Study on the shear capacity of PBH shear connector basing on PBL shear connector

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Abstract

According to the structural characteristics of steel box-concrete composite structure, a new type of shear connector with Perfobond hoop is proposed basing on PBL shear connector (Perfobond Hoop, PBH in short). PBH shear connector is composed of stiffening rib and stirrup, the joint work of steel box and concrete is realized without adding any special connection construction. Push out test of the PBL and PBH were performed, results show that the shear capacity and shear stiffness of PBH are higher than that of the PBL; multi-parameters effect on the mechanical behaviour and the shear capacity of PHB were analysed using FEM analysis in terms of the concrete strength, the perforation diameter and so on; on the basis of the test and analysis, three failure modes of PBH were concluded, the construction requirements were proposed to avoid the welding shear failure and compression buckling of the perforated stiffening rib, and the shear capacity formula of PBH was established according to the fracture or large deformation of the steel concrete tenon.

Keywords: Composite Structure, Shear Connector, Experimental Study, Parameter Analysis, Shear Capacity

1 Introduction

Steel-concrete composite structure which makes full use of the material properties of both steel and concrete is a newly developed structure on the basis of steel structure and steel concrete structure. The steel and concrete composite structure is relying on the joint work of both steel and concrete structure, and the shear connector is the key member to ensure the joint work. The commonly used shear connectors include: stud connector, reinforcement connecter, high strength bolt connector, PBL shear connector, section steel connector and other forms of connector [1-6].

A steel box-concrete composite section named perfobond hoop basing on PBL shear connector that used in steel box-concrete composite arch has proposed in literature 7-9. The experimental and theoretical study of the perfobond hoop composite section (Perfobond Hoop, PBH in short) were carried out [10]. Besides, the shear capacity and the failure mode should be predicted before be used.

The multi-parameters effect on the mechanical behaviour and the shear capacity of PHB were analysed using FEM analysi. And on the basis of the test and analysis, failure modes and the shear capacity of PBH werestudied in this paper.

2 The PBH shear connector basing on PBL

PBL shear connector comprises of the perforated plate and concrete, in which the interface shear forces are accordingly resisted by the reinforced concrete tenon with steel reinforcement in the perforated plate or just the plain concrete tenon. Domestic and foreign scholars have made large number of experimental and theoretical researches on PBL shear connector due to its simplified and reliable construction, which suggest that a notable slippage of the shear connector and a displacement of concrete in the lateral direction occur simultaneously when the load increases [7-11]. Experiments also show that the concrete in the front of the plate will be subjected to significant large shear forces from the plate, which may cause micro-cracks and finally develop to longitudinal splitting cracks. Nowadays, PBL has been widely used in numerous bridges both at home and aboard [12-15].

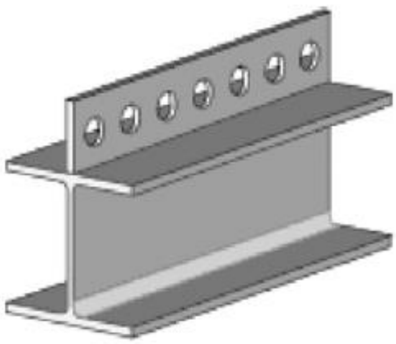

FIGURE 1 The construction of PBL

According to the characteristics of steel box-concrete composite arches, a new style of shear connector named Perfobond Hoop (PBH in short) is proposed , in which the stiffening ribs located at the roof of the steel box are perforated in a constant distance, then the stirrups go through the holes, and the ribs together with stirrups are embedded in the concrete . Therefore, any part of PBH shear connector can absolutely not separate from each other thus the interface shear force between steel box and concrete can be efficiently resisted by the steel concrete tenon in the perforated stiffening ribs without adding any special shear connection construction. (Fig2, Fig3)

