Structural Engineering and Mechanics, *Vol. 67, No. 2 (2018) 131-142*
DOI: https://doi.org/10.12989/sem.2018.67.2.131

Experimental shear strength evaluation of perfobond shear connector with various hole shapes

Shuangjie Zheng[1a], Chen Zhao[2a] and Yuqing Liu*[3]

[1]College of Civil Engineering, Huaqiao University, Xiamen 361021, China
[2]Shanghai Municipal Engineering Design Institute (Group) Co., Ltd., Shanghai 200092, China
[3]Department of Bridge Engineering, Tongji University, Shanghai 200092, China

(Received February 5, 2018, Revised April 21, 2018, Accepted April 30, 2018)

Abstract. The perfobond connector, composed of a steel plate with a number of holes, serves as a certain type of shear connector in steel and concrete composite structures. Depending on limits in hole distances and rib heights, various hole shapes including circular-hole and long-hole are alternatives for perfobond connectors. This study presented the results of tests performed on 72 push-out specimens with perfobond connectors. The purpose was to evaluate the shear strength of perfobond connectors with circular-hole and long-hole. The effects of various parameters were investigated, including the hole diameter, the hole length, the hole height, the concrete strength, the existence, diameter and strength of rebar in the hole, the thickness, height and distance of perfobond ribs, and the thickness of concrete slabs. On the basis of 132 push-out test results in references and in this study, an analytical model was proposed by regression analysis to predict the shear strength of perfobond connectors. The proposed equation agreed reasonably well with the experimental results of perfobond connectors with different hole shapes.

Keywords: composite structures; perfobond connector; shear strength; push-out test; circular-hole; long-hole

1. Introduction

In the past few decades, steel and concrete composite structures have been increasingly used in the construction of buildings and bridges. By taking advantages of different construction materials, the favorable structural behavior and economic cost could be achieved. In order to optimize the structural performance of composite structures, it is critical to ensure the shear connection between steel and concrete components (Ranzi *et al*. 2004). The shear connection is typically achieved by the installation of shear connectors. Different types of shear connectors have been developed and investigated, such as headed studs (Lin *et al*. 2016), perfobond connectors (Cândido-Martins *et al*. 2010, Zheng *et al*. 2016a, b), Y-type perfobond connectors (Kim *et al*. 2017), composite dowels (Lorenc *et al*. 2014a, b), T, T-block and T-perfobond connectors (Rodrigues and Laím 2014). Compared with other shear connectors, headed studs are most widely used in practice. However, headed studs have some disadvantages such as difficulties in installation and fatigue problems of welding under cyclic loading (Dogan and Roberts 2012).

In the 1980s, an alternative shear connector named perfobond connector was first used by the German consulting engineering firm, Leonhardt, Andrä and Partner of Stuttgart (Zellner 1987). The aim was to ease the installation of shear connectors and to increase the fatigue strength (Leonhardt *et al*. 1987). A typical perfobond connector consists of a steel plate with a number of holes, in which concrete dowels are formed to transfer loads at the steel-concrete interface. The perfobond connector has some comparative advantages over headed studs, such as easy installations and favorable fatigue performances. Therefore, the use of perfobond connectors has covered a wide range of composite structures, including the joints of composite decks (Kim and Jeong 2006), composite beams (He *et al*. 2010), hybrid girders (Liu and Liu 2015), and composite trusses (Xue *et al*. 2011).

Recently, several researches have been carried out to study the shear behavior of perfobond connectors (Ahn *et al*. 2010, Al-Darzi *et al*. 2007, Cândido-Martins *et al*. 2010, Furuichi *et al*. 1998, Furuuchi *et al*. 2005, Himukai *et al*. 2007, Hosaka *et al*. 2000, Leonhardt *et al*. 1987, Medberry and Shahrooz 2002, Nishiumi *et al*. 1998, Oguejiofor and Hosain 1997, Taira *et al*. 1998, Tanaka *et al*. 2013, Zheng *et al*. 2016a, b). The investigated parameters included the dimension of the specimen, the number and size of the hole, the configuration of the rebar in hole, the material properties of steel and concrete. A number of equations have been proposed to estimate the shear strength of perfobond connectors (Ahn *et al*. 2010, Al-Darzi *et al*. 2007, Hosaka *et al*. 2000, Leonhardt *et al*. 1987, Medberry and Shahrooz 2002, Oguejiofor and Hosain 1997). According to the experimental and numerical analyses, the shear strength of perfobond connectors differs greatly from each other due to different geometries and material properties.

Due to limits in hole distances and rib heights, various hole shapes including circular-hole and long-hole are alternatives for perfobond connectors. In this study, a total of 72 push-out tests were carried out to evaluate the shear

*Corresponding author, Professor
E-mail: yql@tongji.edu.cn
[a]Ph.D.

http://www.techno-press.com/journals/sem&subpage=7
ISSN: 1225-4568 (Print), 1598-6217 (Online)

Table 1 Design variables of push-out test specimens

Group	d (mm)	d_l (mm)	d_h (mm)	d_s (mm)	f_{cu} (MPa)	f_c (MPa)	f_y (MPa)	f_u (MPa)	t (mm)	h (mm)	e (mm)	a (mm)	b (mm)
PS-1	50	50	50	20	43.3	34.6	373.6	577.4	20	150	200	460	400
PS-2	60	60	60	20	43.3	34.6	373.6	577.4	20	150	200	460	400
PS-3	75	75	75	20	43.3	34.6	373.6	577.4	20	150	200	460	400
PS-4	50	50	50	20	70.3	56.2	381.7	546.6	20	150	200	460	400
PS-5	60	60	60	20	70.3	56.2	381.7	546.6	20	150	200	460	400
PS-6	75	75	75	20	70.3	56.2	381.7	546.6	20	150	200	460	400
PS-7	60	60	60	16	43.3	34.6	373.6	577.4	20	150	200	460	400
PS-8	60	60	60	25	43.3	34.6	373.6	577.4	20	150	200	460	400
PS-9	60	60	60	20	70.3	56.2	480.0	623.0	20	150	200	460	400
PS-10	60	60	60	20	43.3	34.6	373.6	577.4	20	100	200	460	400
PS-11	60	60	60	20	43.3	34.6	373.6	577.4	20	150	75	460	400
PS-12	60	60	60	20	43.3	34.6	373.6	577.4	20	150	150	460	400
PS-13	65	65	65	20	43.3	34.6	373.6	577.4	16	210	200	460	400
PS-14	65	65	65	20	43.3	34.6	373.6	577.4	22	210	200	460	400
PS-15	60	60	60	20	43.3	34.6	373.6	577.4	20	150	200	460	300
PS-16	75	75	75	20	63.4	50.7	335.0	455.0	20	150	150	400	500
PS-17	50	50	50	20	54.6	43.7	335.0	455.0	20	100	150	400	200
PS-18	50	50	50	20	54.6	43.7	335.0	455.0	20	100	150	400	200
PS-19	50	50	50	20	54.6	43.7	335.0	455.0	20	100	150	400	200
PS-20	50	50	50	—	54.6	43.7	335.0	455.0	20	100	150	400	200
PS-21	50	75	50	20	70.3	56.2	381.7	546.6	20	150	200	460	400
PS-22	50	100	50	20	70.3	56.2	381.7	546.6	20	150	200	460	400
PS-23	50	125	50	20	70.3	56.2	381.7	546.6	20	150	200	460	400
PS-24	50	50	100	20	70.3	56.2	381.7	546.6	20	150	200	460	400

