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A COMPARISON OF SHEAR STRENGTH CALCULATION METHODS FOR PERFOBOND LEISTE SHEAR CONNECTORS USING THE CONTROLLED VARIABLE METHOD

Xu Yun[1], Chen Bin[1]*, Wang Xuejiao[2], Liu Yingxin[1], Wang Heng[3], Aleksandr Chernykh[4], Egor Danilov[4], Pavel Koval[4], Du Mingli[1], Zhang Zhonghua[1], Shi Saisai[1], Song Chunbo[1]

[1]School of Civil Engineering and Communication, North China University of Water Resources and Electric Power, Zhengzhou, People's Republic of China
[2]School of International Education, Zhengzhou Railway Vocational and Technical College, Zhengzhou, People's Republic of China
[3]Architectural Design Corporation Limited, Beijing, People's Republic of China
[4]Saint Petersburg State University of Architecture and Civil Engineering, Saint Petersburg, Russia

*Corresponding author's email: chenbncwu@163.com

Abstract: This paper provides a brief overview of the current research on timber-concrete composite beams and PBL shear connectors. Five representative calculation formulas were selected, and the effects of concrete strength and opening diameter on the ultimate bearing capacity of shear connectors were compared and analyzed using the controlled variable method. This study can serve as the basis for further optimizing the design parameters of composite beams.

Keywords: timber-concrete composite beam; PBL shear connector; shear capacity calculation method; design optimization.

Introduction

The Perfobond Leiste (PBL) shear connector consists of a perforated steel plate, concrete tenon, and through steel reinforcement. The PBL shear connector has become the most promising connector due to its high shear stiffness, high bearing capacity, good fatigue resistance, and convenient construction. da C. Vianna et al. (2013) analyzed PBL shear key composite structures experimentally and discovered that the thickness of the steel plate had a significant impact on the anti-slip performance of the shear key. Yang and Chen (2018) conducted monotonic loading push-out tests on PBL connectors and found that the end-bearing type specimens had higher shear bearing capacity and shear stiffness than the non-end-bearing type specimens. Huang et al. (2021) introduced a new type of bent-through steel reinforcement PBL shear key and conducted push-out tests, which revealed that bent-through steel reinforcement could effectively enhance the ductility of PBL shear keys and extend the service life of structures. Zhao et al. (2015) utilized ANSYS 12.0, a large-scale nonlinear finite element analysis software, to investigate the impact of parameters such as concrete grade and diameter of penetrating rebars on the stress distribution and shear bearing capacity of PBL shear keys. This study emphasized the significant influence of factors such as rebar diameter, concrete strength grade, and the bond strength between concrete and steel plate on shear bearing capacity. Zhu and Wang (2016) conducted experimental research on PBL shear keys in steel-concrete composite beam bridges, considering the effect of transverse prestressing. It proved that increasing the diameter of penetrating rebars, the aperture size of steel plate openings, and the thickness of the steel plate effectively increases the shear bearing capacity of PBL shear keys. However, it also noted that the introduction of transverse prestressing accelerated concrete cracking, which limited the full utilization of the potential strength and stiffness of concrete, steel plates, and penetrating rebars, thereby reducing the bearing capacity of PBL shear keys. Cui et al. (2017) conducted a statistical analysis on the load-slip curves of single-hole PBL connectors, which included 22 groups without penetrating rebars and 21 groups with penetrating rebars. According to them, in the plastic phase, the residual shear bearing capacity of single-hole PBL connectors results from the combined effects of bonding force along the shear failure surface of the concrete tenon, the shear bearing capacity provided by lateral restraint, and the anchoring effect of penetrating rebars. Zhao et al. (2018) conducted push-out tests on wave-shaped PBL connectors, varying the diameter of the penetrating rebars. It was found that beyond a certain rebar diameter, the rate of increase in the connector's shear bearing capacity started to decrease. Shi (2019) performed comprehensive experimental research and finite element simulations on lightweight aggregate concrete PBL shear connectors. The research highlighted that the shear bearing capacity of these connectors is mainly influenced by concrete strength,