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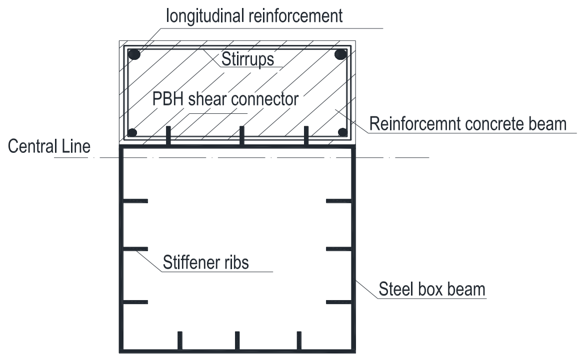


FIGURE 2 Construction of the steel box-concrete composite structure

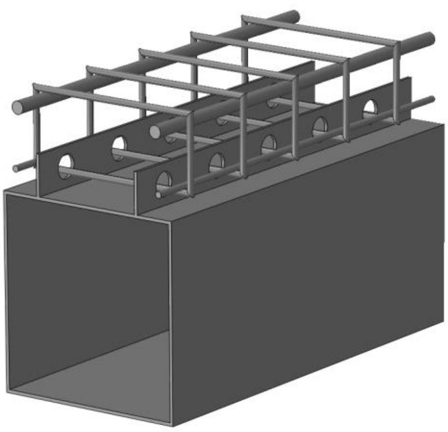
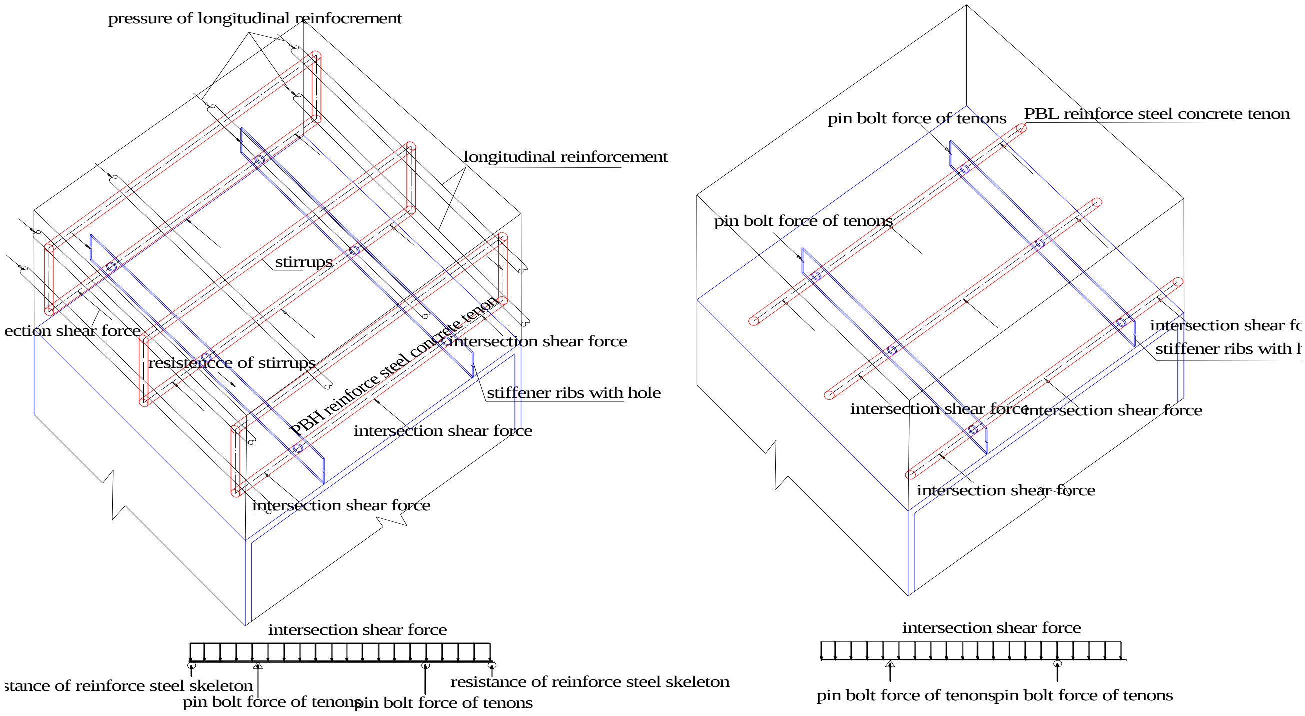


