A perfobond strip is widely used as the validated shear connector in various steel-concrete hybrid structures. 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. However, the effect of the penetrating rebar on the shear resistance, and the effect of the perforation diameter, the penetrating rebar diameter, and the thickness of the steel plate on the behavior of the penetrating rebar have not been clarified until now. In this research, in order to investigate the effect of the penetrating rebar on the shear resistance of the perfobond strip, simple push-out tests were conducted paying attention to the relation between the perforation diameter and the penetrating rebar diameter, and the variations in the steel plate thickness. Furthermore, to obtain the shear contribution of the penetrating rebar to the shear resistance of the perfobond strip, a nonlinear numerical analysis was conducted. As a result, a design formula was constructed to evaluate the shear resistance of the perfobond strip with the penetrating rebar.

**Key Words:** steel-concrete hybrid structure, perfobond strip, penetrating rebar, shear resistance evaluation, nonlinear numerical analysis

1. INTRODUCTION

In steel-concrete hybrid members and structures, the shear connectors are key parts to ensure the required stress transmission between the steel member and the concrete one. In recent years, a perfobond strip which was first proposed by Leonhardt et al.\(^1\) has been widely used as the shear connector in various steel-concrete hybrid structures. Meanwhile, Leonhardt et al.\(^1\) did not always insist that the penetrating rebar should be arranged inside the perforation of the perfobond strip. However, in employing the perfobond strip for actual steel-concrete hybrid structures, the penetrating rebar is generally arranged inside the perforation to suppress the brittle fracture of the perfobond strip after the shear failure of the concrete at the perforation. Hence, many researches have aimed to construct design formulas for evaluating the shear resistance of the perfobond strip with the penetrating rebar inside the perforation.

For example, Hosaka et al.\(^2\) proposed a design formula for evaluating the shear resistance of the perfobond strip with the penetrating rebar. Similar design formulas were also specified in the JSCE Standard Specifications for Hybrid Structures\(^3\). In these design formulas, the shear resistance of the perfobond strip is expressed by the sum of the shear resistance of the concrete at the perforation and the one of the penetrating rebar. Furuuchi et al.\(^4\) also proposed the similar design formula based on the original test results. In contrast, Fujii et al.\(^5\) constructed an original design formula for evaluating the shear resistance of the perfobond strip with the penetrating rebar. They considered that the penetrating rebar did not contribute to the shear resistance of the perfobond strip as the dowel action, but the penetrating rebar contributed to the increasing factor of the shear resistance of the concrete at the perforation. However, the shear resistance of the perfobond strip is affected by the restrained condition of the surrounding concrete and the arrangement of aggregates of concrete in the perf-
foration as well as the perforation diameter and the concrete compressive strength as indicated by Fujii et al.\textsuperscript{6}) and Nakajima et al.\textsuperscript{7}). Therefore, in the perfobond strip with the penetrating rebar, more factors may affect its shear resistance. In order to confirm the shear transmission mechanism of the perfobond strip with the penetrating rebar in detail and construct the design formula for evaluating the shear resistance based on its mechanism, extensive test data are required.

In this research, a push-out test is first conducted employing the specimens whose steel plate with the perforation is embedded in the concrete block. In this test, we examine the relation between the shear force and the relative slip, and the strain behavior of the penetrating rebar by employing specimens with different combinations of perforation diameters, penetrating rebar diameters, and thickness of perfobond steel plates. Second, we obtain the contribution of the penetrating rebar to the shear resistance of the perfobond strip by conducting nonlinear numerical analysis paying attention to the strain behavior of the penetrating rebar. Third, we confirm that the contribution of the penetrating rebar to the shear resistance depends on the penetrating rebar diameter and the thickness of the perfobond steel plate. We then construct the design formula for evaluating the shear resistance of the perfobond strip with the penetrating rebar.

References \textsuperscript{7}) and \textsuperscript{8}) show the results of the test specimens with the same experimental parameters where the specimens do not have the penetrating rebar. In constructing the design formula for evaluating the shear resistance of the perfobond strip with the penetrating rebar, the results in References \textsuperscript{7}) and \textsuperscript{8}) are also employed in this research. The results and their consideration of the effect of the thickness of the perfobond steel plate on the shear resistance of the perfobond strip without the penetrating rebar are shown in the Appendix of this paper.

2. OUTLINE OF PUSH-OUT TEST

(1) Push-out test specimens

Nakajima et al.\textsuperscript{7}) investigated the effect of the perforation diameter, the dimension of the concrete block and the concrete compressive strength on the shear resistance of the perfobond strip in which the perfobond steel plate with a perforation was embedded in the concrete block. In this research, the same type of specimens as shown in Fig. 1 is employed to investigate first the influence of the relation between the perforation diameter, the penetrating rebar diameter, and the thickness of the perfobond steel plate on the shear resistance of the perfobond strip. Hence, the perforation diameter, the penetrating rebar diameter, and the thickness of the perfobond steel plate are set as the parameters. In this test specimen, the applied force to the perfobond steel plate transfers directly to the concrete inside the perforation and the force transmission mechanism is simpler than the general push-out test specimen similar to the one for the stud shear connector\textsuperscript{9}). Therefore, the influence of various parameters such as the perforation diameter and the concrete compressive strength on the mechanism of the shear resistance of the perfobond strip is considered to be easily confirmed by this test method. The test parameters and detailed dimensions of all specimens are shown in Table 1. Here, specimens are represented by the perforation diameter $D$, the perfobond steel plate thickness $T$, and the penetrating rebar diameter $R$. The last characters represent the type of the materials and the specimen number.

