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Shear resistance characteristic and ductility of Y-type perfobond rib shear connector

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Abstract. This study evaluates behavior of the Y-type perfobond rib shear connector proposed by Kim *et al*. (2013). In addition, an empirical shear resistance formula is developed based on push-out tests. Various types of the proposed Y-type perfobond rib shear connectors are examined to evaluate the effects of design variables such as concrete strength, number of transverse rebars, and thickness of rib. It is verified that higher concrete strength increases shear resistance but decreases ductility. Placing transverse rebars significantly increases both the shear resistance and ductility. As the thickness of the ribs increases, the shear resistance increases but the ductility decreases. The experimental results indicate that a Y-type perfobond rib shear connector has higher shear resistance and ductility than the conventional stud shear connector. The effects of the end bearing resistance, resistance by transverse rebars, concrete dowel resistance by holes, and concrete dowel resistance by Y-shape ribs on the shear resistance are estimated empirically based on the push-out test results and the additional push-out test results by Kim *et al*. (2013). An empirical shear resistance formula is suggested to estimate the shear resistance of a Y-type perfobond shear connector for design purposes. The newly developed shear resistance formula is in reasonable agreement with the experimental results because the average ratio of measured shear resistance to estimated shear resistance is 1.024.

Keywords: Y-type perfobond rib shear connector; empirical analysis; shear connection; push-out test; shear resistance formula

1. Introduction

Since the introduction of the stud shear connector, various types of composite structures including the plate girder have been proposed. Composite structures are used not only for bridges but also for many types of building structures. As a variety of composite structures have been proposed, various types of shear connectors have been introduced accordingly. Recently, much research has been conducted on the perfobond rib shear connector and its variations.

The perfobond rib shear connector is a typical rigid shear connector and has flat steel plates

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with holes. This connector obtains shear resistance with the resistance of the end-bearing part in the steel plate, the dowel resistance of the holes, and the resistance of the penetrating rebars placed through the holes. Several authors have studied the behavior of the conventional flat type perfobond rib shear connector with push-out tests. Vianna *et al*. (2009, 2013) conducted two series of push-out tests. They presented the experimental results of shear resistance of conventional flat type perfobond rib shear connector with various concrete classes such as C25, C30, C50, and C60. Baran and Topkaya (2012) described an experimental study on European channel shear connectors. They compared the experimentally obtained shear resistance of the shear connector with the newly proposed shear resistance equation. It was shown that the developed equation is capable of predicting the shear resistance of channel type connectors with reasonable accuracy. Ahn *et al*. (2010) studied the influence of concrete strength and the arrangement of twin perfobond ribs, varying the distance between them. In that study, it was shown that the shear resistance of twin perfobond ribs did not change in response to the number of ribs or to the rib spacing-to-height ratio, although the shear resistance changed depending on the concrete strength. Cândido-Martins *et al*. (2010) investigated the possible interaction of two perfobond rib shear connectors depending on the lateral distance. It was observed that the system with two parallel connectors showed a higher shear resistance, but not reaching twice the capacity of a single connector. Kim and Jeong (2010) conducted an experimental research about a steel-concrete composite deck slab system with profiled steel sheeting and perfobond rib shear connectors. They evaluated shear resistance of the proposed composite deck slab system by push-out tests, and also examined the ultimate load-carrying capacity of the proposed composite deck slab system. Papastergiou and Lebet (2014) suggested a shear connection which is established by adhesion, interlocking and friction. The resistance of the connection to longitudinal shear is based on the development of shear stresses in the confined interfaces that form the connection. The variables considered in those studies are the shape of the steel plates in conventional flat-type perfobond rib shear connectors, the strength of the concrete, the size of the holes and the distance between the holes, and the diameter of the rebars and the distance between the rebars. For other shear connector type, Erdelyi and Dunai (2009) conducted the push-out tests about self-drilling screw shear connector. Also the composite beam tests were conducted.

Kim *et al*. (2013) suggested a Y-type perfobond rib shear connector as a new type of perfobond rib shear connector. The Y-type perfobond rib shear connector can be applied to various types of composite structures to improve the structural characteristics and workability of the conventional flat type perfobond rib shear connector. Push-out tests were conducted to verify shear resistance and ductility. In the research, concrete strength (30 and 40 MPa), the number of transverse rebars (none and four), rib thickness (8 mm and 10 mm), and Y-shape angle (60° and 0°) were considered as variables to evaluate the effect of various design variables. From the experimental results, a shear resistance formula for the Y-type perfobond rib shear connector was suggested by Kim *et al*. (2013).

This study aims to develop an improved shear resistance formula of a Y-type perfobond rib shear connector. Additional shear resistance evaluations based on the research by Kim *et al*. (2013) are conducted in this study through push-out tests on specimens manufactured in accordance with Eurocode-4 (2007). Concrete strength (40 and 50 MPa), the number of transverse rebars (four and two), rib thickness (10 and 12 mm) are additionally considered as variables, and a comparison is conducted with a conventional stud shear connector (D22 and 150 mm height) in terms of the shear resistance and ductility. Empirical analyses based on the early study by Kim *et al*. (2013) and this study is performed on each variable’s impact on the shear resistance. At the end of this study, a newly improved shear resistance formula for the Y-type perfobond rib shear connector is presented. The expected shear resistance of the proposed formula and the measured shear resistance obtained from the push-out tests are compared to verify the accuracy of the formula.

2. Y-type perfobond rib shear connector

The Y-type perfobond rib shear connector is a new type of perfobond rib shear connector of perfobond rib shear connector proposed by Kim *et al*. (2013). The Y-type perfobond rib shear connector improves the structural characteristics and workability of the conventional flat type perfobond rib shear connector. To manufacture the Y-type perfobond rib shear connector, the top of the rib of the conventional flat type perfobond rib shear connector is bent to Y-shape, and to replace the conventional circular hole where the transverse rebars are placed, the rib is cut into a semicircle and the top of the rib is removed so that it would provide sufficient space for workability of transverse rebars. Kim *et al*. (2013) proposed the Y-type perfobond rib shear connector and a shear resistance formula. Fig. 1 describes the shear resistance characteristics of the Y-type perfobond rib shear connector.

It was found that the Y-type perfobond rib shear connector has better shear resistance, ductile behavior and higher initial stiffness than the conventional flat type perfobond rib shear connector. Therefore the Y-type perfobond rib shear connector demonstrated idealized structural behaviors. Kim *et al*. (2013) proposed a shear resistance formula of the Y-type perfobond rib shear connector. The formula considers the effects of the end bearing resistance, resistance by transverse rebars, concrete dowel resistance by holes, and concrete dowel resistance from Y-shape ribs. Eq. (1) is the shear resistance formula for Y-type perfobond rib shear connector.

$$\begin{aligned} Q = 3.428 \cdot (d/2 + 2h) \cdot t \cdot f_{ck} + 1.213 \cdot A_{tr} \cdot f_y \\ + 1.9 \cdot n \cdot \pi \cdot (d/2)^2 \cdot \sqrt{f_{ck}} + 0.438 \cdot m \cdot h \cdot s \cdot \sqrt{f_{ck}} \end{aligned} \tag{1}$$

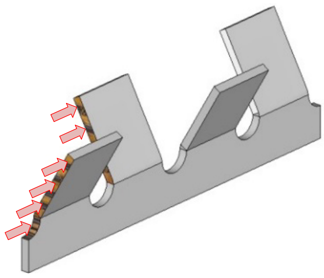
3. Push-out test to evaluate shear resistances of Y-type perfobond rib shear connectors

3.1 Details of experiments

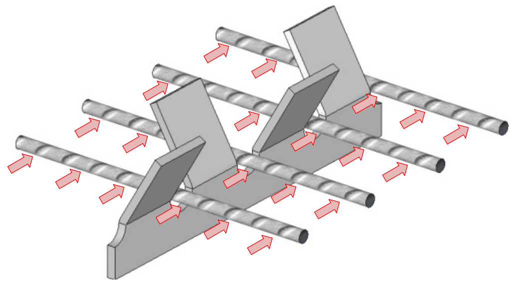
3.1.1 Specimens and material properties

In this study, the shear resistance of the Y-type perfobond rib shear connector is evaluated through push-out tests. Several push-out test results in this study are from the research by Kim *et al*. (2013). To verify accurately the differences of shear resistance characteristics depending design variables, more design variables are considered than in the research by Kim *et al*. (2013). The design variables for push-out tests are concrete strength, the number of transverse rebars, and rib thickness. Specimens are made in accordance with Eurocode-4 (2007). The test results are used to analyze and compare the effect of the variables on the shear resistance of the specimen and a conventional stud shear connector. Finally, the shear resistance and ductility of the Y-type perfobond rib shear connector are evaluated.