FIGURE 3 The construction of PBH



1) Mechanical model of PBH 2) Mechanical model of PBL

FIGURE 4 Mechanical models of PBH and PBL

PBH is developed on the basis of PBL and similarly the shear forces in PBH are also mainly resisted by the reinforced concrete tenon like the one in PBL. Besides, the most important characteristic of PBH is that the reinforcements through perforated stiffening ribs belong to the steel skeleton of the concrete over the steel box so that the compression and shearing behaviours of the reinforced concrete tenon are improved and the deformations are also restrained by the longitudinal reinforcement and the concrete. Generally, shear connection reinforcements and stirrups as a whole in the PBH connector, together with erection bar and longitudinal compressive reinforcements the steel skeleton forms. In this way, the concrete in the steel skeleton contributes to the shear strength of the interface in some degrees.

3 The comparison of transfer mechanism between PBH and PBL

The interface shear force in PBL is mainly isolatedly resisted by the single pin bolt force coming from the reinforced concrete tenons. While in PBH, the interface shear force is not only resisted by the reinforced concrete tenons but also resisted by the longitudinal reinforcements and stirrups. As is shown in Fig.4, the reinforced concrete tenons in PBL are restricted by the stiffening ribs only in the position where they intersect. Therefore, when the tenons are subjected to the interface shear forces, the mechanical model is equivalent to a simply supported beam with cantilever. As to the PBH, the mechanical model is equivalent to the three-span continuous beam due to the co-constraints of the whole steel frame work including longitudinal reinforcements and stirrups. Obviously, the pin bolt force in PBH is smaller than the one in PBL while subjected to equal shear force, that is, when the bar diameter and the concrete strength are the same the PBH apparently obtains a greater shearing strength compared to PBL.

The crushing process of the concrete at the rear of the reinforced concrete tenon is similar to one of the failure modes of PBL and PBH connectors. Therefore, the stress states of the concrete at the rear of the reinforced concrete tenon in the two shear connectors are respectively analysed to learn more about the failure modes of the shear connectors

Reinforced concrete tenons in PBH are closely connected by the steel framework one by one thus each one can deform compatibly with the other. With steel framework, PBH can transfer shear force and deformation between adjacent tenons ensuring that the forces are uniformly distributed on each tenon. The limit shearing resistance of both PBL and PBH is determined by the reinforced concrete tenons, the concrete at the rear of them and the specific loads. As a result, there is a conclusion that the shearing resistance of PBH is greater than one of PBL.

4 The push out test of PBL and PBH shear connector

According to the specimen dimensions and reinforcement requirements for push out test recommended by ECSS, the push test of both connectors were performed to study and compare the mechanical performance of PBH and PBL shear connector.[10]

Figure 4 shows that for a spacemen, the measured load-slippage curves of PBH and PBL under the same parameter conditions, are basically agree with each other within the range of 0 and 40% Pu, afterwards, differences occur gradually and the deformation increasing rate of PBL is notably larger than that of PBL. For example, when the slippage is 1mm the loads of PBH and PBL are 537KN and 429KN, as shown in Fig.5 PH and PL respectively, obviously, the load of PBH is bigger than that of PBL with the same slippage.