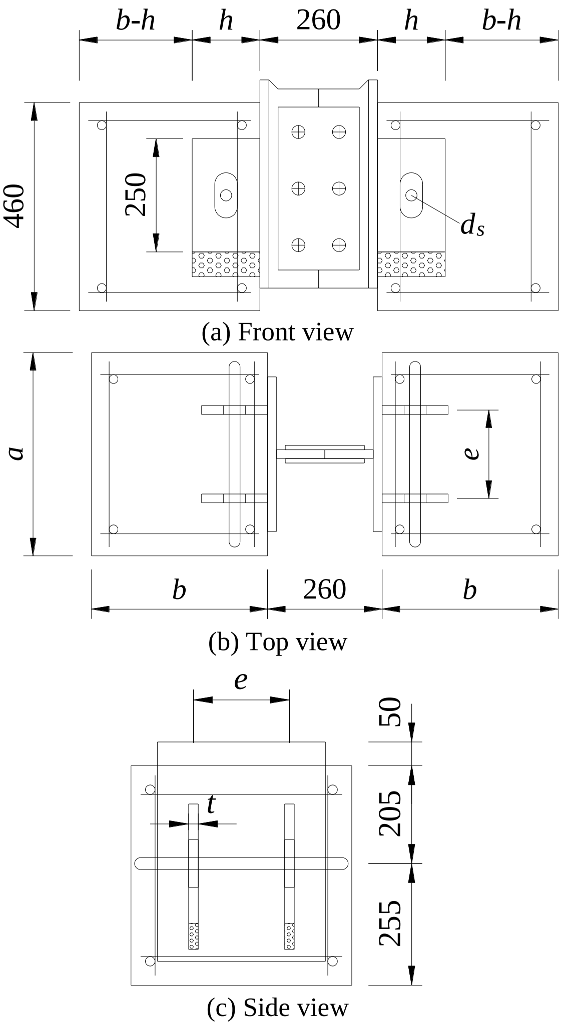


Fig. 1 Layout of push-out test specimen (unit: mm)

strength of circular-hole and long-hole perfobond connectors. The main purpose was to examine the effects of several design variables, including the hole diameter, the hole length, the hole height, the concrete strength, the existence, diameter and strength of rebar in the hole, the thickness, height and distance of perfobond ribs, and the thickness of concrete slabs. On the basis of 132 push-out test results in references and in this study, an analytical model was proposed to predict the shear strength of perfobond connectors with different hole shapes.

2. Experimental program

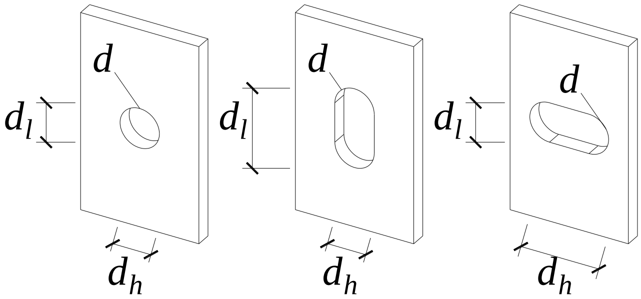
2.1 Test specimens

The push-out tests were performed on 72 specimens divided into 24 groups. Each group had three identical specimens with circular-hole or long-hole perfobond connectors. As shown in Table 1, the design variables of each push-out specimen were provided as follows: the hole diameter d, the hole length d_l, the hole height d_h, the concrete cube strength f_{cu} and uniaxial compressive strength f_c, the diameter d_s, yield strength f_y and tensile strength f_u of the rebar in hole, the thickness t, height h and distance e of the perfobond ribs, the width a and thickness b of the concrete slab. The tests of groups PS-4 to PS-6 and PS-21 to PS-24 have been described by Zheng *et al*. (2016a).

Fig. 1 shows the configuration of push-out specimens, which were designed and fabricated referring to EN 1994-1-1 (2004). A typical specimen was composed of one steel H-beam, two concrete slabs, and four perfobond ribs with holes. The steel H-beam consisted of two identical T-beams. Four perfobond ribs were welded upright to two T-beam flanges. The reinforcing bar were all fixed at the center of the hole for each perfobond rib. A Styrofoam was attached to the bottom of the perfobond ribs to eliminate the end-bearing resistance. The steel plate surface in contact with concrete were greased to minimize the chemical bond and friction (Ahn *et al*. 2010). Two concrete slabs were then cast against both beam flanges. After concrete hardening, these two halves were assembled by bolts and fish plates to form a complete specimen.

As illustrated in Fig. 2, circular-hole and long-hole were both adopted for specimens in this experimental program. The long-hole was formed by combining one rectangle and two semicircles. The hole diameter d was the diameter of

(a) Perfobond connector



PS-1~PS-20 PS-21~PS-23 PS-24

(b) Hole shape

Fig. 2 Perfobond connector with various hole shapes

Fig. 3 Test setup and instrumentation

the circle or semicircle. The hole length d_l and the hole height d_h were defined as the maximum size of each hole in vertical and horizontal directions, respectively.

2.2 Material properties

As listed in Table 1, the concrete cube strength f_{cu} was determined from 150-mm concrete cube tests after 28-day air curing period. The uniaxial compressive strength of concrete f_c was assumed to be $0.8f_{cu}$. The yield strength f_y

(a) Crack of concrete slab

(b) Deformation of rebar

(c) Dowel shear with rebar

(d) Dowel shear without rebar

Fig. 4 Failure modes

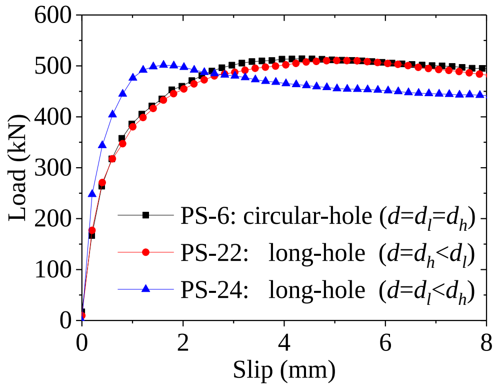


Fig. 5 Typical load-slip curves

and tensile strength f_u of rebar in hole were obtained from tension tests. In addition, the yield strength and tensile strength of the structural steel were 410.0 MPa and 545.0 MPa, respectively.

2.3 Test setup and instrumentation

Fig. 3 shows a typical test setup for push-out specimens with perfobond connectors. These specimens were tested using a hydraulic loading machine of 4000 kN capacity. A steel plate was located at the top of the H-beam to ensure that the loads were well distributed among four connectors. A layer of fine sand was paved under two concrete slabs, aiming to reduce concentrated reaction forces at the bottom of the specimen. Referencing to the study of Ahn *et al.* (2010), the load was slowly applied in several steps until the specimen failure occurred in about 40 minutes.

The instrumentation involved four dial gauges which were positioned at the same height of four perfobond connectors. By averaging the output of these four gauges, the slip between the steel H-beam and the concrete slab was obtained. The shear loads and slip deformations were continuously recorded during the test. As a result, the load-slip curves of the specimens were derived and the shear strength of perfobond connectors could be evaluated.

3. Experimental results

3.1 Failure modes

As shown in Fig. 4, the failure of specimens with perfobond connectors involved cracking of concrete slab, deformation of rebar in hole, and shear failure of concrete dowel. The concrete crack initially occurred at the neighborhood of shear connectors and spread out across the concrete slab as the load increased. The concrete slabs were dismantled after loading. The rebar in hole yielded at the locations of perforation due to large deformation. The concrete dowels of perfobond connectors failed in shear, regardless of the existence of rebar in holes.

3.2 Load-slip behavior

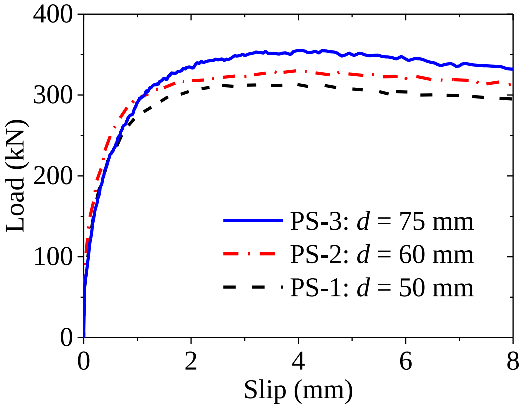
The slip behavior of perfobond connectors was characterized by the load-slip curves. Three stages were observed in the typical load-slip curves of perfobond connectors with almost the same hole area, as shown in Fig. 5. At the first stage, these curves were steep without obvious slips, indicating that perfobond connectors had elastic behavior and large stiffness. The next stage was a nonlinear curve where the load increased and the stiffness reduced slowly with the slip. After the shear strength of perfobond connector was reached, the slip continued to increase as the load decreased. In comparison with the specimens in PS-6, specimens in PS-22 performed more ductile, while those in PS-24 behaved a little brittle, indicating great influence of hole shapes on the ductility of perfobond connector.