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opening size, and rebar diameter. A formula for calculating the ultimate bearing capacity of lightweight aggregate concrete PBL shear connectors was proposed. Wang (2020) investigated the impact of additional constraints on the bearing mechanism of PBL shear connectors. It was shown that such factors as restraining rebars and friction between the specimen and the test base had a significant effect on the failure mode, rebar strain, and load-slip curve of PBL connectors. Furthermore, a method for calculating the bearing capacity of PBL connectors was proposed, taking into account the influence of these additional constraints. Xue et al. (2020) applied finite element analysis to conduct push-out tests on perforated plate connectors. They highlighted the significant influence of both yield strength and rebar diameter on the ultimate shear bearing capacity of these connectors. This study demonstrated a linear relationship, where increased yield strength and rebar diameter led to enhanced shear bearing capacity. Zhang (2021) conducted static push-out tests on 16 U-shaped PBL shear keys across four groups of specimens. Zhang noted that the ultimate bearing capacity of these shear keys was mainly determined by the compressive concrete at the end steel plate, along with the penetrating rebars and concrete tenon. Liao (2022) conducted push-out tests and finite element analysis on UHPC-reinforced PBL connectors. The tests indicated that the use of UHPC approximately doubled the bearing capacity and increased shear stiffness by about 1.75 times. They also confirmed the accuracy of the nonlinear finite element analysis. Ren (2023) conducted a lateral bending static test with varying diameters of perforated rebars. Ren stated that the diameter of the perforated rebars had a relatively minor impact on the failure mode of T-PBL connector specimens. It was suggested that the current industry standard for calculating the lateral bending bearing capacity of T-PBL connectors might be relatively conservative. Yang et al. (2024) conducted push-out tests on bolted PBL connectors in waveform steel-UHPC composite bridge decks, along with finite element analysis of beam tests. This study illustrated that increasing the diameter of short bolts, PBL aperture, and UHPC strength effectively increases the shear bearing capacity of the composite connectors. A modern timber-concrete composite structure is a novel construction that combines wood and concrete materials. By combining wood and concrete flanges with shear connectors, the corresponding good tensile and compressive properties can be fully utilized, effectively transferring longitudinal shear forces and preventing the separation of the wood beams and concrete flanges. Modern timber-concrete composite beams have significantly higher overall integrity, bending stiffness, and fire resistance compared to traditional timber beams. PBL shear connectors have been widely used in timber-concrete composite structures. Many researchers have conducted experimental and theoretical studies on mechanical performance. Schanack et al. (2015) conducted shear, static, and numerical tests on timber-concrete composite beams and compared the numerical results with the experimental ones. It was found that the finite element model could better predict the test results. Li (2017) conducted static tests and numerical simulations on glued laminated timber composite beam bridges, and demonstrated that the support type influenced the beam end slip. Yuan (2019) investigated the bearing capacity of modern timber-concrete composite beam bridges and proposed a formula for bending resistance. The numerical results agreed with the theoretical ones. Kim et al. (2014) conducted static load tests on composite beams with Y-shaped PBL shear keys and demonstrated that Y-shaped PBL shear keys had higher stiffness and ultimate loads than traditional ones.

There is no unified design theory or method for calculating the shear capacity of PBL shear connectors. In the course of this study, five representative calculation formulas were selected and combined with the load characteristics of PBL shear connectors. Using the controlled variable method, the effects of concrete compressive strength and aperture diameter on the shear capacity of PBL connectors were compared and analyzed using different calculation equations. The design parameters of composite beams were also optimized. The research results can serve as a reference for the design of modern timber-concrete composite beam bridges and for optimizing PBL shear connector designs.

Calculation Methods

(1) The Specifications for the Design of Highway Steel Bridges (JTG D64-2015) (Ministry of Transport of the People's Republic of China, 2015) provide a calculation equation for the shear bearing capacity of PBL shear connectors. This equation mainly takes into account the shear resistance of concrete keys and the effect of penetrating steel bars.

$$V_{u_P} = 1.4\left(d^2 - d_s^2\right) f_c + 1.2 d_s^2 f_{sd}, \tag{1}$$

where:

V_{u_P} — ultimate shear capacity of the connection, N;

d — diameter of the opening, mm;

d_s — diameter of the penetrating reinforcement, mm;

f_c — design value of the compressive strength of concrete at the centroid, MPa;

f_{sd} — design value of the tensile strength of the penetrating reinforcement, MPa.

