

ULTIMATE SLIP BEHAVIOR OF PERFOBOND STRIP UNDER THE LATERAL CONFINEMENT PARALLEL TO THE PBL PLATES

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Perfobond strip (called PBL, hereafter) proposed by Leonhardt in Germany is widely used as the validated shear connector in steel-concrete composite structures. Fujii et al. proposed a fracture mechanism of PBL as follows: Slip force (shear force) acting on a PBL causes the expanding force which splits the concrete around the PBL. If restraint force, which is caused by cover concrete, rebar etc., resisting the expanding force exist, the slip strength is enhanced. Consequently, the fracture of PBL will happen when the expanding force exceeds the restraint force. Also, based on the above concept, they have given the evaluation formula of PBL slip strength and verified it by comparing previous experimental results. However, bonding force and frictional force are not taken into account in the formula. Through the loading tests of the composite girder, we found that the bonding and the frictional force, which appear along the boundary surface between concrete deck and steel flange, work as resistance force to not only the slip strength but also the expanding force. In this paper, the effects of the bonding force and the frictional force on the ultimate slip behavior of PBL are investigated experimentally, and an evaluation formula of PBL slip strength is improved by taking their effects into account.

Keywords: Slip strength, Lateral force, Bonding force, Friction force.

1 INTRODUCTION

In Japan, perfobond strip invented by Leonhardt *et al.* (1987) is widely used in many steel-concrete composite structures as an effective shear connector. Fujii *et al.* (2014) have investigated and shown the fracture mechanism of PBL as follows: Slip force (shear force) acting on PBL causes “Expanding force”, which splits the concrete around the PBL and which brings the fracture of PBL. On the other hand, if some restraint forces resisting the expanding force exist, the slip strength will rise because the restraint force delays the crack-outbreak of the concrete at PBL hole. The expanding force becomes large with the increase of the slip force; consequently, the fracture of PBL will occur when the expanding force exceeds the resultant of the restraint forces, which are caused by cover concrete, a rebar set through the hole, etc. Based on the above assumption, they have given an evaluation formula of the ultimate slip strength of PBL, and verified it by comparing previous experimental results. However, bonding force and frictional force are not taken.

By the way, through the loading tests of the composite girder, it was suggested that the bonding and the frictional forces, which appear along the boundary surface between concrete

deck and steel flange, work as resistance force to not only the slip strength but also the expanding force. In this paper, the effects of the bonding force and the frictional force on the ultimate slip strength of PBL are investigated experimentally, and the evaluation formula of PBL slip strength is improved by considering their effects. In the followings, two types of push out test are conducted for two purposes: to clarify the bonding force and the friction coefficient between concrete and steel plate: to get the ultimate slip strength of PBL with effects of bonding and frictional forces. The mix proportion and the material properties of concrete are shown in Table 1 and Table 2, respectively.

Table 1. Mix condition of the concrete.

Compressive strength			Tensile strength			Elastic modulus		
(N/mm ²)			(N/mm ²)			(kN/mm ²)		
Before	After	Average	Before	After	Average	Before	After	Average
39.5	44.5	42.0	4.4	5.4	4.9	30.1	30.5	30.3

Table 2. Material properties of the concrete.

Maximum Aggregate Size	Water-Cement Ratio	Slump	Sand Aggregate Size	Air Content	Quantity of material per unit volume of concrete(kg/m ³)				Air entraining and high-range water reducing agent
					Water	Cement	Fine aggregate	Coarse Aggregate	
(mm)	(%)	(cm)	(%)	(%)					(kg/m ³)
20	65	8.5	49	1.8	168	258	944	998	1.29

2 TESTS TO OBTAIN BONDING FORCE AND FRICTION COEFFICIENT

2.1 Test Summary and Specimens

We made eleven specimens whose steel plate does not have any hole, and is sandwiched with two concrete blocks at the both sides such as Figure 1. At that condition, the concrete and the steel plate are adhered each other by the bonding force only. After applying the lateral force up to a value by using PC rods set at the both sides, the slip force is subjected at the top of the steel plate as shown in Figure 2. Then, the maximum slip forces at slipping are obtained under several lateral forces.

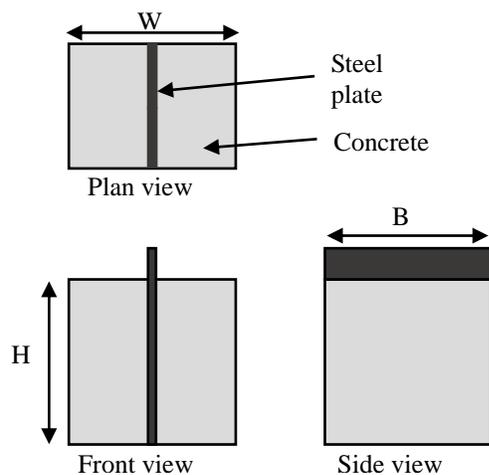


Figure 1. Test specimen.