Table 2 Test results of shear strength of perfobond connectors

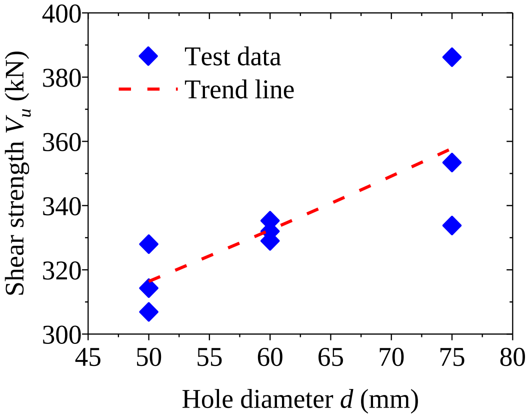
Group	Investigated parameters	Shear strength V_u (kN)				Slip capacity s_u (mm)			
		$V_{u,1}$	$V_{u,2}$	$V_{u,3}$	$V_{u,avg}$	$s_{u,1}$	$s_{u,2}$	$s_{u,3}$	$s_{u,k}$
PS-1	Hole diameter and concrete strength	328.0	306.9	314.3	316.4	8.32	9.74	9.84	7.49
PS-2		335.3	329.0	332.0	332.1	9.85	9.90	9.85	8.87
PS-3		386.2	333.8	353.4	357.8	9.81	9.07	9.87	8.83
PS-4		386.9	430.5	364.9	394.1	9.79	9.84	7.25	6.52
PS-5		420.0	438.5	413.5	424.0	9.87	9.88	9.79	8.81
PS-6		523.6	540.1	479.5	514.4	9.75	9.90	9.70	8.78
PS-7	Diameter of rebar in hole	284.9	284.4	299.1	289.5	8.68	8.18	9.06	7.36
PS-8		397.0	346.1	375.4	372.8	9.74	9.61	8.71	7.84
PS-9	Strength of rebar in hole	440.0	466.0	454.0	453.3	9.88	9.68	9.40	8.46
PS-10	Perfobond rib height	350.5	317.1	321.1	329.6	8.19	4.19	9.57	3.77
PS-11	Perfobond rib distance	335.3	333.8	347.5	338.9	8.19	8.84	9.71	7.37
PS-12		362.7	358.3	318.7	346.6	9.86	8.82	9.18	7.94
PS-13	Perfobond rib thickness	392.6	394.5	394.0	393.7	9.44	9.21	9.84	8.29
PS-14		374.0	415.6	422.4	404.0	9.84	8.61	9.76	7.75
PS-15	Concrete slab thickness	323.6	334.6	322.1	326.8	9.40	9.94	8.31	7.48
PS-16		494.1	474.9	515.0	494.7	3.05	6.34	—	2.75
PS-17	Existence of rebar in hole	340.7	320.0	434.0	364.9	2.21	0.38	1.77	0.34
PS-18		362.8	375.9	339.2	359.3	2.89	1.34	1.58	1.21
PS-19		363.0	351.0	362.2	358.7	1.90	1.93	1.80	1.62
PS-20		204.7	167.2	237.5	203.1	0.67	0.94	1.47	0.60
PS-21	Hole length	501.0	442.5	477.0	473.5	6.81	11.10	12.87	6.13
PS-22		503.0	514.6	515.6	511.1	9.94	9.81	10.44	8.95
PS-23		477.0	556.6	562.1	531.9	9.61	7.93	11.80	7.14
PS-24	Hole height	506.5	505.5	505.0	505.7	4.68	6.65	4.90	4.21

3.3 Shear strength and ductility

The shear strength of perfobond connector was taken as the ultimate load per hole and denoted as V_u. The tested shear strengths of each specimens were denoted as $V_{u,i}$,



(a) Load-slip curves



(b) Shear strength

Fig. 6 Effect of hole diameter

while the average shear strength of each group was denoted as $V_{u,avg}$. According to EN 1994-1-1 (2004), the slip capacity ($s_{u,i}$) was evaluated by the maximum slip at the characteristic load level ($0.9V_{u,i}$), and the characteristic slip capacity ($s_{u,k}$) was taken as the minimum tested slip capacity reduced by 10%. As shown in Table 2, the test results indicated great effects on the shear strength of perfobond connectors by changing the hole diameter, length and height, the concrete strength, the existence, diameter and strength of rebar in hole. In contrast, the thickness of the concrete slab, the thickness, height and distance of the perfobond ribs had negligible effects on the shear strength within the scope of this study. Except those with thin concrete slab and great hole height, the perfobond connector behaved ductile, as $s_{u,k}$ was at least 6 mm, according to EN 1994-1-1 (2004).

4. Parametric study

In the following content, the mean load-slip curve of three specimens in each group was presented.

4.1 Effect of hole diameter

The specimens in groups PS-1, PS-2 and PS-3 were similar in every respect except that the hole diameters of perfobond connector were 50 mm, 60 mm and 75 mm,

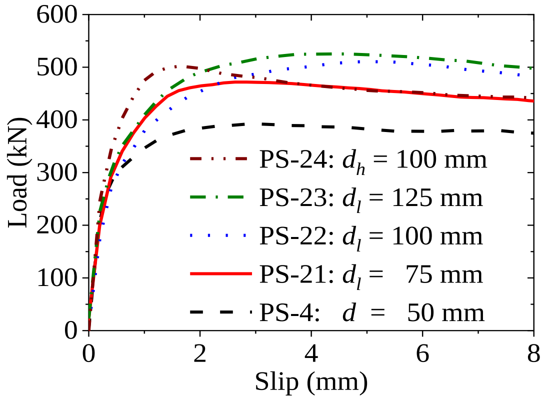
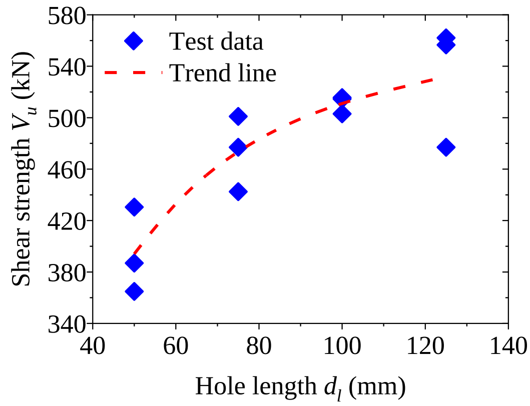
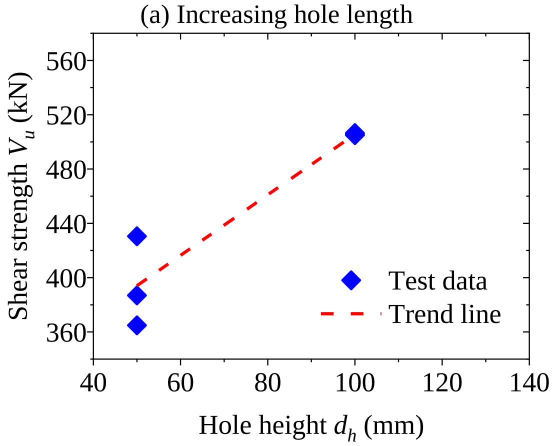


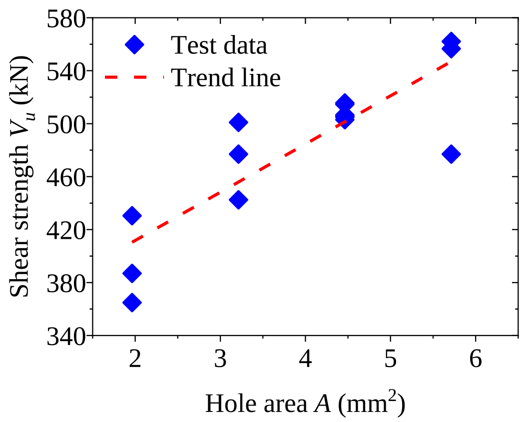
Fig. 7 Load-slip curves of specimens elongating the hole



