AN EXPERIMENTAL STUDY ON PENETRATING REBAR EFFECT ON SHEAR RESISTANCE OF PERFOBOND STRIP

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ABSTRACT

A perfobond strip is widely used as the validated shear connector in the various steel-concrete hybrid structures and in general the penetrating rebar is arranged in the perforation to suppress the brittle fracture of the perfobond strip due to the shear failure of the concrete at the perforation. Therefore, the shear resisting mechanism becomes more complicated, since the penetrating rebar also contributes to the shear resistance by the dowel action. The design formula for the perfobond strip with the penetrating rebar has been already proposed by some researchers. However, the shear resisting mechanism of the perfobond strip with the penetrating rebar is not always confirmed sufficiently. In this research, in order to investigate the effect of the penetrating rebar on the shear resistance of the perfobond strip, two series of simple push-out tests are conducted paying attention to the relation between the perforation diameter and the penetrating rebar diameter.

Keywords: Perfobond strip, Penetrating rebar, Shear resistance, Push-out test

1. INTRODUCTION

A perfobond strip is widely used as the validated shear connector in the various steel-concrete hybrid structures, since the fatigue strength of the perfobond strip is larger and its constructability is better than those of the other types of shear connectors such as the headed stud shear connectors. A perfobond strip as the shear connector for composite girders was proposed first by Leonhardt et al. (Leonhardt et al. 1987) and many related researches have been widely conducted throughout the world (Oguejiofor and Hosain 1994).

In the perfobond strip, the penetrating rebar is arranged in the perforation to suppress the brittle fracture of the perfobond strip due to the shear failure of the concrete at the perforation. Therefore, the shear resisting mechanism becomes more complicated, since the penetrating rebar also contributes to the shear resistance by the dowel action. The design formula for the perfobond strip with the penetrating rebar has been already proposed by some researchers in Japan (Hosaka et al. 2002; Fujii et al. 2003; Furuuchi et al. 2005) and the design formula was also specified in JSCE

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Standard Specification for Hybrid Structures (JSCE 2009). However, the shear resisting mechanism of the perfobond strip with the penetrating rebar is not always confirmed sufficiently.

In this research, two series of simple push-out tests are conducted paying attention to the relation between the perforation diameter and the diameter of the penetrating rebar to investigate the effect of the penetrating rebar on the shear resistance of the specimen. In the experiment, the strain behavior of the penetrating rebar is measured in detail. As a result, the shear resisting mechanism of the perfobond strip with the penetrating rebar is described based on the experimental results.

2. EXPERIMENT OVERVIEW

2.1. Test specimen

In this research, the test specimen whose steel plate with the perforation is embedded in the concrete block is employed and two series of push-out tests with parameters of the perforation diameter and the penetrating rebar diameter are conducted (Nakajima et al. 2012). Figure 1 shows the outline of test specimen, and Table 1 shows their parameters and detailed dimensions. Although, specimens are named considering the perforation diameter (D), the steel plate thickness (T) and the penetrating rebar diameter (R), the notation “NR” means that the specimen doesn't have the penetrating rebar. In all specimens, four hoop reinforcements are arranged, and grease is attached on the steel plate before placing the concrete so as to reduce the effect of bond between the steel plate and the surrounding concrete. The material properties are also shown in Table 2 and the corresponding letters are described in Table 1.

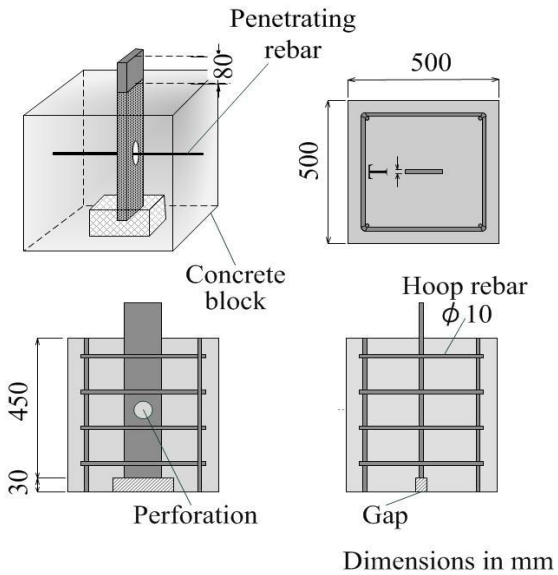


Figure 1: Test specimen

The standard steel plate noted SS400, the longitudinal reinforcement and hoop reinforcement of 10mm, and a ready mixed concrete with the maximum coarse aggregate size of 25mm are used for the whole test series.