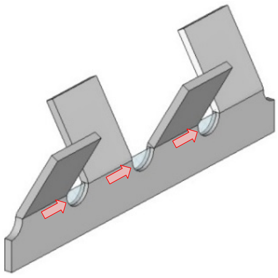
The range of each variable applied to the specimens is determined in accordance with Korea



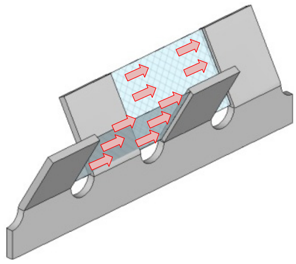
(a) Bearing resistance



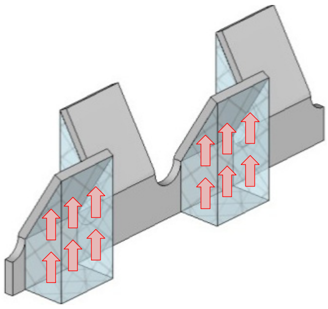
(b) Longitudinal resistance by transverse rebars



(c) Concrete dowel resistance by holes



(d) Concrete dowel resistance by Y-shape ribs



(e) Vertical resistance by Y-shape ribs

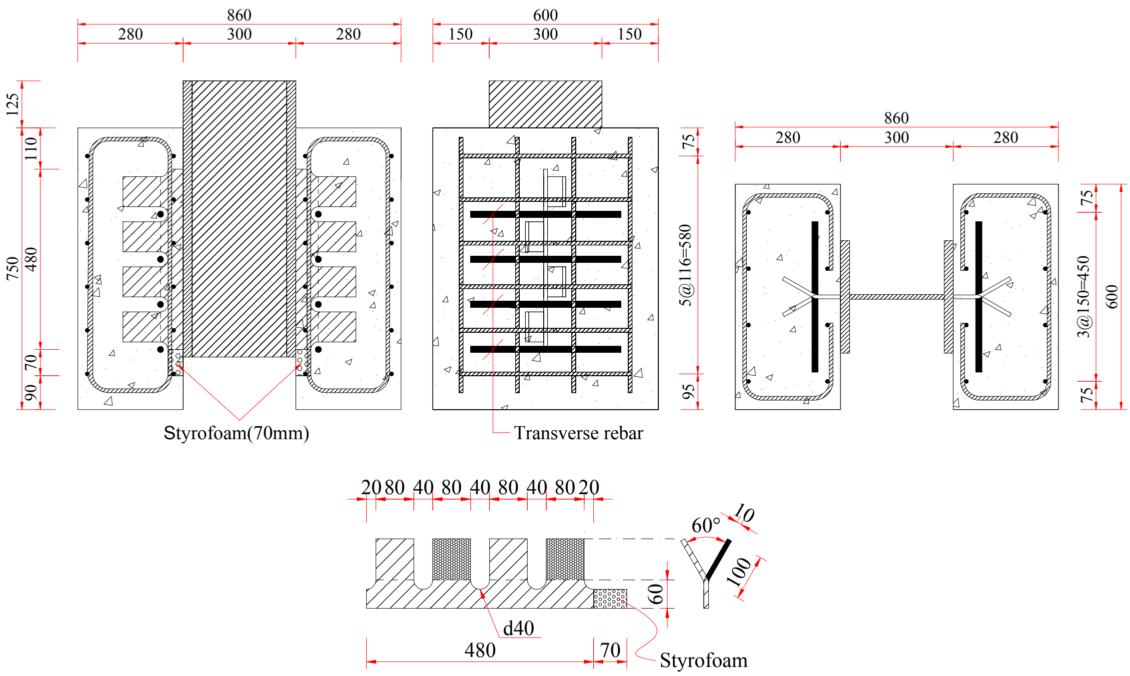
Fig. 1 Shear resistance characteristics of Y-type perfobond rib shear connector (Kim *et al*. 2013)

Highway Bridge Specifications (KHBS 2010) and the results by Kim *et al*. (2013). First of all, in case of concrete strengths, 50 MPa as an additional variable is used to see the effect of the concrete strength. Second, in case of rib thickness, 12 mm thickness specimens are tested to evaluate more accurately the effects on end bearing resistance. Third, in case of transverse rebar spacing, it is regulated in KHBS that the spacing of the transverse rebars is made more than 100 mm and less than 600 mm. The transverse rebar spacing is also related with the center-to-center spacing of holes in the ribs. Based on the research by Oguejiofor and Hosain (1997), the center-to-center spacing of holes is at least 2.25 times of the diameter of the holes. Therefore, the minimum spacing of transverse rebars has to be more than 90 mm. To examine the effects of the number of transverse rebars, additional tests to the research by Kim *et al*. (2013) are conducted with two transverse rebars. As same as the research by Kim *et al*. (2013), 40 MPa concrete, 10 mm rib thickness, four transverse rebars, and 60 degree Y-shape angle were selected as the representative specimens' design variables. Finally, conventional stud shear connector specimens are manufactured with 40 MPa concrete strength, and D22/H150 mm stud shear connectors. The estimated shear resistance of the stud shear connector specimen is designed at a similar level to the estimated shear resistance of the representative Y-type perfobond rib shear connector specimen (1721.6 kN). Eq. (2) is used to estimate shear resistance of the stud shear connector (KHBS 2010).

$$Q = 0.4 \cdot d_s^2 \cdot \sqrt{f_{ck} \cdot E_c} \tag{2}$$

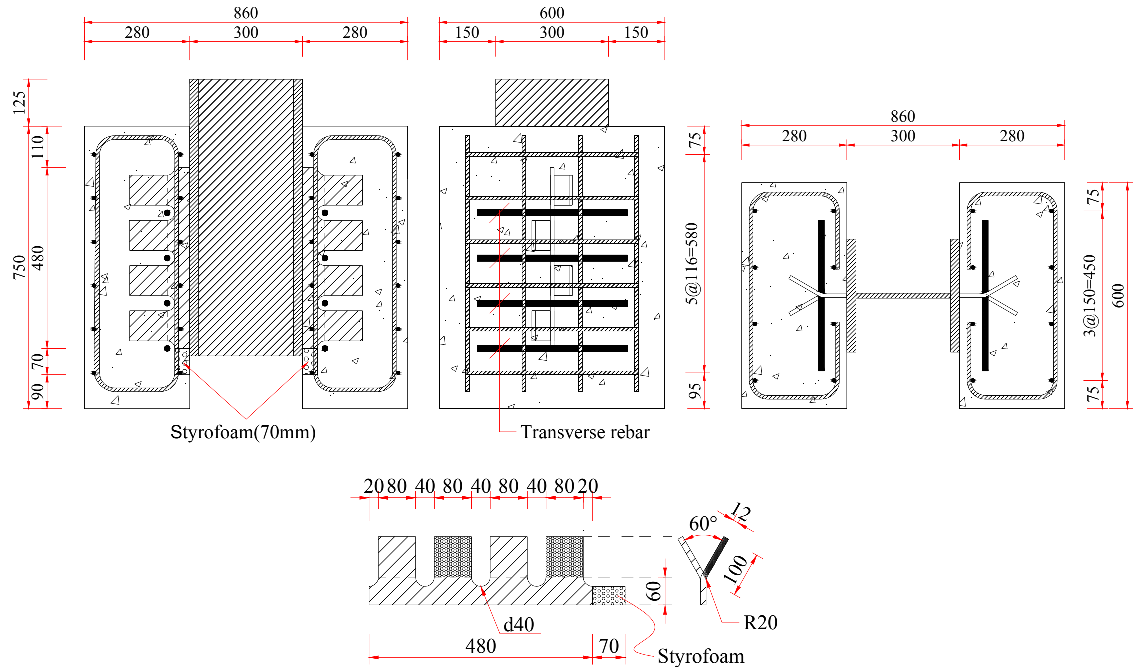
where, the Q (N) represents the shear capacity of conventional stud shear connector, d_s (mm) is diameter of stud, f_{ck} (MPa) is concrete compressive strength, and E_c (MPa) is elastic modulus of concrete.

