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An experimental study on the shear strength of FRP perfobond shear connector

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Abstract. In this study, push-out tests were conducted to investigate shear behaviour of FRP perfobond shear connector. The parameters influencing shear capacity of FRP perfobond shear connector are concrete dowel effect, shear resistance effect of the laterally reinforced FRP re-bar, and frictional effect between shear connector and concrete. The specimens were designed to consider these parameters. The specimens coated with sand to increase frictional resistance between the FRP re-bar and concrete. Based on the test results and the parameters, new equation was suggested to predict shear strength of FRP perfobond shear connectors. The predicted results and the experimental results were compared to check the feasibility of prediction.

1. Introduction

Different deformation characteristics of concrete and FRP used in FRP-Concrete composite deck plate cause horizontal shear stress and slip at the interface of concrete and FRP when flexural deformation is occurred. Excessive slip leads to the destruction of the bonded surface and the independent behaviours of the two materials. It reduces the load carrying capacity of the FRP-Concrete composite deck. FRP perfobond shear connectors are widely used to induce efficient stress transmission and composite behaviour by resisting to slip. Studies have been extensively conducted to predict shear capacity of perfobond shear connectors [1-5].

In 1987, steel perfobond shear connector was firstly introduced to solve the fatigue problem of steel stud [1]. In 1992, research was conducted to compare shear capacity of steel stud and steel perfobond shear connectors [2]. In 2002, push-out tests to evaluate shear capacity of steel perfobond shear connectors were carried out and shear strength equation was proposed based on the test results [3]. After that, the spring model for FRP perfobond shear connector was proposed based on the pull-out test results and finite element analysis [4], and the slip modulus of FRP perfobond shear connector was proposed based on the push-out test and finite element analysis [5]. But, the research associated with the shear design equation for FRP perfobond shear connectors is relatively limited unlike steel perfobond shear connectors. Therefore, the equation predicting the shear strength of FRP perfobond shear connectors was proposed based on push-out tests of FRP perfobond shear connector and Medberry's equation [3].

2. Shear strength equation of the steel perfobond shear connector

Shear connectors are classified into flexible shear connectors and rigid shear connectors depending on the magnitude of the stiffness. Flexible shear connectors have longitudinal flexibility and low resistance to shear force. Rigid shear connectors have a higher resistance to shear force and less deformation in longitudinal direction than flexible shear connectors. The steel perfobond shear connector is a type of rigid shear connector and used at the interface of a composite members to maximize composite force between the two materials. Figure 1 shows mechanical behaviour of steel perfobond shear connector. The parameters affecting the shear capacity of the steel perfobond shear connectors are concrete dowel effect, shear resistance effect of the laterally reinforced re-bar, the frictional effect between shear connector and concrete, and the bearing effect from bottom concrete.

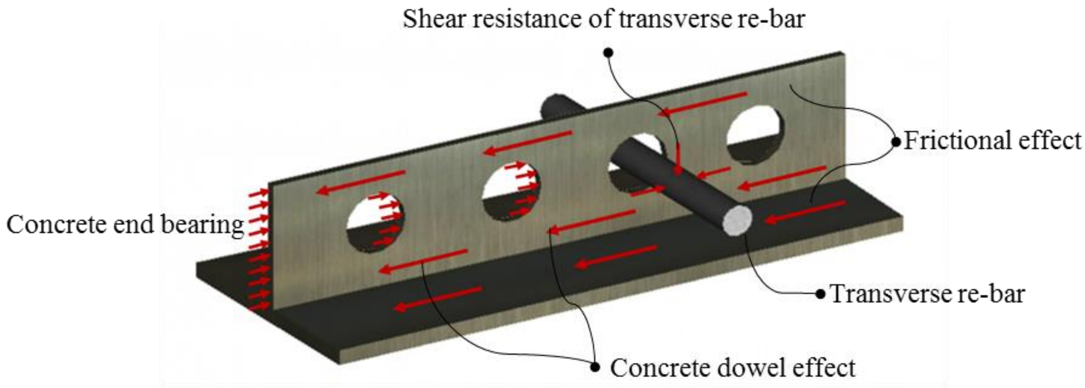

Figure 1. Mechanical behaviour of steel perfobond shear connector.