2.2. Loading system and measurement items

During the test, the specimen is placed on the loading frame with 1000kN hydraulic jack. The load is applied to the specimen at the top of the steel plate until the relative slip goes beyond 20mm. Moreover, sand is inserted between the test bed and the bottom of the concrete block to keep the steel plate vertical and to reduce the friction between the test bed and the concrete block as possible as we can. The relative slip between the steel plate and the concrete block is measured by

displacement transducers. Furthermore, the longitudinal strain of the penetrating rebar is measured by 18 strain gauges which are attached every 20mm interval on both sides of grooves cut along the rebar. However, for the specimens with the penetrating rebar and the material property "A", strain doesn't measured and grooves is not cut along the rebar.

Table 1: Description of all specimens (Series1, 2)

Series	*Specimen name*	*Material property*	*Perforation diameter* (mm)	*Plate Thickness*(mm)	*Penetrating rebar diameter* (mm)	*Shear resistance* (kN)
1	D30T12NR-1,2,3	A	30	12	-	49
	D30T12NR-4	B	30	12	-	59
	D60T12NR-1,2,3	A	60	12	-	221
	D60T12NR-4	B	60	12	-	176
	D60T12NR-5,6	C	60	12	-	220
	D90T12NR-1,2,3	A	90	12	-	386
	D90T12NR-4	B	90	12	-	395
	D30T12R10-1,2	A	30	12	10	106
	D30T12R10-4,5	B	30	12	10	82
	D60T12R10-1,2,3	A	60	12	10	280
	D60T12R10-4,5	B	60	12	10	253
	D90T12R10-1,2,3	A	90	12	10	410
	D90T12R10-4,5	B	90	12	10	388
2	D60T12R10-6,7	C	60	12	10	204
	D60T12R13-1,2	C	60	12	13	238
	D60T12R16-1,2	C	60	12	16	271

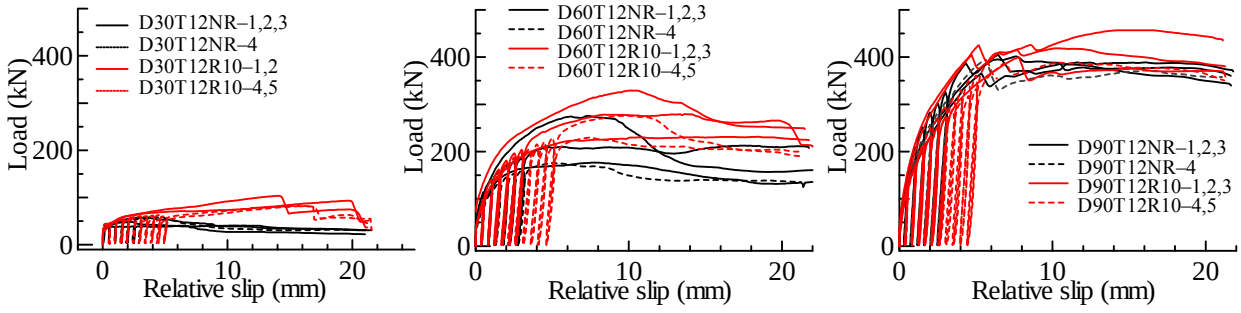
Table 2: Material property

Type	*Steel plate*		*Penetrating rebar*		*Concrete*		
	Yield strength (N/mm^2)	*Tensile strength* (N/mm^2)	*Yield strength* (N/mm^2)	*Tensile strength* (N/mm^2)	*Compressive strength* (N/mm^2)	*Tensile strength* (N/mm^2)	*Young's modulus* (kN/mm^2)
A	361	439	409	548	31.1	2.8	29.2
B	355	443	394	520	33.2	3.3	27.3
C	354	441	356	505	32.5	3.3	26.5

3. RESULTS OF EXPERIMENT SERIES 1

3.1. Load-relative slip relation

Figure 2 shows the load-relative slip relation of all specimens in series 1. The ordinate is applied load and the abscissa is the relative slip between the steel plate and the upper surface of the concrete block. Figures 2(a), (b) and (c) correspond to the relations of the perforation diameter 30, 60 and 90mm. In all figures, the load-relative slip relation of the specimens with the penetrating rebar are shown by red line and the one without penetrating rebar are shown by black line to compare the two cases mutually. Furthermore, difference in material properties of these specimens is expressed by the solid line and the dashed line.



