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Experimental studying the effect of transverse reinforcement passing through perfobond holes on the structural behavior of perfobond shear connection

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KEYWORDS

Structural behavior
Connection dowel
Hot-rolled steel Perfobond shear connector
The relative slip
Shear capacity

ABSTRACT

The push-out test program was carried out on three groups of nine small specimens to investigate the effect of the transverse reinforcement passing through the perfobond holes on the structural behavior of perfobond shear connector. The number of transverse reinforcements passing through the perfobond holes was changed in each group. One of the groups had no transverse reinforcement, and the other groups had one and two transverse reinforcements passing through the perfobond holes. The quantities observed in this program were the load capacity, the relative slip between the hot-rolled steel and the concrete slab, and the failure mode of specimens. The results showed that the transverse reinforcement passing through the perfobond holes enhanced the load capacity and significantly reduced the relative slip between the hot-rolled steel and the concrete slab.

1. Introduction

The shear connector plays an important role in the steel-concrete composite beam. Without the shear connector, the steel-concrete composite structure can not utilize effectively its inherent advantages because the structural steel and the concrete slab will behave independently. There are many types of shear connectors, such as headed studs, perfobond ribs, T-rib connectors, oscillating perfobond strips, waveform strips, T-connectors, channel connectors, angle connectors, and non-welded connectors. Among these shear connectors, headed studs have been popularly used. However, perfobond shear connectors have been widely studied around the world.

M. U. Hosain et al. carried out push-out tests on many experiments of perfobond shear connectors [1, 2]. In these studies, perfobond shear connectors are steel rectangular plate with some round holes on steel plates. The authors evaluated the effect of parameters on load capacities and the relative slip between the structural steel and the concrete slab. From the test results, the authors also analyzed regression and gave prediction expression to determine the load capacity of perfobond shear connector. Isabel Valente and Paulo J.S. Cruz studied perfobond connectors with lightweight concrete to analyze and compare the contribution of the different elements to the slip measured between the steel profile and the concrete slab [3]. P.C.G. da S. Vellasco et al. proposed a perfobond rib shear connector and a connection element, denominated "T-rib" for composite action. Furthermore, the authors also carried out the full-scale composite semi-rigid portal frame to evaluate the transmission of the force developed in the reinforcing bars to the column flange using perfobond shear connectors [4]. L.F. Costa-Neves tested eighteen push-out tests of perfobond shear connectors to investigate variables: concrete slab thickness, concrete compressive strength, connector geometry, the relative position of the connector to the direction of loading, shear connector hole number and disposition [5, 6, 7]. Qingtian Su et al. investigated the modes of failure of perfobond shear connections using a novel push-out test procedure. The mechanisms for the resistance to a load of perfobond rib shear connectors were analyzed, and the effects of the concrete and transverse reinforcement on the shear resistance were investigated [8]. Duy Kien Dao et al. studied shear resistance behaviors of a newly puzzle shape of crestbond rib shear connectors based on fifteen push-out specimens. This study evaluated the effects of shear resistance parameters such as the dimensions of the crestbond rib, transverse rebars in the crestbond dowel, concrete strength, rebar strength, and dowel action on the shear strength [9]. Mohammed A. Al-Shuwaili carried out ten one-sided push-out tests (OSPOT) to investigate the behavior and the shear resistance of the PSC. The results were compared against POT results from other researchers and the predictions offered by several shear resistance equations [10]. Shuangjie Zheng studied six specimens by push-out test to compare the failure mode, shear capacity, and slip behavior of perfobond shear connectors using circular holes and notched holes [11]. Shuangjie Zheng conducted nine push-out tests to compare the failure mode and the load-slip behavior of the headed stud, perfobond rib, and mixed shear connector. The author also simulated 19 nonlinear finite elements to evaluate the effects of connector dimension and material properties on the structural behavior of mixed shear connectors [12]. Zhenxuan Yu performed six push-out specimens with recycled aggregate concrete for the upper slabs in steel-concrete composite beams and perfobond rib connectors. Finite element (FE) models for PBLs embedded in recycled aggregate concrete were developed, and corresponding experimental results validated numerical results. This study presents the results of an experimental and numerical simulation

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study that focused on characterizing the behavior of perfobond rib connectors fabricated using recycled aggregate concrete [13]. Kun-Soo Kim et al. applied various cyclic loading cases to analyze and verify the effect of cyclic behavior on Y-type shear connection. The test result shows that the shear strength under cyclic loads was lower than that under monotonic load [14].

