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Evaluation of the Shear Strength of Perfobond Rib Connectors in Ultra High Performance Concrete

Jae Yoon Kang*, Jong Sup Park, Woo Tai Jung, Moon Seoung Keum

Structural Engineering Research Division, Korea Institute of Civil Engineering and Building Technology, Goyang, Korea
Email: *jykang@kict.re.kr, jspark1@kict.re.kr, woody@kict.re.kr, moonseoung@kict.re.kr

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Abstract

Since the previous strength prediction models for the perfobond rib connector were proposed based upon the results of push-out tests conducted on concretes with compressive strength below 50 MPa, push-out test is performed on perfobond shear connectors applying ultra high performance concretes with compressive strength higher than 80 MPa to evaluate their shear resistance. The test variables are chosen to be the diameter and number of dowel holes and, the change in the shear strength of the perfobond rib connector is examined with respect to the strength of two types of UHPC: steel fiber-reinforced concrete with compressive strength of 180 MPa and concrete without steel fiber with compressive strength of 80 MPa. The test results reveal that higher concrete strength and larger number of holes increased the shear strength, and that higher increase rate in the shear strength was achieved by the dowel action. The comparison with the predictions obtained by the previous models shows that the experimental results are close to the values given by the model proposed by Oguejiofor and Hosain [1].

Keywords

Perfobond Rib Connector, Ultra High Performance Concrete, Push-Out Test, Shear Strength

1. Introduction

The most popular shear connector used in composite structures is the headed stud. However, this connector is vulnerable to fatigue and is prone to sudden failure through breakage in the weld of the stud. Accordingly, pre-

*Corresponding author.

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ference has been recently shifted to stiffer shear connectors like the perfobond rib. The perfobond rib is fabricated by boring a number of holes in a steel plate so as realize a structure with improved shear performance by exploiting the dowel action generated by concrete placed in the holes.

Figure 1 illustrates the mechanical elements resisting shear in the perfobond rib connector involving the shear resistance in the concrete dowel, the shear resistance of the transverse steel reinforcement and, the concrete bearing pressure over the whole steel plate.

2. Review of Strength Prediction Models for Perfobond Rib Connector

Oguejiofor and Hosain [1], Medberry and Shahrooz [2], Verissimo *et al*. [3], Al-Darzi *et al*. [4] and, Ahn *et al*. [5] conducted push-out test to propose different empirical models evaluating the strength of the perfobond rib connector. Ushijima *et al*. [6] and Cho *et al*. [7] suggested evaluation formulae accounting for the contribution of the concrete dowel action to the shear resistance in the perfobond rib connector. In **Table 1** arranging these models, it can be seen that the shear is predicted by summing up distinctive terms relating separately the shear resistance contributed by the end bearing pressure, by the concrete dowel and, by the transverse steel reinforcement.

Figure 2 compares the shear strength predictions of each model assuming a perfobond rib with plate thickness t = 15 mm, plate height h = 100 mm and, hole diameter D = 30 mm. The comparison shows that the model of Oguejiofor and Hosain [1] predicts relatively larger strength whereas Verissimo *et al*. [3] provides a lower bound and, the formula of Ahn *et al*. [5] gives median prediction.

Moreover, **Figure 3** compares the shear strength calculated for concrete with compressive strength of 80 MPa. It can be seen that the shear strength computed for the perfobond rib connector is approximately 1.6 to 3.7 times larger than that of the stud defined in Eurocode.

It is noteworthy that most of the prediction models were established based upon push-out test for concrete with compressive strength running around 27 MPa. Since only Ahn *et al.* [5] considered concretes with com-

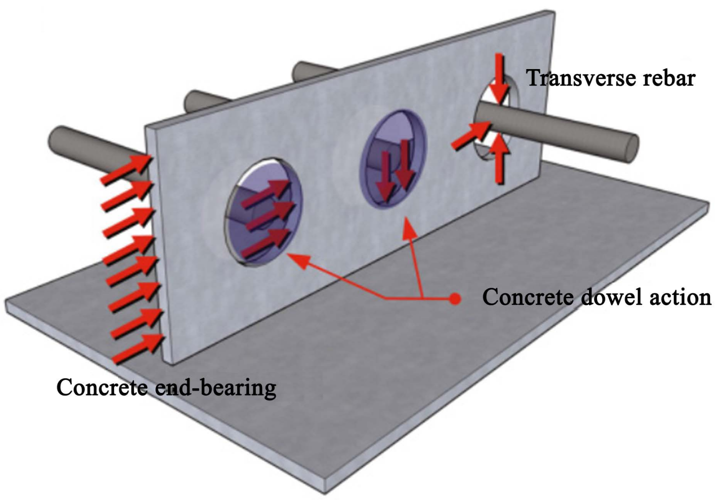


Figure 1. Shear-resisting mechanism of perfobond rib.