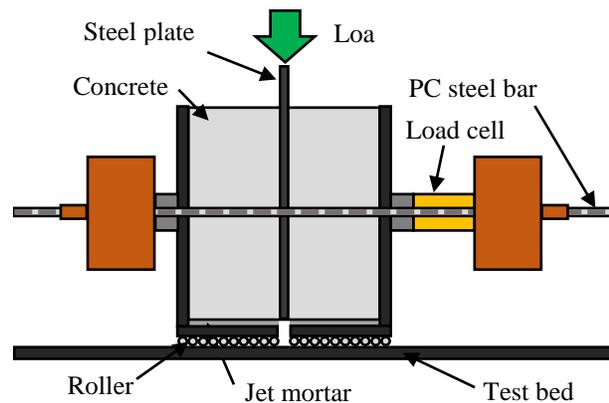


Figure 2. Loading condition.

2.2 Test Results

Test results are shown in Table 3 and a typical example (I-Pl.150 test specimen) of the load vs. slip curve is also shown in Figure 3. From the figure, it is noticed that the slip between concrete and steel plate appears even when the slip load is small. If steel and concrete are rigid body, the slip will not appear until the slip load reaches a value. Though we cannot clarify whether the slip at small slip load is caused by the deformation of concrete and steel or not, regarding the maximum force as the slip load, the relationship between slip load and lateral force is plotted in Figure 4. It is noticed from the figure that as lateral force becomes larger, the slip loads increase approximately linearly, where the coefficient of correlation is 0.93. Based on the test results, the regression line between the slip load and lateral force can be obtained. The intercept and the slope of the regression line mean the bonding force and the frictional coefficient, respectively. These values are shown in Table 4.

Table 3. Dimensions of specimen and test results.

The year of the tests conducted	Name of specimen	Width of specimen	Depth of specimen	Height of specimen	Thickness of plate	Initial lateral force	Lateral force at Slipping	Load at slipping
		W (mm)	B (mm)	H (mm)	t (mm)	Pl. (kN)	Pl' (kN)	Vu (kN/surface)
2016	I-Pl.0-A	200	200	300	9	0.00	0.00	4.15
	I-Pl.0-B					0.00	0.00	1.03
	I-Pl.50-A					50.00	52.00	28.53
	I-Pl.50-B					50.00	89.50	89.79
	I-Pl.100-A					100.00	100.00	36.41
	I-Pl.100-B					100.00	114.50	81.86
	I-Pl.180-A					180.00	197.33	112.63
	I-Pl.180-B					180.00	203.67	141.96
2017	I-Pl.50-C	200	200	300	9	50.00	52.00	31.83
	I-Pl.100-C					100.00	107.73	67.63
	I-Pl.150					150.00	165.33	97.13

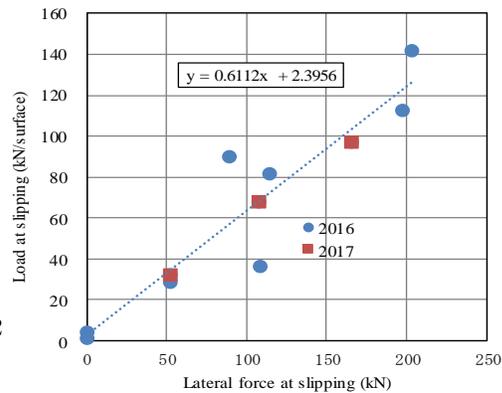
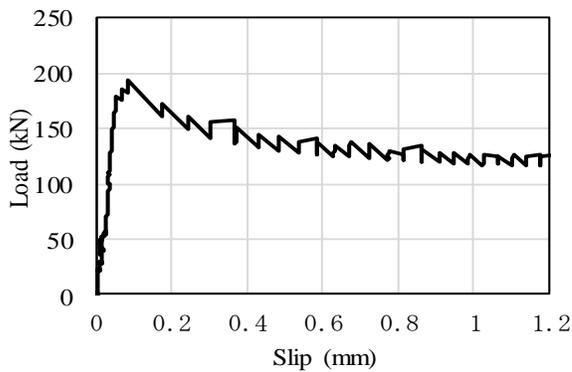


Figure 3. Load-Slip curve.

Figure 4. Relation between slip load and lateral force.

Table 4. The results of bonding force and frictional coefficient.