This study conducted nine push-out specimens to evaluate the effect of the transverse reinforcement passing through the pefobond holes on the structural behavior of shear connectors. The perfobond connector has the shape of an omega letter (Ω) with some open holes in case easy to place the transverse reinforcements.

2. Test program

2.1. Specimens

Three groups of nine small specimens were made from hot-rolled steel of H200 × 200 × 8 × 12 and concrete slabs with a thickness of 90 mm, as shown in Figure 1. The perfobond shear connector with 8 mm in thickness was attached to hot-rolled steel flanges to prevent the relative slip between the hot-rolled steel and the concrete slab. There was a gap at the end of perfobond shear connector to exactly model the practical behavior of the specimen. The transverse reinforcement 12 mm in diameter was placed through the perfobond holes to increase the load capacity of the perfobond shear connectors. Linear Variable Differential Transformers (LVDT) were attached to the hot-rolled steel and the concrete slab to measure the vertical and lateral deformation, and the relative slip between the hot-rolled steel and the concrete slab of specimens.

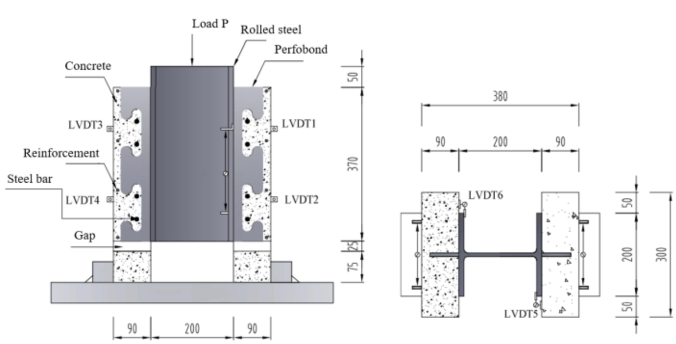


Figure 1. Push-out test model.

2.2. Material properties

2.2.1 Concrete

The concrete used for the specimens is B35. The aggregate gradation is shown in Table 1. The concrete was cured in 28 days and tested in compliance with TCVN 3118-1993 [15]. The concrete compressive strength test was carried out at the same time as the push-out test. The test results of concrete compressive strength are shown in Table 2.

Table 1. The aggregate gradation for 1 m^3 concrete.

Material component	Unit	Quantity
Holcim cement PCB40 PowerS	kg	330
Bank sand	kg	495
Crushed sand	kg	335
Stone	kg	1115
Water	littre	165
Addition agent BASF Sky 8735	kg	3.3

Table 2. Mechanical characteristic of concrete.

Specimen	Dimensions (mm)	Failure load (kN)	Compressive strength (MPa)
SP-1	150×150×150	751.5	33.4
SP-2	150×150×150	801.0	35.6
SP-3	150×150×150	769.5	34.2
Average value		774.0	34.4

2.2.2 Hot-rolled steel and reinforcement

Hot-rolled steel and perfobond steel used in this test is CT34 and the transverse reinforcement 12 mm in diameter is Vina Kyoei. Steel test was carried out in compliance with ASTM A370 – 14 [16]. The mechanical characteristic of reinforcement and hot-rolled steel is presented in Table 3.

Table 3. Mechanical characteristics of reinforcement and hot-rolled steel.

Quantity	Transverse reinforcement	Hot-rolled steel
Yield strength (MPa)	347	320
Ultimate strength (MPa)	488	425
Elastic modulus (MPa)	200×10^3	200×10^3

2.3 Push-out test

2.3.1 Tested specimen preparation

The push-out test was carried out on three groups of nine specimens. The parameters of specimens are shown in Figure 2 and summarized in Table 4. The detail of perfobond is shown in Figure 3 and the experimental specimen creation is illustrated in Figure 4.

