

ULTIMATE STRIP STRENGTH OF PERFOBOND STRIP WITH SMALL HOLE CONFINED BY CONCRETE COVER

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ABSTRACT: The ultimate slip strength of a perfibond strip (called “PBL” hereafter) depends significantly on the concrete confinement conditions around PBL hole as well as concrete shear fractures at the hole. If the hole is small, the effect of concrete confinement will still more strongly appear. In this paper, focusing on the concrete confinement due to only concrete cover by removing other confinements perfectly, the ultimate slip strength of PBL with small hole is investigated by conducting push-out tests, in which the diameter of the PBL hole is set at 30 mm and the thickness of concrete cover is varied from 0 to 100 mm. Test results show that the concrete separates into two blocks with concrete crack parallel to the PBL plate and that the ultimate slip strength of a 50-mm-thick concrete cover is 34.4 kN, which is about 10 times of the slip strength without concrete cover (=3.5 kN). Thus, it can be concluded that thicker concrete cover makes the slip strength remarkably larger, in the case of small-hole PBLs. In accordance with the experimental results in this paper, a method for PBL slip strength evaluation is shown based on the concept proposed by Fujii et al.

Keywords: Perfibond strip, Ultimate slip strength, Concrete cover, Confinement, Push-out test

1. INTRODUCTION

PBL proposed by Leonhardt is a shear connector to resist the slippage between different materials in composite structures [1]. In order to design PBL, the evaluation formula of the ultimate slip strength was proposed by Leonhardt et al. [1]. And also indicated by the Standard Specifications for Hybrid Structures in Japan [2]. These formulas, as shown later, are formulated by the diameter of the PBL hole and the compressive strength of concrete, which indicates the ultimate slip strength is decided by only these two parameters. However, Nishiumi and Okimoto and Fujii et al. indicated that the ultimate slip strength of PBL depends significantly on the confinement condition of the concrete around the hole [3-5]. Fujii et al. clarified the confined effects by conducting PBL tests and listed up confinement factors, namely, concrete cover, rebar going through PBL hole, other rebars parallel to the rebar going through PBL hole, and frictional force at the bottom surface of a specimen [5]. These confinement factors resist the splitting force which will be induced by the slip force and which will cause the fracture of concrete at the hole. Consequently, when some confinement factors exist around PBL, its ultimate slip strength is enhanced. Furthermore, Fujii et al. derived theoretically an ultimate slip strength evaluation formula of PBL considering the effects of confinement factors [6]. Also Andrä, Hosain et al. and Nakajima et al. have proposed formulas of a different type, respectively, based on the experimental data [7-9].

Although PBLs have been used for preventing slip between steel girders and concrete floor deck slabs in composite girders, in recent years, their use is spreading widely to various composite structures, such as composite slab, the connection between pre-cast members, etc. In particular, for application to thin composite slabs, PBL with a small hole will be used. Then, its ultimate slip behavior and strength should be clarified by considering the effect of concrete confinement for economical design.

In this paper, push-out tests are conducted on PBL with the small-hole size of 30 mm diameter, in order to clarify the effects of confinement by the concrete cover, in particular, changes in the thickness of the concrete cover.

2. OUTLINE OF PUSH-OUT TEST

Two types of test specimens were made, in which one (A series) has a concrete block inserted a PBL plate with a hole, as shown in Figure 1, the other (B series) has two concrete blocks sandwiching a cross-shape steel column whose two plates have a hole respectively, as shown in Figure 2 [10].

Dimensions and material properties of specimens are indicated in Table 1. In the table, concrete cover thickness means the distance from the PBL-plate tip to the concrete surface as shown in Figure 1 and 2.

