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Summary of the Calculation of the Shear Capacity of Perfobond Rib Shear Connectors

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

The analysis of longitudinal shear resistance based on shear capacity is the basis for assessing the reliability of steel-concrete joint structures. It is of great significance for the longitudinal shear of bridge structures and even for the establishment of a shear-resistant design code for steel-concrete bridge structures based on reliability theory. In this article, a more comprehensive overview of the test methods, the current state of research, and the remaining problems in the field of connectors for perfobond rib shear connectors (PBL) are presented. Firstly, the test methods for PBL connectors are categorized. The applicable characteristics of each test method and their advantages and disadvantages are summarized, and the research progress on the calculation of shear load-capacity in this structure is discussed in detail. Finally, it is concluded that the international research on the shear capacity of PBL connectors is still at a stage where the scope of their adaptation is small. Reasonable and accurate quantification of the sensitivity parameters of the PBL connectors was studied. The normality of the test form and other relevant factors should be taken into account to establish a set of more effective shear capacity calculation methods. This can be used to guide the shear capacity design of the structure more directly.

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1. INTRODUCTION

PBL connectors have a high load-bearing capacity and good fatigue resistance due to the structure, and compared with welded nail connectors, PBL connectors have the advantages of greater shear load-bearing capacity, better fatigue resistance, greater shear stiffness, and simpler welding. In the actual application of steel-concrete composite structures subjected to high shear forces, the performance of PBL connectors to withstand the longitudinal shear load-capacity is more excellent [1-2]. The application of PBL connectors in practical engineering has become more and more widespread, especially more often used in large-span bridge structures [2].

PBL connectors affect the shear performance of many factors, initially by the German Leonhardt in the 1980s, the size of the PBL connectors of the open hole aperture research, and put forward the first bearing capacity calculation formula [3]. Later, many international scholars, such as Oguejiofor and Hossain [4-7], Candido et al. [8], Xiao et al. [9], and others [10] investigated the factors affecting the shear bearing capacity of PBL connectors by conducting tests respectively. The study mainly includes the concrete strength, the diameter of the reinforcement, the plate thickness of the open steel plate, the spacing between the openings, the number of openings, the size of the holes, etc. On the basis of the test results, the load-bearing capacity equations of the PBL connectors are proposed.

At present, the international specification for the mechanical properties of PBL connectors test method is not uniform, scholars in various countries mainly use the roll-out test to study the shear performance of PBL connectors. Since the shear capacity of PBL connectors is closely related to the damage pattern, the damage pattern of PBL connectors in the steel-concrete combined structure and steel-concrete mixed section is different, and the calculation of its capacity should be combined with the connectors' structure.

2. PBL CONSTRUCTIVE FEATURES

The PBL connector is a new shear-resistant connector proposed by Leonhardt and Partners [3] in Germany to solve the potential fatigue problems associated with traditional weld-nail connectors. After more than three decades of development, PBL connectors have been widely used in actual bridge projects. After more than three decades of development, PBL connectors have been widely used in actual bridge projects. Unlike traditional welded nail connectors that resist shear on one side, PBL works along both sides of the open plate and has a relatively higher shear load-capacity. For steel-concrete composite structural girder bridges, the open steel plates of the PBL connectors are welded to the steel girder flanges by longitudinal fillet welds, which also have less impact on the steel girders due to the smaller size of the welding foot of the fillet welds as compared to the weld nails of the section fusion welds as shown in Fig. 1(a). For steel-concrete hybrid girder bridges, its combined section is generally constructed with lattice chambers, in which vertical partitions are perforated and penetrated with reinforcing bars to form PBL connectors with the infilled concrete for load transfer.