Table 1 summarizes the conditions of variables for each specimen. For each variable condition, three specimens with the same specifications are manufactured to make sure the test results are reliable. Fig. 2 shows the shapes and details of each specimen. All specimens are fabricated in a manufacturing plant to maintain consistency in materials and shape. To maintain the same experiment conditions as the previous research by Kim *et al*. (2013), grease and Styrofoam are used. Grease is applied to the steel rib before pouring concrete to remove adhesive force caused by the chemical bonding between concrete and steel rib. A 70 mm-long Styrofoam is attached at the bottom end in the opposite direction of the applied load of the steel rib in order to prevent concrete bearing resistance in all parts except in the Y-shape and dowel hole.

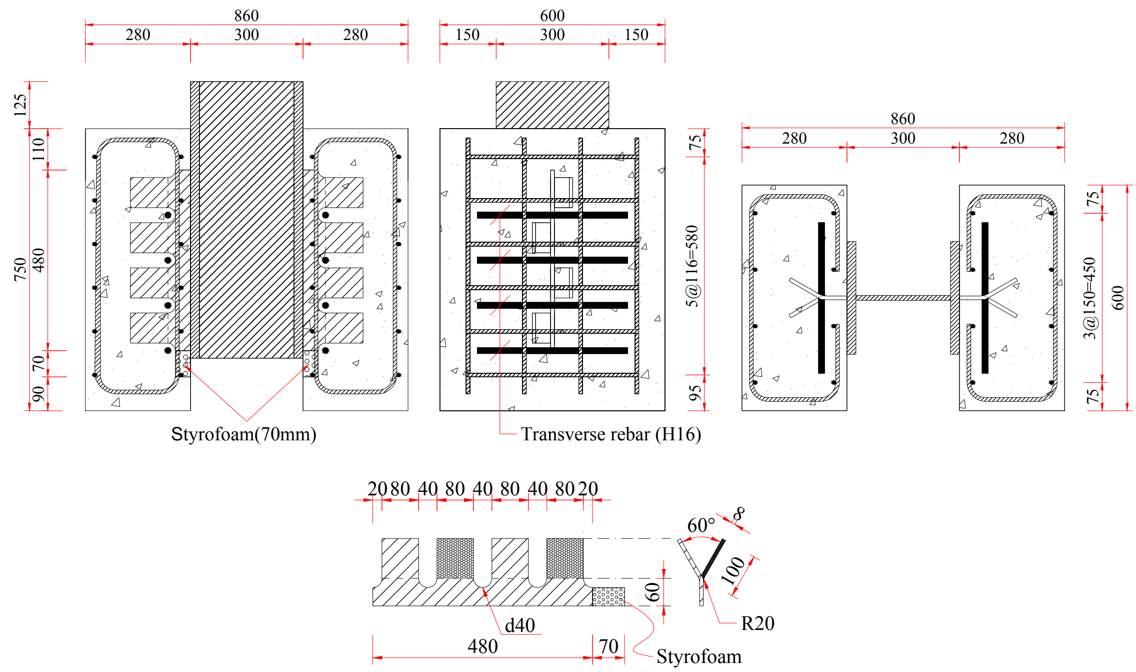


(a) Y-type perfobond (Representative), Y-type perfobond (Representative (Kim *et al.* 2013)), Y-type perfobond (f_{ck} = 50), and Y-type perfobond (f_{ck} = 30 (Kim *et al.* 2013))

Fig. 2 Layout of specimens

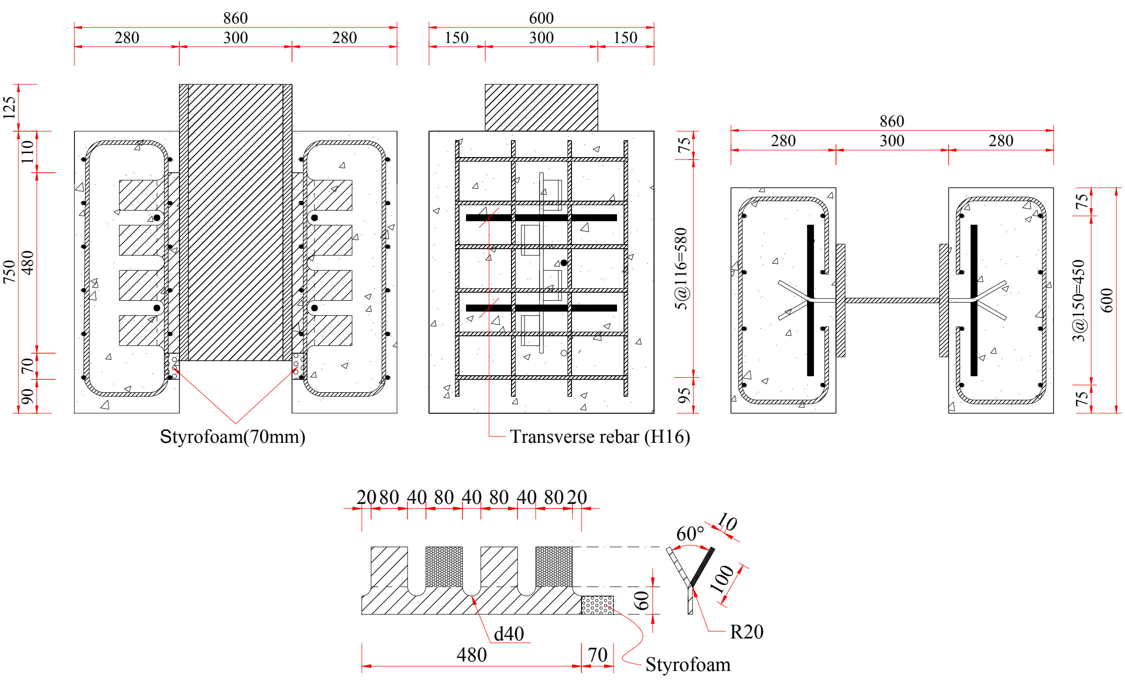


(b) Y-type perfobond (Rib thickness = 12)

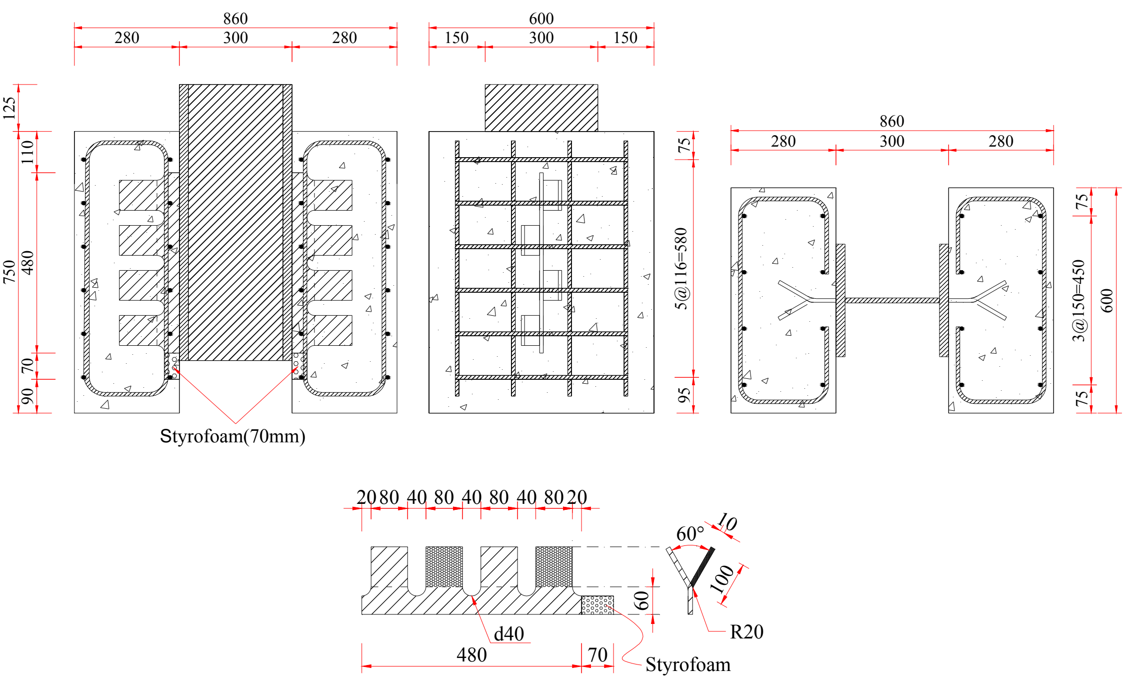


(c) Y-type perfobond (Rib thickness = 8 (Kim *et al*. 2013))