(a) Increasing hole length

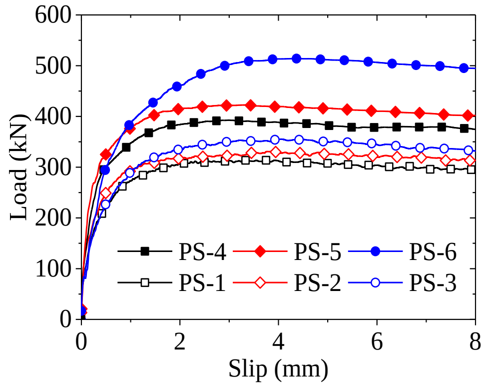


(b) Increasing hole height

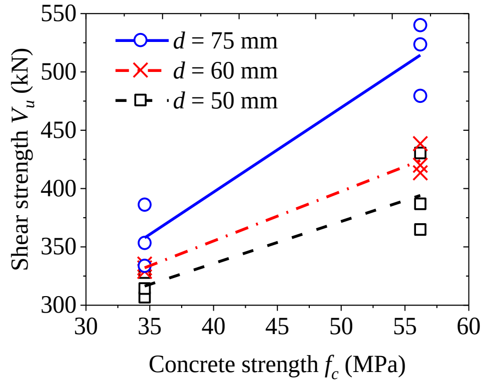


(c) Elongating the hole

Fig. 8 Effect of hole length and height

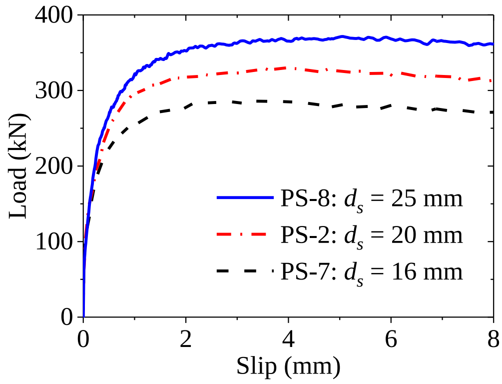


(a) Load-slip curves

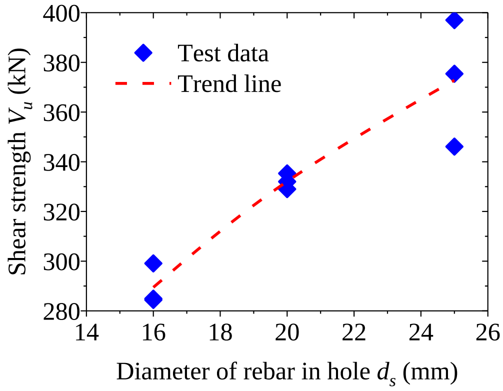


(b) Shear strength

Fig. 9 Effect of concrete strength



(a) Load-slip curves



(b) Shear strength

Fig. 10 Effect of diameter of rebar in hole

respectively. The load-slip curves in Fig. 6(a) indicate obvious effects of increasing the hole diameter on the shear strength of perfobond connectors. As shown in Fig. 6(b), the shear strength increased by 5% and 13% when the hole diameter was changed from 50 mm to 60 mm, and from 50 mm to 75 mm, respectively. The reason may be that increasing hole diameter led to larger concrete dowel and thus increased the shear strength of perfobond connectors.

4.2 Effect of hole length and height

The specimens in groups PS-4, PS-21 to PS-24 were identical in every respect except that the hole length and height were changed. In comparison with specimens in group PS-4, the hole length of specimens in groups PS-21, PS-22 and PS-23 were increased from 50 mm to 75 mm, 100 mm and 125 mm, while the hole height of those in group PS-24 were increased from 50 mm to 100 mm. As shown in Fig. 7, the hole length and height had obvious effect on the load-slip behavior of perfobond connectors. It was indicated that elongating the hole led to increase in the shear strength of perfobond connector.

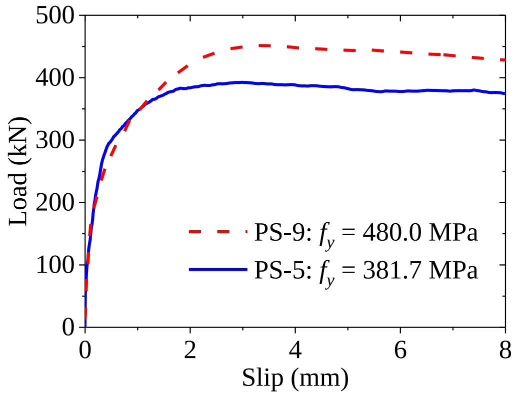
As shown in Fig. 8(a), when the hole length varied from 50 mm to 75 mm, 100 mm and 125 mm, the shear strength of perfobond connector increased by 20%, 30% and 35%, respectively. When the hole height changed from 50 mm to 100 mm, as shown in Fig. 8(b), the shear strength of perfobond connector increased by 28%. It was indicated that the shear strength of perfobond connector could be increased by elongating the hole either by adding the hole length or hole height. As shown in Fig. 8(c), the shear strength of perfobond connector increased as the hole area increased. The hole areas of specimens in groups PS-22 and PS-24 were both 4464 mm^2. The difference between the shear strengths of these two groups was only 1%. It can be concluded that the direction of hole axis has negligible effect on the shear strength of perfobond connectors.

4.3 Effect of concrete strength

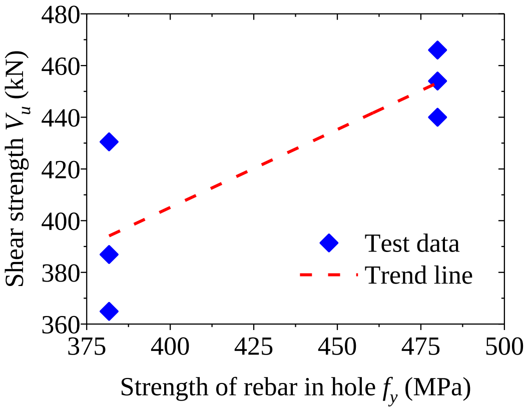
The specimens in groups PS-1, PS-2 and PS-3 were similar except that their hole diameters of perfobond connectors were 50 mm, 60 mm and 75 mm. The corresponding specimens in groups PS-4, PS-5 and PS-6 had the same details of design, except that the concrete compressive strength increased from 34.6 MPa to 56.2 MPa. As shown in Fig. 9, for specimens with the hole diameter of 50 mm, 60 mm and 75 mm, increasing the concrete strength from 34.6 MPa to 56.2 MPa led to increase in the shear strength by 25%, 28% and 44%, respectively. The reason may be that the shear strength was largely contributed by the concrete dowel force which increased with the concrete compressive strength.

4.4 Effect of diameter of rebar in hole

The specimens in groups PS-7, PS-2 and PS-8 were identical in every respect except that the diameters of rebar in hole were 16 mm, 20 mm and 25 mm, respectively. As shown in Fig. 10(a), the load-slip behavior of perfobond



(a) Load-slip curves



(b) Shear strength

Fig. 11 Effect of strength of rebar in hole

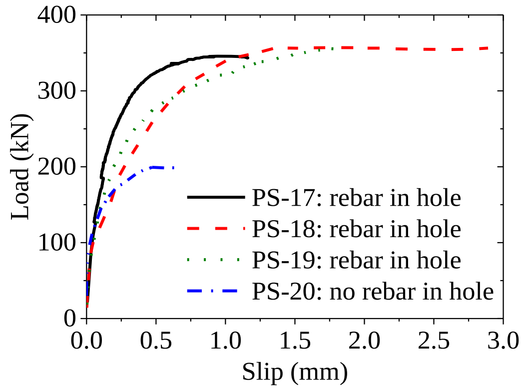


Fig. 12 Effect of existence of rebar in hole

connectors was greatly influenced by changing the diameter of rebar in hole. When the diameter of rebar in hole was increased from 16 mm to 20 mm and from 16 mm to 25 mm, as shown in Fig. 10(b), the shear strength of perfobond connector increased by 15% and 29%, respectively. The reason may be that larger rebar in hole had greater interlock effect and thus increased the shear strength of perfobond connectors.

4.5 Effect of strength of rebar in hole

Fig. 11(a) shows the load-slip curves for specimens in groups PS-5 and PS-9 which were similar except that the yield strengths of rebar in hole were 381.7 MPa and 480.0 MPa, respectively. The comparison of load-slip curves indicated obvious effect of rebar strength on the shear strength of perfobond connectors. As illustrated in Fig. 11(b), the shear strength increased by 15% when the yield strength of rebar increased from 381.7 MPa to 480.0 MPa. The results revealed that the shear strength of perfobond connectors could be increased by providing high-strength rebar in hole.

4.6 Effect of existence of rebar in hole

The load-slip curves of perfobond connectors with and without rebar in hole were compared in Fig. 12. A rebar of 20 mm in diameter was positioned in the hole of specimens in groups PS-17, PS-18 and PS-19. In comparison, no rebar in hole was provided for specimens in group PS-20. Compared with the specimens without rebar in hole, the shear strength of specimens with rebar in hole increased by 78% on average. The reason may be that the shear of rebar in hole contributed to the shear strength of perfobond connectors and the confinement effect on concrete was strengthened as well.