Table 1. Strength prediction models for perfobond rib.

Authors	Strength prediction models
Oguejiofor and Hosain [1]	$q_u = 4.5 h_{sc} t_{sc} f_{ck} + 0.91 A_{tr} f_y + 3.31 n D^2 \sqrt{f_{ck}}$
Medberry and Shahrooz [2]	$q_u = 0.747 bh \sqrt{f_{ck}} + 0.413 b_f L_c + 0.9 A_{tr} f_y + 1.66 n\pi \left(\frac{1}{2} D\right)^2 \sqrt{f_{ck}}$
Verissimo *et al*. [3]	$q_u = 4.04 (h_{sc}/b) h_{sc} t_{sc} f_{ck} + 2.37 n D^2 \sqrt{f_{ck}} + 0.16 A_{cc} \sqrt{f_{ck}} + 31.85 \times 10^6 (A_{tr}/A_{cc})$
Al-Darzi *et al*. [4]	$q_u = 255.31 + 7.62 \times 10^{-4} h_{sc} t_{sc} f_{ck} - 7.59 \times 10^7 A_{tr} f_y + 2.53 \times 10^{-3} A_{sc} \sqrt{f_{ck}}$
Ahn *et al*. [5]	$q_u = 3.14 h_{sc} t_{sc} f_{ck} + 1.21 A_{tr} f_y + 3.79 n\pi \left(\frac{1}{2} D\right)^2 \sqrt{f_{ck}}$

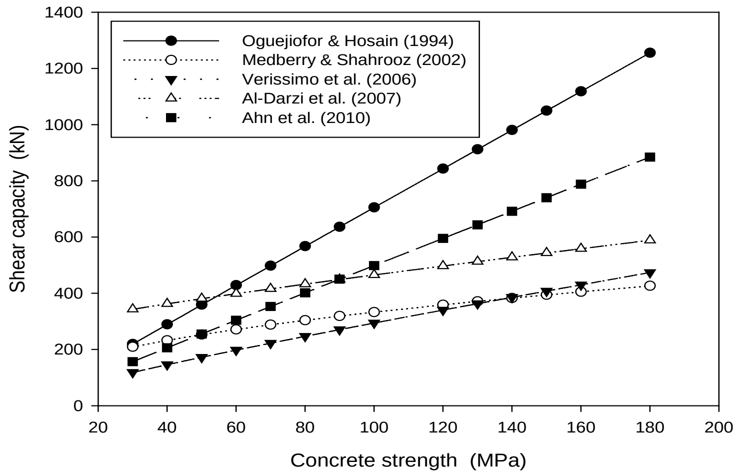


Figure 2. Comparison of shear strength of perfobond rib connector predicted by previous models.

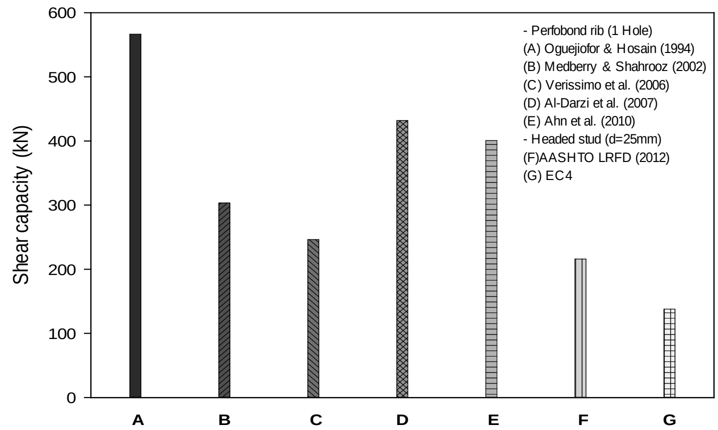


Figure 3. Comparison of shear strength computed for concrete with compressive strength of 80 MPa.

pressive strength up to 50 MPa in their experiments, the applicability of these shear connector strength prediction models for high strength concrete and, particularly steel fiber-reinforced ultra high strength concrete, should be examined experimentally.

