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EXPERIMENTAL STUDY ON SHEAR RESISTANCE EVALUATION OF PERFOBOND STRIP WITHOUT PENETRATING REBAR

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In steel-concrete hybrid members and structures, to ensure required stress transmission between the steel and the concrete members, shear connectors are generally arranged between the two. A perfobond strip is widely used as the shear connector in various hybrid structures, and when applying the perfobond strip it is important to confirm its shear resistance. In this study, the shear resistance of the perfobond strip without the penetrating rebar is investigated experimentally by employing a simple push-out specimen. As a result, a design formula is proposed for evaluating the shear resistance of the perfobond strip, taking into account the dimensions of concrete block and the thickness of the perfobond plate, as well as the perforation diameter, and the concrete compressive strength.

Keywords: Hybrid structure, Shear connector, Push-out test, Design formula.

1 INTRODUCTION

Much research has been done on applying perfobond strips to various hybrid structures. A few design formulas for evaluating its shear resistance have been proposed by Leonhardt *et al.* (1987), Oguejiofor and Hosain (1994), and JSCE (2009). However, these formulas are constructed based on the general push-out test similar to the one for a stud shear connector. Therefore, a part of the stress in this test method may be transferred through not only the shear connector itself, but also the interface between the flange plate surface and the surrounding concrete. Moreover, in these test specimens, the dimension of the concrete block is not usually varied. However, the shear resistance of the perfobond strip also depends on the roughness of the shear fracture surface at the perforation, and the confinement effect due to the surrounding concrete.

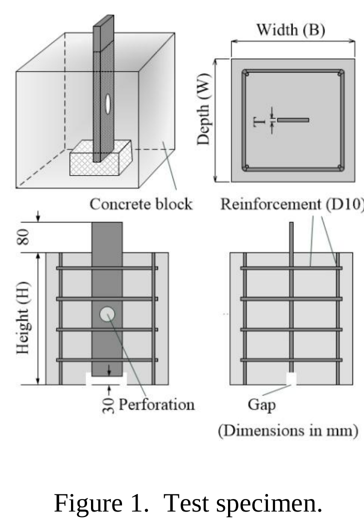

Figure 1. Test specimen.

In this study, push-out tests were conducted usng specimens whose steel plate with the perforation is embedded in the concrete block. The influence of the concrete compressive strength, the perforation diameter, the thickness of the perfobond steel plate, and the dimensions of the concrete block on the shear resistance of the perfobond strip was investigated. A design formula was constructed for evaluating the shear resistance of the perfobond strip taking into account these factors.

Table 1. Description of push-out specimens.

Specimen name – No.	D	T	B	W	H	f'$_c$	n	Note
D50T12B3W3H4-1,2	50	12	300	300	420	32.6	2	D: Perforation diameter (mm),
D50T12B4W4H4-1,2,3	50		400	400	420	29.0	3	T: Steel plate thickness (mm),
D50T12B5W5H4-1,2	50		500	500	420	32.6	2	B: Concrete block width (mm),
D50T12B4W4H3-1,2	50		400	400	320	32.6	2	W: Concrete block depth (mm),
D50T12B4W4H5-1,2	50		400	400	520	32.6	2	H: Concrete block height (mm),
D60T12B5W4H4-1,2	50		500	400	450	32.5	2	f'$_c$: Concrete compressive
D60T12B5W5H4-1,2	50		500	500	450	32.5	2	strength (N/mm2),
D60T12B5W6H4-1,2	50		500	600	450	32.5	2	n: number of specimens
D50T12B4W4H4-4,5,6	50	12	400	400	420	48.6	3	
D50T12B4W4H4-7,8,9	50					53.8	3	
D30T12B5W5H4-1,2,3	30	12	500	500	420	30.9	3	
D30T12B5W5H4-4	30					33.2	1	
D40T12B5W5H4-1,2	40					29.0	2	
D60T12B5W5H4-1,2,3	60					30.9	3	
D60T12B5W5H4-4	60					33.2	1	
D70T12B5W5H4-1,2	70					29.0	2	
D90T12B5W5H4-1,2,3	90					30.9	3	
D90T12B5W5H4-4	90					33.2	1	
D40T12B5W5H4-3,4	40	12	500	500	450	32.5	2	
D40T19B5W5H4-1,2	40	19					2	
D40T25B5W5H4-1,2	40	25					2	
D60T12B5W5H4-5,6	60	12					2	
D60T19B5W5H4-1,2	60	19					2	
D60T25B5W5H4-1,2	60	25					2	