(2) Material properties

In all specimens, steel plates of SS400 are used for the perfobond steel plate and the longitudinal and the hoop reinforcements whose diameter is 10mm are arranged inside the concrete block. Moreover, diameters of 10mm, 13mm, and 16mm are used for the penetrating rebar. The length of the penetrating rebar is the same as the width of the concrete block, that is, 500mm and the grade
of the rebar is SD295. The steel plate of SS400 and the penetrating rebar of SD295 are commercial ones. Table 1 shows the detailed parameters of the specimens and Table 2 shows their material properties such as the yield strength and the tensile strength of the perfobond steel plate, the penetrating rebar, the longitudinal and hoop reinforcements. In the experiment, a ready mixed concrete with maximum coarse aggregate size of 25mm is used for all specimens and the push-out tests are conducted from 28 to 60 days after the concrete placement. The average value of the concrete compressive strength, the tensile strength, and Young’s modulus of concrete are also shown in Table 2.

Here, although there is a large difference in the yield strength of the perfobond steel plate, it is considered that the difference in the yield strength does not affect the shear resistance of the perfobond strip. The reason is that the stress which is obtained from the shear resistance of specimens with the largest perforation diameter of 90mm divided by the cross-section area of the steel plate, is sufficiently smaller than the yield strength of the steel plate.

(3) Test setup and instrumentation

During the experiment, the specimen is placed on the loading frame with the hydraulic jack of 1MN and the load is applied to the top of the perfobond steel plate. Sand is 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. Moreover, grease is applied on the perfobond steel plate before placing the concrete so as to reduce the effect of the bond between the steel plate and the surrounding concrete. In placing the concrete, the perfobond steel plate is placed horizontally in the formwork as shown in the lower right portion of Fig. 1 and the concrete was placed in the perpendicular direction to the plane of the paper. This concrete placement procedure is the same as the ones in References 7) and 8).

The relative slip between the top of the perfobond steel plate and the concrete block is measured by the displacement transducers which are connected to the angle fixed to the top of the steel plate. Moreover, in order to measure the longitudinal strain of the penetrating rebar, grooves
3. EXPERIMENTAL RESULTS

(1) Shear force-relative slip relation

a) Description of figures

The shear force-relative slip relation of specimens with the penetrating rebar in Table 1 are shown in Fig. 2. In these figures, 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. Each colored line corresponds to the relation with each experimental parameter. As discussed in Reference 8), since the influence of the cyclic loading on the envelope of the shear force-relative slip relation and its shear resistance is small, in the cases of the cyclic loading, the envelope of the relation is shown here. Figure 2-a shows the relation of the specimens with perforation diameters of 30mm, 60mm, and 90mm, thickness of perfobond steel plate of 12mm, and penetrating rebar diameter of 10mm. Figure 2-b shows the relation of the specimens with perforation diameters of 40mm, 60mm, and 70mm, thickness of perfobond steel plate of 12mm, and penetrating rebar diameter of 13mm. Figure 2-c shows the relation of the specimens with perforation diameters of 40mm, 60mm, and 70mm, thickness of perfobond steel plate of 12mm, and penetrating rebar diameter of 16mm. Furthermore, Fig. 2-d shows the re-
lation of the specimens with thicknesses of perfobond steel plate of 12mm, 19mm, and 25mm, perforation diameter of 60mm, and penetrating rebar diameter of 16mm.

b) Effect of perforation diameter

It can be seen from Fig. 2-a which shows the relation of specimens with the same penetrating rebar diameter of 10mm and thickness of perfobond steel plate of 12mm that the shear force at the same relative slip increases clearly with the perforation diameter. In black lines which represent the relation of specimens with the perforation diameter of 30mm, the shear force increases proportionally with the relative slip, after the relative slip goes beyond about 4mm. This is the reason why the penetrating rebar moves through the concrete in the perforation and comes close to the edge of the perforation with the increase of the shear force. On the contrary, the shear force decreases rapidly after the relative slip goes beyond about 15mm because of the breaking of the penetrating rebar. The shear force is considered to increase slightly after the breaking of the penetrating rebar due to the aggregate interlocking at the shear surface of the concrete. Moreover, in green lines which represent the relation of specimens with the perforation diameter of 90mm, the shear force decreases temporarily at the relative slip from about 5mm to 7mm. This is the reason why the concrete shear fracture at the perforation spreads peripherally and the crack appears on the surface of the concrete block at this time. However, the shear force does not decrease rapidly, since the hoop reinforcements are arranged inside the concrete block. On the other hand, in red lines which represent the relation of specimens with the perforation diameter of 60mm, after the shear force goes beyond a maximum value at relative slip from about 6mm to 10mm, in some cases, the shear force decreases with the increase of the relative slip, while in other cases, the shear force hardly decreases with the increase of the relative slip. This is attributed to the combination of the flexural behavior of the penetrating rebar and the relative position of the penetrating rebar in the perforation, in addition to the shear resistance of the shear fracture surface of the concrete at the perforation.

c) Effect of combination of perforation diameter and penetrating rebar diameter

From Fig. 2-b and Fig. 2-c which show the relation of specimens with the perforation diameters of 40mm, 60mm, and 70mm, and the penetrating rebar diameters of 13mm and 16mm, it can be said that the shear forces at the same relative slip are larger, when the perforation diameters are larger. In purple lines which represent the relations of specimens with the perforation diameter of 40mm, the shear force also increases proportionally with the increase of the relative slip after the relative slip goes beyond about 3mm. Consequently, the penetrating rebar in one of the specimens breaks at the relative slip of 20mm as shown in Fig. 2-b. The shear resistance of the specimen is considered to be dominated by the dowel action of the penetrating rebar, since the perforation diameter of 40mm is relatively small in comparison to the penetrating rebar diameters of 13mm and 16mm. In contrast, the shear force of specimens with perforation diameter of 70mm decreases temporarily at the relative slip of about 10mm due to the occurrence of cracks on the surface of the concrete block similar to the case of the perforation diameter of 90mm in Fig. 2-a. However, the shear force-relative slip relation of the specimens with the perforation diameter of 60mm in Fig. 2-b and 70mm in Fig. 2-c are similar to the ones with the perforation diameter of 60mm in Fig. 2-a.