Based on these four parameters, previous research proposed the shear strength equation of steel perfobond shear connectors. Equation (1) shows the shear strength equation of steel perfobond shear connectors [3].

$$Q_{steel} = 0.75bh\sqrt{f'c} + 0.41b_f L_c + 1.66\pi\sqrt{f'c}\left(\frac{d}{2}\right)^2 + 0.9A_{vf}f_y \quad (1)$$

Where, Q_{steel} is the maximum shear resistance capacity of the steel perfobond shear connector, b is the depth of the slab, h is the height of the bottom slab, $f'c$ is the compressive strength of concrete, b_f is the width of the flange, L_c is the contact length between the flange and concrete of the steel girder, n is the number of holes, d is the diameter of the holes, A_{vf} is the cross-sectional area of the transverse reinforcements, and f_y is the yield strength of the steel re-bar.

First term in the equation (1) is the bearing effect from bottom concrete, 0.75 is obtained by the linear finite element analysis. Second term is the frictional resistance between concrete and connector, 0.41 which is average bond stress determined by the push-out tests. The third term is the dowel effect of concrete, 1.66 which is the average shear strength obtained from the experiment. The last term is the shear resistance effect of steel re-bar, 0.9 which is the reduction factor to consider 90% of the yield stress of steel re-bars.

3. Experiment

3.1. Tensile strength test on FRP re-bar

FRP re-bars were used to increase shear resistance of the FRP perfobond shear connector. Five specimens were fabricated in accordance with ASTM D 7205 [6]. Loading was applied by displacement control testing method with rate of loading of 5mm/min. The load and displacements for the specimens were measured by load cells and LVDTs. Figures 2 and 3 show the specimens and test set up, respectively.

Figure 2. Specimens of FRP re-bars.

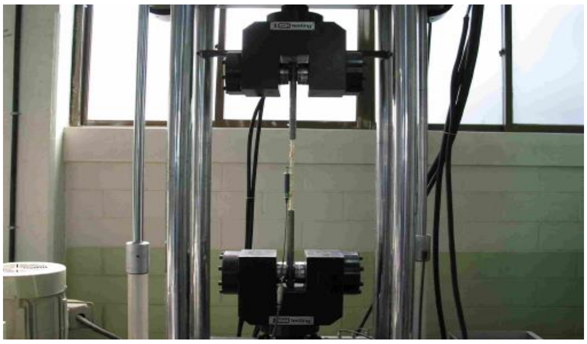

Figure 3. Test set up.

Figure 4 shows the stress-strain relation for the specimen No. 1. Specimen No. 1 showed brittle failure and linear elastic behaviour and all specimens showed similar behaviours. Table 1 shows the summary of tensile test results of all FRP re-bar specimens. The average tensile strength for the FRP re-bar specimens and the average elastic modulus of elasticity for the specimens are 737.9 MPa, 24.5 GPa, respectively.