2 TEST SPECIMEN AND TEST SET-UP

In this study, the test specimens were perforated steel plates embedded in concrete blocks as shown in Figure 1. The experimental parameters were the dimensions of the concrete block, the perforation diameter, the concrete compressive strength, and the steel plate thickness. The detailed parameters of the specimens are shown in Table 1. In all specimens, the longitudinal and hoop reinforcements of diameter 10mm were arranged inside the concrete block. A space was arranged under the bottom of the steel plate, so that the applied load from the top of the steel plate would be transferred to the surrounding concrete block only through the filled concrete inside the perforation. Grease was applied to the steel plate surface before placing the concrete, so as to reduce the effect of bonding between the steel plate and the surrounding concrete. Moreover, a ready-mixed concrete with a maximum coarse aggregate size of 25mm was used for all specimens, and its compressive strength after 28-days age are also shown in Table 1.

During the experiment, the specimen was placed on a loading frame with a hydraulic jack of 1MN, and the load was applied to the top of the perfobond steel plate. Sand was inserted between the test bed and the bottom of the concrete block, so as to keep the steel plate vertical and to reduce the friction between the test bed and the concrete block as much as possible. The relative slip between the steel plate and the concrete block at the top was measured by the displacement transducer. The load was applied to the specimen until the relative slip went beyond 20 mm. In this study, the shear force in which it clearly decreases with an increase of the relative slip was defined as the shear resistance.

3 EXPERIMENTAL RESULTS

3.1 Influence of Concrete Block Dimensions

The shear force-relative slip relations of the specimens with different concrete block dimensions are shown in Figure 2. Figure 2(a), Figure 2(b), and Figure 2(c) respectively correspond to the relationship in changing both the width and depth, the height, and the depth of the concrete block. The ordinate is the applied load as the shear force, and the abscissa is the relative slip between the perfobond steel plate and the concrete block.

In all specimens, the shear force reaches the maximum at the relative slip in the range of 2 to 6 mm, and then the shear force decreases gradually with the increase of the relative slip. From Figure 2(a) and Figure 2(b), the shear resistance increases averagely with the concrete block dimensions. In contrast, as shown in Figure 2(c), the difference in the shear resistance between the specimens with different depths of concrete block is small. It can be seen that the block depth does not significantly affect the shear resistance, but its width and height – that is, the side area of the concrete block in a plane parallel to the steel plate (hereafter referred to as the side area) – significantly affects the shear resistance of the perfobond strip. This is the reason why the shear resistance increases with an increase of the confinement effect produced by the surrounding concrete, and this effect increases with the side area of the concrete block.

Figure 3 shows the relationship between the shear resistance of the specimen and their side area of the concrete block. In this figure, the solid line shows the shear resistance using a formula proposed by Leonhardt *et al.* (1987), the dashed line shows the one by Oguejiofor and Hosain (1994), and the dotted line shows the one by the formula in JSCE's Standard Specification for Hybrid Structures (2009). It is confirmed from this figure that the shear resistance increases definitely with an increase of the concrete block side area, but this result is not represented by past formulas.

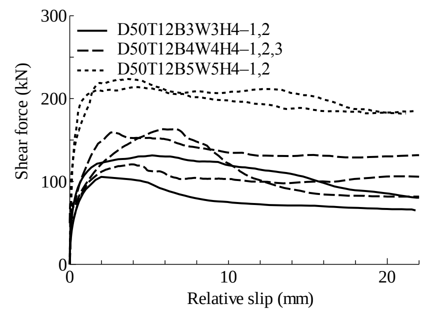

Figure 2(a). Change in width and depth.

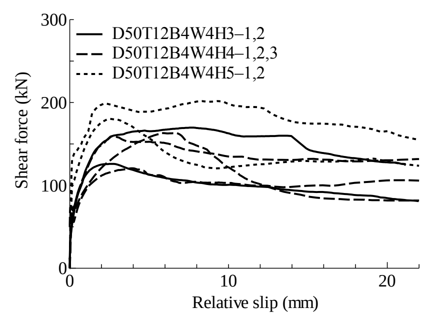

Figure 2(b). Change in height.