On the other hand, in the red lines which represent the relation of the specimens with the same perforation diameter of 60mm and the penetrating rebar diameters of 10mm, 13mm, and 16mm as shown in Fig. 2-a, Fig. 2-b and Fig. 2-c, the shear resistance values are almost equal regardless of the penetrating rebar diameter. While the dowel action of the penetrating rebar increases with its diameter, the penetrating rebar moves through the concrete in the perforation and this behavior reduces the shear resistance of the concrete at the perforation. Therefore, the shear resistance of the specimens with different penetrating rebar diameters and the same perforation diameter become almost equal to each other.

d) Effect of steel plate thickness

In addition, from Fig. 2-d which represents the relation of specimens with perforation diameter of 60mm, penetrating rebar diameter of 16mm, and thicknesses of the perfobond steel plates of 12mm, 19mm, and 25mm, it can be seen that the initial rigidity up to the relative slip of 3mm increases with the increase of the thickness of the perfobond steel plate. Their shear resistance also increases slightly with the thickness of the perfobond steel plate, but the difference in the shear resistances is not so large. However, the influence of the thickness of the perfobond steel plate on the behavior of the penetrating rebar will be discussed later based on the results of the numerical analysis and the experiment on the specimens without the penetrating rebar.
(2) Relation between shear force and axial strain, bending strain of penetrating rebar

a) Description of figures

Figure 3 shows the relation between the shear force and the axial strain of the penetrating rebar, and Fig. 4 shows the relation between the shear force and the bending strain of the penetrating rebar. In these figures, the ordinate is the shear force, and the abscissa is the axial strain or the bending strain of the penetrating rebar. Each colored line corresponds to the relation of the specimen with the different experimental parameters. While the solid line shows the strain at central position of the penetrating rebar, the dash line shows the strain at the position of ±20mm away from the central position. It should be noted that the axial strain is the average one of the upper and lower surface strains of the penetrating rebar, and the bending strain is half of the strain difference between the upper and lower surface strains of the penetrating rebar. Here, the bending strain where the upper surface of the penetrating rebar shows the compressive strain and its lower surface shows the tensile strain, is expressed as the positive strain. Furthermore, Fig. 3-a and Fig. 4-a represent the relations of specimens changing in the perforation diameter, Fig. 3-b and Fig. 4-b represent the relations of specimens changing in the penetrating rebar diameter, and Fig. 3-c and Fig. 4-c represent the relations of specimens changing in the thickness of the perfobond steel plate.

b) Effect of perforation diameter on strain behavior

It can be seen from Fig. 3 and Fig. 4 that the axial strain and the bending strain of the penetrating rebar are produced after the shear force reaches about 40kN where the bond between the concrete and the perfobond steel plate is lost at the shear force. Moreover, it can be seen from the solid red lines in Fig. 3-a and Fig. 4-a which...
show the relations of specimens with the perforation diameter of 60mm, that the bending strain increases initially with the shear force and thereafter the axial strain also increases with the further increase of the shear force. This behavior is considered to result from the following facts: first the crack occurs in the concrete at the perforation due to the shear, as the shear force increases, and then the penetrating rebar develops the dowel action and the bending strain of the penetrating rebar gradually increases at its central position. Second, the axial strain of the penetrating rebar increases at its central position due to the push-out force which is produced by the relative slip of the shear fracture surfaces of the concrete at the perforation. In contrast, in the solid black lines of Fig. 3-a and Fig. 4-a which show the relation of specimens with the perforation diameter of 30mm, the bending strain increases with the shear force, and thereafter the axial strain also increases immediately. The perforation area in this case is considered small and the shear fracture surface occurs rapidly on the entire surface of the concrete at the perforation. Moreover, in the solid green lines of Fig. 3-a and Fig. 4-a which show the relation of specimens with the perforation diameter of 90mm, both the bending strain and the axial strain increase gradually with the shear force. This is the reason why the perforation area in this case is large enough and the shear fracture surface occurs gradually.

c) Effect of penetrating rebar diameter on strain behavior

On the other hand, the bending strain at the position of ±20mm from the central position of the penetrating rebar increases largely into the negative side in specimens with penetrating rebar diameter of 10mm as shown in Fig. 4-a and Fig. 4-b. However, as shown in Fig. 4-b and Fig. 4-c, the bending strain at the position of ±20mm from the central one initially develops into the positive side, but after the bending strain at the central position reaches about $2000 \times 10^{-6}$ as the shear force increases, the strain develops into the negative side. It can be noted that in these specimens with the penetrating rebar diameter of 16mm, since the bending stiffness of the penetrating rebar is large relative to the bearing force of the surrounding concrete, the penetrating rebar bent initially in a convex downward in the both sides of ±20mm near the central position.

Furthermore, in specimens with penetrating rebar diameter of 10mm, since its bending stiffness is small according to the bearing force of the surrounding concrete, the penetrating rebar bends inversely at the position of ±20mm near

(3) Situation of shear fracture surface at perforation

It can be predicted from the axial and bending strain behavior as described above that the penetrating rebar contributes to the shear resistance of the perfobond strip by the restraint effect where the penetrating rebar suppresses the opening of the concrete shear fracture surface at the perforation, in addition to the dowel action by the bending of the penetrating rebar. However, since the penetrating rebar moves in the concrete at the perforation, the penetrating rebar reduces the shear resistance of the concrete at the perforation. Then, the shear fracture surface in some specimens is observed after the loading test.

For example, while Photo 1-a shows the shear fracture surface at the perforation of specimen D60T12R10-B2 with perforation diameter of 60mm and penetrating rebar diameter of 10mm, Photo 1-b shows specimen D60T12R16-C2 with perforation diameter of 60mm and penetrating rebar diameter of 16mm. It can be observed from Photo 1-a that the penetrating rebar locates almost in the original center of the perforation, that is, the penetrating rebar does not move in the
concrete at the perforation. On the contrary, the penetrating rebar in Photo 1-b locates in the upper side in the concrete at the perforation; that is, the penetrating rebar moves definitely in the concrete at the perforation. From this fact, it can be predicted that when the penetrating rebar diameter is large relative to the perforation diameter and the flexural stiffness is also large, the penetrating rebar moves in the concrete at the perforation and then may reduce the shear surface of the concrete at the perforation.