Fig. 2 Continued

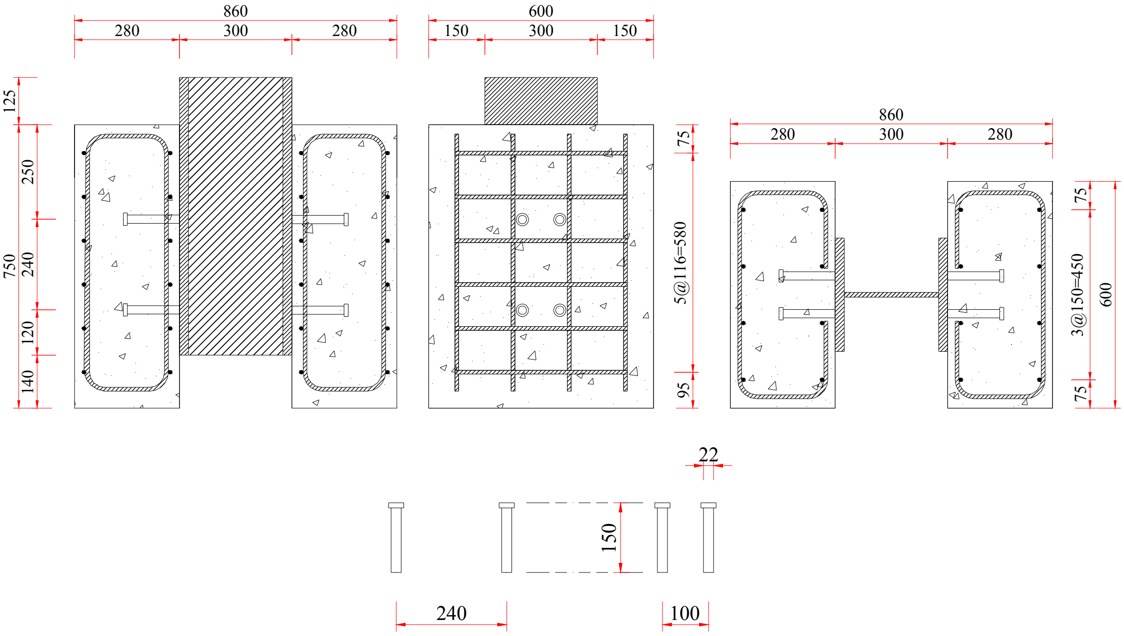


(d) Y-type perfobond (Transverse rebar = 2)

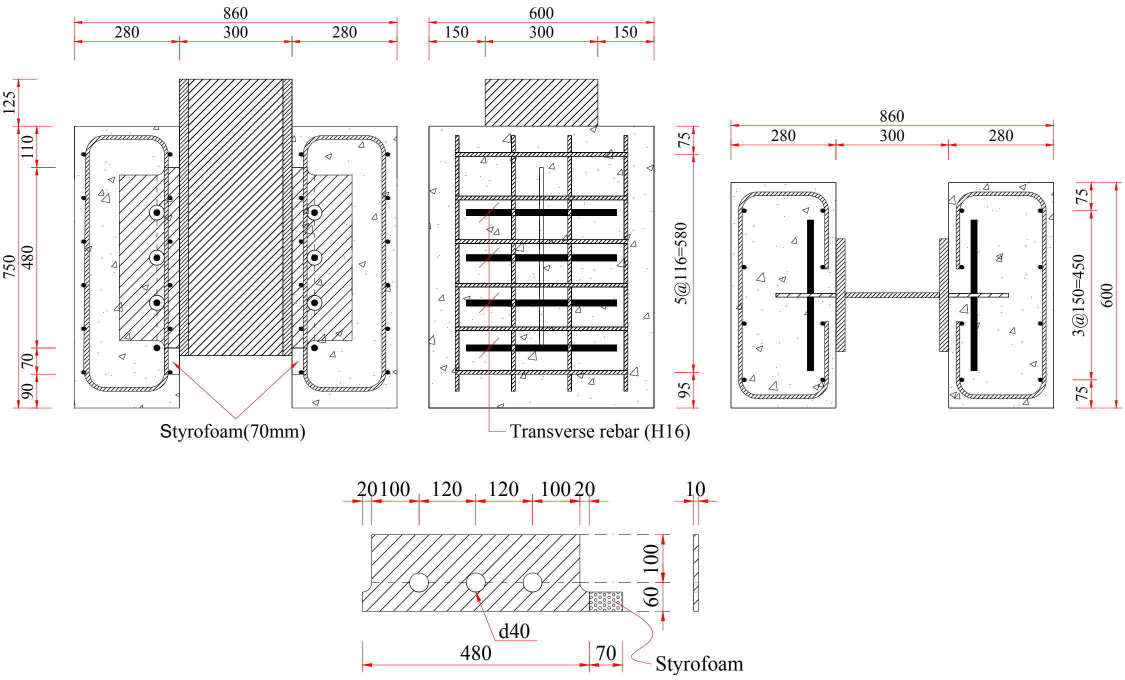


(e) Y-type perfobond (Transverse rebar = 0 (Kim *et al*. 2013))

Fig. 2 Continued



(f) Stud (D22/H150)



(g) Flat type (Kim *et al*. 2013)

Fig. 2 Continued

Table 1 Variations of specimens

Variations	Concrete strength (f_{ck}, MPa)	Number of transverse rebar (H16)	Y-shape angle (°)	Rib thickness (mm)	Number of specimens
1) Y-type perfobond rib (Representative)	40	4	60	10	3
2) Y-type perfobond rib (Representative)	40	4	60	10	3
3) Y-type perfobond rib (f_{ck} = 50 MPa)	50	4	60	10	3
4) Y-type perfobond rib (f_{ck} = 30 MPa) (Kim *et al*. 2013)	30	4	60	10	3
5) Y-type perfobond rib (Rib thickness = 12 mm)	40	4	60	12	3
6) Y-type perfobond rib (Rib thickness = 8 mm) (Kim *et al*. 2013)	40	4	60	8	3
7) Y-type perfobond rib (Rebar = 2)	40	2	60	10	3
8) Y-type perfobond rib (Rebar = 0) (Kim *et al*. 2013)	40	-	60	10	3
9) Stud (D22/H150 mm)	40	-	-	-	3
10) Flat type perfobond rib (Kim *et al*. 2013)	40	4	-	10	3

Table 2 Results of concrete cylinder compressive strength

Specimen	Strength (MPa)		
	Design	28-day	Before push-out test
Y-type perfobond (Representative)	40.0	41.0	41.7
Y-type perfobond (f_{ck} = 50)	50.0	49.2	51.0
Y-type perfobond (Transverse rebar = 2)	40.0	40.4	42.2
Y-type perfobond (Rebar = 2)	40.0	40.4	42.2
Stud (D22/H150)	40.0	41.0	41.7

The concrete compressive strength tests are performed to check quality of materials and to compare material strength differences between previous study by Kim *et al*. (2013) and present study. A cylinder specimen is manufactured using a cylinder of 100 mm in diameter and 200 mm in height. A total of 9 cylinder specimens are manufactured for 40 MPa concrete, and 9 for 50 MPa concrete. Cylinder specimens are cured under the same conditions as the specimens. Evaluations of concrete compressive strength are conducted at the concrete age reaches 28th day and right before the push-out tests. Table 2 shows the average value of the results of concrete compressive strength tests.