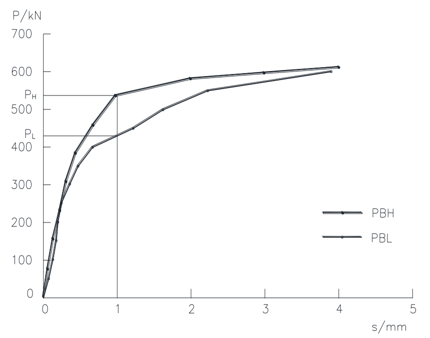


FIGURE 5 Comparison of measured load-slippage curves between PBH and PBL

The calculation method of PBH shear capacity

5.1 FAILURE MODES

Analysis show that the failure modes of PBH can be concluded in three patterns

Mode A: The shear failure of welding in the perforated stiffening ribs: when the weld length is insufficient, it will be shear off when it subjects to large shear force, in this failure mode, the material strength are not fully developed, therefore, the minimum length of weld should be calculated to avoid the shear off weld.

B. the compression buckling of the perforated stiffening ribs: when the perforated area in the stiffening rib is too large, or the steel plate is not thick enough, or the height of the stiffening rib is too large, compression buckling may occur when it is subjected to shear force, the material strength are also not fully developed in this failure mode, besides, the brittle feature in compression buckling is significant, therefore, essential construction requirements for the stiffening rib should be proposed.

C. the of fracture or excessive-deformation of tenon: this mode happens when shear failure occurs to the steel concrete tenon in the hole and crush occurs to the concrete behind the steel concrete tenon, thus the tenon dislocated and can no longer provide shear resistance, and the adjacent concrete will be split. The material strength are fully developed in this failure modes.

The calculation of the minimum weld length in failure mode A:

According to the code for design of steel structure [11], when $0.7 \cdot l^w \cdot f_t^w / 100 \geq Q_u$, the weld will not end in shear failure, for PBH, to avoid A failure mode, the minimum weld length is given by

$$l^w \geq \frac{100 Q_u}{0.7 \cdot f_t^w} . \tag{1}$$

Calculation of the maximum height to thickness ratio of failure mode B:

According to the construction requirements for the stiffening rib specified in the code for design of steel structure [11], when the thickness of the stiffening rib meets

$$t_s \geq \frac{b_s}{15} . \tag{2}$$

The buckling of stiffening rib will not happen, where the bs is the width of stiffening rib.

When the weld length and the height to thickness ratio of PHB meet formula (1), (2), failure mode A and B are avoided, therefore, the following chapter focus on the discussion of the calculation method and the factors that influencing the shear capacity of PBH.

5.2 THE FINITE ELEMENT MODEL

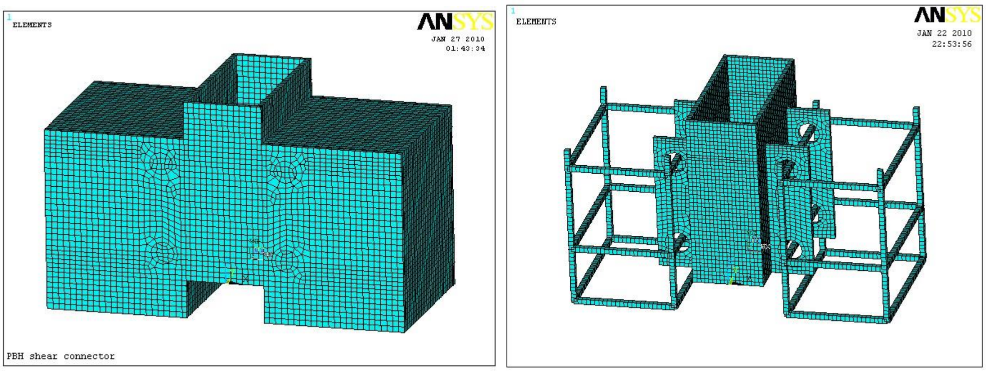


FIGURE 6 FEM model of PBH

The FEM analysis of PBH was conducted using ANYSY (Figure 6); figure 6 is the comparison of load-slippage curves between measured data and FEM results.