4. NUMERICAL ANALYSIS ON BENDING BEHAVIOR OF PENETRATING REBAR

(1) Analysis model

As described in the experimental results, it is expected that the contribution of the penetrating rebar to the shear resistance of the perfobond strip is not only dependent on the penetrating rebar diameter but also on the perforation diameter and the thickness of the perfobond steel plate. The contribution of the penetrating rebar to the shear resistance is mainly produced by its bending deformation. Therefore, in order to investigate quantitatively the contribution of the bending deformation of the penetrating rebar, that is, its dowel action, a nonlinear analysis is carried out here. Figure 5 shows the analysis model employed to simulate the stress transmission from the perfobond steel plate to the penetrating rebar and the surrounding concrete. Therefore, the bearing springs are arranged at the upper side and lower side of each beam element which is the model for the penetrating rebar, and one end of the bearing spring is connected to the beam element node and the other end is connected to the virtual fixed point. Moreover, since the longitudinal slip of the penetrating rebar to the surrounding concrete is considered to be negligible, the sufficient rigid springs (the spring constant is $10^7$N/mm) are also arranged in the horizontal direction at each node of the beam element. In the analysis, the geometrical nonlinearity of the beam element is also considered since the vertical displacement of the penetrating rebar is relatively large.

Here, the penetrating rebar is assumed to have an equivalent circular cross-section and the section is divided into 12 segments to simulate the progress of the plastic zone. The perfect elastic-plastic stress-strain relation is assumed for the beam element and the value shown in Table 2 is set as the yield strength. Moreover, as will be described later, since the penetrating rebar is hardly deformed at the position more than about 50mm away from its central position, the length of the penetrating rebar in the analysis model is set as 250mm, which is half of the total length of the penetrating rebar in the experiment. Incidentally, since the influence of the cross-section reduction of the penetrating rebar by grooving on its bending strain behavior is not so large, the cross-section reduction of the penetrating rebar is ignored in this analysis.

On the other hand, by referring to the stress-strain relation of a general concrete material, the relation between the bearing force $f$ (N) and the displacement $u$ (mm) of the bearing spring is set as the relation shown in Fig. 6. Here, $F_c$ in Fig. 6 is the bearing capacity of the spring and the bearing capacity is obtained from the bearing strength by multiplying the area that is subjected to the bearing force directly. The bearing strength is as stated in the JSCE Standard Specifications for Concrete Structures. Further analysis is needed to consider the actual conditions of the bearing spring.
thermore, the bearing spring constant $k$ is determined by referring to the method of Maekawa and Qureshi\(^{11}\), and the yield displacement of the bearing spring is calculated by the following equation (3). However, if the penetrating rebar is detached from the surrounding concrete at the node, the bearing force for the tension side of the spring is set as zero.

\[
F_c = f'_c \sqrt[4]{\frac{A}{A_a}} A_a \quad (1)
\]

\[
k = \frac{150 f'_c}{\phi} A_a \quad (2)
\]

\[
U_c = \frac{F_c}{k} \quad (3)
\]

where, $A$ (mm\(^2\)) is the area that is subjected to the bearing force at the bottom surface of the concrete block; $A_a$ (mm\(^2\)) is the area that is subjected to the bearing force directly at the bottom surface of the penetrating rebar, $A_a = l_{st} \phi$ (mm\(^2\)); $l_{st}$ (mm) is the length of a beam element; and $\phi$ (mm) is the penetrating rebar diameter. $U_c$ is also the yield displacement of the bearing spring. Here, the length of a beam elements is set equal to 5mm and the entire penetrating rebar is divided into 50 elements. The bearing spring is not arranged within the length which corresponds to the thickness of the perfobond steel plate, and then the length is 10mm for the plate thickness of 12mm and is 20mm for the plate thickness of 19mm or 25mm. Moreover, the value of $\sqrt{A/A_a}$ in equation (1) is assumed as the upper limit value of 2.

Since the force applied to the perfobond steel plate is partially transmitted to the penetrating rebar through the concrete in the perforation, the penetrating rebar is assumed to be subjected to the uniform nodal loads near its central position as shown in Fig. 5 considering the spread of the transmitted force from the edge of the perforation to the concrete in the perforation. The width of the uniform load is determined through a trial-and-error method to make the analytical strain distribution of the penetrating rebar agree with the experimental one, since the width of the uniform load varies with the perforation diameter and the thickness of the perfobond steel plate. Incidentally, the total applied force to the penetrating rebar is not the entire shear force that is resisted by the perfobond strip, but is equal to the shear force that is resisted by the dowel action of the penetrating rebar.

(2) Longitudinal bending strain distribution of penetrating rebar

When the specimen has different parameters in perforation diameter and thickness of the perfobond steel plate, the longitudinal bending strain distribution of the penetrating rebar obtained from the experiment is different from each other. One of the reasons is that the longitudinal bending strain distribution of the penetrating rebar is considered to be affected by the width of the distributed load applied to the penetrating rebar. Therefore, as described in the previous term, the penetrating rebar is assumed to be subjected to the uniform load, and the width of the load is determined via a trial-and-error method so that the analytical strain distribution of the penetrating rebar agrees with the experimental one. In order to confirm the agreement of both strain behaviors in wide range as much as possible, the strain behaviors are compared with each other at four stages when the bending strain of the central portion of the penetrating rebar approaches about 1000, 2000, 5000 and 10000 $\times 10^{-6}$. In the case of the perforation diameter of 90mm, since the cracks occur on the surface of the concrete block before the bending strain of the central position of the penetrating rebar has reached 10000 $\times 10^{-6}$, a comparison at this stage is not performed.