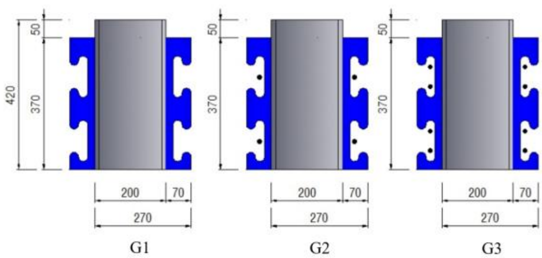


Figure 2. Tested specimens of perfobond shear connection.

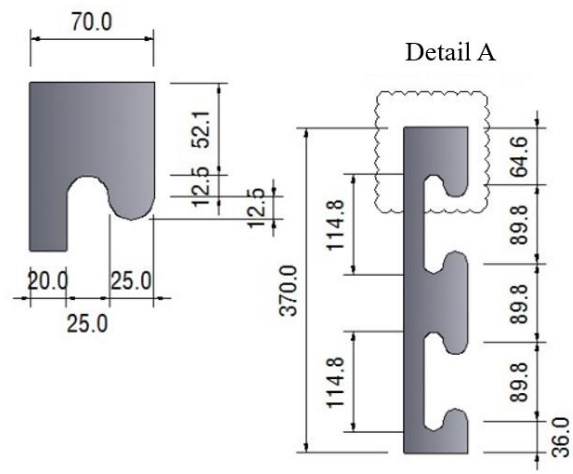
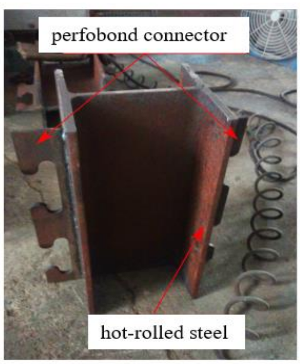


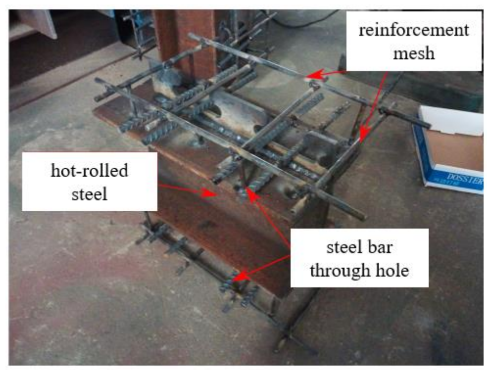
Figure 3. Detail of perfobond.

Table 4. Tested specimens of perfobond shear connection.

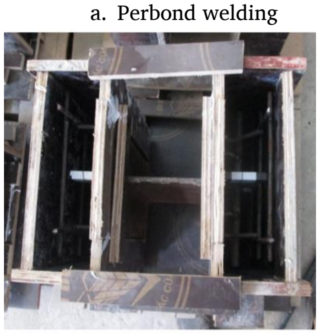
Group	Cross-section area per one dowel (mm²)	Concrete compressive strength (MPa)	Number of steel bar	Number of specimens
G1	4490	34.4	None	3
G2	4490	34.4	1Ø12	3
G3	4490	34.4	2Ø12	3



a. Perbond welding



b. Reinforcement process



c. Encasement process

d. Specimens after concreting

Figure 4. Specimen fabrication.

2.3.2 Test setup

The load capacity and the relative slip between the hot-rolled and the concrete slab were two important quantities that needed to be measured during testing. Linear variable displacement transducers recorded this relative slip: LVDT1 and LVDT2. The concrete crack was measured by LVDT3, LVDT4, LVDT5, and LVDT6. The applied load on the specimen was recorded by a load cell of 2000 kN, as shown in Figure 5.