Bonding force	Coefficient of friction
C' (kN/m ²)	μ
40.0	0.61

3 TESTS TO OBTAIN THE SLIP STRENGTH OF PBL

3.1 Test summary and Specimens

Push out test is conducted for eight push-out specimens in order to investigate the effect of frictional force and bonding force on slip strength, changing the initial lateral force and the height of concrete block. During the tests, the lateral force is subjected to the both sides of concrete parallel to the PBL plates, as illustrated in Figure 6.

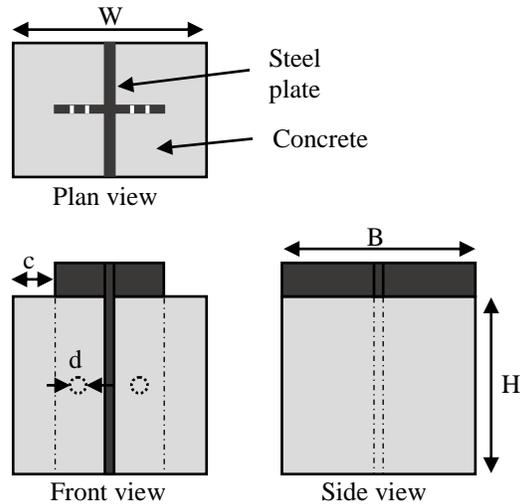


Figure 5. Test specimens.

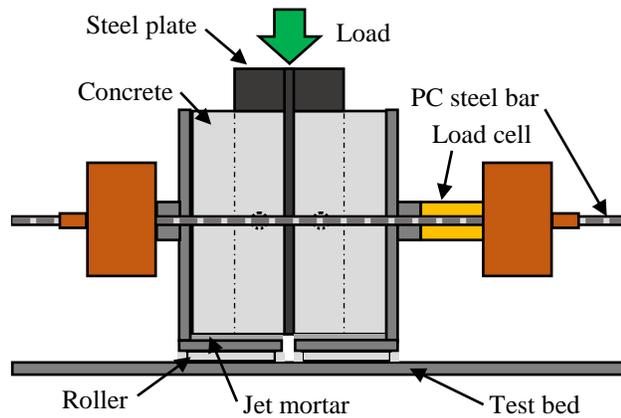


Figure 6. Loading condition.

3.2 Test Results

Test results are summarized in Table 5. “Lateral forces at slipping” and “Slip strength” show the values per one PBL hole. As the slip force increases, the lateral force varies and becomes larger from the initial lateral force, as shown in Table 5. This phenomenon is clearly due to the surface irregularity at the boundary between steel and concrete.

At the fracture of PBL, the slip force reaches the maximum; and concrete crack, which separates a concrete block to two blocks, appears; then the slip force decreases. After loading test, the concrete in the hole remained with two fracture surfaces parallel to PBL plate.

Table 5. The size of specimens and results.

Name of specimen	Diameter of PBL hole	Thickness of cover concrete	Width of specimen	Depth of specimen	Thickness of PBL plate	Height of specimen	Initial lateral force	Lateral force at Slipping	Slip strength
	d (mm)	c (mm)	W (mm)	B (mm)	t (mm)	H (mm)	P_L (kN)	P_L' (kN)	V_u (kN/hole)
J-H300- P_L 0	60	100	420	400	12	300	0	0.00	77.39
J-H500- P_L 0						500		0.00	100.41
J-H300- P_L 20						300	20	34.08	130.44
J-H500- P_L 20								500	28.00
J-H300- P_L 50						300	50	61.75	138.27
J-H500- P_L 50								500	68.33
J-H300- P_L 80						300	80	81.92	203.27
J-H500- P_L 80								500	87.75

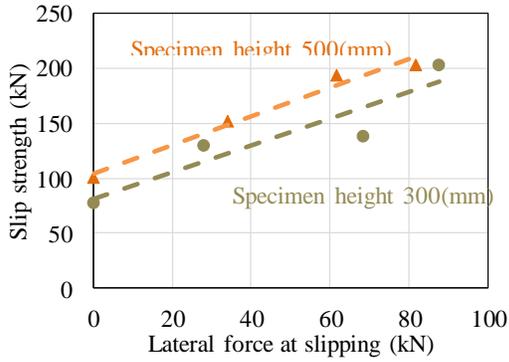


Figure 7. Relationship between lateral force and slip strength.

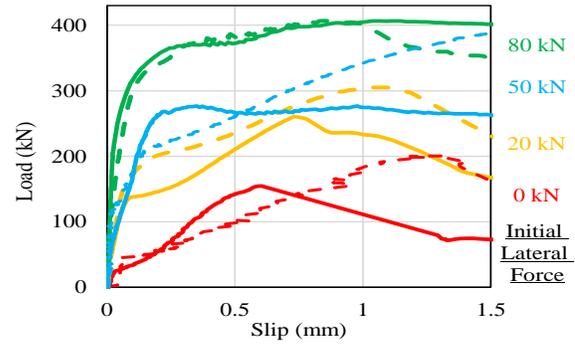


Figure 8. Slip load vs. slip curve.