(a) Steel-concrete combination beams-PBL

(b) Steel-concrete bonding section-PBL

Fig. 1. Structure and layout of PBL

3. PBL LAUNCH TEST

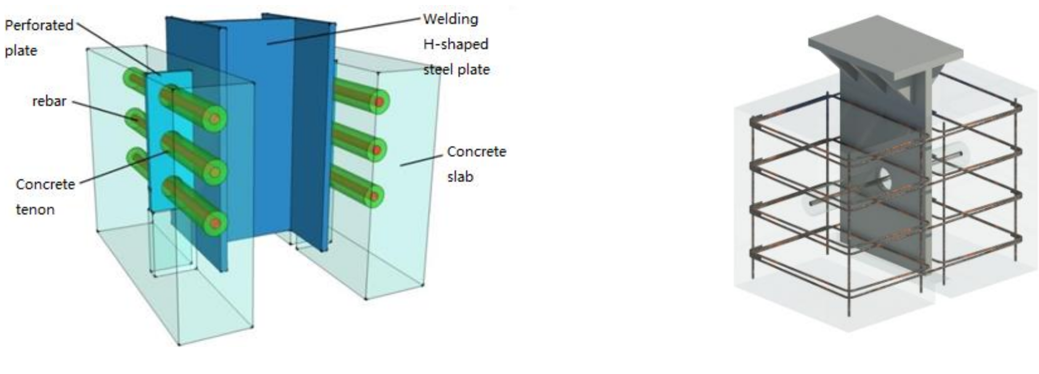
For the mechanical properties of PBL connectors characteristics, international scholars have conducted a lot of research through the push-out test. The more common forms of push-out specimens are standard push-out specimens and inserted push-out specimens. The standard roll-out specimen, which mainly refers to the Euro Code 4 specification, consists of an H-beam and an open steel plate welded vertically to the flange plate, as shown in Fig. 2(a). Since the concrete of the combined beam is usually thin, the end of the open steel plate bears the pressure under the external load, which leads to stress concentration in the concrete, and splitting damage of the wing plate is prone to occur in the limit state. The standard launch specimen of PBL connectors is more concrete splitting damage control, which can better reflect the force characteristics of PBL connectors in steel-concrete combination beams, and most of the previous formulas about its shear capacity calculation are also proposed on the basis of the standard launch test results.

The inserted roll-out specimen refers to the construction characteristics of the steel-concrete bond section of a hybrid girder bridge, where an open steel plate is inserted into the concrete and passes transversely through the reinforcement to form the PBL connector, as shown in Fig. 2(b). As the steel-concrete combination section is generally distributed with a large number of PBL connectors to ensure the transfer of internal forces, the stress level at the end of the open hole steel plate is low, and there will be no splitting damage similar to that of the concrete in the combination beam in the limit state, and more fracture damage occurs in the steel-concrete tenon in the hole. The PBL connectors of inserted push-out specimens are more fracture control of the steel-concrete tenon in the open hole, which can better reflect the force characteristics of PBL connectors in steel-mixed concrete hybrid beams. In the past, the formulas for its shear capacity calculation were also proposed more based on the results of inserted push-out tests.

4. PBL SHEAR CAPACITY CALCULATION FORMULAS

The shear bearing capacity and force transfer mechanism of PBL connectors are closely related to their constructional characteristics. Previous studies on the shear calculation of PBL connectors under different constitutive forms are relatively numerous, and studies on the main factors affecting its load-carrying capacity are also relatively common. According to the existing research results, the shear-bearing capacity of PBL connectors is mainly affected by the material strength of each component, the construction form of open the steel plate, the diameter of penetrating reinforcement, concrete thickness, and the reinforcement rate of transverse reinforcement. According to the parameters described above and the results of the launch test, a large number of PBL bearing capacity calculation methods have been proposed by international scholars.

Oguejiofor and Hossain [5-7] proposed “two regression equations for predicting the shear capacity V_u (expressed in n) of PBL shear connectors using the results of roll-out tests and numerical simulations”. The following two Equations (1) and (2), consider the effects of concrete end bearing, transverse reinforcement resisting shear, and concrete tenon resisting shear:



(a) Push-out **(b) Inserted**

Fig. 2. Push out the PBL specimen structure form

$$V_u = 0.590 A_{cc}\sqrt{f_{ck}} + 1.233 A_{tr} f_y + 2.871 n d^2 \sqrt{f_{ck}} \quad (1)$$

$$V_u = 4.5 h_{sc} t_{sc} f_{ck} + 0.91 A_{tr} f_y + 3.31 n d^2 \sqrt{f_{ck}} \quad (2)$$

where A_{cc} = shear area of the concrete slab (mm^2); A_{tr} = total area of the transverse reinforcement (mm^2); f_{ck} = compressive strength of concrete (MPa); f_y = yield strength of the transverse reinforcement (MPa); n = number of rib holes; d = diameter of the rib hole (mm); h_{sc} = height of the rib plate; and t_{sc} = thickness of the rib plate (mm).