(a) Perforation diameter 30mm **(b) Perforation diameter 60mm** **(c) Perforation diameter 90mm**

Figure 2: Load-relative slip relation in series 1

It can be said from these figures that the maximum load increases with the perforation diameter irrespective of the presence or absence of the penetrating rebar, and that the maximum load with the penetrating rebar is generally larger than the one without the penetrating rebar.

For the specimen with the perforation diameter 90mm, the load decreases temporarily when the load is beyond about 400kN. This is the reason why the crack occurs on the concrete block of the specimen. On the contrary, for the specimen with the perforation diameter 30mm and the penetrating rebar, the load increases with the relative slip up to about 15mm and thereafter the load decreases suddenly because of the fracture of the penetrating rebar.

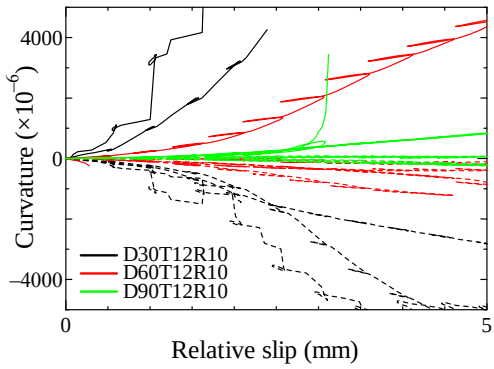


Figure 3: Curvature-relative slip relation in series 1

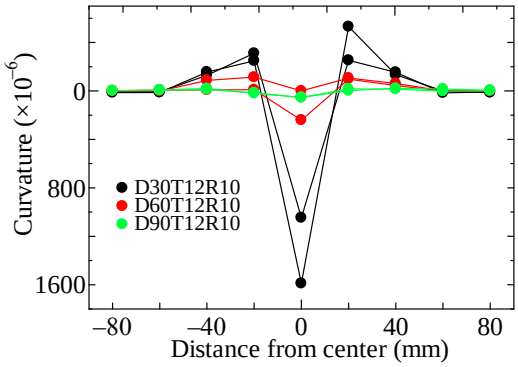


Figure 4: Curvature distribution at 1mm relative slip in series 1

3.2. Strain behavior of penetrating rebar

In order to know the behavior of the penetrating rebar under the shear force, the longitudinal strain of the penetrating rebar is measured by 18 strain gauges as mentioned above. Figure 3 shows the curvature-relative slip relation at the center position and at ±20mm positions away from the center. In this figure, the ordinate is the curvature and the abscissa is the relative slip. The curvature is evaluated from the top and bottom strain of the penetrating rebar. The solid lines correspond to the

change in the curvature of the center position and the dotted lines correspond to the ones at ±20mm positions from the center. It can be said from this figure that at the center position, the positive curvature increases with the relative slip and that the curvature increases rapidly in the case of the smaller perforation diameter. On the contrary, the curvature at the both side positions from the center increases with the relative slip in the negative direction.

Figure 4 shows the curvature distribution of the penetrating rebar along with the longitudinal direction at the relative slip of 1mm. In this figure, the abscissa is the distance from the center position. It can be said that the curvature at the center position is positive and the curvature at both side positions is negative, and then the respective curvature is larger, the perforation diameter is smaller. This implies that the penetrating rebar near the perforation is bent locally by the action of the shear force between the steel plate and the surrounding concrete, and that the penetrating rebar is bent severely, when the perforation diameter is small.

4. RESULTS OF EXPERIMENT SERIES 2

4.1. Load-relative slip relation

The specimens in series 2 have the same perforation diameter 60mm and the different penetrating rebar diameter such as 10, 13 and 16mm. Figure 5 shows the load-relative slip relation of all case in series 2. In this figure, the relation of the specimen without the penetrating rebar is shown by the black line and the relation of the specimen with the different diameter of the penetrating rebar is distinguished by line colors of red, green and yellow. It can be said from this figure that the maximum load becomes larger, when the diameter of the penetrating rebar becomes larger. However, in this case the maximum load of the specimen without the penetrating rebar is larger than the one with the penetrating rebar of 10mm. This is the reason why the maximum load is affected by the shear fracture surface condition at the perforation and its coarse aggregate arrangement condition as well as the penetrating rebar.