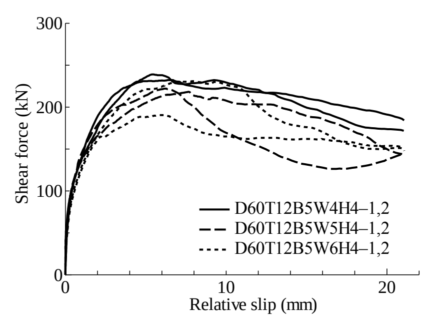

Figure 2(c). Change in depth.

Figure 2. Shear force-relative slip relationship.

3.2 Influence of Concrete Strength

Figure 4 shows the shear force-relative slip relationship of the specimens with a concrete compressive strength of 29.0, 48.6 and 53.8 N/mm^2. It is revealed that the shear resistance of the specimen increases averagely with the concrete compressive strength, although there is a wide variation in the shear force-relative slip relations and their shear resistance. Figure 5 shows the shear resistance-concrete compressive strength relationship based on the result in Figure 4. It is clear from Figure 5 that the shear resistance increases with the concrete compressive strength.

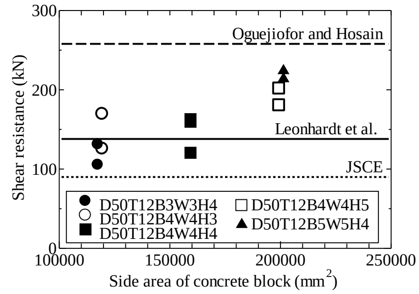

Figure 3. Shear resistance-side area of concrete block relationship.

3.3 Influence of Perforation Diameter

The shear force-relative slip relations of the specimens with different perforation diameter are shown in Figure 6 and the shear resistance-perforation area relations are shown in Figure 7. It can be said from Figure 6 that the shear resistance increases with the perforation diameter, and the relative slip at the maximum shear force of the specimens with the perforation diameter 60, 70 and, 90 mm are larger than the ones with the perforation diameter 30 and, 40 mm. Furthermore, Figure 7 also shows clearly that the shear resistance increases with the perforation area and that the relationship is almost linear. In this relation, the correlation coefficient (R) of this data is 0.971.

3.4 Influence of Perfobond Steel Plate Thickness

To investigate the influence of the steel plate thickness on the shear resistance of the perfobond strip, we conducted a test for two cases with a perforation diameter of 40 and 60 mm. The shear force-relative slip relationship of these specimens is shown in Figure 8. From Figure 8(a), a significant difference in the shear resistance was not observed for a perforation diameter of 40 mm, but it was observed from Figure 8(b) for a perforation diameter of 60 mm, in that the shear resistance of the specimens with the plate thickness of 12 mm are larger than the ones of 19 and 25 mm. It can be said from Figure 8 that the influence of the steel plate thickness on the shear resistance varies depending on the perforation diameter.

In order to know the correlation between the shear resistance and these parameters, a multiple regression analysis was performed. Here, the shear resistance (Q_u) was set as the objective variable, and the perforation area (A), and the steel plate thickness (T) were set as the explanatory variables. As a result, the following equation was obtained:

$$Q_u = 0.20AT^{-0.5} \tag{1}$$

Further, Figure 9 shows the relationship between the objective variable and the explanatory variables, with a correlation coefficient of the data of 0.943. It can be said that the shear resistance is fairly correlated with the value of $AT^{-0.5}$.

4 EVALUATION FORMULA FOR SHEAR RESISTANCE

Through the experimental results, the shear resistance of the perfobond strip is not only affected by the perforation diameter and the concrete compressive strength, but also by the dimension of the concrete block and the thickness of the steel plate. In addition, as mentioned above, the shear resistance of the perfobond strip is closely related to the perforation area and the steel plate thickness as expressed in Eq. (1). Based on the results, the evaluation formula of the shear resistance can be constructed by a multiple regression analysis, in which the value of $(Q_u T^{0.5} A^{-1})$ is set as an objective variable, and the concrete compressive strength and the side area of the concrete block are set as the explanatory variables. Therefore, the following exponential function is obtained as:

$$Q_u = 0.15Af'_c{}^{0.65}A_s{}^{0.43}T^{-0.5} \tag{2}$$

in which Q_u = shear resistance (N), A = perforation area (mm^2), f'_c = concrete compressive strength (N/mm^2), A_s = side area of concrete block (mm^2), and T = perfobond steel plate thickness (mm). Moreover, the relationship between the experimental value of shear resistance (Q_{uexp}) and the value evaluated by the constructed formula (2) (Q_{uest}) are shown in Figure 10. In this comparison, other data in previous studies (Nakajima *et al*. 2012) were also used. Moreover, the equation of the regression line, the correlation coefficient, and the standard error are also documented in Figure 10. It is confirmed from this figure that the shear resistance evaluated by the constructed formula shows the good correlation with the experimental shear resistance.