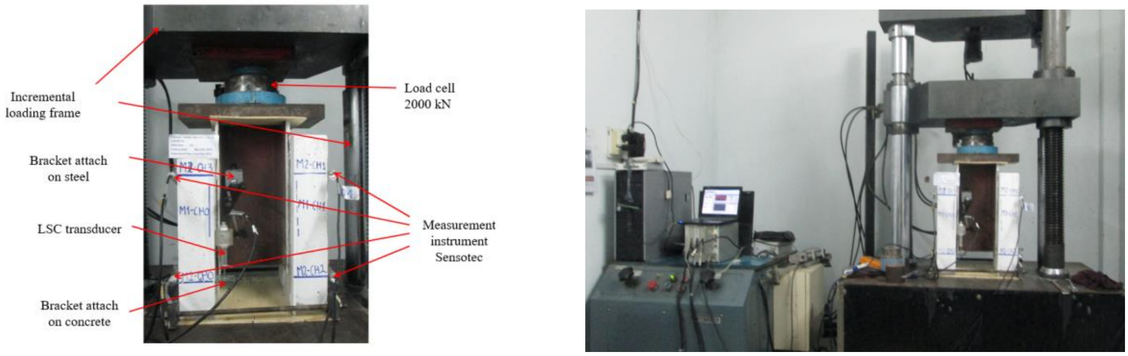


Figure 5. Test setup.

2.3.3 Incremental loading process

The incremental loading process was performed complying with Eurocode 4 [17]. This procedure had 3 phases, as shown in Figure 6:

- Phase 1: Increasing load from 0 to 40% failure load (P_{max}), and then repeating 2 times.
- Phase 2: Increasing load from 10% P_{max} to 40% P_{max}, and then repeat 25 times. This stage is to eliminate the adhesive force, friction, and residual strain of testing.
- Phase 3: After ending phase 2, increase load from 10% P_{max} to failure load, continue increasing load until the load remains 90% P_{max}, and stop testing.

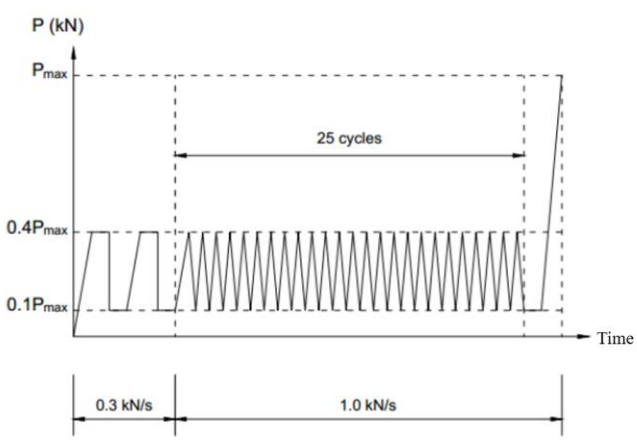


Figure 6. Incremental loading process.

Table 5. Push-out test results.

Value	Unit	Group		
		G1	G2	G3
P_{max}	kN	389.46	494.80	565.69
P_{uk}	kN	350.51	445.32	509.12
δ_u	mm	2.25	3.75	2.52
δ_{uk}	mm	3.48	6.05	5.81

In which:

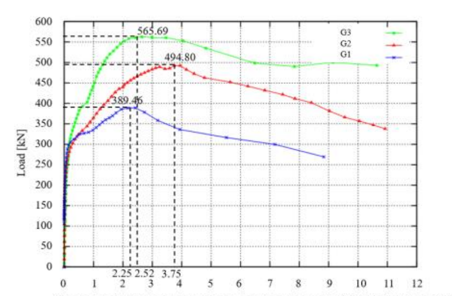
P_{max} is the failure load

$P_{uk} = 90\%P_{max}$

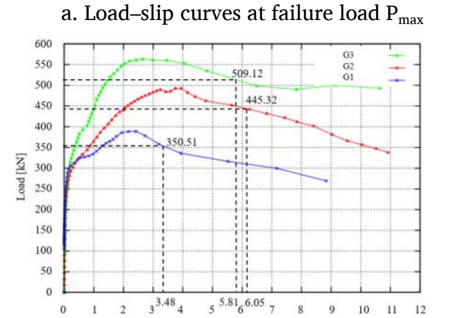
$P_{uk,1}$ is the shear capacity per dowel hole

δ_u is the relative slip between hot-rolled steel and the concrete slab at failure load P_{max}

δ_{uk} is the relative slip between hot-rolled steel and the concrete slab at $P_{uk} = 90\% P_{max}$



a. Load–slip curves at failure load P_{max}



b. Load–slip curves at $P_{uk} = 90\% P_{max}$

Figure 7. Load–slip curves.