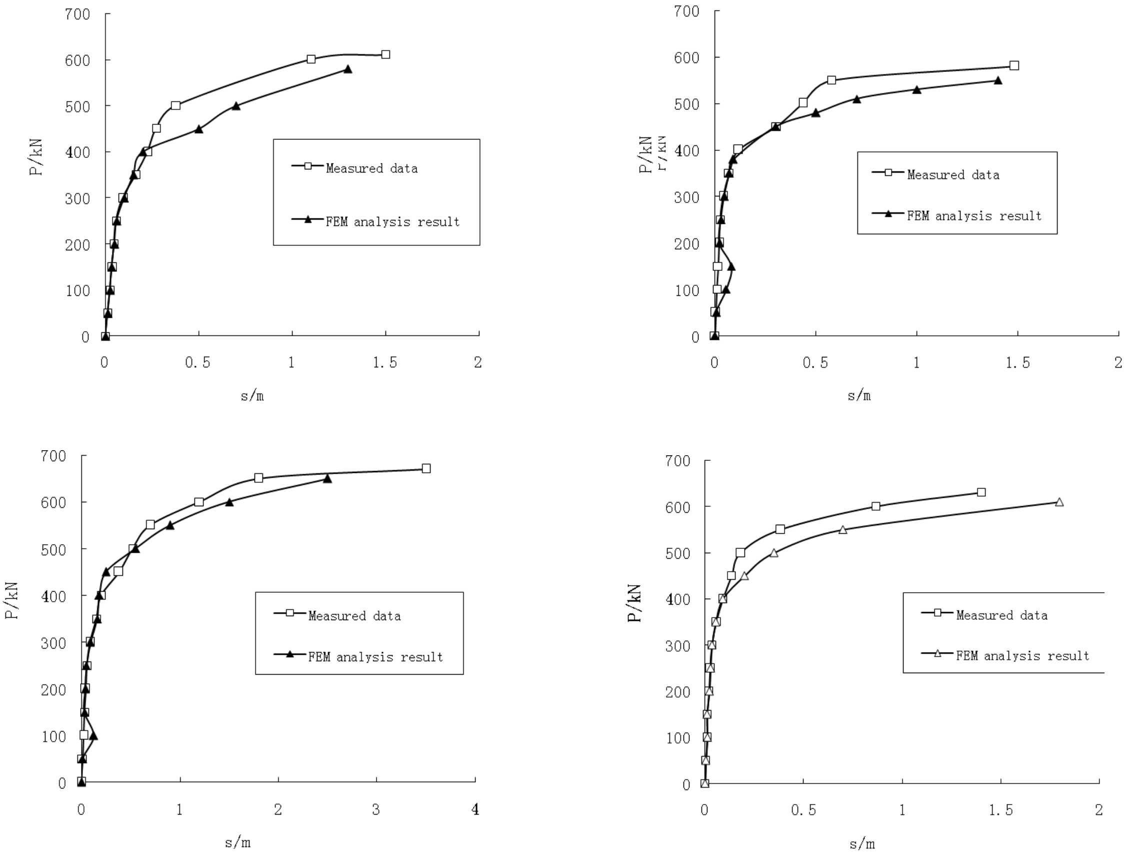


FIGURE 7 Comparisons of load-slippage curves between measured data and FEM results

Figure 7 shows that the results of FEM analysis of PBH agree well with the measured data, which indicates that the accuracy of FEM analysis is enough, the FEM analysis combined with experiment to analyze the mechanical behaviour of PBH is reliable. The stiffness of PBH obtained from FEM analysis is slightly smaller than that of the measured data, this may be due to the constitutive model of concrete used in the FEM is different from that of the test, especially, according to the performance of concrete, the later difference is much bigger than the early difference. The yield load of PBH obtained from FEM analysis is about 2.5%~7% less than that of the measured data, and the ultimate load obtained from FEM analysis is about 3%~9% less than that of the measured data. Part of the reason that resulted in the gap might be that the convergence problem in the FEM analysis make the structure buckled and finally fake an ultimate state.