5. Prediction of shear strength

5.1 Components of shear strength

In previous researches, a number of analytical models have been proposed to calculate the shear strength of perfobond connectors. Oguejiofor and Hosain (1997), Ahn *et al*. (2000), Al-Darzi *et al*. (2007) proposed shear strength equations of perfobond connectors by using the ultimate load divided by the rib number. Medberry and Shahrooz (2002) developed another equation to calculate the shear strength per slab of perfobond connectors. Leonhardt *et al*. (1987), Hosaka *et al*. (2000) suggested different equations to predict the shear strength per hole of perfobond connectors. According to these equations (Ahn *et al*. 2010, Al-Darzi *et al*. 2007, Hosaka *et al*. 2000, Leonhardt *et al*. 1987, Medberry and Shahrooz 2002, Oguejiofor and Hosain 1997), the shear strength of perfobond connector were mostly contributed by the concrete dowel, the rebar in hole, the concrete end-bearing effect, the splitting resistance of concrete slab, the transverse reinforcement, and the chemical bond.

As shown in Fig. 13, perfobond connectors are typically arranged with multi-holes at the steel-concrete interface of composite bridge structures. The shear forces among these holes diverge with each other to a great extent. It is more favorable to evaluate the shear strength per hole for the convenience in design and check of perfobond connectors in composite bridges. The shear strength of perfobond connector is largely affected by the shear resistances of the concrete dowel and the rebar in hole. The concrete end-bearing resistance reduces quickly with distance to the end-bearing region. The contributions of the splitting resistance of concrete slab, the transverse reinforcement, and the chemical bond are quite difficult to decompose from the test results. To avoid double counting, these effects could be

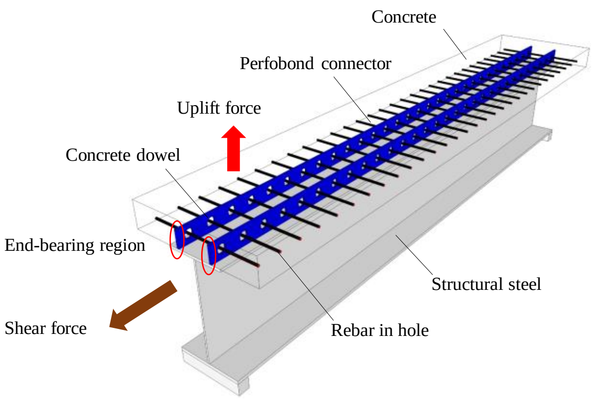


Fig. 13 Mechanical behavior of perfobond connector in composite structure

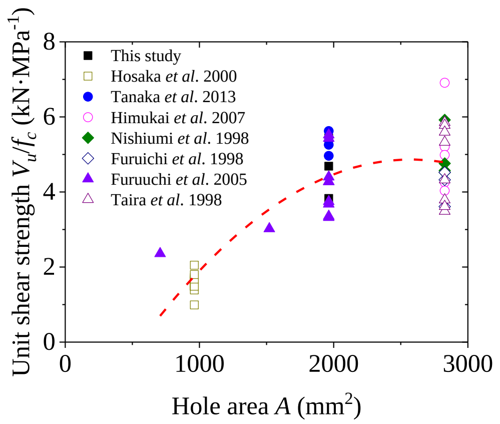


Fig. 14 Relationship of V_u/f_c and A without rebar in hole

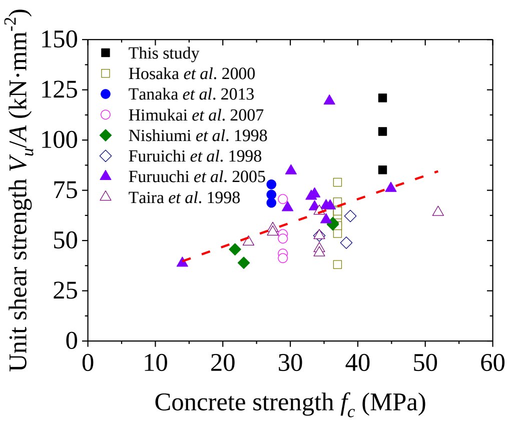


Fig. 15 Relationship of V_u/A and f_c without rebar in hole

included in the contribution of the concrete dowel.

5.2 Equation without rebar in hole

As presented in Table 3, the push-out test results of perfobond connectors without rebar in hole were collected from references (Furuichi *et al.* 1998, Furuuchi *et al.* 2005, Himukai *et al.* 2007, Hosaka *et al.* 2000, Nishiumi *et al.* 1998, Taira *et al.* 1998, Tanaka *et al.* 2013). These specimens in references had similar design to those in this study. No rebar perforated the holes of perfobond ribs. Styrofoam was used to eliminate the end-bearing resistance.

Table 3 Test data of specimens without rebar in hole

Specimen	d (mm)	f_c (MPa)	t (mm)	V_u (kN)	Reference	Specimen	d (mm)	f_c (MPa)	t (mm)	V_u (kN)	Reference
Type 1-1	35	37.0	16	76.0		C-12-140-L	60	23.1	12	110.0	
Type 1-2	35	37.0	16	55.0		C-12-140-H	60	36.3	12	164.0	Furuichi *et al.* (1998)
Type 1-3	35	37.0	16	60.6		C-25-140-L	60	21.8	25	129.0	
Type 3-1	35	37.0	12	36.6		C-25-140-H	60	36.3	25	166.0	
Type 3-2	35	37.0	12	57.2		1-1	50	33.6	12	143.7	
Type 3-3	35	37.0	12	60.4	Hosaka *et al.* (2000)	1-2	44	33.6	12	101.5	
Type 4-1	35	37.0	8	54.9		1-3	50	35.9	22	132.0	
Type 4-2	35	37.0	8	51.5		2-1	50	30.1	12	166.2	
Type 4-3	35	37.0	8	55.2		2-2	30	35.8	12	84.4	
Type 6-1	35	37.0	16	63.5		2-3	50	29.6	12	130.2	Furuuchi *et al.* (2005)
Type 6-2	35	37.0	16	62.2		2-4	50	35.3	12	118.4	
Type 6-3	35	37.0	16	66.6		2-5	50	33.1	12	141.4	
P6-0	50	27.2	6	143.0		2-6	50	14.0	12	76.0	
P9-0	50	27.2	9	153.0	Tanaka *et al.* (2013)	2-7	50	44.9	12	149.1	
P12-0	50	27.2	12	135.0		2-10	50	35.3	12	132.2	
S.D-B100-L300-H100	60	28.9	12	150.4		1-1	60	34.3	12	148.3	
S.D-B50-L300-H100	60	28.9	12	123.0		1-2	60	34.3	12	182.7	
S.D-B200-L300-H100	60	28.9	12	199.7	Himukai *et al.* (2007)	1-3	60	34.3	12	130.0	
S.D-B100-L300-H150	60	28.9	12	144.1		1-4	60	51.9	12	181.0	Taira *et al.* (1998)
S.S-B100-H100	60	28.9	12	116.6		1-5	60	23.8	12	139.3	
3-1	60	34.3	12	148.3		1-6	60	34.3	12	124.0	
3-2	60	38.9	12	175.9	Nishiumi *et al.* (1998)	2-1	60	27.4	12	158.3	
3-3	60	38.3	12	138.3		2-2	60	27.4	12	153.3	

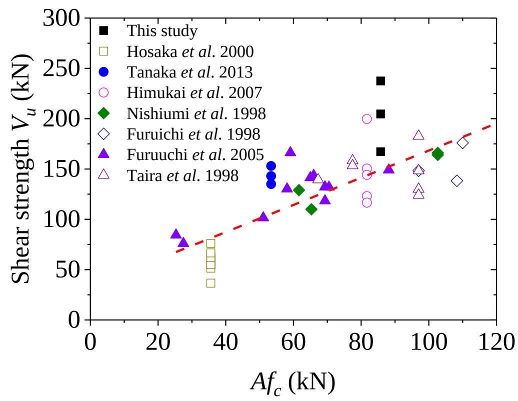


Fig. 16 Relationship of V_u and Af_c without rebar in hole

Greasing were applied to minimize the chemical bond and friction.