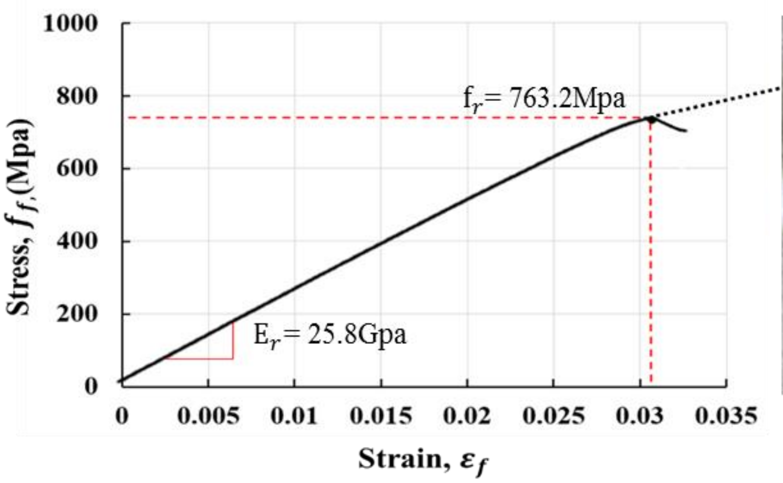

Figure 4. Stress strain relationship of specimen No. 1.

Table 1. FRP re-bar tensile test results.

Specimens	No. 1	No. 2	No. 3	No. 4	No. 5	Average
Tensile Strength (MPa)	763.2	656.9	763.3	752.1	753.8	737.9
Elastic Modulus (GPa)	25.8	17.4	26.3	29	23.8	24.5

Table 2. Compressive strength test results of concrete.

Curing (Days)	3 Days	7 Days	14 Days	23 Days
	33.7	41.5	44.8	43.9
Compressive strength (MPa)	31.4	22.6	45.3	51.2
	33.2	39.3	39.1	46.8
Average (MPa)	32.8	34.5	43.1	47.3

3.2. Compressive strength test on concrete

Concrete cylinder specimens for compressive strength tests were taken with respect to ages, 3 days, 7 days, 14 days and 23 days. Each three specimens were prepared with respect to ages and hence the total number of specimens are twelve. Table 2 shows test results for concrete compressive strengths. The average strength of concrete is 47.3 MPa.

3.3. Push-out test

3.3.1. Specimens. Three specimens coated with sand were fabricated to increase frictional resistance between concrete and FRP module. And the steel re-bars were placed in concrete to control the cracks caused by shrinkage. Figures 5 and 6 show the specimens used in push-out tests of FRP perfobond shear connector.

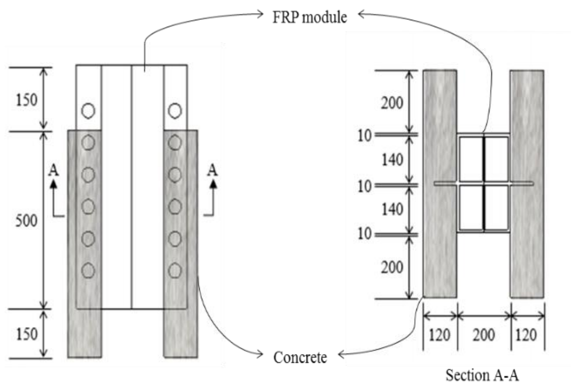

Figure 5. Specimens No. 1, No. 2.

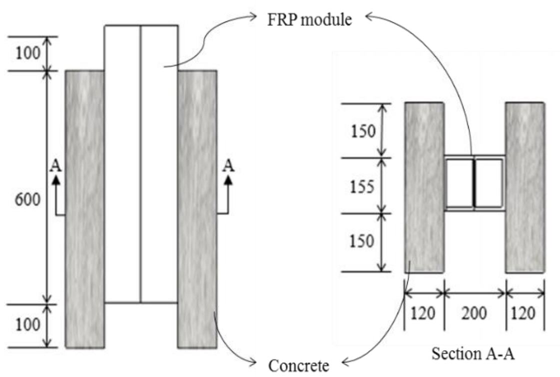

Figure 6. Specimen No. 3.

Figure 5 shows specimens No. 1 and No. 2. The specimens No. 1 and No. 2 were fabricated by pultrusion technique to make FRP shear connector and FRP module into one. The transmission of the shear force in specimens No. 1 and No. 2 is formed by transverse reinforcement placed at intuitional angles to the axis of the specimens. Figure 6 shows specimen No. 3 which is the FRP module without shear connector. It is manufactured to examine the bond strength of the sand coated surface.