On the behavior of stud connector in high strength concrete, An and Cederwall [8] conducted push-out tests to understand the strength of a stud depends on the concrete property with compressive strength of 100 MPa. They concluded that the stud in the high strength concrete tends to be sheared-off from the steel beam at the maximum load, while it shows very ductile behavior of stud in the normal strength concrete. As headed studs don't have enough shear capacity in high strength concrete, a continuous shear connectors such as puzzle strip has been suggested. Hegger *et al.* [9] investigated load-carrying behavior of puzzle strip connectors in ultra high performance concrete with compressive strength of 180 MPa, and they reported that the continuous type of shear connectors like the puzzle strip are appropriate for the high strength concrete as it is capable of carrying high shear loads with an appropriate ductility.

3. Push-Out Test of Perfobond Rib Connector Using Ultra High Performance Concrete

3.1. Objectives of Test

The previous strength prediction models proposed for the perfobond rib connector were established based on experiments conducted on concretes with compressive strength lower than 50 MPa. Therefore, the establishment of a strength prediction model for the perfobond rib connector using ultra high performance concrete (UHPC) with compressive strength higher than 80 MPa needs to rely on the results of push-out test using such concrete. Accordingly, this study performs push-out test on mixes with compressive strengths of 80 MPa and 180 MPa, and compares the experimental results with the predictions of the previous models.

3.2. Test Variables and Material Properties

The basic dimensions of the perfobond rib are a thickness (t) of 12 mm, a height (h) of 100 mm, and a length (L) of 310 mm. The considered test variables arranged in **Table 2** are the number of holes and their diameter. For each test variable, two series of specimens were fabricated using two types of concrete with respective block compressive strength of 80 MPa and 180 MPa. The 180-MPa perfobond specimens were fabricated using UHPC reinforced with steel fiber at a ratio of 1.5% and exhibited a mean compressive strength of about 176.9 MPa in the cylinder test. The 80-MPa perfobond specimens were fabricated using high strength concrete mixed with 20-mm coarse aggregate and blast furnace slag and without steel fiber reinforcement. These specimens developed a mean compressive strength of approximately 80.1 MPa in the cylinder test.

3.3. Test Method

Loading was applied stepwise by displacement control under initial application of a load of 5 kN for stabilization. The loading range and speed at each loading stage are listed in **Table 3**.

The measurands of the tests are the relative slip between the steel girder and the concrete block measured at 2 spots in the front face and 2 spots in the rear face, the horizontal displacement of the concrete blocks measured at each center of the two blocks, and the vertical displacement of the steel girder measured at 1 spot at the center of the girder. **Figure 4** shows the layout of the 7 displacement sensors installed on the specimen. **Figure 5** presents scenes of the test setup.

3.4. Test Results

Figure 6 and **Figure 7** plot the load-relative slip curves for each specimen. For the comparison of the shear strengths obtained experimentally and from the prediction models, the characteristic load (P_{rk}) is calculated as

Table 2. Test variables of perfobond rib specimens.

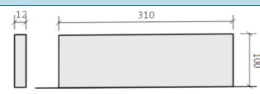
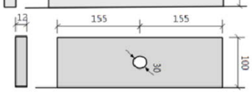
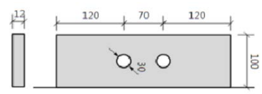
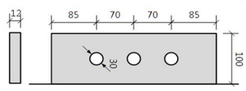
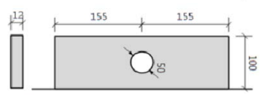
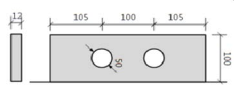
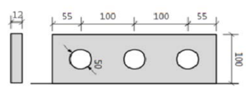
Specimen designation	No. of holes	Diameter of hole (mm)	Plate thickness (mm)	Shape of shear connector
P12	–	–	12	
P12-D30x1	1	30	12	
P12-D30x2	2	30	12	
P12-D30x3	3	30	12	
P12-D50x1	1	50	12	
P12-D50x2	2	50	12	
P12-D50x3	3	50	12	

Table 3. Loading range and speed per loading stage of push-out test.

Loading stage	Loading range	Loading speed (mm/s)	Remarks
Stage 1	5 kN	–	Stabilization load (zeroing)
Stage 2	3 mm	0.004	–
Stage 3	6 mm	0.006	–
Stage 4	10 mm	0.01	–
Stage 5	20 mm	0.04	–
Stage 6	>20 mm	0.06	Until failure