5.3 MULTI-PARAMETER ANALYSIS

Combined with results obtained from the FEM analysis and the measured data, multi-parameter analysis was conducted which includes the concrete strength, diameter of stirrup, perforation spacing of stiffening rib, perforation diameter, height of the stiffening rib.

1) The strength of concrete

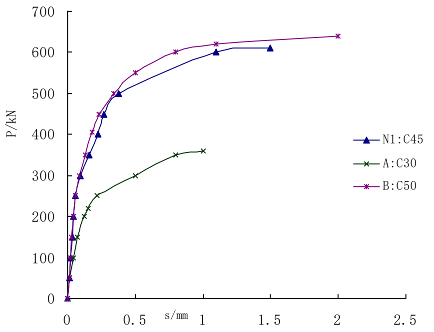


FIGURE 8 Load-slippage curves of PBH with different concrete strength

Figure 8 shows that when the concrete strength are C30, C45 and C50, the shear capacity of PBH are 360kN, 610kN and 640kN, respectively, which indicates that the concrete strength is greater, the ultimate capacity of PBH is higher, the concrete strength has a significant influence on the shear capacity of PBH.

2) Diameter of stirrup

Figure 9 shows that when the diameter of stirrup are φ6, φ8 and φ10, the ultimate shear capacity of PBH are 580kN, 610kN and 670kN, respectively, the ultimate shear capacity for φ6 stirrup is about 14% less than that of φ10 stirrup, which indicates that the diameter of stirrup has a certain influence on the shear capacity of PBH.

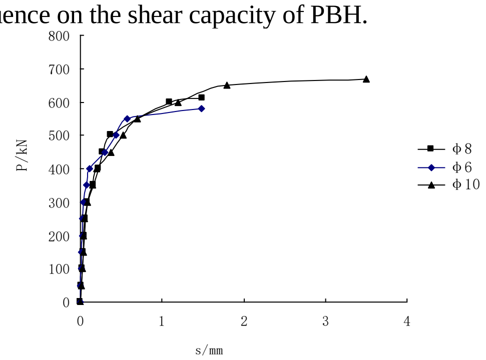


FIGURE 9 Load-slippage curves of PBH with different steel diameter

3) Perforation spacing in the stiffening rib

Figure 10 shows that as the concrete strength, diameter of the stirrup and the thickness of plate remain constant, when the perforation spacing in the stiffening rib are 120mm and 90mm, the ultimate shear capacity of PBH are 610kN and 630kN, respectively, the former is about 96% of the later, which indicates that the perforation spacing has a slight influence on the shear capacity of PBH.

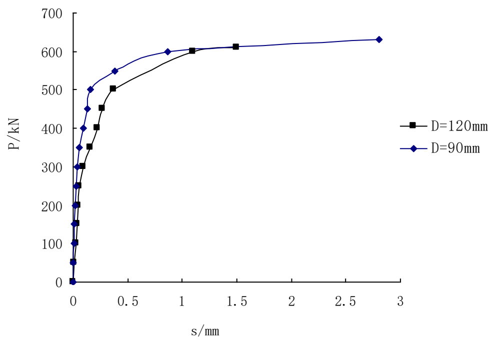


FIGURE 10 Load-slippage curves of PBH with different perforation distance

4) Perforation diameter on the stiffening rib

Figure 11 shows that when the perforation diameter are 30mm, 40mm and 50mm, the ultimate shear capacity of PBH are 610kN, 670kN and 740kN, respectively, which indicates that the diameter of stirrup has a significant influence on the shear capacity of PBH. It has been found that when the stiffening rib of PBH is not weakened significantly, the shear capacity increases with the increase of perforation diameter.

