is also worth attention, including the fatigue of steel members, shear connectors, concrete members and steel–concrete connection interface in the steel–concrete composite joint. Welded joints, residual stress after welding and initial defects are widespread in the steel structure of steel–concrete composite joint. In addition, steel members are usually provided with shear studs or PBL perforated plates, where obvious local stress concentration is prone to fatigue cracks. The fatigue detachment of the steel–concrete interface seriously reduces the overall performance under stress of the steel–concrete composite joint. Although concrete members do not have obvious fatigue problems, they are prone to cracks, thus affecting their durability. The large proportion and high density of train load makes railway bridges more vulnerable than highway bridges to fatigue problem. Moreover, the obvious vehicle–bridge coupling vibration effect caused by running trains (Luo and Liu, 2017) will cause fatigue ruptures on stiffeners and at prestressed anchorage positions in the steel-concrete composite joint. In addition, with the increase of bridge span, the bending moment under live load of the main girder is constantly increasing (For Tanjiang Super Major Bridge of Shenzhen–Maoming Railway with a main span of 256 m, Yongjiang Super Major Bridge of Ningbo Railway Hub with a main span of 468 m and Bianyuzhou Yangtze River Bridge of Anqing–Jiujiang Railway with a main span of 672 m, the bending moments under the live load of the train are 58 572, 79 101 and 144 128 kN · m (Shi *et al.*, 2021a; Yang *et al.*, 2020; Zhou, 2012), respectively. However, these three bridges have similar girder heights. This aggravates the fatigue stress of the steel–concrete composite joint of long-span railways.

At present, the fatigue of steel structures in the steel–concrete composite joint can refer to the fatigue analysis of conventional steel structures (Xiao, Yamada, Ya, & Zhao, 2008): (1) evaluation based on *S-N* curve, (2) fatigue cracking evaluation based on metal fracture mechanics and (3) fatigue evaluation based on model test and simulation analysis. In engineering practice, the fatigue damage degree of structure is often analyzed based on the *S-N* curve and Miner linear cumulative damage criterion, and the fatigue life is further evaluated. Zhou *et al.* (2015) and Shi *et al.* (2019) based on the research of the fatigue test on the full-scale model of the steel–concrete composite joint of Yongjiang Super Major Bridge of Ningbo Railway Hub, showed that after two million times of equivalent fatigue load, low overall stress level of the model had no great change with fatigue, which reflects that it has good performance under fatigue stress. They also derived that the minimum fatigue life is about 167.5a according to Miner criterion; after another one million times of fatigue load, it was found that the stress level at the root of shear studs at the steel roof plate and bearing plate was high and the fatigue crack at the weld began to develop, which indicates that areas near the steel roof plate and bearing plate in the composite joint are fatigue sensitive.

Since the steel–concrete composite joint is applied to railway bridges in China for more than 10 years, the engineering fatigue problem has not been verified in reality. However, with the continuous increase of bridge span, the characteristics of large bending moment under live load and the obvious dynamic effect of railway bridges have aggravated the trend of fatigue problems on steel–concrete composite joint. At present, there are few studies on the fatigue performance of railway steel–concrete composite joint. The fatigue performance of the steel structure in the steel–concrete composite joint and the rules of influence of surrounding concrete have not been clarified. The fatigue detachment failure of the steel–concrete interface and the fatigue of shear connectors have not been studied in depth. The fatigue cracking, propagation and failure law of concrete members also need further study.

4. Conclusion

With the development of railway long-span cable-stayed bridges, the research on the structure, stress characteristics, force transmission mechanism and fatigue characteristics of hybrid girder steel–concrete composite joint is also developing.

With the continuous increase of bridge span, the steel–concrete composite joint is mostly of shear-compression structure. The steel–concrete composite joint of railway bridge is relatively long and complex in structure due to large force transmission, but its development trend is to shorten the length, simplify the structure, further optimize the overall structure and make the layout more flexible. According to the structural parameters of the composite joint, the length of composite joints between 1.5 m and 3.0 m has no significant effect on the stress and force transmission laws of the main girder, which meets the uniform force transmission requirements of the composite joint. The bearing plate should be 40–70 mm thick. Adding stiffeners (PBL plate) on the concrete side of the bearing plate for higher rigidity and force transmission performance is a development tendency. The reasonable spacing of the shear studs is about 150 mm. Combined use of the shear studs and the PBL shear connectors as well as using the trapezoid and other new PBL shear connectors are the development tendency.

Model test and simulation analysis are the main methods for stress research and evaluation of steel–concrete composite joints at present. Based on the stress law of the composite joint and the force distribution characteristics among steel and concrete members, the research on calculation theory and simplified calculation formula of the overall bearing capacity of the steel–concrete composite joint considering nonuniform force transmission is one of the important directions for structural research, and the results can provide valuable reference for the design and checking calculation of the composite joint. The nonuniformity and distribution laws of stress in the longitudinal and transverse directions of the shear stud, the shear-resistant theory and calculation analysis method for the combined use of the shear studs and PBL shear connector, the force transferring ratio of steel and concrete components in the composite joint and other shear-resistant and force transferring theories of the steel-concrete composite joint, the influence of the fatigue failure mechanism, and detail characteristics and structural parameters of the steel–concrete composite joint on the fatigue properties of steel, steel–concrete interface, shear connectors and concrete are key subjects for future studies.

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