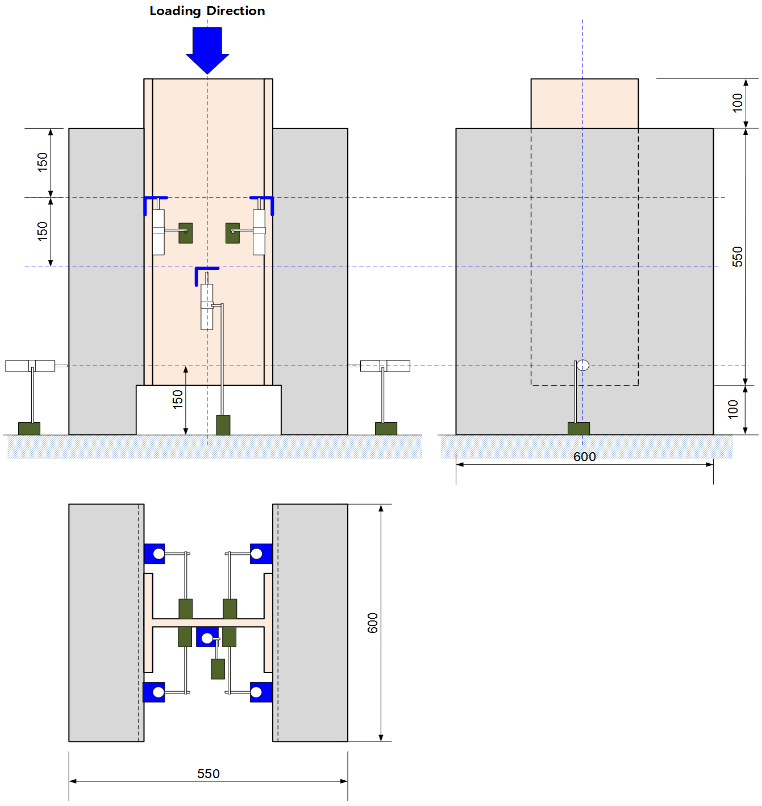
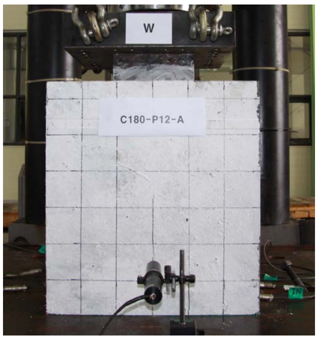


Figure 4. Layout of displacement sensors.



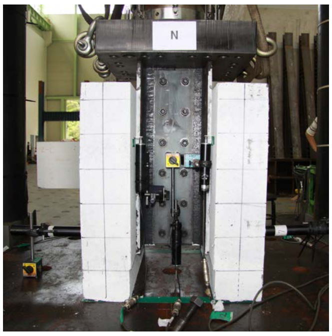


Figure 5. Views of push-out test: front (left), rear (right).

90% of the ultimate load (P_u) based on Eurocode. **Table 4** arranges the experimental results for each specimen.

The results are rearranged in **Figure 8** in which the shear strength is seen to increase with larger number of holes and higher compressive strength of concrete. Larger diameter of the holes appears to enlarge the dowel ac-