3. Test results and discuss

3.1 Test results

The push-out test results of the perfobond shear connection are presented in Table 5. The relationship between load capacity and the relative slip between the hot-rolled steel and the concrete slab is plotted in Figure 7. The results show that specimen G3 with two transverse reinforcements Ø12 passing through the perfobond holes has the highest load capacity.

3.1.1 The load capacity

The load capacity of specimens G1, G2, and G3 is 389.46 kN, 494.80 kN, and 565.69 kN, respectively, as presented in Table 6. The load capacity of specimen G1 without the transverse reinforcement passing through the perfobond holes gives the lowest value. The load capacity of G2 and G3 increases by 27.95 % and 45.25 % compared to that of G1. The load capacity of G3 is higher than that of G2 about 14.32 %. This indicates the number of transverse reinforcements passing through perfobond holes enhances the load resistance of perfobond shear connectors.

Table 6. Load capacity comparison of specimens.

Value	Unit	G1	G2	G3
P_{max}	kN	389.46	494.80	565.69
P_{uk}	kN	350.51	445.32	509.12
$\Delta P = (P_i - P_1)/P_1$	%	1.00	27.05	45.25

This increment can be explained by the expression for predicting the capacity of perfobond rib connection of E. C. Oguejiofor and M. U Hosain [2]:

$$q = 0.590A_{cc}\sqrt{f_c'} + 1.233A_{tr}f_y + 2.871nd^2\sqrt{f_c'} \qquad (1)$$

In which:

A_{cc} is the shear area of concrete per connector

A_{tr} is the total area of transverse reinforcement

n is the shear capacity per dowel hole

f'_c is the compressive strength of concrete

f_y is the yield strength of transverse reinforcement

The second term of the expression above is the contribution of transverse reinforcement in the load capacity of perfobond shear connector, and this explains the reason for the load capacity of specimen G3 being higher than that of specimens G1 and G2.

3.1.2 The relative slip

The relative slips between the hot-rolled steel and the concrete slab of specimens G1, G2, and G3 at the failure load are 2.25 mm, 3.75 mm, and 2.52 mm, respectively. These values of specimens G1, G2, and G3 at the load of P_{uk} are sequentially 3.48 mm, 6.05 mm, and 5.81 mm, as shown in Table 6 and Figure 7. The specimens with transverse reinforcements tend to ductile connectors while specimens without transverse reinforcements are still pristle connectors.

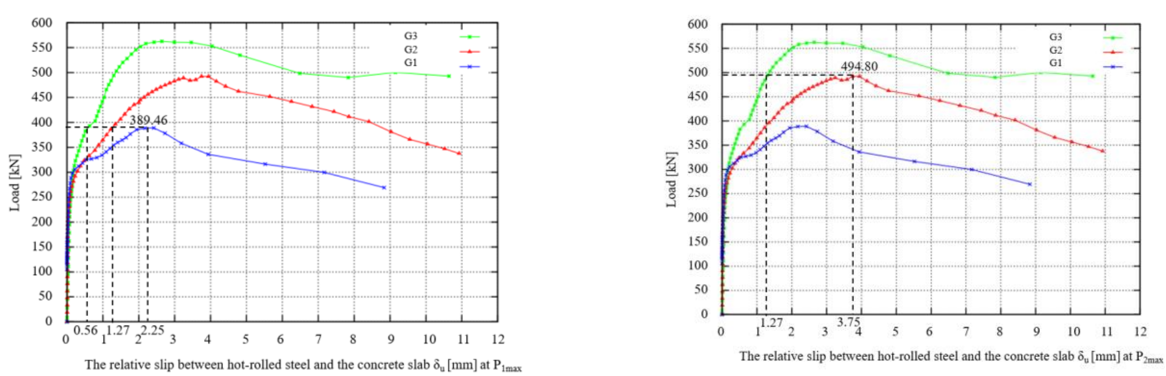
Table 7. The relative slip comparison of specimens at $P_{1,max}$ = 389.46 kN.