Fig. 14 shows the influences of hole area on the shear strength of perfobond connector. The horizontal axis is taken as the hole area A, and the vertical axis represents the

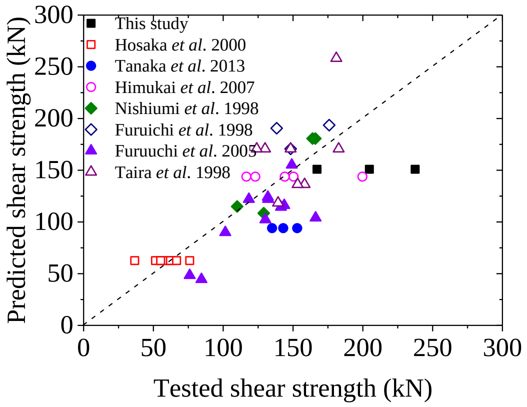


Fig. 17 Comparison of Eq. (1) and test results

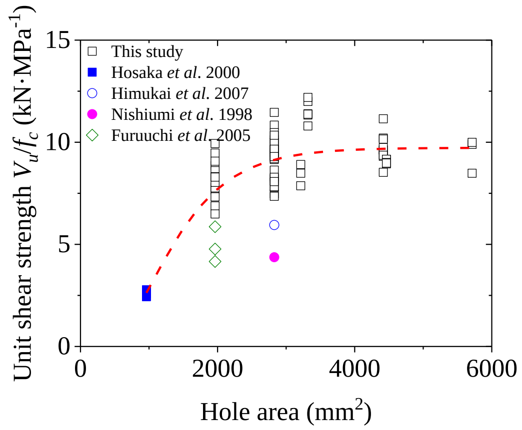


Fig. 18 Relationship of V_u/f_c and A with rebar in hole

Table 4 Test data of specimens with rebar in hole

Specimen	d (mm)	d_s (mm)	f_c (MPa)	f_y (MPa)	f_u (MPa)	t (mm)	V_u (kN)	Reference
Type 2-1	35	13	37.0	295.0	440.0	16	90.0	Hosaka et al. (2000)
Type 2-2	35	13	37.0	295.0	440.0	16	95.4	
Type 2-3	35	13	37.0	295.0	440.0	16	90.8	
Type 5-1	35	13	37.0	295.0	440.0	8	96.5	
Type 5-2	35	13	37.0	295.0	440.0	8	97.2	
Type 5-3	35	13	37.0	295.0	440.0	8	102.4	
Type 7-1	35	13	37.0	295.0	440.0	16	99.5	
Type 7-2	35	13	37.0	295.0	440.0	16	101.3	
Type 7-3	35	13	37.0	295.0	440.0	16	102.7	
S.D-B100-L300-H100-R.1-13	60	13	34.6	318.0	462.0	12	205.8	Himukai et al. (2007)
3-5	60	19	36.5	345.0	490.0	12	159.5	Nishiumi et al. (1998)
1-4	50	13	34.2	330.0	440.0	12	163.2	Furuuchi et al. (2005)
2-8	50	10	32.4	386.0	440.0	12	134.8	
2-9	50	22	32.4	358.0	490.0	12	190.0	

unit shear strength V_u/f_c. As shown in Fig. 14, the unit shear strength V_u/f_c increased with the increase of hole area A.

The effect of concrete strength on the shear strength of perfobond connector without rebar in hole is illustrated in Fig. 15. The horizontal axis is the concrete compressive strength f_c, while the vertical axis represents the unit shear strength V_u/A. As indicated in Fig. 15, the unit shear strength V_u/A increased with the concrete compressive strength f_c.

As shown in Fig. 16, the shear strength V_u of perfobond connector was found to increase in proportion to the product of the hole area A and the concrete compressive strength f_c. The reason may be that significant portions of the shear strength was contributed by the concrete dowel when no rebar was provided in hole for perfobond connectors.

Nonlinear regression analysis was performed on a total of 49 test results in references (Furuichi *et al.* 1998, Furuuchi *et al.* 2005, Himukai *et al.* 2007, Hosaka *et al.* 2000, Nishiumi *et al.* 1998, Taira *et al.* 1998, Tanaka *et al.* 2013) and in this study. Based on the analytical results, the

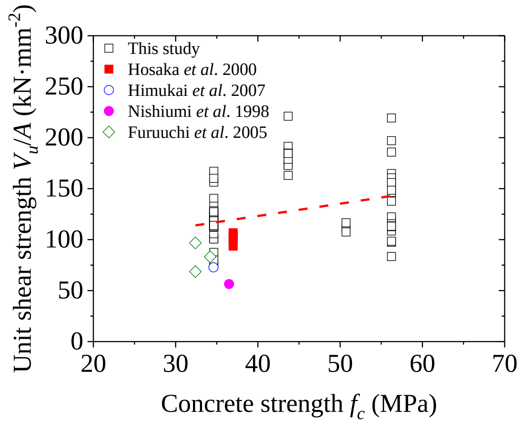


Fig. 19 Relationship of V_u/A and f_c with rebar in hole

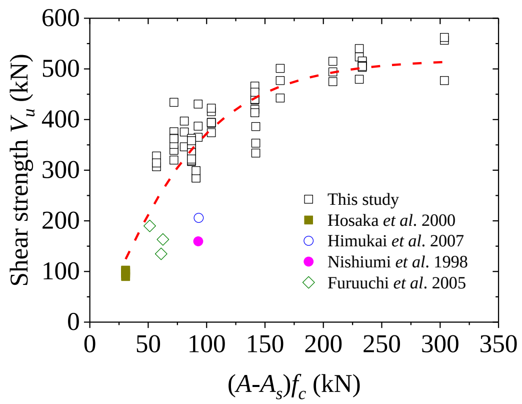


Fig. 20 Relationship of V_u and $(A-A_s)f_c$ with rebar in hole

shear strength of perfobond connector without rebar in hole can be evaluated by Eq. (1).

$$V_u = 1.76 A f_c \tag{1}$$

where V_u is the shear strength per hole of the perfobond connector (N); A is the hole area (mm^2); f_c is the concrete compressive strength (MPa).

As shown in Fig. 17, the calculated shear strength of specimens without rebar in hole agreed reasonably well with the test results in references (Furuichi *et al.* 1998, Furuuchi *et al.* 2005, Himukai *et al.* 2007, Hosaka *et al.* 2000, Nishiumi *et al.* 1998, Taira *et al.* 1998, Tanaka *et al.*

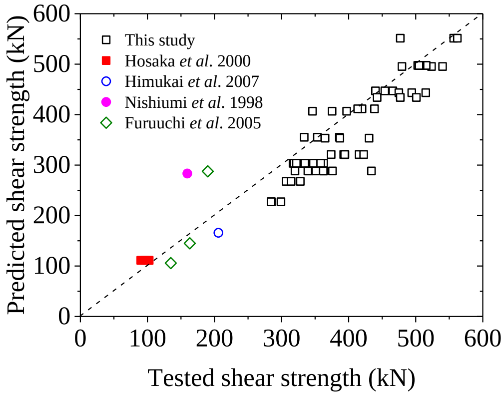


Fig. 21 Comparison of Eq. (2) and test results

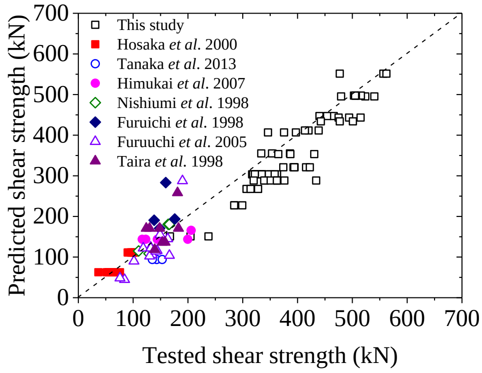


Fig. 22 Validation of proposed Eq. (3)

2013) and in this study.

5.3 Equation with rebar in hole

Table 4 shows the push-out test results of perfobond connectors with rebar in hole from references (Furuuchi *et al*. 2005, Himukai *et al*. 2007, Hosaka *et al*. 2000, Nishiumi *et al*. 1998). These specimens had similar configurations to those in this study. Each hole of the perfobond ribs were perforated with a rebar. The end-bearing resistance was eliminated by using Styrofoam. The chemical bond and friction were minimized by greasing.