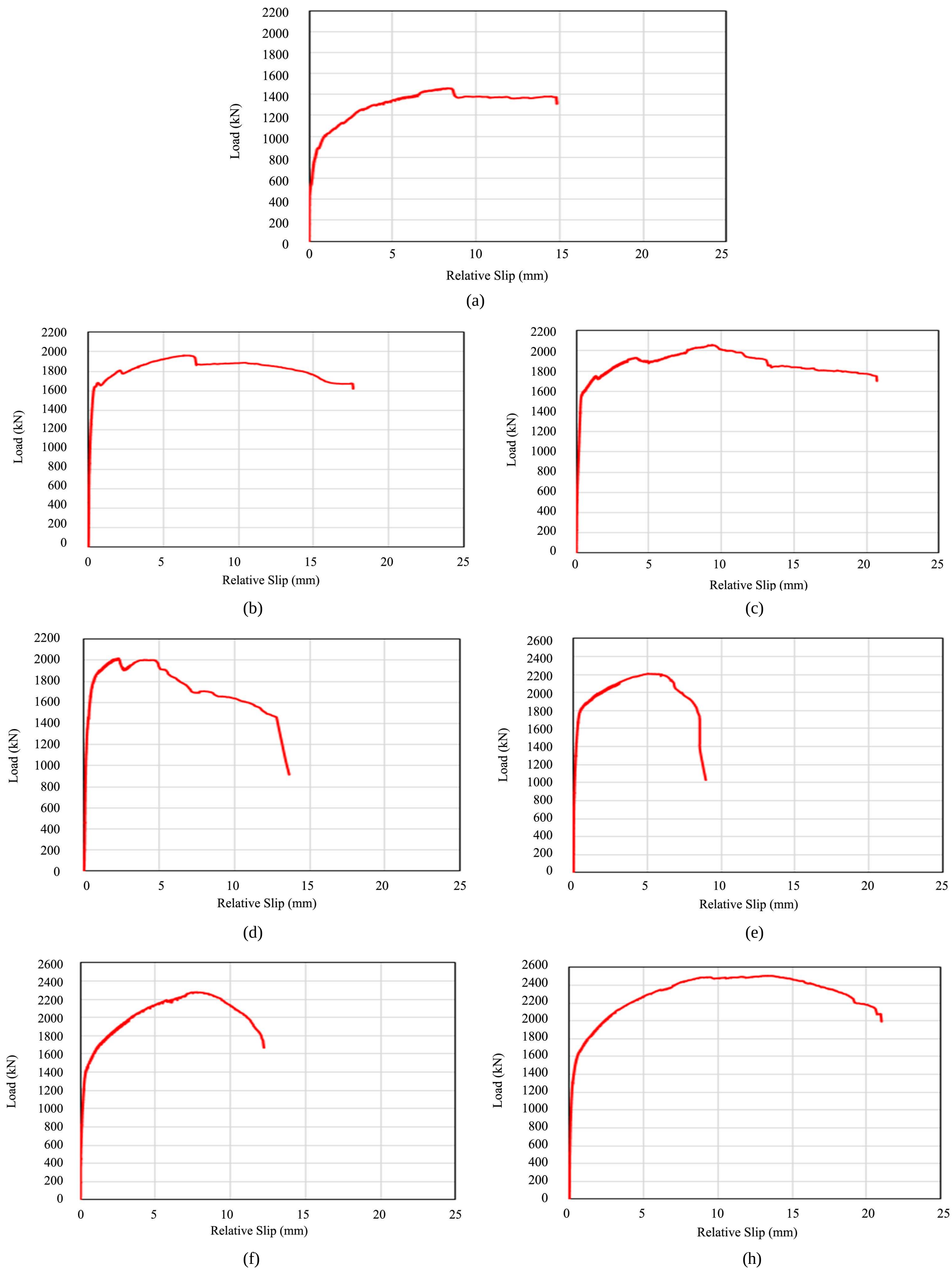


Figure 6. Measured load-relative slip curves (180-MPa perfobond rib specimens, load per 2 perfobond ribs). (a) C180-P12; (b) C180-P12-D30x1; (c) C180-P12-D30x2; (d) C180-P12-D30x3; (e) C180-P12-D50x1; (f) C180-P12-D50x2; (g) C180-P12-D50x3.