3.1.2 Push-out test description

In this study, the shear resistance of the Y-type perfobond rib shear connector and the structural behaviors depending on each variable will be analyzed based on the results of push-out tests proposed by Eurocode-4 (2007). For loading, 2,500 kN actuator is used. The relative slip is measured under the same conditions as the previous research (Kim *et al.* 2013) and the displacement increase rate of actuator is applied in the same manner. Four 50 mm LVDTs are installed at 350 mm below the top of the concrete slab to measure the relative slip between the concrete and steel. Loading is conducted by controlling the displacement. The speed of the increase in the displacement is controlled according to the methods proposed by Eurocode-4 (2007) to prevent the failure of the specimen in less than 15 minutes. The speed of the displacement increase is controlled at 0.05 mm/sec until the load becomes 500 kN, and after that it is maintained at 0.02 mm/sec. The development of the surface cracks during the loading is observed at each level of loading. The test is finished when the load decreases 20% from its ultimate load as commented in Eurocode-4 (2007). Fig. 3 shows the test set-up of the push-out tests.

The results of the relative displacement between concrete and steel are used to evaluate shear resistance and ductility of shear connector. Fig. 4 shows the criteria of result evaluation used in

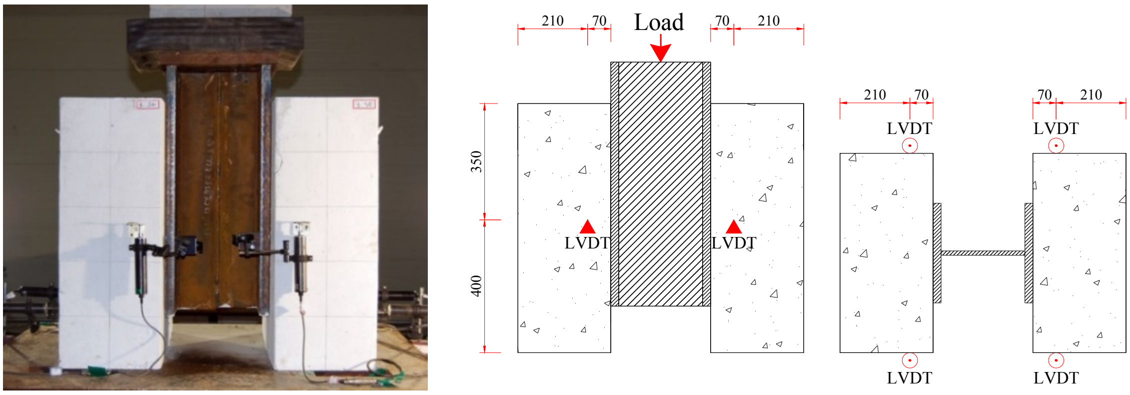


Fig. 3 Test set-up of push-out test

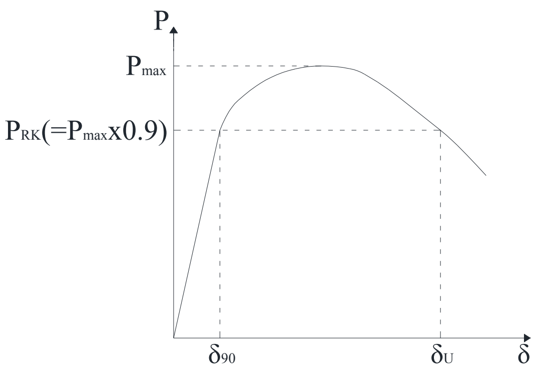


Fig. 4 Evaluation methods of push-out test results (Kim *et al.* 2013)

this study. The concepts of slip capacity (δ_u) and characteristic load value (P_{RK}) presented by Eurocode-4 (2007) are used in this study. This study uses the initial relative displacement (δ_{90}) based on P_{RK}, and δ_u / δ_{90} is compared. δ_u / δ_{90} refers to the ratio of slip capacity to the initial relative displacement. The larger the ratio, the bigger the ductility of the shear connector compared to the initial stiffness (Kim *et al*. 2013).

3.2 Evaluation of test results

This study aims to improve the shear resistance formula of the Y-type perfobond rib shear connector by considering other design variables in addition to the previous study by Kim *et al.* (2013). To achieve that objective, push-out tests are conducted on two ways. One is a representative specimen with the same concrete strength and shear connector shape as the previous study by Kim *et al*. (2013) and the other is a specimen for which the additional design variables are considered. First, the results from the representative specimen of Kim *et al*. (2013) are compared to the results from the representative specimen of this study. The comparison results are shown in Fig. 5 and Table 3. The comparison shows that the results from the two specimens are in agreement. Thus, it is deemed reasonable to evaluate the results of this study by comparing them with the results of the previous study by Kim *et al*. (2013).

3.2.1 Comparison by the type of the shear connector

For the comparison of the conventional stud shear connector, the conventional flat type perfobond rib shear connector, and the Y-type perfobond rib shear connector, the push-out tests are conducted. Test results are compared to the Y-type perfobond rib shear connector specimen. First, the average ultimate load of the three specimens of the conventional stud shear connector is 1,694.3 kN. Differences in the test results of each specimen are about 1.4%, meaning the test results are valid. Y-type perfobond rib shear connector shows higher stiffness in the elastic

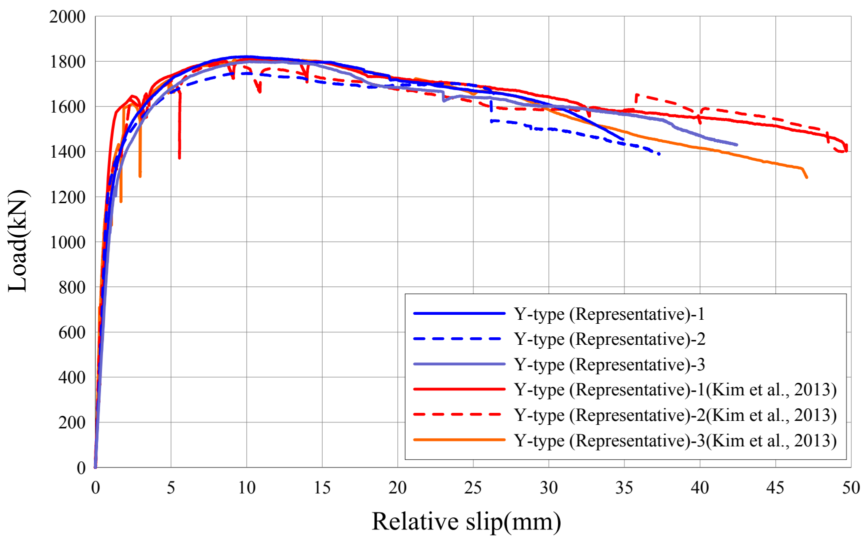


Fig. 5 Load-relative slip relationship of Y-type (Representative) by current study and Y-type (Representative) (Kim *et al*. 2013)

Table 3 Comparison between Y-type (Representative) by current study and Y-type (Representative) by Kim *et al*. (2013)

Specimens		P_{max} (kN)	P_{RK} (kN)	δ_{90} (mm)	δ_u (mm)	δ_u / δ_{90}
A) Y-type perfobond (Representative)	1	1821.0	1638.9	3.7	28.3	7.7
	2	1746.7	1572.0	3.4	27.5	8.2
	3	1798.7	1618.8	4.0	27.6	6.9
	Avg.	1788.8 (100.0) [1)]	1609.9	3.7	27.8	7.6
B) Y-type perfobond (Representative) (Kim *et al*. 2013)	1	1811.1	1630.0	3.6	30.9	8.7
	2	1789.1	1610.2	3.5	25.6	7.3
	3	1803.4	1623.1	3.3	28.7	8.6
	Avg.	1801.2 (100.7) [1)]	1621.1	3.5	28.4	8.2

[1)] Ratio (based on (A)) (unit: %)