As shown in Fig. 18, the hole area A had great influence on the shear strength of perfobond connector. It was indicated that the unit shear strength V_u/f_c increased with the increase of the hole area A, regardless of the hole shape. When the hole area A was greater than about 3000 mm^2, the unit shear strength V_u/f_c increased very slowly. The effect of the hole geometry on the shear strength of perfobond connector could be characterized by the hole area A.

Fig. 19 presents the effect of concrete strength on the shear strength of perfobond connector with rebar in hole. It was indicated that the unit shear strength V_u/A increased with the concrete compressive strength f_c.

As shown in Fig. 20, the shear strength V_u of perfobond connector was found to increase nonlinearly with the product of the dowel area (A-A_s) and the concrete compressive strength f_c. The result revealed that the concrete dowel has significant effect on the shear strength of perfobond connector with rebar in hole.

At specimen failure of perfobond connector, the rebar in hole yielded and the concrete dowels failed in shear. Since the shear strength of the rebar was $\sqrt{1/3}$ times of the yield strength f_y, and the shear area was twice of the cross-sectional area A_s, the contribution of the rebar in hole to the shear strength of perfobond connector could be taken as $1.15A_sf_y$. On the basis of Eq. (1), the hole area A was replaced with the dowel area (A-A_s), and an influence factor α_A was introduced to reflect the confinement effect of rebar on concrete. Therefore, the contribution of the concrete dowel to the shear strength of perfobond connector was assumed to be $1.76\alpha_A(A\text{-}A_s)f_c$, referring to the study of Zheng *et al*. (2016a).

Based on nonlinear regression analysis on a total of 83 test results both in references (Furuuchi *et al*. 2005, Himukai *et al*. 2007, Hosaka *et al*. 2000, Nishiumi *et al*. 1998) and in this study, the influence factor α_A was derived as $3.2\sqrt{A_s/A}$. As a result, the shear strength of perfobond connector with rebar in hole can be evaluated by Eq. (2).

$$V_u = 1.76\alpha_A\left(A - A_s\right)f_c + 1.15A_s f_y \tag{2}$$

where A_s is the area of the rebar in hole (mm^2); f_y is the yield strength of the rebar in hole (MPa); and α_A is the influence factor reflecting the confinement effect of rebar on concrete.

As shown in Fig. 21, the predicted shear strength of specimens with rebar in hole agreed well with the test results in references (Furuuchi *et al*. 2005, Himukai *et al*. 2007, Hosaka *et al*. 2000, Nishiumi *et al*. 1998) and in this study.

5.4 Proposal and validation

On the basis of Eqs. (1)-(2), a comprehensive analytical model, Eq. (3), was proposed to predict the shear strength of perfobond connector, regardless of the existence of rebar in hole and the variation of hole shapes.

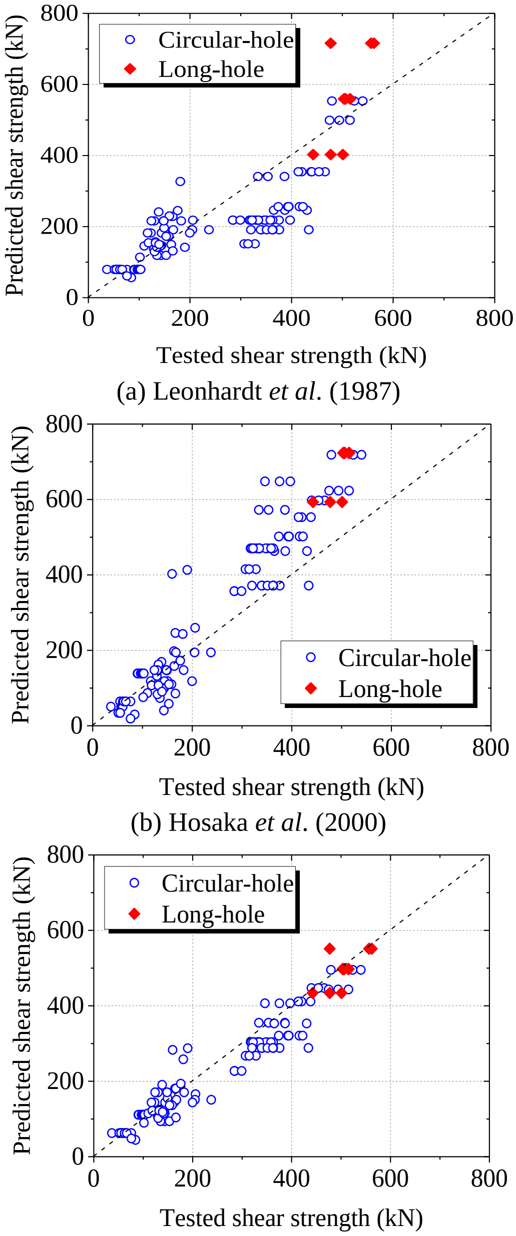
$$V_u = 1.76\alpha_A\left(A - A_s\right)f_c + 1.15A_s f_y$$
$$\text{with } \alpha_A = \begin{cases} 1.0 & \text{no rebar} \\ 3.2\sqrt{A_s/A} & \text{rebar} \end{cases} \tag{3}$$

The predicted results of Eq. (3) were in good agreement with 132 push-out test results in references (Furuichi *et al*. 1998, Furuuchi *et al*. 2005, Himukai *et al*. 2007, Hosaka *et al*. 2000, Nishiumi *et al*. 1998, Taira *et al*. 1998, Tanaka *et al*. 2013) and in this study, as shown in Fig. 22.

Among the available literatures, Eq. (4) suggested by Leonhardt *et al*. (1987) and Eq. (5) developed by Hosaka *et al*. (2000) estimated the shear strength per hole of perfobond connectors, which were similar to the proposal in this study.

$$V_u = 1.4d^2 f_{cu} \tag{4}$$

$$V_u = \begin{cases} 3.38\sqrt{t/d}\cdot d^2 f_c - 39.0\times10^3 & \text{no rebar} \\ 1.45\left[\left(d^2 - d_s^2\right)f_c + d_s^2 f_u\right] - 26.1\times10^3 & \text{rebar} \end{cases} \tag{5}$$



(a) Leonhardt *et al*. (1987)

(b) Hosaka *et al*. (2000)

(c) Proposed equation

Fig. 23 Comparison of different shear strength equations

where f_{cu} is the concrete cube strength (MPa); t is the thickness of the perfobond rib; f_u is the tensile strength of the rebar in hole (MPa).

Eqs. (4)-(5) were proposed for circular-hole perfobond connectors. To adapt to different hole shapes, these equations were modified by replacing d and d_s with $\sqrt{4A/\pi}$ and $\sqrt{4A_s/\pi}$, respectively. Thus, the modified versions of Eqs. (4)-(5) were derived as follows.

$$V_u = 2.23Af_c \tag{6}$$

$$V_u = \begin{cases} 4.57\sqrt[4]{t^2/A} \cdot Af_c - 39.0\times10^3 & \text{no rebar} \\ 1.85\left[\left(A - A_s\right) f_c + A_s f_u\right] - 26.1\times10^3 & \text{rebar} \end{cases} \tag{7}$$

As shown in Fig. 23, the predictions of Eqs. (2), (6)-(7) were compared to the test results of perfobond connector with various hole shapes in references (Furuichi *et al*. 1998, Furuuchi *et al*. 2005, Himukai *et al*. 2007, Hosaka *et al*. 2000, Nishiumi *et al*. 1998, Taira *et al*. 1998, Tanaka *et al*. 2013) and in this study. It can be seen that the equation proposed by Leonhardt *et al*. (1987) underestimated the shear strength for small holes and overestimated for large holes. The mean and variance of the ratio of experimental to predicted shear strength were 0.96 and 0.34, respectively. The reason may be that the contribution of rebar in hole and the variation of confinement effect were not considered in Eq. (6). The equation suggested by Hosaka *et al*. (2000) were in good agreement with test results of specimens with small hole and no rebar in hole. However, this equation overestimated the shear strength of perfobond connector with large hole and rebar in hole. The mean and variance of the ratio of experimental to predicted shear strength were 1.18 and 0.35, respectively. It was possibly because the tensile strength f_u was used in Eq. (7) to calculate the contribution of rebar in hole, while yielding of the rebar was observed at specimen failure instead of fracture. In comparison, the proposed equation, Eq. (3), yielded fairly reliable results, regardless of the existence of rebar in hole and the variation of hole shapes. The mean and variance of the ratio of experimental to predicted shear strength were 0.96 and 0.19, respectively.