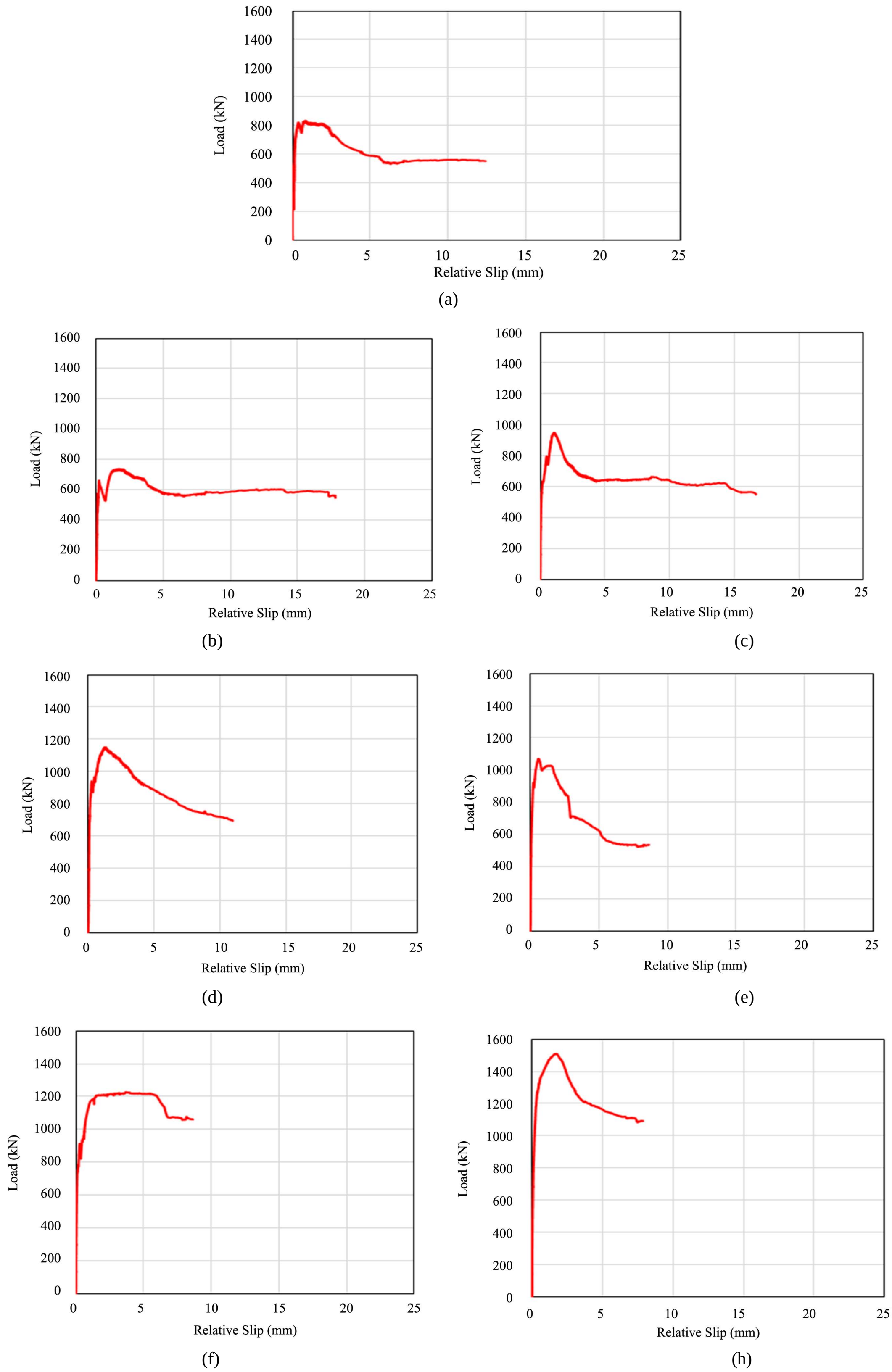
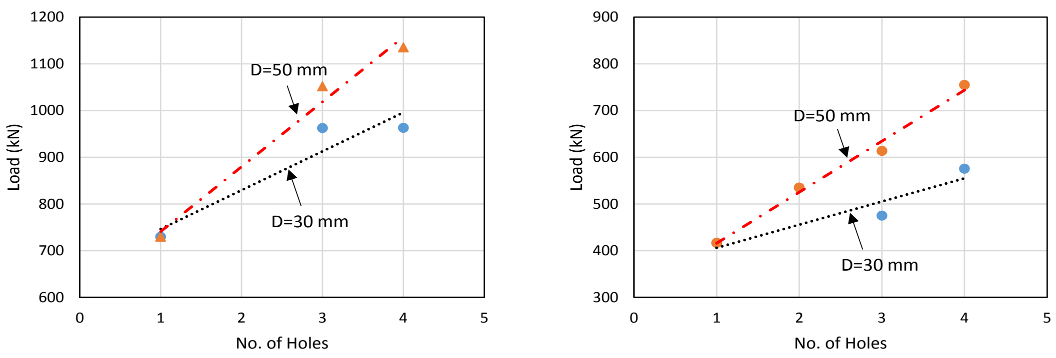


Figure 7. Measured load-relative slip curves (80-MPa perfobond rib specimens, load per 2 perfobond ribs). (a) C80-P12; (b) C80-P12-D30x1; (c) C80-P12-D30x2; (d) C80-P12-D30x3; (e) C80-P12-D50x1; (f) C80-P12-D50x2; (g) C80-P12-D50x3.



(a) (b)

Figure 8. Change in shear strength according to number of holes. (a) 180-MPa strength; (b) 80-MPa strength.

Table 4. Push-out test results of perfobond rib specimens using high strength concretes.