For example, Fig. 7 shows a comparison of the strain distribution of specimens with thickness of perfobond steel plate of 12mm, penetrating rebar diameter of 10mm, and perforation diameters of 30mm, 60mm, and 90mm when the bending strain at the central position of the penetrating rebar reaches about 2000$\times10^{-6}$. In these figures, the ordinate is the bending strain and the abscissa is the distance from the central position of the penetrating rebar. Furthermore, black circles show the analysis results, while blue, red, and green circles show the experimental results with each perforation diameter. The specimen names are also written in each figure. It is assumed that the width of the distributed load is set as 10mm, 20mm, and 30mm according to the respective perforation diameters of 30mm, 60mm, and 90mm. It can be seen from Fig. 7 that the analysis results of the strain distribution almost agree with the experimental results. Moreover, the comparison results are not shown, but it can be confirmed that the analysis results also almost agree with the experimental results even in the other magnitude of the central strain. Therefore, it can be said that the bending deformation of the penetrating rebar can be analyzed quantitatively by the above numerical model with the assumed
width of the applied load to the penetrating rebar.

From the same comparison between the analysis results and the experimental results, the width of the distributed load is 20mm, 30mm, and 30mm, when the thickness of the perfobond steel plate is 12mm, 19mm, and 25mm respectively, and the perforation diameter is 60mm and penetrating rebar diameter is 16mm. In contrast, when the specimen has perforation diameter of 60mm, thickness of the perfobond steel plate of 12mm, and penetrating rebar diameters of 10mm, 13mm, and 16mm, the width of the distributed load becomes 20mm. Based on these results, it is not easy to identify the precise numerical value of the width, but it can be said that the width of the distributed load applied to the penetrating rebar through the concrete in the perforation increases with the perforation diameter and the thickness of the perfobond steel plate.

3. Relation between applied force and bending strain of penetrating rebar

Figure 8 shows the relation between the total applied force to the penetrating rebar and the bending strain of the penetrating rebar at the central position and the position of ±20mm away from the central position obtained in the analysis. In this figure, the ordinate is the total applied force to the penetrating rebar and the abscissa is the bending strain. Here, the total applied force corresponds to the shear force resisted by the penetrating rebar due to its dowel action. Moreover, the colored lines in the figure correspond to the parameters of the perforation diameter, the penetrating rebar diameter, and the thickness of the perfobond steel plate. The solid line shows the strain at the central position of the penetrating rebar, and the dotted line also shows the strain at the position of ±20mm away from the central position. In this case, since the bending strain at both sides of the position of ±20mm away from the central position is symmetrical, the dotted line corresponds to the bending strain on both sides. It can be seen from Fig. 8 that the bending strain at the central position increases in the positive side and the almost bending strain at the both side positions of ±20mm away from the central position increases in the negative side, as the applied force increases. However, when the penetrating rebar diameter is 16mm, the bending strain at the both side positions initially moves in the positive side and subsequently the bending strain shifts from the positive side to the negative side. These bending strain behavior closely corresponds to the experimental ones discussed in 3.(2).
On the other hand, focusing on the black, red, and green lines that correspond to the results with the perforation diameters of 30mm, 60mm, and 90mm, the applied force at the same bending strain decreases with the decrease of the perforation diameter, but the difference in the applied force is not so large. However, it can be seen from the relation between the bending strain and the shear force during the push-out test as shown in Fig. 4-a that the shear force at the same bending strain remarkably increases with the perforation diameter. Therefore, the degree of contribution of the penetrating rebar to the shear resistance of the perfobond strip is predicted; that is, the dowel action becomes large with the decrease of the perforation diameter. The shear forces in the case of the specimens with perforation diameters of 30mm, 60mm, and 90mm at the relative slip of about 1mm also correspond to about 56kN, 148kN, and 184kN averagely as shown in Fig. 2-a. The corresponding bending strain of the penetrating rebar at the central position to these shear forces also become about 6000×10^{-6}, 1500×10^{-6} and 500×10^{-6} respectively as shown in Fig. 4-a. Moreover, the approximate shear force of the penetrating rebar corresponding to the estimated bending strain at the central position becomes about 15kN, 9kN, and 4kN respectively, by using the relation in Fig. 8 obtained from the numerical analysis.

By using the same relation at the relative slip of about 2mm, the approximate shear force of the penetrating rebar corresponding to the perforation diameters of 30mm, 60mm, and 90mm becomes about 17kN, 19kN and 8kN respectively, and at the relative slip of about 6mm, the approximate shear force of the penetrating rebar corresponding to the perforation diameters of 60mm and 90mm becomes about 25kN and 30kN. On the contrary, we cannot measure the strain of the penetrating rebar at the central position due to severe yielding when the relative slip of the specimen with the perforation diameter of 30mm reaches 6mm. However, since the increase of the shear force of the penetrating rebar is small against the further increase of its bending strain as shown in Fig. 8, it can be predicted that the shear force of the penetrating rebar at this time is smaller than 20kN. Therefore, it can be said that the large shear force of the penetrating rebar is transmitted from the perfobond steel plate after the relative slip has reached a large value when the perforation diameter is large.

On the other hand, in the case of relations with the perforation diameter of 60mm, and the penetrating rebar diameters of 10mm, 13mm, and 16mm or the relations with the perforation diameter of 60mm, and the thicknesses of the perfobond steel plate of 12mm, 19mm, and 25mm as shown in Fig. 8, it can be said that the shear force of the penetrating rebar increases with the increase of the penetrating rebar diameter and the thickness of the perfobond steel plate. However, in the relation between the shear force and the bending strain of the penetrating rebar as shown in Fig. 4-b and Fig. 4-c, the significant difference in the shear force at the same bending strain is not observed. Thus, it can be said that the dowel action of the penetrating rebar against the shear resistance of the perfobond strip becomes large, as the diameter of the penetrating rebar and the thickness of the perfobond steel plate increase. The relation between the shear force of the penetrating rebar and the bending strain of the specimen with the thickness of the perfobond steel plate of 19mm and 25mm coincides with each other, since the both widths of the distributed load identified by the numerical analysis are the same.