In order to investigate the contribution of penetrating reinforcement to the shear capacity of PBL connectors at openings, Yoshitaka et al. [11] and Hosaka et al. [12] proposed "Equations (3) and (4) for calculating V_u. Eq. (3) applies when no transverse reinforcement is placed in the opening. Eq. (4) applies when there is transverse reinforcement in the opening. Thus, the former equation considers only the shear resistance of the concrete tenon, while the latter equation considers the shear resistance of both the concrete tenon and the transverse reinforcement".

$$V_u = 3.38 d^2 \sqrt{t_{sc}/d} \times f_{ck} - 39.0\times 10^3 \quad (3)$$

with $22.0\times 10^3 < \left[d^2 \sqrt{t_{sc}/d} \right] < 194.0\times 10^3$

$$V_u = 1.45 \times \left[\left(d^2 - \phi_{st}^2 \right) \times f_{ck} + \phi_{st}^2 \times f_{st} \right] - 26.1\times 10^3 \quad (4)$$

with $51.0\times 10^3 < \left[\left(d^2 - \phi_{st}^2 \right) \times f_{ck} + \phi_{st}^2 \times f_{st} \right] < 488.0\times 10^3$

where ϕ_{st} = diameter of the transverse reinforcement (mm); f_{st} = tensile strength of the transverse reinforcement (MPa); and t = thickness of the rib plate (mm). The other terms have already been defined in Equations (1) and (2).

Medberry and Shahrooz [13] proposed the following V_u equation. The equations include, in addition to the shear capacity provided by the concrete tongue and groove and transverse reinforcement, the effect of chemical bonding at the steel-concrete interface:

$$V_u = 0.747 b h_{ecs} \sqrt{f_{ck}} + 0.413 b_f L_c + 0.9 A_{tr} f_y + 1.66 n\pi \sqrt{f_{ck}} \left(d/2 \right)^2 \quad (5)$$

where b = thickness of the concrete slab (mm); h_{ecs} = distance between the end of the perfobond rib and the end of the concrete slab (mm); b_f = width of the steel beam flange (mm); and L_c = contact length between the concrete deck and the steel beam flange (mm). The other terms are defined in Equations (1) and (2).

Ahn et al. [14] presented the shear capacity equations for single-open-hole steel plates [Eq. (6)] and double-open-hole steel plates [Eq. (7)] as follows:

$$V_u = 3.14 h_{sc} t_{sc} f_{ck} + 1.21 A_{tr} f_y + 3.79 n\pi \left(d/2 \right)^2 \sqrt{f_{ck}} \quad (6)$$

$$V_u = 2.76 h_{sc} t_{sc} f_{ck} + 1.06 A_{tr} f_y + 3.32 n\pi \left(d/2 \right)^2 \sqrt{f_{ck}} \quad (7)$$

He et al. [15], based on the results of roll-out tests, proposed the V_u equation considering the effects of steel-concrete bond interface, concrete tenon, and transverse reinforcement:

$$V_u = \tau_b A_b + 1.06 A_c f_{ck} + 2.09 A_{tr} f_y \quad (8)$$

where A_b = contact area between the steel plate and concrete; A_c = cross-sectional area of the concrete dowel minus the cross-sectional area of the transverse reinforcement; and τ_b = bond strength between the steel plate and concrete given by the following equations:

$$\tau_b = \begin{cases} (s/0.61)^{0.29} \times \left(-0.045 f_{ck} + 0.638\sqrt{f_{ck}} - 1.193 \right) & 0 \le s \le 0.61 \\ (1.24 - 0.47 s)\left(-0.45 f_{ck} + 0.0638\sqrt{f_{ck}} - 1.193 \right) & 0.61 \le s \le 1.65 \\ 0.48\left(-0.045 f_{ck} + 0.638\sqrt{f_{ck}} - 1.193 \right) & s > 1.65 \end{cases} \quad (9)$$

where s = amount of slip between the steel plate and concrete. The other terms are defined in Equations (1) and (2).