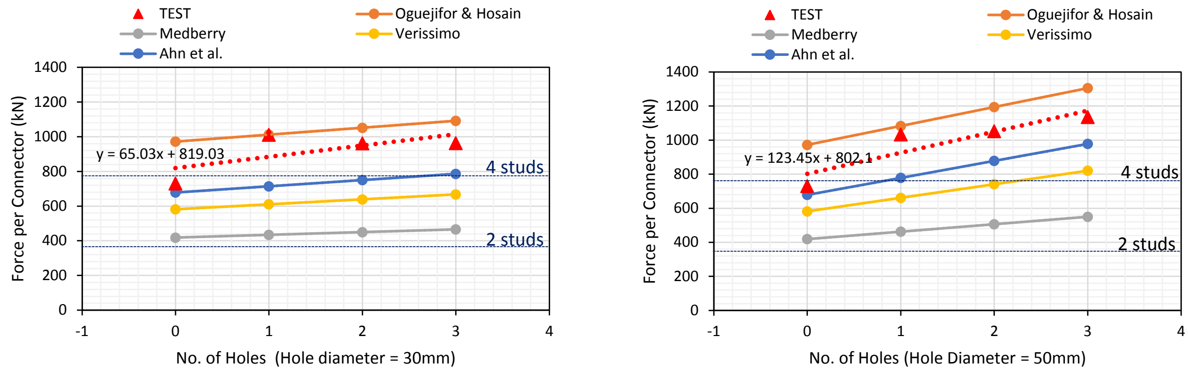
Specimens	Concrete strength (MPa)	No. of holes	Diameter of hole (mm)	Ultimate load, P_u (kN)	Relative slip, δ_u (mm)	Characteristic values		Ductility, δ_{uk}/δ_u
						Load, P_{rk} (kN)	Relative slip, δ_{uk} (mm)	
C180-P12	180	–	–	730.0	8.34	657.0	14.38	1.78
C180-P12-D30x1		1	30	1011.0	6.57	909.9	14.93	2.27
C180-P12-D30x2		2	30	962.3	9.34	866.1	13.22	1.42
C180-P12-D30x3		3	30	963.0	2.29	866.7	6.18	2.70
C180-P12-D50x1		1	50	1032.3	5.05	929.1	7.38	1.46
C180-P12-D50x2		2	50	1051.8	7.76	946.6	10.70	1.37
C180-P12-D50x3		3	50	1135.0	13.46	1021.5	19.03	1.41
C80-P12	80	–	–	416.6	0.84	374.9	2.47	2.95
C80-P12-D30x1		1	30	368.8	1.76	331.9	3.61	2.05
C80-P12-D30x2		2	30	474.9	1.04	427.4	1.59	1.53
C80-P12-D30x3		3	30	575.3	1.32	517.8	1.48	1.12
C80-P12-D50x1		1	50	535.0	0.61	481.5	1.82	2.98
C80-P12-D50x2		2	50	613.7	3.68	552.3	6.62	1.80
C80-P12-D50x3		3	50	754.7	1.73	679.2	2.57	1.30

tion, which in turn accentuates the tendency of the shear strength to increase. Furthermore, higher strength of concrete also promotes the increase of the shear strength by the dowel action. Here, specimen C80-P12-D30x1 applying 80-MPa concrete and with one dowel hole was expected to develop higher shear strength than specimen C80-P12 without hole but exhibited contrarily reduced shear strength. This result can be attributed to some problem in the fabrication of the specimen.

4. Comparison of Test Results and Previous Prediction Models

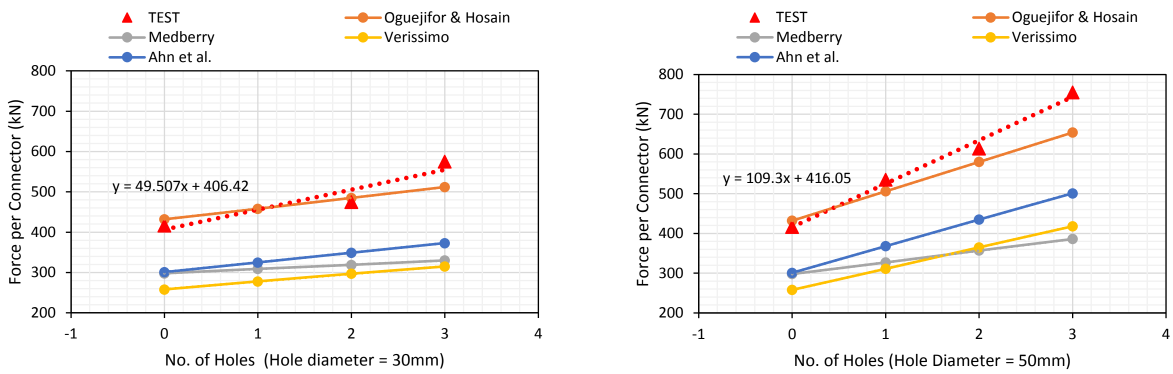
In order to verify the applicability of previous models for the prediction of the shear strength of UHPC exhibiting higher strength than conventional concrete, **Table 5** compares the experimental results to the shear strength predicted by these models. It can be observed that the experimental results approach well the predictions of the shear strength given by the model proposed by Oguejiofor and Hosain [1] and that the predictions of the model proposed by Medberry and Shahrooz [2] differ from the test results by maximum 2.33 times.