Incidentally, the shear force of the penetrating rebar increases with the thickness of the perfobond steel plate, while the shear resistance of the perfobond strip without the dowel action of the penetrating rebar decreases with the increase of the thickness of the perfobond steel plate as shown in Appendix A. Therefore, the effect of the thickness of the perfobond steel plate on the shear resistance of the perfobond strip with the penetrating rebar cannot be observed definitely as shown in Fig. 2-d.

(4) Estimation of shear contribution of penetrating rebar to shear resistance of perfobond strip

As described above, by making the connection between the bending strain of the penetrating rebar-shear force of the perfobond strip relation during the test and the shear force of the penetrating rebar-bending strain of the penetrating rebar relation obtained by the numerical analysis, the shear force of the penetrating rebar during the test; that is, the dowel action can be predicted. Therefore, the shear force of the penetrating rebar at the shear resistance of the perfobond strip during the test is obtained through the above procedure, when the perforation diameter, the diameter of the penetrating rebar, and the thickness of the perfobond steel plate are varied. In this case, the maximum shear force applied to the specimen is regarded as the shear resistance of the perfobond strip irrespective of the magnitude of the relative slip. If the cracks occur on the
5. EVALUATION FORMULA OF SHEAR RESISTANCE OF PERFOBOND STRIP

(1) Evaluation formula considering influence of perfobond steel plate thickness

In Nakajima et al.’s past research\(^7\), the formula for evaluating the shear resistance of the perfobond strip without the penetrating rebar was constructed taking into consideration of the dimension of the concrete block as well as the perforation diameter and the concrete compressive strength as follows:

\[
Q_u = 0.044 A f_c^{0.65} A_s^{0.43}
\]

where, \(Q_u\) is the shear resistance (N), \(A\) is the perforation area (mm\(^2\)), \(f_c\) is the concrete compressive strength (N/mm\(^2\)), and \(A_s\) is the side area of the concrete block (mm\(^2\)). However, this formula does not take into account the influence of the thickness of the perfobond steel plate. In the evaluation formula specified in the JSCE Standard Specifications for Hybrid Structures\(^3\), it is considered that the shear resistance of the perfobond strip without the penetrating rebar increases with the thickness of the perfobond steel plate.

In contrast, according to the authors’ experimental results with variations in the perforation diameter and the thickness of the perfobond steel plate whose outline is shown in Appendix A, it can be observed that the shear resistance of the perfobond strip without the penetrating rebar decreases with the increase of the thickness of the perfobond steel plate. Here, the shear resistance of the perfobond strip is described by the function of the perforation area and the thickness of the perfobond steel plate. In this formula, the shear resistance of the perfobond strip is proportional to the power of -0.5 of the plate thickness, as shown in equation (A.1) in Appendix A. Therefore, the renewed formula for evaluating the shear resistance of the perfobond strip without the penetrating rebar is constructed including the term of the thickness of the perfobond steel plate as follows:

\[
Q_u = 0.15 A f_c^{0.65} A_s^{0.43} T^{-0.5}
\]

where, \(Q_u\) is the shear resistance (N), \(A_s\) is the side area of concrete block (mm\(^2\)), \(f_c\) is the concrete compressive strength (N/mm\(^2\)), \(A_s\) is the perforation area (mm\(^2\)), and \(T\) is the thickness of the perfobond steel plate (mm). Note that, in constructing formula (6), the same power of each influencing parameter is used in formula (5) and

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**Fig. 9** Relation between equation (4) and analysis value of shear contribution of penetrating rebar.
In order to confirm the applicability of this formula, the correlation between the shear resistance of the experimental results and the ones obtained from formula (6) is investigated here. In this case, Nakajima et al.’s results\(^7,8\) and the results of other researchers\(^2,4,12\)\(^\text{–}20\) are used. Moreover, for the reference, the correlation between the shear resistance of the same experimental data and the ones obtained from the formula specified in the JSCE Standard Specifications for Hybrid Structures\(^3\) are also confirmed. While Fig. 10-a shows the correlation between the experimental results and the ones obtained from formula (6), Fig. 10-b shows the correlation between the experimental results and the ones obtained from the formula specified in the JSCE Standard Specifications for Hybrid Structures\(^3\), that is, shown in equation (B.1) in Appendix B. In these figures, the ordinate is the value \(Q_{\text{u exp}}\), and the abscissa is the value \(Q_{\text{u est}}\) evaluated from the respective formulas. Here, \(Q_{\text{u exp}}\) is the experimental shear resistance. Furthermore, the line \(y=ax\) in the figure is the regression line, \(R\) is the correlation coefficient, and \(SD\) is the standard deviation. It is confirmed from these figures that the data evaluated by the constructed formula in this research are well correlated with the experimental value, and the regression line is closer to the line \(y=x\) than the ones specified in the JSCE Standard Specifications for Hybrid Structures.

(2) Evaluation formula considering influence of penetrating rebar

As explained in Experimental Results Section, it can be considered that the shear resistance of the perfobond strip with the penetrating rebar is expressed by the sum of the shear resistance of the concrete at the perforation and the shear contribution; that is, the dowel action of the penetrating rebar. Since the push-out force is produced by the relative slip of the shear fracture surfaces of the concrete at the perforation, the penetrating rebar resists the push-out force and then the penetrating rebar contributes to the shear resistance of the shear fracture surface of the concrete at the perforation. When the diameter of the penetrating rebar is large and its flexural rigidity is also large, the penetrating rebar moves in the concrete at the perforation and this reduces the area of the shear surface of the concrete, and then the penetrating rebar reduces the shear resistance of the concrete at the perforation.