Wang et al. [16], based on the results of the launching tests, proposed the V_u equation considering the effects of concrete tongue and groove action in the openings of the steel plate, bonding action between the steel flange and the concrete, and the action of penetrating reinforcement in the open steel plate:

$$V_u = 13.972 k_\alpha \sqrt{t_{sc}/d} \times nD^2 \sqrt{f_{ck}} + 3.41 b_f L_c + 1.334 A_{tr} f_y \quad (10)$$

where D = hole diameter of the open plate (mm); k_α = reduction factor for concrete strength, taken as 1 or 0.9. The other terms are defined in Equations (1) and (2).

Wu et al. [17] introduced steel-fiber high-strength concrete (SFHSC) for testing with no structural change and proposed the V_u equation considering the pressure-bearing action at the end of the steel plate, the action of concrete tenon in the hole of the open steel plate, the action of the steel flange bonded to the concrete, and the action of the penetrating reinforcement in the hole.

$$V_u = \left(1.205 + \frac{0.515 V_f L_f}{\varphi_f}\right)\left(0.4 A_{cd} + A_{eb}\right) f_{cu} + \left(0.016 + \frac{0.017 V_f L_f}{\varphi_f}\right) A_{sp} \sqrt{f_{cu}} + 3.493 A_{pr} f_y \quad (11)$$

where V_f = steel fiber volume content; L_f = steel fiber length; φ_f = steel fiber diameter; A_{cd} = shear area of concrete; f_{cu} = concrete shear strength; A_{sp} = steel plate-concrete contact area; A_{pr} = cross-sectional area of penetrating bars.

Based on Equations (1) to (11), the following conclusions can be made:

1. V_u is proportional to f_{ck} or $\sqrt{f_{ck}}$. The higher the compressive strength of the concrete, the higher the shear capacity of the connection.

2. V_u is proportional to f_y . The higher the yield strength of the steel, the higher the shear capacity of the connection.

3. V_u is directly proportional to A_{tr} , b_f and L_c . The larger the total cross-sectional area of the penetrating reinforcement, the larger the width of the steel girder flange welded to the connector, the larger the contact length between the concrete deck and the steel girder flange, and the higher the shear capacity of the connector.

4. V_u is directly proportional to nd^2 . The greater the number of openings in the open steel plate and the larger the size of the openings, the higher the shear capacity of the connection.

5. V_u is proportional to t_{sc} or $\sqrt{t_{sc}}$. The thicker the open steel plate, the higher the shear capacity of the connection.

6. The addition of steel fibers plays a positive role in the V_u of the joints, which can even delay the cracking of the concrete and increase the ductility of the structure, resulting in a better durability of the structure.

The formulas given by different scholars for calculating the shear capacity vary considerably. For PBL connectors in steel-concrete combination beams, the concrete on both sides of the PBL in the standard launch specimen usually splits first, so the upper limit of the load-carrying capacity of the PBL connectors is controlled by the splitting of the concrete.

Since concrete splitting is controlled by the distributed reinforcement within the slab, the shear calculation equation for PBL connectors proposed by scholars usually contains multiple parts. These include: the pressure-bearing role of the steel plate ends, the role of reinforced concrete tenons in the openings, and the role of transverse reinforcement in the concrete, and some scholars have considered the adhesion between the steel plate and the concrete into the equation as well.

For steel-concrete hybrid girder bridges, due to the large contact area between the open steel plates and concrete in the bond section and the strong restraining effect of the steel lattice chamber on the core concrete. Therefore, the steel plate-concrete interface bonding effect is commonly considered an important component of the load-carrying capacity of PBL connectors.

5. CONCLUSIONS

Over the past years, with the gradual deepening of the research related to the steel-concrete combination of bridge structures, certain achievements have been made in the steel-concrete combination structures. However, from the present point of view, the research results on the shear-bearing capacity of PBL connectors are relatively independent of each other and have not yet been able to systematically form research results with practical significance in engineering and with wide application value.

Based on the existing research on the shear resistance of various types of connectors, it is necessary to take into account a variety of uncertainties in the open steel plate and concrete as well as penetration reinforcement and the transfer linkage effect between them. It also quantifies various relevant factors such as porous working conditions and steel-concrete combination properties with reasonable accuracy. The establishment of a set of more effective theories for analyzing PBL connectors, which can be used to directly guide the design of PBL connectors based on shear performance, requires the unremitting efforts of experts and scholars.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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