(2) Eurocode 4 (European Committee for Standardization, 2004) provides specific calculation

formulas that account for the influence of through-bars and concrete, based on a statistical analysis of a large number of test results.

$$V_{uP} = \left[1.85\left(\frac{\pi\left(d^2-d_s^2\right)f_c}{4}+\frac{\pi d_s^{\times 2} f_{sd}}{4}\right)-106.1\cdot 10^3\right]. \quad (2)$$

(3) Hu et al. (2006) derived a calculation formula for the bearing capacity of the connection member consisting of transverse ordinary steel bars, penetrating steel bars, and concrete tenons.

$$V_{uP} = \frac{\alpha\pi d_s^2 f_y}{4}+\beta A'_{tr} f'_y+\frac{\gamma\pi\left(d^2-d_s^2\right)\sqrt{f_c}}{4}, \quad (3)$$

where:

α — coefficient of influence of the penetrating steel bar, taken as 1.32;

f_y — yield strength of the penetrating steel bar, MPa;

β — coefficient of influence of the transverse steel bar, taken as 1.204479;

$A'_{t\gamma}$ — sectional area of hoop reinforcement, mm²;

f'_y — yield strength of hoop reinforcement, MPa;

γ — coefficient of influence of concrete keys, taken as 1.95.

(4) Zheng et al. (2016) derived a calculation formula for the connection capacity of PBL shear connectors, which takes into account the contributions of the end concrete, hole concrete, and penetrating steel bars. Their formula was based on the experimental results.

$$V_{uP} = 1.76\alpha_A\left(\frac{\pi d^2}{4}-\frac{\pi d_s^2}{4}\right)f_c+1.58\frac{\pi d_s^2}{4}f_y; \quad (4)$$

$$\alpha_A = 3.8\left(\frac{d_s^2}{d^2}\right)^{2/3},$$

where: α_A reflects the restraining effect of the penetrating steel bars on the concrete in the hole.

Yang and Chen (2018) argued that the compressive action of the concrete at the end of the perforated plate, the shear resistance of the concrete in the hole, and the shear resistance of the penetrating steel bar are the main components of the shear bearing capacity of the PBL shear connector. The following calculation formula was derived:

$$V_{uP} = 5.15htf_{cu}+5.41\left(\frac{\pi d^2}{4}-\frac{\pi d_s^2}{4}\right)f_{cu}^{0.57}+$$

$$+2.24\frac{\pi\times d_s^2}{4}f_y, \quad (5)$$

where:

f_{cu} — compressive strength of concrete in cubic form, MPa;

h — height of the perforated plate, mm;

t — thickness of the perforated plate, mm.

Comparison and Analysis

To compare the effects of concrete compressive strength and opening diameter on the shear bearing capacity of PBL shear connectors using different calculation formulas, Eqs. (1)–(5) were used, and a PBL opening diameter of 50 mm was selected. The relationship between the concrete compressive strength and the shear bearing capacity of PBL shear connectors is presented in Fig. 1. The relationship between the opening diameter and shear bearing capacity of PBL shear connectors is clear from Fig. 2, when a concrete cube compressive strength of 40 MPa is selected.

As shown in Figs. 1 and 2, the relationship between the concrete compressive strength, opening diameter, and PBL shear capacity exhibits a linear positive correlation among Eqs. (1)–(5). The shear capacity calculated by Eqs. (1) to (4) mainly ranges

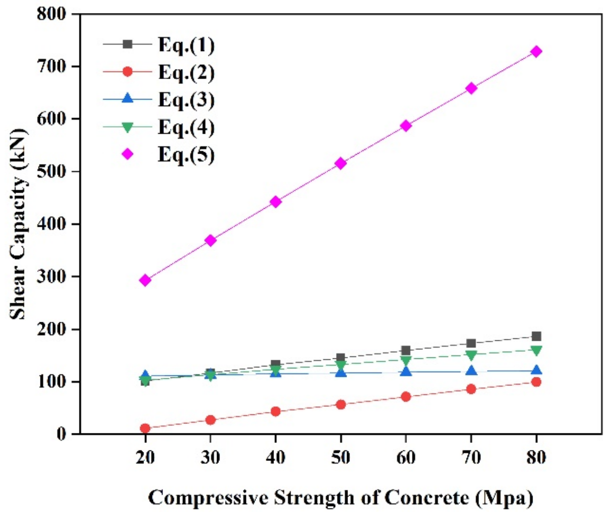

Fig. 1. Relationship between the concrete compressive strength and the shear bearing capacity of PBL shear connectors