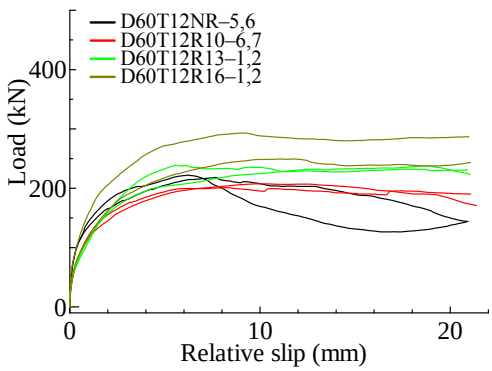


Figure 5: Load-relative slip relation in series 2

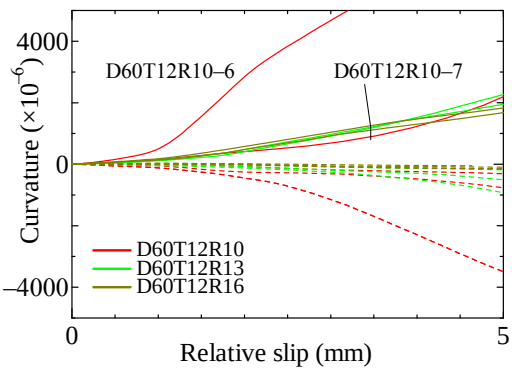
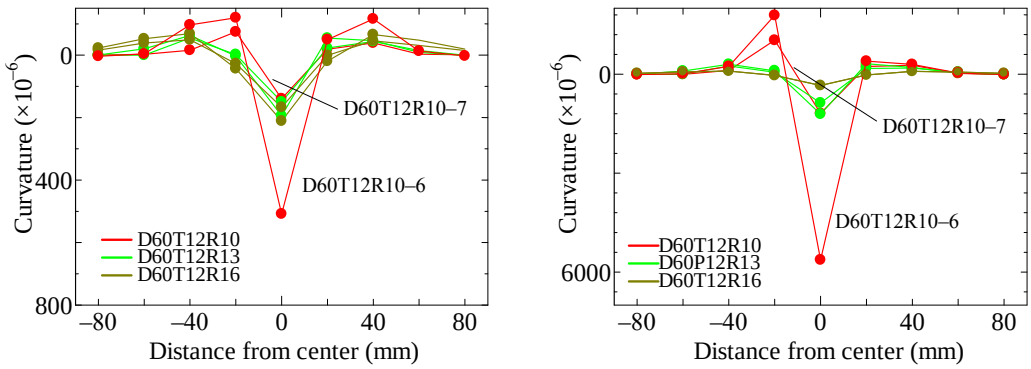


Figure 6: Curvature-relative slip relation in series 2

4.2. Strain behavior of penetrating rebar

Figure 6 shows the curvature-relative slip relation at the center position and at ±20mm positions away from the center. The solid lines correspond to the change in the curvature of the center position and the dotted lines correspond to the ones at ±20mm positions from the center. It can be said from this figure that at the center position, the positive curvature also increases with the relative slip in the same manner as the case in Figure 3 and that the curvature of the specimen with the penetrating rebar diameter 10mm increases faster than the other cases averagely.



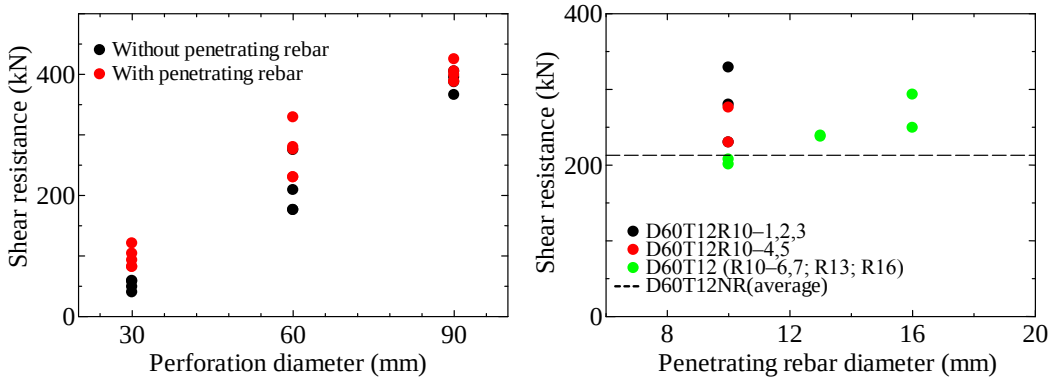
(a) Distribution at 1mm relative slip **(b) Distribution at 180kN load**