Figure 9 and **Figure 10** compare the increase pattern of the ultimate shear load of the test results to the shear strength curves provided by the previous prediction models. Here also, the model proposed by Oguejiofor and Hosain [1] approaches closely the test results. In **Figure 9**, the test results for the cases applying 2 and 4 headed studs are plotted concurrently. Their respective shear forces are 377.1 kN and 780.3 kN. This indicates that the



(a) (b)

Figure 9. Comparison of shear prediction models (180-MPa concrete). (a) D = 30 mm; (b) D = 50 mm.



(a) (b)

Figure 10. Comparison of shear prediction models (80-MPa concrete). (a) D = 30 mm; (b) D = 50 mm.

Table 5. Comparison of experimental and predicted shear capacities.

Specimens	Shear capacity per connector (kN)					Test/(1)	Test/(2)	Test/(3)	Test/(4)
	Test	Oguejiofor *et al.* (1)	Medberry *et al.* (2)	Verissimo *et al.* (3)	Ahn *et al.* (4)				
C180-P12	730.0	972	419	582	678	0.75	1.74	1.25	1.08
C180-P12-D30x1	1011.0	1012	434	610	714	1.00	2.33	1.66	1.42
C180-P12-D30x2	962.3	1052	450	639	750	0.91	2.14	1.51	1.28
C180-P12-D30x3	963.0	1092	466	668	786	0.88	2.07	1.44	1.23
C180-P12-D50x1	1032.3	1083	462	661	778	0.95	2.23	1.56	1.33
C180-P12-D50x2	1051.8	1194	506	741	878	0.88	2.08	1.42	1.20
C180-P12-D50x3	1135.0	1305	550	820	978	0.87	2.06	1.38	1.16
C80-P12	416.6	432	298	258	301	0.96	1.40	1.61	1.38
C80-P12-D30x1	368.8	458	309	278	325	0.81	1.19	1.33	1.13
C80-P12-D30x2	474.9	485	319	297	349	0.98	1.49	1.60	1.36
C80-P12-D30x3	575.3	512	330	315	373	1.12	1.74	1.83	1.54
C80-P12-D50x1	535.0	506	327	311	368	1.06	1.64	1.72	1.45
C80-P12-D50x2	613.7	580	357	365	435	1.06	1.72	1.68	1.41
C80-P12-D50x3	754.7	654	386	418	501	1.15	1.96	1.81	1.51

perfobond rib specimen C180-P12 without dowel hole develops shear strength comparable to the case applying 4 headed studs, and means that one perfobond rib provides a level of shear strength sufficient to replace 4 headed studs.

The specimens using concrete with compressive strength of 180 MPa in **Figure 9** are seen to develop shear strength lower by about 10% than that calculated by the prediction formula of Oguejiofor and Hosain [1]. The increase rate of the shear strength shows similar trend to the predictions according to the number of dowel holes. The specimens applying concrete with compressive strength of 80 MPa in **Figure 10** develop shear strength larger by 5% to 15% than the predictions. Larger difference in the shear strength can be observed compared to the predictions as much as the number of dowel holes increases.

Moreover, in all cases, the increase rate of the shear strength caused by the dowel action augmented with larger diameter of the dowel hole regardless of the compressive strength of concrete. The enlargement of the diameter of the holes appears to have larger influence on the increase of the dowel action in case of low compressive strength.

5. Conclusions

This study conducted push-out test to measure the shear strength of the perfobond rib connector in ultra high performance concrete member with compressive strength of 80 MPa and 180 MPa and compared the results with those of previous prediction models. The test results revealed that the concrete dowel action provided by the holes of the perfobond rib did not show clear difference in the shear strength for the 180-MPa specimens whereas clear increase of the shear strength occurred owing to the dowel action in the 80-MPa specimens.

The comparison with the increase trend of the shear strength obtained by the prediction models indicated that the experimental results could be predicted using these models within their prediction range. Among these models, the formula proposed by Oguejiofor and Hosain [1] provided the most accurate predictions, and the model proposed by Ahn *et al*. [5] was seen to be conservative.

Considering the small number of specimens adopted in this study, it is presumptuous to suggest a model covering the strength range of ultra high performance concrete. However, the comparison of the previous shear strength prediction models enabled to assess the models applicable in design. It is expected that a shear strength prediction model for perfobond rib using ultra high performance concrete could be proposed through further tests considering diversified compressive strengths ranging between 80 and 180 MPa.

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