5 CONCLUSIONS

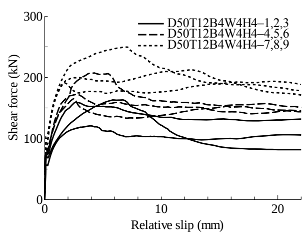

Figure 4. Shear force-relative slip relationship (Change in concrete strength).

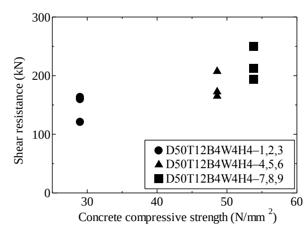

Figure 5. Shear resistance-concrete compressive strength relationship.

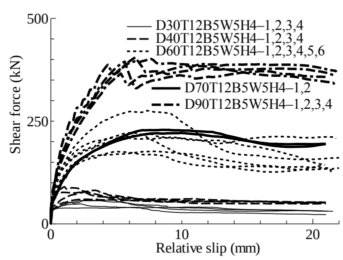

Figure 6. Shear force-relative slip relationship (Change in perforation diameter).

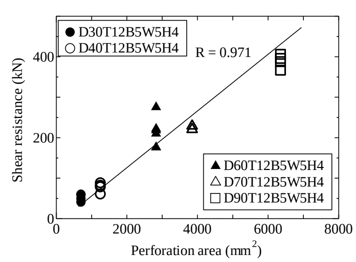

Figure 7. Shear resistance-perforation area relationship.

In this paper, we conducted a simple push-out test of the perfobond strip specimens with various parameters. Next, a design formula was proposed for evaluating the shear resistance of the perfobond strip, taking into account the dimension of the concrete block, the perforation diameter, the concrete compressive strength, and the thickness of the perfobond steel plate. From the comparison between the evaluated shear resistance and the experimental values, it can be said the constructed formula can evaluate the experimental shear resistance reasonably.

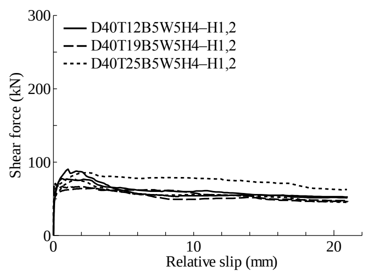

Figure 8(a). The case of D = 40mm.

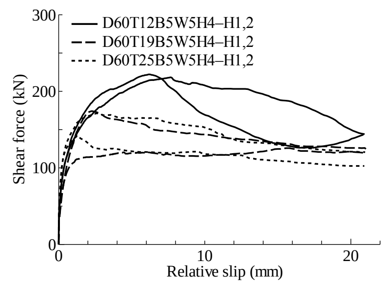

Figure 8(b). The case of D = 60mm.

Figure 8. Shear force-relative slip relationship (Change in steel plate thickness).

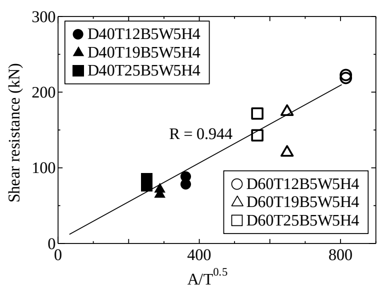

Figure 9. Shear resistance-perforation area, steel plate thickness relationship.

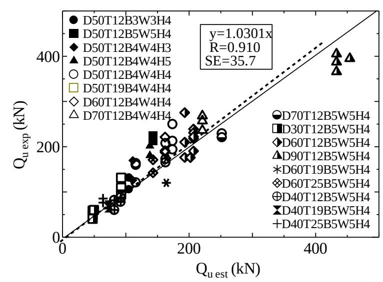

Figure 10. Relationship between shear resistances obtained from proposed formula and experiment.

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