Figure 7: Curvature distribution in series 2

On the other hand, Figure 7 shows the curvature distribution of the penetrating rebar along with the longitudinal direction at the relative slip of 1mm in Figure 7(a) and at the load of 180kN in Figure 7(b). It can be said that the curvature at the center position is positive and the curvature at both side positions from the center is negative, and then the respective curvature is larger than the others, when the diameter of the penetrating rebar is 10mm. However, in the distribution at 1mm relative slip in Figure 7(a), the any difference is not observed between the distribution of the specimen with the penetrating rebar diameter 13mm and the one with the penetrating rebar diameter 16mm. This is the reason why the latter case load is larger than the former case load.

5. DISCUSSION OF PENETRATING REBAR EFFECT

As shown in Figure 2 and Figure 5, the maximum load of the specimens with the penetrating rebar is generally higher than the one without the penetrating rebar, when the steel plate has the same perforation diameter. This is the reason why the penetrating rebar changes the mechanism of the shear resistance of the perfobond strip and the penetrating rebar also resists the shear force. Therefore, the effect of the penetrating rebar on the maximum shear force is defined as the difference of the shear resistance between the specimen with and without the penetrating rebar, when the steel plate has the same perforation diameter. In order to investigate the effect, the shear resistance for all specimens is shown in Figure 8. In these figures, the ordinate is the shear resistance and the abscissa is the diameter of the perforation in Figure 8(a) and the diameter of the



(a) Effect of perforation diameter **(b) Effect of penetrating rebar diameter**

Figure 8: Comparison of shear resistance

penetrating rebar in Figure 8(b). In Figures 8(a), the shear resistance of the specimen with and without the penetrating rebar is distinguished by red mark and black mark in series 1 experiment. On the contrary, in Figure 8(b), each colored mark corresponds to the shear resistance with the different material property and the dashed line is the average shear resistance of the specimen without penetrating rebar.

It can be said from Figure 8(a) that the penetrating rebar effect of the specimens with the perforation diameter of 30, 60 and 90 mm are 45, 59 and 13kN respectively. Since the crack occurs on the concrete block of the specimen with the perforation diameter 90mm before the load reaches the actual maximum value, the effect is significantly small. Moreover, the effect of the specimen with the perforation diameter 30mm is smaller than the one with the perforation diameter 60mm. This is the reason why the penetrating rebar moves in the concrete filled inside the perforation and the filled concrete is crushed. Then the shear resistance of the shear surface of the filled concrete reduces due to the crush of the filled concrete.

On the other hand, the penetrating rebar effect of the specimens with the different diameter of the penetrating rebar is not clearly observed and the difference of the shear resistances of the specimen with and without the penetrating rebar is not so large. However, the shear resistance of the specimen with the same material property increases with the penetrating rebar diameter shown by the green marks in Figure 8(b). This is the reason why the maximum load is affected by the shear fracture surface condition at the perforation, its coarse aggregate arrangement condition and so on as mentioned above.

6. CONCLUDING REMARKS

In this research, in order to investigate the effect of the penetrating rebar on the shear resistance of the perfobond strip, two series of simple push-out tests are conducted paying attention to the

relation between the perforation diameter and the diameter of the penetrating rebar. The main conclusions of this research may be summarized as follows:

- The effect of the penetrating rebar on the shear resistance of the perfobond strip varies with the perforation diameter, if the specimen has the same diameter of the penetrating rebar. In this case, the penetrating rebar is bent severely at the perforation position, when the perforation diameter is small.
- The effect of the penetrating rebar on the shear resistance of the perfobond strip increases with the diameter of the penetrating rebar, if the specimen has the same perforation diameter.

In future, it is possible to construct the design formula for the perfobond strip with the penetrating rebar based on the shear resisting mechanism considering the behavior of the penetrating rebar.

7. ACKNOWLEDGMENTS

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