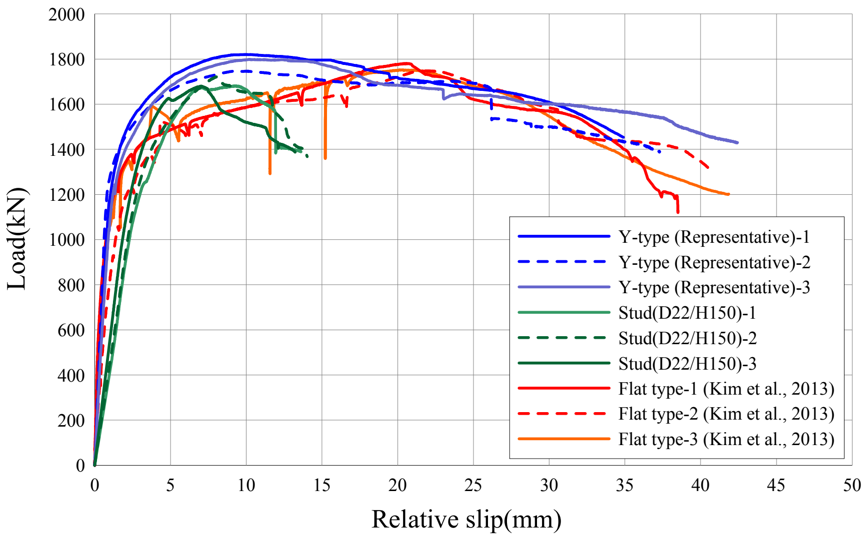


Fig. 6 Load-relative slip relationship depending on the type of shear connector

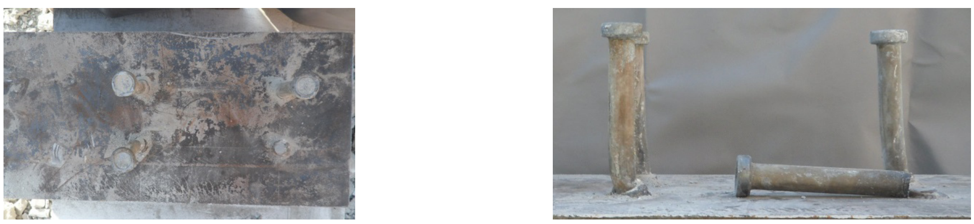
region than other shear connectors. In case of the energy dissipation capacity which is obtained by calculating the area of load-relative slip curve from the origin point to the δ_u, the area of the Y-type perfobond rib is 6% greater than the area evaluated from the conventional flat type perfobond rib and the area of the Y-type perfobond rib is 308 % greater than the area from the conventional stud shear connector. The Y-type perfobond rib shear connector shows higher δ_u / δ_{90} than the other two types of shear connectors, indicating that it has advantage in obtaining ductility. In case of the stud shear connector, the fracture behavior of the specimen is affected by the failure of the stud collar. Thus, it is confirmed that the stud shear connector is relatively at a disadvantage in terms of ductile behavior. Table 4 and Fig. 6 show comparisons based on the shear connector types. Fig. 7 shows deformation and failure of shear connectors.

Table 4 Comparison between Y-type (Representative), Stud (D22/H150), and flat type (Kim *et al*. 2013)

Specimens		P_{max} (kN)	P_{RK} (kN)	δ_{90} (mm)	δ_u (mm)	δ_u / δ_{90}
A) Y-type perfobond (Representative)	1	1821.0	1638.9	3.7	28.3	7.7
	2	1746.7	1572.0	3.4	27.5	8.2
	3	1798.7	1618.8	4.0	27.6	6.9
	Avg.	1788.8 (100.0) [1)]	1609.9	3.7	27.8	7.6
B) Stud (D22/H150)	1	1681.3	1513.2	5.0	11.9	2.4
	2	1721.6	1549.4	5.2	12.1	2.3
	3	1680.0	1512.0	3.8	10.3	2.7
	Avg.	1694.3 (94.1) [1)]	1524.9	4.6	11.5	2.5
C) Flat type perfobond (Kim *et al*. 2013)	1	1780.2	1602.2	11.1	26.1	2.4
	2	1748.1	1573.3	9.1	30.6	3.4
	3	1752.0	1576.8	7.0	29.2	4.2
	Avg.	1760.1 (98.4) [1)]	1584.1	9.0	28.6	3.3

[1)] Ratio (based on (A)) (unit: %)

(a) Y-type perfobond (Representative)



(b) Stud (D22/H150)

(c) Flat type perfobond (Kim *et al*. 2013)

Fig. 7 Deformation of shear connectors

Table 5 Comparison of concrete strength variation specimens

Specimens		P_{max} (kN)	P_{RK} (kN)	δ_{90} (mm)	δ_u (mm)	δ_u / δ_{90}
A) Y-type perfobond (Representative, f_{ck} = 40)	1	1821.0	1638.9	3.7	28.3	7.7
	2	1746.7	1572.0	3.4	27.5	8.2
	3	1798.7	1618.8	4.0	27.6	6.9
	Avg.	1788.8 (100.0) [1)]	1609.9	3.7	27.8	7.6
B) Y-type perfobond (f_{ck} = 50)	1	1949.0	1754.1	3.8	23.1	6.1
	2	1923.7	1731.3	3.5	29.0	8.3
	3	1903.4	1712.9	3.7	25.0	6.8
	Avg.	1925.4 (107.6) [1)]	1732.8	3.6	25.7	7.1
C) Y-type perfobond (f_{ck} = 30) (Kim *et al*. 2013)	1	1687.4	1518.7	2.8	33.0	11.8
	2	1636.8	1473.1	2.9	33.0	11.6
	3	1691.3	1522.2	3.0	31.5	10.7
	Avg.	1671.9 (93.5) [1)]	1504.7	2.9	32.5	11.4

[1)] Ratio (based on (A)) (unit: %)

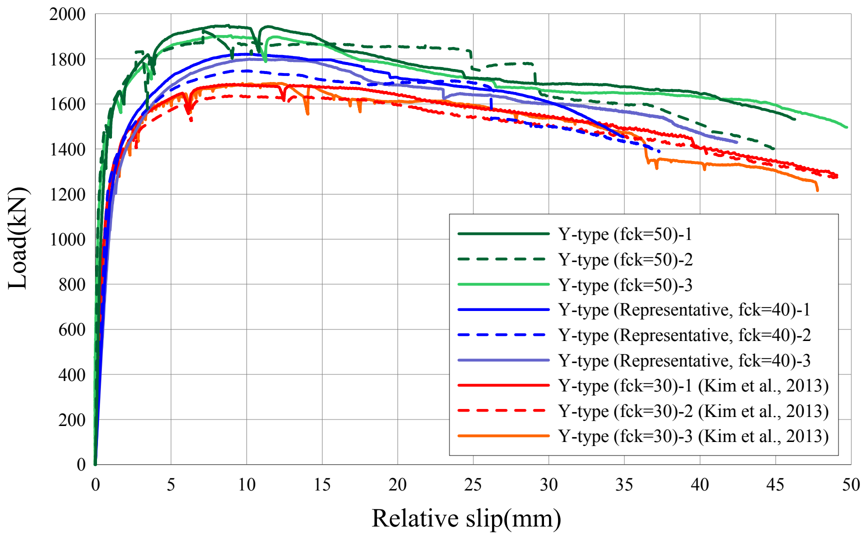


Fig. 8 Load-relative slip relationship depending on the concrete strength

3.2.2 Effects of concrete strength

To evaluate the effect of the concrete strength on the behavior of the Y-type perfobond rib shear connector, three specimens with 50 MPa concrete are manufactured and push-out tests are conducted. The average ultimate load of the three specimens is 1925.4 kN. Differences in the test results of each specimen are about 3%, meaning the test results are valid. δ_u / δ_{90} is 7.1 on average. In Table 5 and Fig. 8, test results are compared between the Y-type perfobond (Representative, f_{ck}

= 40 MPa), Y-type perfobond (f_{ck} = 50 MPa), and Y-type perfobond (f_{ck} = 30 MPa) (Kim *et al*. 2013). As shown in the comparison, when the concrete strength falls from 50 MPa to 30 MPa, the shear resistance of the specimen drops about 14% and the initial relative displacement (δ_{90}) decreases 20%. Therefore, the shear resistance and initial stiffness of the Y-type perfobond rib shear connector change in proportion to concrete strength. However, the δ_u and δ_u / δ_{90} are in inverse proportion to concrete strength. It is observed that the ductile behavior of the Y-type perfobond rib shear connector decreases as the strength of the concrete increases. This is in line with the general knowledge that stronger concrete has less strain capacity. In case of the energy dissipation capacity, Y-type perfobond (f_{ck} = 30 MPa) is 10% on average greater than the representative specimens and Y-type perfobond (f_{ck} = 50 MPa) is 13% on average less than the representative specimens.