3.3.2. Loading and measurements. Push-out tests for FRP perfobond shear connectors were carried out similarly with the test method conducted in steel perfobond shear connectors [3]. The load was applied through displacement control system at a rate of 0.2 mm/min using an actuator with the maximum capacity of 2940 kN. The relative displacements of the specimens were measured by the LVDTs installed at the both sides of specimens.

3.3.3. Test results. Figures 7 and 8 show the load-displacement curves and failure modes of specimens No. 1 and No. 2. At the early loading stage, the slopes of the load-displacement curves were increased with load value. After then, the fine cracks were occurred at the interface of FRP module and concrete. The slopes of the load-displacement curves were decreased at this stage. It is estimated that the fine cracks of specimens No. 1 and No. 2 were occurred at 1,200 kN and 1,500 kN, respectively. The specimens No. 1 and No. 2 were failed when the sand coated surfaces were debonded. At this stage, the relative displacements were 1.5mm. Since the failures were occurred at the bonded surface, it is estimated that the main parameter influencing the shear strength of specimens is the bond strength of sand coated surface.

Specimen No. 3 was designed to investigate only the bond strength of sand coated surface. The specimen No. 3 has smaller contact surface area between concrete and FRP module than specimens No. 1 and No. 2. Therefore, specimen No. 3 has smaller displacement and load at the failure than those of specimens No. 1 and No. 2. Table 3 shows summary of test results of the push-out tests.

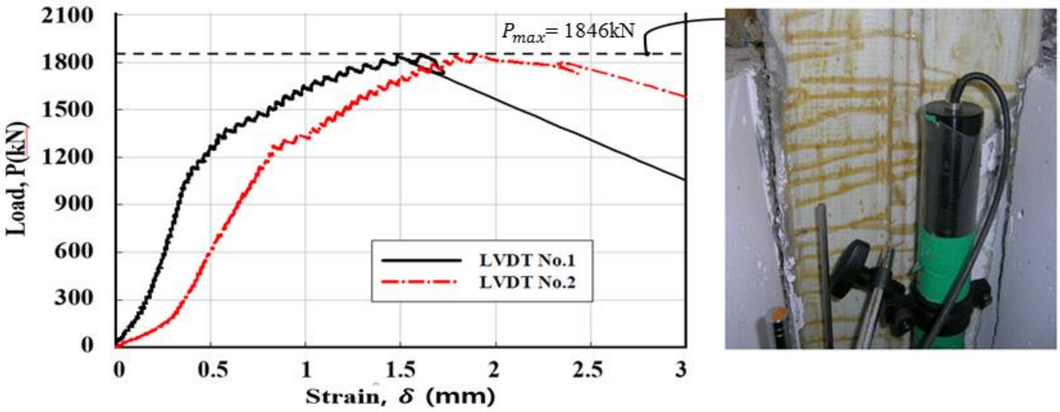

Figure 7. Test result of specimen No. 1.

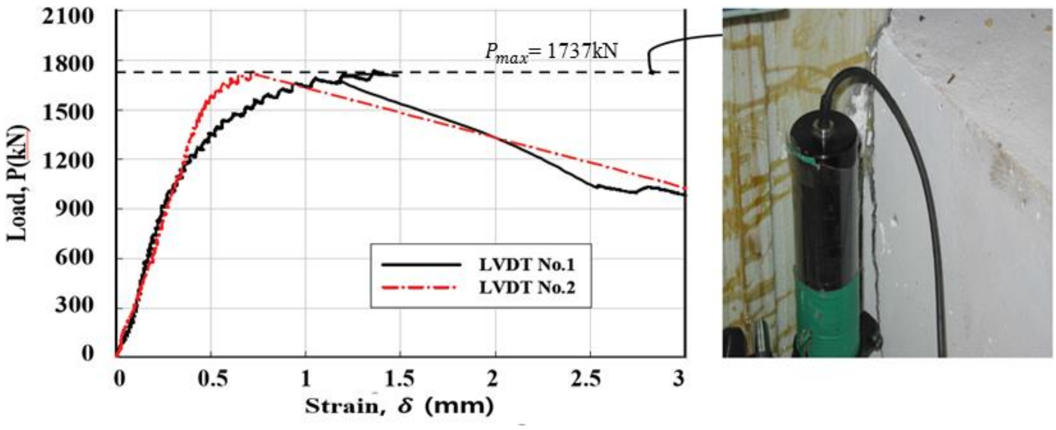

Figure 8. Test result of specimen No. 2.