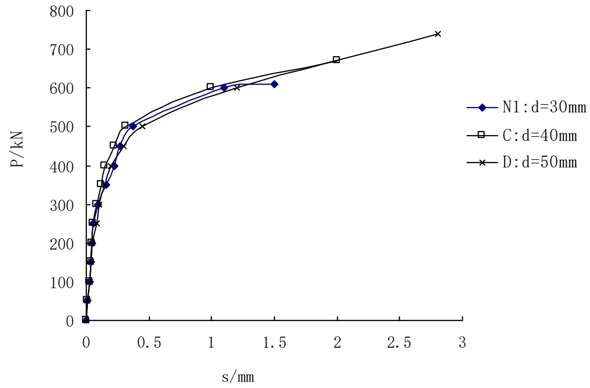


FIGURE 11 Load-slippage curves of PBH with different perforation diameter

5) The height of stiffening rib

Figure 12 shows that as other factors of PBH remain constant, when the height of stiffening rib are 50mm 60mm and 70mm, the ultimate shear capacity of PBH are 570kN ,610kN and 670KN, respectively, which indicates that the height of stiffening rib has a significant influence on the shear capacity of PBH. This factor mainly reflects that the influence of the concrete inside of the stirrup and stiffening rib.

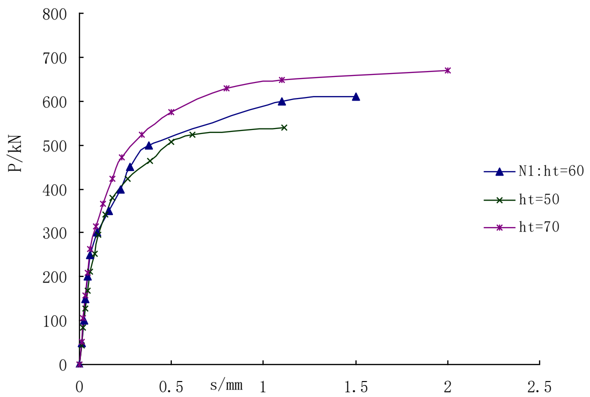


FIGURE 12 Load-slippage curves of PBH with different stiffeners heights

5.4 THE SHEAR CAPACITY FORMULA OF PBH

On the basis of the calculation formula of the shear capacity of PBL, the shear capacity of PBH is contributed by the stiffening rib and concrete, the steel concrete tenon and the stirrups passing through the hole. The shear capacity of each part is relative to the material strength, dimensions and construction. Therefore, the shear capacity of BPH is given by:

$$Q_u = b_1 A_c \sqrt{f_c'} + b_2 d^2 \sqrt{f_c'} + b_3 A_{tr} f_s, \quad (3)$$

where, Q_u __ the ultimate shear capacity of a single perforation.

A_{tr} — the cross-section area of the stirrup passing through the hole

f_s—the yield strength of the stirrup passing through the hole

d —the perforation diameter

f_c—the cube compressive strength of concrete.

TABLE 1 Shear strength of single perforation of PBH

Concrete strength (MPa)	Qu (kN)	Steel strenght (MPa)	Qu (kN)	Diameter of stirrup (mm)	Qu (kN)	Diameter of perforation (mm)	Qu (kN)	Heighof stiffening rib (mm)	Qu (kN)
C30	45.0	235	72.5	6	66.3	30	72.5	50	71.3
C40	72.5	335	82.5	8	72.5	40	83.8	60	76.3
C50	80.0	375	86.3	10	81.3	50	92.5	70	83.8

Note: the datum are from the test and FEM analysis

According to the data in Table 1, the parameters in formula (3) are obtained, and the shear capacity of PBH is given by:

$$Q_u = 1.1823 A_c \sqrt{f_c'} + 2.8972 d^2 \sqrt{f_c'} + 1.2897 A_{tr} f_s . \quad (4)$$

The symbols meaning are the same as formula (3).