3.2.3 Effects of transverse rebar

The shear resistance and ductility are estimated based on the number of the transverse rebars. The credibility of the tests results are ensured because the differences in the ultimate load of Y-type perfobond (Rebar = 2) specimens are less than 5%. Fig. 9 and Table 6 compare the test results of Y-type perfobond (Representative, Rebar = 4), Y-type perfobond (Rebar = 2) and Y-type perfobond (Rebar = 0) (Kim *et al*. 2013). In case of Y-type perfobond (Rebar = 2) specimens, the ultimate load ($P_{\max}$) of the specimen decreases about 22% and the initial relative slip (δ_{90}) decreases 57%. The ultimate load and the initial relative slip are decreased significantly if the transverse rebar is not placed. This means the transverse rebar has a significant influence on the shear resistance performance. Meanwhile, the ductility (δ_u / δ_{90}) is higher in the Y-type perfobond (Rebar = 2) than in the representative specimens. But the slip capacity (δ_u) of Y-type perfobond (Representative, Rebar = 4) is twice of Y-type perfobond (Rebar = 2). Therefore, the energy dissipation capacity of the representative specimen is greater than the case of Y-type perfobond (Rebar = 2) even though the ductility of Y-type perfobond (Rebar = 2) is higher than Y-type perfobond (Representative, Rebar = 4).

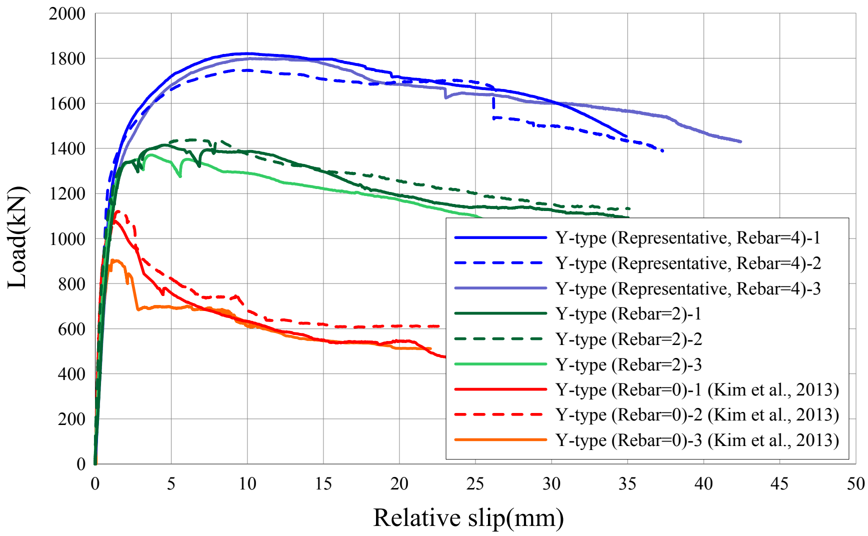


Fig. 9 Load-relative slip relationship depending on the number of transverse rebars

Table 6 Comparison of the number of transverse rebar variation specimens

Specimens		P_{max} (kN)	P_{RK} (kN)	δ_{90} (mm)	δ_u (mm)	δ_u / δ_{90}
A) Y-type perfobond (Representative, f_{ck} = 40)	1	1821.0	1638.9	3.7	28.3	7.7
	2	1746.7	1572.0	3.4	27.5	8.2
	3	1798.7	1618.8	4.0	27.6	6.9
	Avg.	1788.8 (100.0) [1)]	1609.9	3.7	27.8	7.6
B) Y-type perfobond (Rebar = 2)	1	1415.2	1274.1	1.6	15.9	10.1
	2	1439.0	1294.9	1.5	15.6	10.5
	3	1370.5	1233.4	1.3	13.9	10.5
	Avg.	1408.2 (78.7) [1)]	1267.5	1.5	15.2	10.3
C) Y-type perfobond (Reba = 0) (Kim *et al*. 2013)	1	1079.1	972.5	0.7	2.4	3.55
	2	1120.2	1010.0	1.0	2.6	2.67
	3	904.7	814.5	0.8	2.1	2.71
	Avg.	1034.7 (57.8) [1)]	932.3	0.8	2.7	3.0

[1)] Ratio (based on (A)) (unit: %)

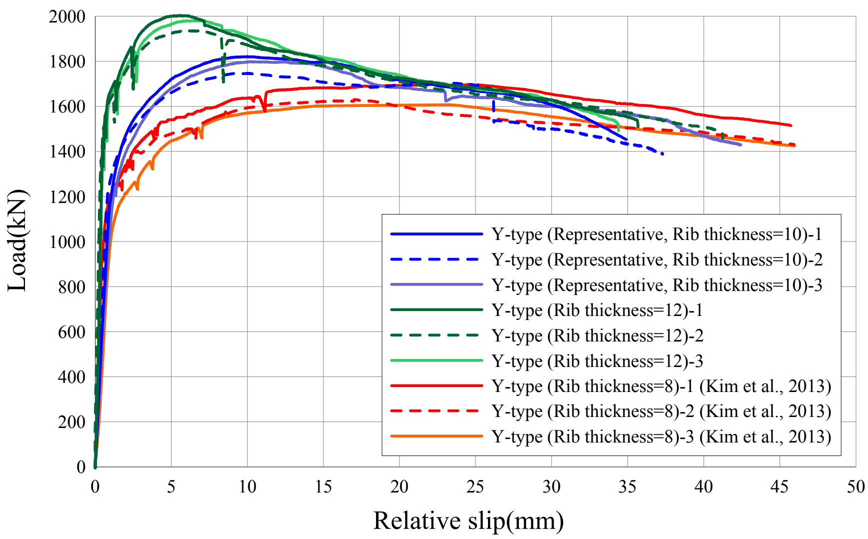


Fig. 10 Load-relative slip relationship depending on rib thickness

3.2.4 Influence of rib thickness

Fig. 10 and Table 7 show comparison of test results between the Y-type perfobond (Representative, Rib thickness = 10 mm), Y-type perfobond (Rib thickness = 12 mm), and Y-type perfobond (Rib thickness = 8 mm) (Kim *et al*. 2013). As the rib thickness decreased 2 mm, the ultimate load dropped 9%. The initial relative displacement (δ_{90}) and slip capacity (δ_u) of Y-type

Table 7 Comparison of rib thickness variation specimens

Specimens		P_{max} (kN)	P_{RK} (kN)	δ_{90} (mm)	δ_u (mm)	δ_u / δ_{90}
A) Y-type perfobond (Representative, Rib thickness = 10)	1	1821.0	1638.9	3.7	28.3	7.7
	2	1746.7	1572.0	3.4	27.5	8.2
	3	1798.7	1618.8	4.0	27.6	6.9
	Avg.	1788.8 (100.0) [1)]	1609.9	3.7	27.8	7.6
B) Y-type perfobond (Rib thickness = 12)	1	2003.1	1802.9	2.5	15.0	6.1
	2	1935.3	1742.5	1.9	17.8	9.4
	3	1980.4	1782.5	2.1	17.2	8.2
	Avg.	1972.9 (110.3) [1)]	1776.0	2.2	16.7	7.9
C) Y-type perfobond (Rib thickness = 8) (Kim *et al*. 2013)	1	1698.7	1528.8	4.3	44.4	10.3
	2	1630.4	1467.4	4.2	42.0	10.0
	3	1607.7	1446.9	5.0	43.0	8.6
	Avg.	1645.6 (91.9) [1)]	1481.1	4.5	43.1	9.6

[1)] Ratio (based on (A)) (unit: %)

perfobond (Rib thickness = 8 mm) increased 32% and 52% respectively. δ_u / δ_{90} increased 15%. The initial relative displacement (δ_{90}) and slip capacity (δ_u) of Y-type perfobond (Rib thickness = 12 mm) decreases 36% and 41% respectively. δ_u / δ_{90} decreases 8%. The test results show that the shear resistance is proportional to the rib thickness. As the rib thickness increases, the failure behavior of the shear connection part becomes the brittle failure of the concrete. Consequently, the increase in the rib thickness leads to the decrease of the ductility. However, the Y- type perfobond (Rib thickness = 12 mm) also shows sufficient slip capacity and ductility.