Table 3. Push-out tests results.

Specimens		No. 1	No. 2	No. 3
P_{max} (kN)		1,846	1,737	341.57
Relative displacement (mm)	LVDT #1	1,610	1,360	0.041
	LVDT #2	1,895	0.715	0.090
d_{12}		0.285	0.645	0.320

P_{max} is the maximum load of the specimens when the bonded surface between concrete and FRP module was failed. d_{12} represents the interval of relative displacements measured from the LVDTs installed in the axial direction of each specimen. Table 3 shows that d_{12} is larger then the load is smaller. Therefore, the difference of the maximum load between specimen No. 1 and No. 2 seems to be attributed due to the moment induced by the eccentricity of loading.

4. Shear strength equation of the FRP perfobond shear connector

Shear strength evaluation equation of the FRP perfobond shear connectors was proposed based on the test results and equation (1). Since the FRP perfobond shear connector is manufactured with FRP module in one piece, the bearing effect between concrete and connectors does not occur.

The parameters affecting the shear capacity of the FRP perfobond shear connectors are concrete dowel action, shear resistance of the laterally reinforced FRP re-bar, the friction between shear

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connector and concrete. Based on these three parameters, shear strength equation of FRP perfobond shear connector was proposed as follow.

$$Q_{FRP} = 1.84 b_f L_c + 7.346 n\pi\sqrt{f'c}\left(\frac{d}{2}\right)^2 + 0.95 A_{vf} f_r \quad (2)$$

Where, Q_{FRP} is the maximum shear resistance of the FRP perfobond shear connector, f_r is the tensile strength of the FRP re-bar. 1.84 MPa in the first term is bond strength between concrete and FRP module of specimen No. 3. The second term is dowel effect of concrete. 7.347 in the second term is the spring factor based on the previous research [4]. The third term is the shear resistance of FRP re-bar. 0.95 in the third term is recommended as a reduction factor of FRP re-bar [7]. Table 4 shows the comparison of test results with predicted results by equation (2).

Table 4. Comparison test results with predicted results (equation (2)).

Specimens	Q_d	Q_r	Q_b	Q_{FRP}	Q_{exp}	Q_{FRP}/Q_{exp}
No.1	119.5	299.8	563	897.1	923	1.115
No.2					869	1.06

Where, Q_d is the concrete dowel effect, Q_r is shear resistance effect of FRP re-bar and Q_b is the frictional effect between shear connector and concrete. Q_{exp} is the value of test results converted into one shear connector. Comparing Q_{FRP} and Q_{exp}, the differences were in the range of +6% ~ +11.5% approximately.

5. Conclusion

In this study, push-out test were conducted to investigate the shear capacity of FRP perfobond shear connector. The shear strength equation was proposed based on the push-out test and previous equation model. The results obtained by the investigation are as follow:

- The parameters influencing the shear capacity of FRP perfobond shear connector are the bond strength of the sand coated surface, dowel action caused by hole in the shear connector, and shear strength of FRP re-bars.
- The main parameter influencing the shear capacity of FRP perfobond shear connector is bond strength of sand coated surface. Concrete dowel effect has little effect to the shear capacity.
- Comparing the predicted and tested results, the differences were in the range of +6%~11.5%. It found that the proposed shear strength equation estimates the shear strength of FRP perfobond shear connectors conservatively.

Acknowledgment

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