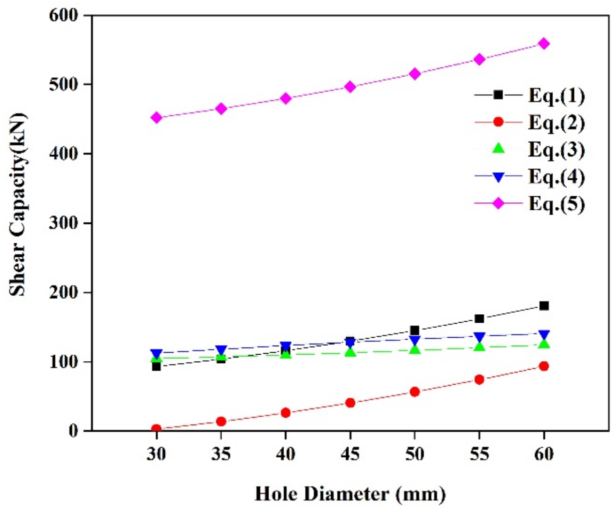

Fig. 2. Relationship between the opening diameter and the shear bearing capacity of PBL shear connectors

around 100 kN, while the shear capacity calculated by Eq. (5) is much higher than that of other formulas, with a maximum difference of 629 kN. Yang and Chen (2018) explained that Eq. (5) accounts for the compressive action at the end of the perforated plate, while other formulas only account for the shear resistance of the concrete tenon and the penetrating steel bar, neglecting the compressive action of the end concrete. Furthermore, the slopes of the curves obtained by calculating Eqs. (1), (3), and (5) are relatively gentle, indicating that the calculated shear capacity is less sensitive to the concrete compressive strength and opening diameter. In summary, the shear capacity calculated by Eqs. (2) and (5) deviates considerably from other calculation formulas. Given the general nature of the calculation method, it is important to specifically consider the applicability of the formulas in the design of modern timber-concrete composite beam bridges and in the optimization of PBL shear connector design. Alternatively, Eqs. (1), (3), and (4) can be used for calculation to prevent significant errors in the results. As a result, some suggestions for the optimal use of the formulas are shown below:

- Eqs. (1) and (3) are suitable for estimating the shear capacity of PBL shear connectors with low concrete compressive strength and small opening diameter, as they are relatively conservative and stable.
- Eq. (4) is suitable for estimating the shear capacity of PBL shear connectors with moderate concrete compressive strength and opening diameter, as it is close to the average value of other formulas.

Conclusions

In the course of this study, five representative calculation formulas were selected and combined with the load characteristics and test data of PBL shear connectors. The study analyzed the effects of concrete strength and aperture diameter on the ultimate bearing capacity of the connectors using the controlled variable method. The main conclusions were as follows: concrete strength and aperture diameter had a significant impact on the shear capacity of Eqs. (2) and (5), but a minor impact on the other three formulas. Concrete strength had a significant impact on Eq. (4), while the impact of aperture diameter was not significant and requires further verification by increasing the variables. The calculation results using Eq. (5) indicate that the compressive effect at the end of the perforated plate might cause a significant deviation in the calculated bearing capacity, which could affect the evaluation of the shear capacity of PBL connectors.

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СРАВНЕНИЕ МЕТОДОВ РАСЧЕТА ПРОЧНОСТИ НА СДВИГ СОЕДИНИТЕЛЬНЫХ ЭЛЕМЕНТОВ PERFOBOND LEISTE, РАБОТАЮЩИХ НА СДВИГ, С ИСПОЛЬЗОВАНИЕМ МЕТОДА КОНТРОЛИРУЕМЫХ ПЕРЕМЕННЫХ

Сюй Юнь[1], Чэнь Бинь[1]*, Ван Сюэцзяо[2], Лю Инсинь[1], Ван Хэн[3], Александр Черных[4], Егор Данилов[4], Павел Коваль[4], Ду Минли[1], Чжан Чжунхуа[1], Ши Сайсай[1], Сун Чуньбо[1]

1Факультет гражданского строительства и коммуникаций, Северо-китайский университет водных ресурсов и электроэнергетики, Чжэнчжоу, Китайская Народная Республика
[2]Факультет международного образования, высшее профессионально-техническое железнодорожное училище Чжэнчжоу, Чжэнчжоу, Китайская Народная Республика
[3]Architectural Design Corporation Limited, Пекин, Китайская Народная Республика
[4]Санкт-Петербургский государственный архитектурно-строительный университет, Санкт-Петербург, Россия

*E-mail: chenbncwu@163.com

Аннотация: В данной статье представлен краткий обзор современных исследований составных деревобетонных балок и соединительных элементов PBL, работающих на сдвиг. Выбраны пять репрезентативных расчетных формул, проведены сравнение и анализ влияния прочности бетона и диаметра отверстия на предельную несущую способность соединительных элементов, работающих на сдвиг, с использованием метода контролируемых переменных. Данное исследование может послужить основой для дальнейшей оптимизации параметров проектирования составных балок.

Ключевые слова: составная деревобетонная балка; соединительный элемент PBL, работающий на сдвиг; метод расчета прочности на сдвиг; оптимизация конструкции.