Therefore, the shear resistance of the perfobond strip with the penetrating rebar can be assumed by the sum of the shear resistance of the concrete at the perforation \(Q_c\), which is obtained by considering the reduction of the concrete shear surface due to the movement of the penetrating rebar, and suppressing effect of the opening of the shear fracture surface by the penetrating re-
bar, and the shear resistance of the dowel action of the penetrating rebar $Q_{st}$. The shear resistance of the dowel action of the penetrating rebar $Q_{st}$ can be expressed by the result of the numerical analysis in 4. (4) as shown in equation (4).

On the other hand, the shear resistance of the shear surface of the concrete at the perforation $Q_c$ can be expressed by formula (6) which is constructed for evaluating the shear resistance of the perfobond strip without the penetrating rebar. However, the reduction of the concrete shear surface due to the movement of the penetrating rebar and the suppressing effect of the opening of the shear fracture surface by the penetrating rebar as described above should be considered. These effects are related to the factor of the shear resistance of the shear surface of the concrete at the perforation. These effects are then evaluated as a coefficient $\alpha$. Thus, the shear resistance of the shear surface of the concrete at the perforation is expressed by the following equation:

$$Q_c = 0.15\alpha(A - A_{st})f_{c}^{0.65}A_s^{0.43}T^{-0.5}$$  \hspace{1cm} (7)

where $A_{st}$ is the area of the penetrating rebar (mm$^2$), and $\alpha$ is the coefficient that is determined by the effect of the penetrating rebar on the shear resistance of the shear surface of the concrete at the perforation.

Incidentally, as discussed in 3. (2), the axial strain behavior of the penetrating rebar; that is, the restraint effect of the penetrating rebar is considered to be changed by the relative relation between the perforation diameter and the penetrating rebar diameter. As described in 3. (3), the relative movement of the penetrating rebar in the perforation and the perfobond steel plate is also affected by the perforation diameter and the penetrating rebar diameter. Thus, it can be said that the coefficient $\alpha$ is dependent on the perforation diameter and the penetrating rebar diameter.

Therefore, in order to determine the coefficient $\alpha$, a multiple regression analysis is conducted.

Here, the ratio of the shear resistance of the shear surface of the concrete at the perforation $(Q_u - Q_{st})$, which is obtained by subtracting equation (9) from the shear resistance of the perfobond strip with the penetrating rebar to the term which, in turn is obtained by extracting $\alpha$ from equation (7) are set as the dependent variable, while the perforation diameter $D$ and the penetrating rebar diameter $\phi$ are set as explanatory variables. Consequently, the coefficient $\alpha$ is obtained as follows:

$$\alpha = 6.9\phi^{0.4}D^{-0.7}$$  \hspace{1cm} (8)

By combining these equations, the formula for evaluating the shear resistance of the perfobond strip with the penetrating rebar is expressed as follows:

$$Q_u = Q_c + Q_{st}$$  \hspace{1cm} (9)

where,

$$Q_c = 0.15\alpha(A - A_{st})f_{c}^{0.65}A_s^{0.43}T^{-0.5}$$

$$Q_{st} = 0.84\phi f_{yd}D^{0.1}T^{-0.8}$$

$$\alpha = 6.9\phi^{0.4}D^{-0.7}$$
In the same way as shown in Fig. 10-a and Fig. 10-b, the correlation between the shear resistance of the experimental results and the ones obtained from formula (9) or the ones obtained from the formula specified in the JSCE Standard Specifications for Hybrid Structures is investigated. Fig. 11-a shows the comparison to the ones obtained from formula (9) and Fig. 11-b shows the comparison to the ones obtained from the formula specified in the JSCE Standard Specifications for Hybrid Structures, as shown in equation (B.2) in Appendix B. In these figures, the ordinate is the experimental value $Q_{\text{exp}}$, and the abscissa is the value $Q_{\text{est}}$ evaluated from the respective formulas. Furthermore, the line $y=ax$ in the figure is the regression line, $R$ is the correlation coefficient, and $SD$ is the standard deviation. It can be seen from these figures that the data evaluated by the constructed formula in this research are well correlated with the experimental value, and the regression line is closer to the line $y = x$ than the ones of the JSCE Standard Specifications for Hybrid Structures as is the case without the penetrating rebar.

It should be noted that the perforation diameter, the thickness of the perfobond steel plate, the concrete compressive strength, the penetrating rebar diameter, the yield strength of the penetrating rebar, and the dimensions of the concrete block are the parameters in the formula constructed in this research. Therefore, the range of these parameters except for the dimension of the concrete block are as follows: Perforation diameter $D$ (mm) $30 \leq D \leq 90$, perfobond steel plate thickness $T$ (mm) $12 \leq T \leq 25$, penetrating rebar diameter $\phi$ (mm) $10 \leq \phi \leq 16$, yield strength of penetrating rebar $f_{\text{yld}}$ (N/mm$^2$) $356 \leq f_{\text{yld}} \leq 410$, concrete compressive strength $f'_{c}$ (N/mm$^2$) $29.0 \leq f'_{c} \leq 34.1$. Moreover, the maximum size of the coarse aggregate of concrete is 25mm.

It is presumed that the fracture of the concrete in the perforation occurs in a double shear fracture. Therefore, although it is important to pay attention to the ratio of the thickness of the perfobond strip to the perforation diameter, in fact the double shear fracture occurs in the specimen with the thickness of the perfobond steel plate of 12mm and the perforation diameter of 90mm. Furthermore, the dimension of the concrete block against the perforation of the specimen in this research is considered to be sufficiently larger than the ones in the actual structures.

6. SUMMARY

The purpose of this research is to investigate the strain behavior of the penetrating rebar in the perfobond strip and to make an attempt to construct the formula for evaluating the shear resistance of the perfobond strip with the penetrating rebar. In the experiment, by employing specimens in which the steel plate with the perforation is embedded in the concrete block, we conducted a push-out test of the specimens, which change the relation between the perforation diameter and the penetrating rebar diameter, and the thickness of the perfobond steel plate. We also studied the contribution of the penetrating rebar to the shear resistance of the perfobond strip by conducting a nonlinear numerical analysis paying attention to the strain behavior of the penetrating rebar. The main findings of this research may be summarized as follows:

1. The penetrating rebar contributes to the shear resistance of the perfobond strip by the suppressing effect of the opening of the shear fracture surface and the dowel action. However, a negative effect is that the area of the penetrating rebar and its movement in the perforation reduces the shear surface of the concrete at the perforation.