6. Conclusions

This paper presents 72 push-out test results to investigate the shear strength of perfobond connectors with various hole shapes. According to the experimental results, parametric analysis and theoretical study, the following conclusions can be drawn:

- The failure modes of perfobond connectors with various hole shapes are similar to each other in terms of concrete cracking, deformation of rebar in hole, and shear failure of concrete dowel. The concrete crack initially occurs at the neighborhood of shear connectors and spread out across the concrete slab as the load increases. The rebar in hole yields at the locations of perforation due to large deformation. The concrete dowels of perfobond connector fail in shear, regardless of the existence of rebar in holes.
- The slip behaviors of perfobond connector with different hole shapes are characterized by load-slip curves. At the first stage, the load-slip curves are all steep without obvious slips, indicating that perfobond connectors have elastic behavior and large stiffness. The next stage is a nonlinear curve where the load increases and the stiffness reduce slowly with the slip. After the shear strength of perfobond connector is reached, the slip continues to increase as the load decreases gradually.
- Due to different geometries and material properties, the shear strength of perfobond connectors differs obviously from each other. The shear strength of perfobond connectors are greatly affected by changing the hole diameter, the hole length, the hole height, the concrete strength, the existence, diameter and strength of rebar in hole. On the contrary, the thickness of the concrete slab, the thickness, height and distance of the perfobond ribs have

negligible effects on the shear strength of perfobond connectors.

• The effect of the hole geometry on the shear strength of perfobond connector can be characterized by using the hole area, regardless of the hole shapes. Based on 132 experimental results and nonlinear regression analysis, an analytical model is proposed to predict the shear strength of perfobond connectors. The contributions of the concrete dowel and the rebar in hole, the influences of the confinement effect and the hole geometry are considered in the proposed equation. Compared with the existing equations, the proposal has a better fit with test results both in references and in this study, and thus may be used to predict the shear strength of perfobond connector with various hole shapes.

• The shear strength equation was proposed based on the experimental data of perfobond connectors with circular-hole and long-hole. For other types of hole-shapes, further experimental and numerical studies are required to validate the proposed shear strength equation.

All the findings in this study may provide references for the design and construction of perfobond connectors in steel and concrete composite structures.

Acknowledgements

The research described in this paper was financially supported by Grants from Fujian Provincial Natural Science Foundation of China (2018J05083) and Huaqiao University Scientific Research Funding (16BS804).

References

Ahn, J.H., Lee, C.G., Won, J.H. and Kim, S.H. (2010), "Shear resistance of the perfobond-rib shear connector depending on concrete strength and rib arrangement", *J. Constr. Steel Res.*, **66**(10), 1295-1307.

Al-Darzi, S.Y.K., Chen, A.R. and Liu, Y.Q. (2007), "Finite element simulation and parametric studies of perfobond rib connector", *Am. J. Appl. Sci.*, **4**(3), 122-127.

Cândido-Martins, J.P.S., Costa-Neves, L.F. and Vellasco, P.C.G.S. (2010), "Experimental evaluation of the structural response of perfobond shear connectors", *Eng. Struct.*, **32**(8), 1976-1985.

Dogan, O. and Roberts, T.M. (2012), "Fatigue performance and stiffness variation of stud connectors in steel-concrete-steel sandwich systems", *J. Constr. Steel Res.*, **70**(2), 86-92.

Eurocode (2004), *Design of Composite Steel and Concrete Structures. Part 1-1: General Rules and Rules for Buildings*, Brussels, Belgium.

Furuichi, K., Taira, Y. and Yamamura, M. (1998), *Experimental Study on Shear Strength of Shear Connectors Using Perforated Plate*, Report No. 46, Kajima Technical Research Institute, Kajima, Japan.

Furuuchi, H., Ueda, T., Suzuki, O. and Taguchi, H. (2005), "A study on shear transfer capacity of perfobond strip", *Proceedings of the 6th Symposium on Development of Hybrid Structures*, Tokyo, Japan, November.

He, J., Liu, Y., Chen, A. and Yoda, T. (2010), "Experimental study on inelastic mechanical behaviour of composite girders under hogging moment", *J. Constr. Steel Res.*, **66**(1), 37-52.

Himukai, M., Fujii, K. and Fukada, K. (2007), "Ultimate slip behavior of double-lined perfobond rib connector", *J. Struct. Eng.*, **53A**, 1089-1098.

Hosaka, T., Mitsuki, K., Hiragi, H., Ushijima, Y., Tachibana, Y. and Watanabe, H. (2000), "An experimental study on shear characteristics of perfobond strip and its rational strength equations", *J. Struct. Eng.*, **46A**, 1593-1604.

Kim, H.Y. and Jeong, Y.J. (2006), "Experimental investigation on behaviour of steel-concrete composite bridge decks with perfobond ribs", *J. Constr. Steel Res.*, **62**(5), 463-471.

Kim, S.H., Park, S., Kim, K.S. and Jung, C.Y. (2017), "Generalized formulation for shear resistance on Y-type perfobond rib shear connectors", *J. Constr. Steel Res.*, **128**, 245-260.

Leonhardt, F., Andrä, W., Andrä, H.P. and Harre, W. (1987), "New, improved bonding means for composite loadbearing structures with high fatigue strength", *Beton-Und Stahlbetonbau*, **82**(12), 325-331.

Lin, Z., Liu, Y. and Roeder, C.W. (2016), "Behavior of stud connections between concrete slabs and steel girders under transverse bending moment", *Eng. Struct.*, **117**, 130-144.

Liu, R. and Liu, Y. (2015), "Analysis of auxiliary ribs in steel-concrete joint of hybrid girder", *J. Constr. Steel Res.*, **112**, 363-372.

Lorenc, W., Kożuch, M. and Rowiński, S. (2014a), "The behaviour of puzzle-shaped composite dowels-part I: Experimental study", *J. Constr. Steel Res.*, **101**, 482-499.

Lorenc, W., Kożuch, M. and Rowiński, S. (2014b), "The behaviour of puzzle-shaped composite dowels-part II: Theoretical investigations", *J. Constr. Steel Res.*, **101**, 500-518.

Medberry, S.B. and Shahrooz, B.M. (2002), "Perfobond shear connector for composite construction", *Eng. J.*, **39**(1), 2-12.

Nishiumi, K., Tominaga, T., Muroi, S. and Furuichi, K. (1998), "Experimental study on shear connectors using perforated plate under the confinement", *Proc. JCI*, **20**(3), 865-870.

Oguejiofor, E.C. and Hosain, M.U. (1997), "Numerical analysis of push-out specimens with perfobond rib connectors", *Comput. Struct.*, **62**(4), 617-624.

Ranzi, G., Bradford, M.A. and Uy, B. (2004), "A direct stiffness analysis of a composite beam with partial interaction", *Int. J. Numer. Meth. Eng.*, **61**(5), 657-672.

Rodrigues, J.P.C. and Laím, L. (2014), "Experimental investigation on the structural response of T, T-block and T-Perfobond shear connectors at elevated temperatures", *Eng. Struct.*, **75**, 299-314.

Taira, Y., Furuichi, K., Yamamura, M. and Tominaga, T. (1998), "Experimental research on fundamental characteristics of perfobond connector", *Proc. JCI*, **20**(3), 859-864.

Tanaka, T., Sakai, J. and Kawano, A. (2013), "Development of new mechanical shear connector using burring steel plate", *J. Struct. Constr. Eng.*, **78**(694), 2237-2245.

Xue, D., Liu, Y., He, J. and Ma, B. (2011), "Experimental study and numerical analysis of a composite truss joint", *J. Constr. Steel Res.*, **67**(6), 957-964.

Zellner, W. (1987), "Recent designs of composite bridges and a new type of shear connectors", *Proceedings of the ASCE Engineering Foundation Conference on Composite Construction*, Henniker, U.S.A., June.

Zheng, S., Liu, Y., Yoda, T. and Lin, W. (2016a), "Parametric study on shear capacity of circular-hole and long-hole perfobond shear connector", *J. Constr. Steel Res.*, **117**, 64-80.

Zheng, S., Liu, Y., Yoda, T. and Lin, W. (2016b), "Shear behavior and analytical model of perfobond connectors", *Steel Compos. Struct.*, **20**(1), 71-89.

CC