4. Development of shear resistance formula for Y-type perfobond rib shear connector

4.1 Design variables affecting shear resistance

Shear resistance formulas for the Y-type perfobond rib shear connector was proposed by Kim *et al*. (2013). But the design variables considered in the shear strength formula were not sufficient, and thus the accuracy of the formula was limited. Thus this study considers the push-out test results additionally, in order to improve the previously proposed shear strength formula. The composition of formula is the same as the formula proposed by Kim *et al*. Eq. (2) shows the basic composition of the formula. The first term indicates the end bearing resistance by Y-type perfobond rib; the second term, resistance by transverse rebar; the third term, concrete dowel resistance by holes; and the fourth term, concrete dowel resistance by Y-shape ribs.

$$Q = \beta_1 \cdot (d/2 + 2h) \cdot t \cdot f_{ck} + \beta_2 \cdot r \cdot A_r \cdot f_y + \beta_3 \cdot n \cdot \pi \cdot (d/2)^2 \cdot \sqrt{f_{ck}} + \beta_1 \cdot m \cdot h \cdot s \cdot \sqrt{f_{ck}} \tag{3}$$

where, the Q (N) represents the shear resistance of Y-type perfobond rib shear connector, d (mm) is dowel hole's diameter, h (mm) is individual rib height, t (mm) is rib thickness, f_{ck} (MPa) is concrete strength, A_r (mm^2) is section area of a transverse rebar, f_y (MPa) is transverse rebar's yield strength, r is the number of transverse rebars, n is the number of holes between the ribs, m is the number of dowel areas between Y-shape ribs, and s (mm) is net distance between ribs that are bent in same direction. β_1, β_2, β_3, and β_4 are values acquired by the empirical analysis on the push-out test results.

Considering the variables corresponding to each term, the regression analysis is conducted and came to the following results of β_1, β_2, β_3, and β_4: β_1 = 3.372, β_2 = 1.213, β_3 = 1.9, and β_4 = 0.757. β_2 and β_3 have the same value as Kim *et al*. (2013) [1], but β_1 and β_4 are adjusted by the additional variables considered in this study. Hence, the shear resistance formula would be given by Eq. (4).

$$\begin{aligned} Q = 3.372 \cdot (d/2 + 2h) \cdot t \cdot f_{ck} + 1.213 \cdot r \cdot A_r \cdot f_y \\ + 1.9 \cdot n \cdot \pi \cdot (d/2)^2 \cdot \sqrt{f_{ck}} + 0.757 \cdot m \cdot h \cdot s \cdot \sqrt{f_{ck}} \end{aligned} \quad (4)$$

4.2 Verification of shear resistance formula

The measured shear resistance, which has been divided by the number of shear connection parts, the shear resistance evaluated by Eq. (1), and the shear resistance evaluated by Eq. (4) are compared to verify the newly proposed shear resistance formula, Eq. (4). The average ratio of measured shear resistance to estimated shear resistance for Kim *et al*. (2013) is 1.102, but the average ratio of measured shear resistance to estimated shear resistance for Eq. (4) is 1.024. Therefore it can be seen that the newly proposed shear resistance formula, Eq. (4), are in more reasonable agreement than the formula by Kim *et al*. (2013). Table 8 is comparisons between the measured shear resistance and estimated shear resistance of Y-type perfobond rib shear connector.

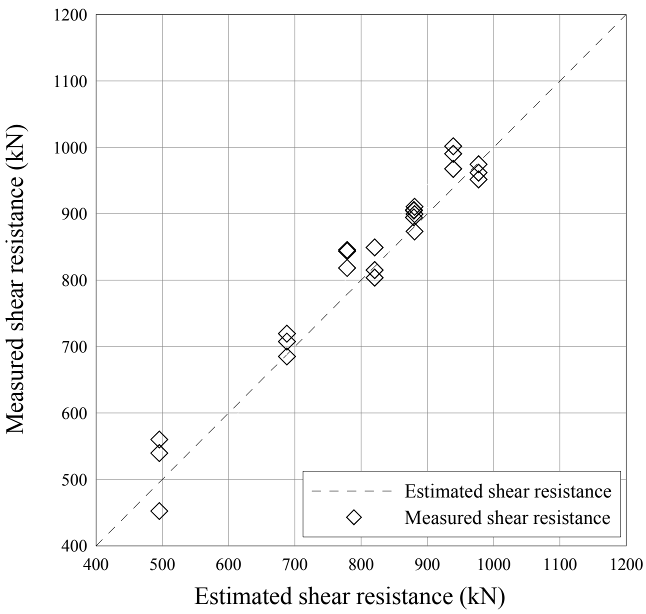


Fig. 11 Evaluation of proposed shear resistance formula

Table 8 Comparisons between the measured shear resistance and estimated shear resistance of Y-type perfobond rib shear connector

Specimens	No.	Measured shear resistance (kN)	Estimated shear resistance (Kim *et al*. 2013) (kN)	Ratio[1)]	Estimated shear resistance by Eq. (4) (kN)	Ratio [1)]
Representative	1	910.5	821.0	1.109	880.7	1.028
	2	873.4		1.064		1.016
	3	899.4		1.095		1.028
Representative (Kim *et al*. 2013)	1	905.6	821.0	1.103	880.7	1.034
	2	894.6		1.090		0.992
	3	904.9		1.102		1.021
f_{ck} = 30 MPa (Kim *et al*. 2013)	1	843.7	727.7	1.159	779.9	1.082
	2	818.4		1.125		1.049
	3	845.7		1.162		1.084
f_{ck} = 50 MPa	1	974.5	912.3	1.068	978.3	0.996
	2	961.9		1.054		0.983
	3	951.7		1.043		0.973
Rib thickness = 8 mm (Kim *et al*. 2013)	1	849.4	760.7	1.117	821.3	1.034
	2	815.2		1.072		0.993
	3	803.8		1.057		0.979
Rib thickness = 12 mm	1	1001.6	881.4	1.136	940.0	1.065
	2	967.7		1.098		1.029
	3	990.2		1.123		1.053
Rebar = 2	1	707.6	628.3	1.126	687.9	1.029
	2	719.5		1.145		1.046
	3	685.2		1.091		0.996
		Avg.		1.102		1.024

[1)] Ratio = Measured / Estimated

Fig. 11 compares the measured and estimated shear perfobond rib shear connector. The diagonal dash line is an imaginary line assuming the measured and estimated shear resistance is the same. Thus, if the dots, which plot the measured and estimated shear resistance by the X-axis and Y- axis, are close to the diagonal dash line, it means the measured and estimated resistance by the Y-type value match well. In Fig. 11, the dots are close the diagonal dash line, meaning that the formula is fairly accurate in estimating the shear resistance of the Y-type perfobond rib shear connector.

5. Conclusions

In this study, push-out tests are conducted following Eurocode-4 (2007) on the Y-type perfobond rib shear connectors to which three variables are applied. This study aims to further develop the previous study by Kim *et al*. (2013) by considering additional design variables on a specimen under the same test conditions. The variables are the concrete strength (f_{ck} = 50 MPa), the number of the transverse rebars (Rebar = 2), and rib thickness (Rib thickness = 12 mm). Through the tests, the shear resistance and ductility of the Y-type perfobond rib shear connectors are evaluated. They are then compared to the structural behaviors of the conventional stud shear connector. An empirical shear resistance formula for the Y-type perfobond rib shear connector is developed based on the push-out test results.

The results of the push-out tests indicate that the Y-type perfobond rib shear connector has better shear resistance and ductility than the conventional stud shear connector. The Y-type perfobond specimens show about 277% higher initial stiffness and 308% higher ductility than the conventional stud specimen. With this higher initial stiffness and ductile behavior, the Y-type perfobond rib shear connector demonstrates more ideal behavior than the conventional stud shear connector.

As found in the evaluation of the design variables affecting the shear resistance and ductility of the Y-type perfobond rib shear connector, the shear resistance of the Y-type perfobond rib increases when the concrete strength increases. The ductile behavior after the ultimate load decreases because of the lower strain capacity of the stronger concrete. The shear resistance increases with the rib thickness, whereas the ductility decreases. The increase of the number of transverse rebars contributes to the shear resistance and ductility. The transverse rebars improve the concrete dowel performance and directly reduce the drop of the stiffness after the cracking load.

An empirical formula is proposed to estimate the shear resistance of the Y- type perfobond rib shear connector for design purposes. This formula considers the effects of the end bearing resistance, resistance by transverse rebars, concrete dowel resistance by holes and concrete dowel resistance from Y-shape ribs by adopting the following design variables – the end bearing area, the concrete strength, the number of the transverse rebars, the dowel area between the Y-shape ribs, and the other factors.

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