2. In order to simulate the bending behavior of the penetrating rebar in the perfobond strip, we conducted a nonlinear numerical analysis where the penetrating rebar was modeled as the beam element and the surrounding concrete was modeled as the bearing spring. Therefore, the dowel action of the penetrating rebar in the perfobond strip was predicted quantitatively by comparing the numerical result with the experimental one.

3. The design formula for evaluating the shear resistance of the perfobond strip with the penetrating rebar was constructed taking into consideration the dowel action of the penetrating rebar and the shear resistance of the shear surface of the concrete at the perforation. It can be concluded that the constructed formula can evaluate the shear resistance of the perfobond strip of the experimental results not only of this research but also of other authors’ researches.

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APPENDIX A Influence of perfobond steel plate thickness on shear resistance of perfobond strip without penetrating rebar

In the main text, the push-out tests were conducted by employing specimens with perforation diameters of 40mm and 60mm, penetrating rebar diameters of 10mm, 13mm, and 16mm and thicknesses of the perfobond steel plate of 12mm, 19mm, and 25mm. The relation of the shear force and the relative slip of the specimens was then obtained. The experimental results of the corresponding push-out tests of the specimens with perforation diameters of 40mm and 60mm, thickness of the perfobond steel plate and without the penetrating rebar are shown in Reference 9). The types of the specimens and their shear resistances are summarized in Table 3.

In the formula for evaluating the shear resistance of the perfobond strip without the penetrating rebar specified in the JSCE Standard Specifications for Hybrid Structures, the shear resistance of the perfobond strip without the penetrating rebar increases with the thickness of the perfobond steel plate. However, this tendency is not observed in Table 3. Moreover, in this case, the influence of the thickness of the perfobond steel plate on the shear resistance of the perfobond strip is deemed dependent on the perforation diameter, and there is a correlation between the perforation area and the thickness of the perfobond steel plate.

Here, we conduct the multiple regression analysis by setting the shear resistance $Q_u$ of the perfobond strip without the penetrating rebar in Table 3 as the objective variable, and setting the perforation area $A$ and the thickness of the perfobond steel plate $T$ as the explanatory variables. As a result, equation (A.1) is obtained as follows:

$$Q_u = 0.20 \frac{A}{T^{0.5}}$$  \hspace{1cm} (A.1)

Moreover, the correlation between the shear resistance and the value of $A/T^{0.5}$ is shown in Fig. 12. The ordinate is the shear resistance obtained from the experiment and the abscissa is the value of $A/T^{0.5}$. As a result, the correlation coefficient for the regression equation is 0.94. Therefore, it is necessary to take into account the influence of the thickness of the perfobond steel plate for evaluating the shear resistance of the perfobond strip.

Specimen name

| Specimen name-number | Material property | Perforation diameter (mm) | Perforation steel plate thickness (mm) | Shear resistance (kN) |
|----------------------|-------------------|---------------------------|---------------------------------------|-----------------------|
| D40T12NR-C1          | C                 | 40                        | 12                                    | 77.8                  |
| D40T12NR-C2          | C                 | 40                        | 12                                    | 87.9                  |
| D40T19NR-C1          | C                 | 40                        | 19                                    | 71.5                  |
| D40T19NR-C2          | C                 | 40                        | 19                                    | 64.7                  |
| D40T25NR-C1          | C                 | 40                        | 25                                    | 85.6                  |
| D40T25NR-C2          | C                 | 40                        | 25                                    | 76.4                  |
| D60T12NR-C1          | C                 | 60                        | 12                                    | 218.2                 |
| D60T12NR-C2          | C                 | 60                        | 12                                    | 222.2                 |
| D60T19NR-C1          | C                 | 60                        | 19                                    | 120.2                 |
| D60T19NR-C2          | C                 | 60                        | 19                                    | 174.1                 |
| D60T25NR-C1          | C                 | 60                        | 25                                    | 142.4                 |
| D60T25NR-C2          | C                 | 60                        | 25                                    | 171.2                 |
without the penetrating rebar.

APPENDIX B JSCE evaluation formula for shear resistance of perfobond strip

The evaluation formula for shear resistance of the perfobond strip specified in the JSCE Standard Specifications for Hybrid Structures\(^3\) is explained here. In the JSCE Standard Specifications, two formulas are defined according to the perfobond strip with and without the penetrating rebar.

1. Formula without penetrating rebar

\[
V_{psud} = \left( 4.31A - 39.0 \times 10^3 \right) / \gamma_b \quad (B.1)
\]

\[
A = \frac{\pi d^2}{4} \left( \frac{t}{d} \right)^{0.5} f'_{cd}
\]

and \(17.3 \times 10^3 \leq A \leq 152.4 \times 10^3\)

2. Formula with penetrating rebar

\[
V_{psud} = \left( 1.85A - 26.1 \times 10^3 \right) / \gamma_b \quad (B.2)
\]

\[
A = \frac{\pi (d^2 - \phi^2)}{4} f'_{cd} + \frac{\pi \phi^2}{4} f_{ud}
\]

and \(40.1 \times 10^3 \leq A \leq 383.3 \times 10^3\)

where, \(V_{psud}\) : Design shear resistance of perfobond strip with one perforation (N), \(d\) : Perforation diameter (mm), \(t\) : Thickness of steel plate (mm), \(f'_{cd}\) : Design concrete compressive strength (N/mm\(^2\)), \(\gamma_b\) : Member factor, \(\phi\) : Penetrating rebar diameter (mm), \(f_{ud}\) : Design tensile strength of steel plate (N/mm\(^2\)).

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