Value	Unit	G1	G2	G3
δ_i	mm	2.25	1.27	0.56
$\delta_i/\delta_{1,max}$		1.00	0.56	0.25

Table 8. Comparison of the relative slip at $P_{2,max}$ = 494.80 kN.

Value	Unit	G1	G2	G3
δ_i	mm	-	3.75	1.27
$\delta_i/\delta_{2,max}$		-	1.00	0.39

At the failure load of specimen G1, the relative slip of specimens G2 (1.27 mm) equals 0.34 times of that of specimen G1, and the relative slip of specimens G3 (0.56 mm) equals 0.15 times of that of specimen G1. At the failure load of specimen G2, the relative slip of specimen G3 just equals 0.39 times the relative slip of specimen G2. This result indicates the existence of transverse reinforcements passing through the perfobond holes significantly resists the relative slip between the hot-rolled steel and the concrete slab.



a. The relative slip at P_{1max}

b. The relative slip at P_{2uk}

Figure 8. Comparison of the relative slip at P_{1max} and P_{2max}.

3.1.3 The failure mode

Under applied load, the hot-rolled steel moved down and slipped along the concrete slab. When the applied load reached 80 % Pmax, cracks appeared along the concrete slab from top to bottom of the concrete slab. Then, the cracks grew up into pieces and broke down. Continued increasing load, the diagonal cracks occurred at the bottom of the concrete slab, and then the specimens were destroyed.

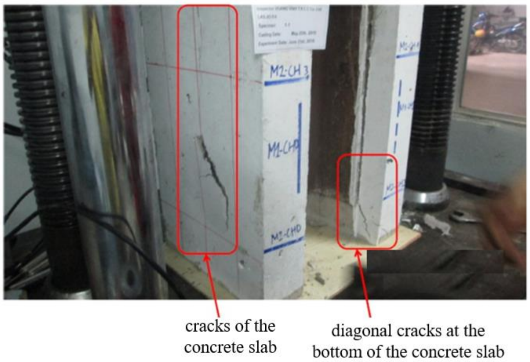


Figure 9. Cracks on the concrete slab surface.

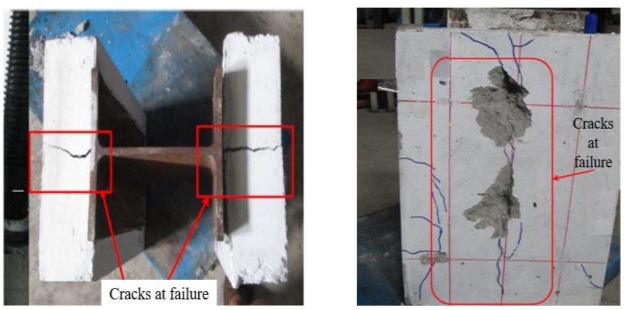


Figure 10. Cracks on the concrete slab at the end of testing.

4. Conclusions

A test program was carried out on three groups of nine push-out specimens to investigate the effect of the transverse reinforcements passing through perfobond holes on the structural behavior of shear connectors. The test results show that:

The transverse reinforcements passing through the perfobond holes significantly enhance the load capacity of perfobond shear connectors. The load capacity of specimens G1 with one transverse reinforcement increases by about 27.05 % and specimen G2 with two transverse reinforcements passing the perfobond hole increases by about 45.25 % in comparison with that of specimen G1 without transverse reinforcement.

The transverse reinforcements passing through the perfobond holes tend to rise the ductility of the perfobond shear connectors.

The transverse reinforcements passing through the perfobond holes also considerably reduce the relative slip between the hot-rolled steel and the concrete slab of perfobond shear connectors. At the failure load of specimen G1, the relative slip of specimens G2 and G3 just equal 0.56 and 0.25 times in comparison with that of specimen G1.

Acknowledgment

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