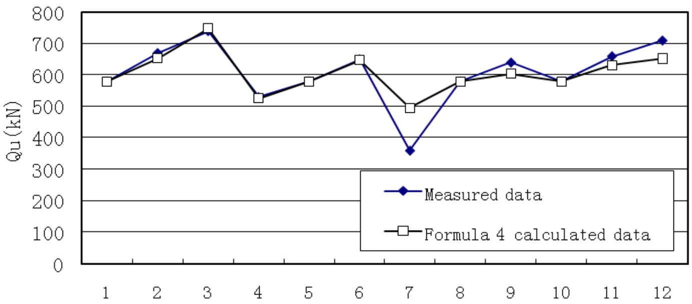


FIGURE 12 Comparisons of the results between measured data and calculation according to formula (4)

Figure 12 indicates that the results calculated by formula (4) agrees well with the measured data, the 95% confidence of datum were checked, results show that the regression model is correct.

TABLE 2 Shear strength of single perforation with different formulas (Unit: kN)

Author	Formula	N1	N2	N3	(FEM/Measured data)
Leonhardt[12]	$Q_u = 1.79 d^2 f_c$	72.5	72.5	72.5	0.939
Hosakat[13]	$q_u = 1.45\left[\left(d^2 - d_s^{\,2}\right) f_c + d_s^{\,2} f_y\right] - 26.1$	55.4	45.1	68.2	0.721
Oguejiofor[14]	$Q_u = 0.6348 A_c \sqrt{f_c'} + 1.1673 A_{tr} f_y + 1.6396 A_{bs} \sqrt{f_c'}$	46.1	55.6	38.6	0.611
Hosain[14]	$Q_u = 0.590 A_c \sqrt{f_c'} + 1.233 A_t f_y + 2.871 \ln d^2 \sqrt{f_c'}$	37.9	30.0	48.0	0.495
	$Q_u = 4.5 ht \sqrt{f_c'} + 0.91 A_t f_y + 3.3 \ln d^2 \sqrt{f_c'}$	24.3	18.5	31.7	0.317
Zong Zhouhong[15]	$Q_u = \alpha_1 \beta_1 A_c \sqrt{E_c f_c'} + \alpha_2 \beta_2 A_{tr} f_y$	29.8	25.0	36.0	0.388
The proposed formula	formula（4-28）	75.9	67.7	86.5	0.987
The measured data		76.25	72.5	83.75	

Table 2 shows that the PBH shear capacity calculated by PBL formula is generally small, which indicates the shear capacity of PBH is higher than that of PBL. In formula (4), the parameters of stiffening rib and concrete and the stirrup are significantly higher than that of the formula calculating the shear capacity of PBL, which indicates that bond effect of concrete is strengthened by the steel skeleton and the stirrup in PBH.

6 Conclusions

This paper introduced the push out test and the FEM analysis of PBL and PBH shear connector, the mechanical characteristics comparison of PBH and PBL was performed and the multi-parameter analysis was conducted, the formula that calculating the shear capacity of PBH was established. The following conclusions can be drawn from this research:

PBH is a new shear connector for steel box-concrete composite structure basing on PBL. By comparison with PBL, PBH is simpler comprising of steel box stiffener and stirrup without adding any special connection construction.

Experiment results indicates that load-slippage curves agree well with each other within the range of 0 and 40% Pu, afterwards, differences occur gradually and the deformation increase rate of PBL is notably larger than PBL's. When the slippage is 1mm, the load of PBH is 25% higher than that of PBL, which indicates that for a certain slippage, the load of PBH is significantly larger than that of PBL.

Failure modes of PBH were concluded in three patterns in terms of the shear failure of welding in the perforated stiffening ribs, the compression buckling of perforated stiffening ribs and the fracture or excessive-deformation of tenon. Essential construction requirements for the stiffening rib are proposed to avoid failure modes A and B, the method calculating the shear capacity of PBH is proposed according to failure mode C, by comparison with the calculation method of PBL shear capacity, the proposed method is suitable to calculate the PBH shear capacity with different parameters.

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