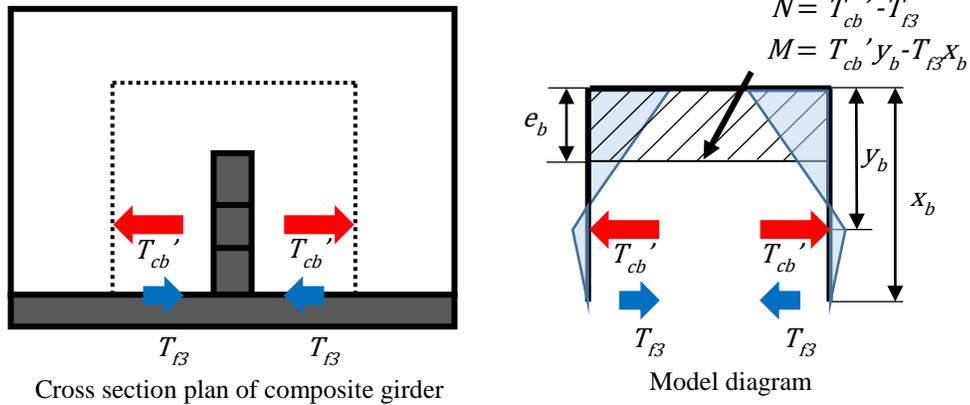


Figure 9. Rigid frame model.

4 CONSIDERATION

4.1 Effects of Bonding and Frictional Force

The relationship between the slip strength of one PBL hole and the lateral force is shown in Figure 7. From this figure, it can be noticed that the slip strength rises as the lateral force increases. This increase of the slip strength is clearly due to the bonding force and the friction force appearing at the interface of concrete and steel plate.

Slip load vs. slip curve for each lateral force is shown in Figure 8. Here, slip means the relative slip-value between steel and concrete. As is shown in Figure 8, it can be also noticed that lateral force can make enhance not only the slip strength, but also the slip rigidity.

4.2 Evaluation Formula of Slip Strength

In the followings, we try to improve the slip strength evaluation formula proposed by Fujii *et al.* (2014), considering with the bonding force and the friction force at the interface of steel and concrete.

Taking the bonding force and friction force into account, the slip strength evaluation formula proposed by Fujii *et al.* (2014) can be rewritten as the following equations. At this time, the assumption for the concrete fracture is the quite same as that by Fujii *et al.* (2014). Namely, the fracture of PBL occurs when the normal stress of concrete at the top of PBL plate reach to the tensile stress.

$$V_u = V_{\text{int}} + 2.5T_{cb}' + T_{f2} \quad (1)$$

$$V_{\text{int}} = \frac{\pi d^2}{2} \times f_{ct} \quad (2)$$

$$T_{cb}' = \frac{f_{ct} + T_{f3} \left(\frac{e_b x_b}{I_{cb}} + \frac{1}{A_{cb}} \right)}{\frac{e_b y_b}{I_{cb}} \times \frac{1}{A_{cb}}} \quad (3)$$

The evaluated slip strengths obtained from the modified formula are plotted in Figure 10, comparing with experimental results. In the figure, those based on Fujii *et al.*(2014) are also shown. As is shown in Figure 10, it can be concluded that the modified formula can evaluate well the experimental results with coefficient of correlation of 0.95, though the values from Fujii *et al.* (2014) are not in accordance.

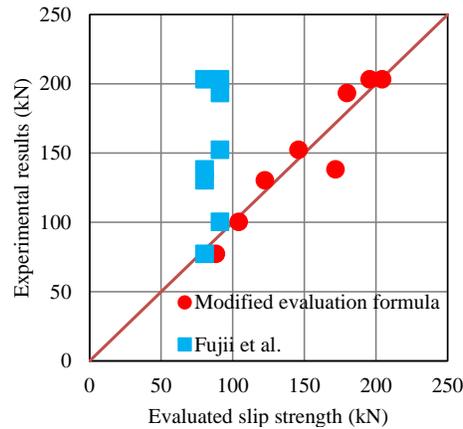


Figure 10. Relationship between evaluated strength and test results.

5 CONCLUSIONS

The results obtained from this study can be summarized as below:

1. According to the bonding force and the friction force, the slip strength and the slip rigidity increase, and they become larger as the lateral force increases.
2. Though the bonding and frictional forces have been usually ignored in the previous researches, it is clarified that they cannot be ignored because the slip strength of PBL is not a little influenced by them.
3. The modified evaluation formula indicated here in is able to evaluate the slip strength well in consideration with the bonding force and the frictional force.

References

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