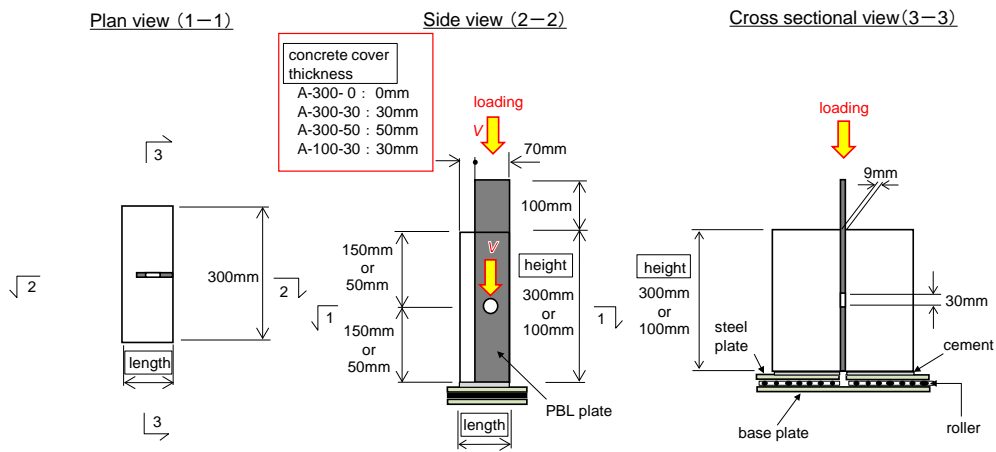


Fig.1 Push-out specimen (A series)

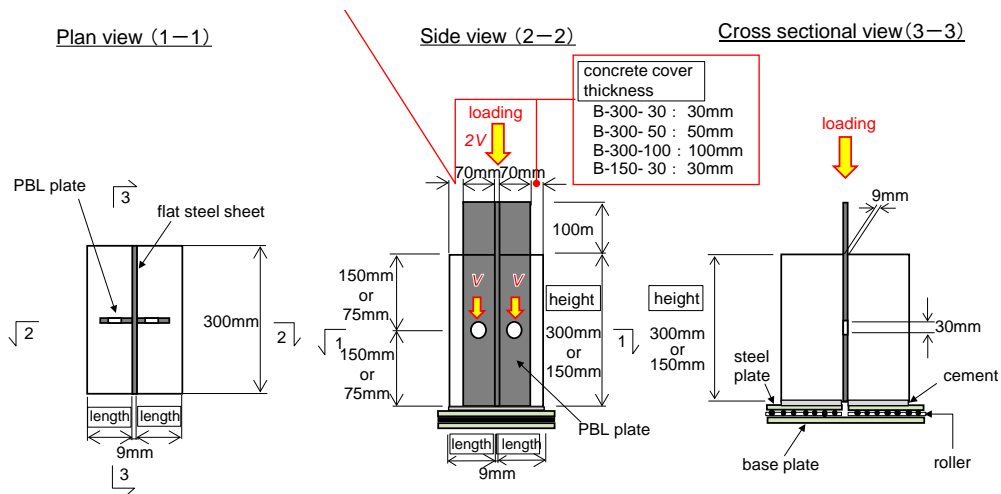


Fig.2 Push-out specimen (B series)

Table 1 Dimensions and material properties

Series	Test sample	Concrete			PBL Plate		
		Length (mm)	Height (mm)	Cover Thickness (mm)	Aggregate Diameter (mm)	Plate Thickness (mm)	Yield Strength (MPa)
A	A-300-0 (1)	70	300	0	20	9	more than 245
	A-300-0 (2)						
	A-300-0 (3)						
	A-300-30 (1)	100	300	30			
	A-300-30 (2)						
	A-300-30 (3)						
A-300-50	120	300	50				
A-100-30	100	100	30				
B	B-300-30	100	300	30	20	9	more than 245
	B-300-50	120	300	50			
	B-300-100	170	300	100			
	B-150-30	100	150	30			

Focusing on the confined effect of concrete cover, in this paper, all specimens have a different concrete cover (0, 30,50 and 100 mm), respectively, whereas the diameter of PBL hole is the same as 30mm. For the size of concrete block, the height of almost all specimens is set 300mm, but adding to these, the specimens of A-100-30 and B-150-30 are also made in order to investigate the effect of concrete confinement due to the height of the concrete block.

Leonhardt indicated failure modes of two types, one depends on yielding of PBL steel plate, another is caused by the concrete fracture at the PBL hole [1]. In the latter type of failure, the concrete is divided into two blocks at the maximum slip load as shown in Figure 3, then the slip load drops down rapidly. This fact shows that the slip load will produce a splitting force which will make the concrete split into two blocks at the hole. Accordingly, if the specimen is set directly on the layer such as gypsum or mortar laid on test bed (this condition has been usually adopted in a lot of past push-out tests) at loading, the frictional force which resists the splitting force will be produced by the slip load at the bottom. As a result, the slip strength obtained from the push-out test will differ significantly from that of actual composite structures, because the frictional force in the case of push-out test never appears in the actual composite structures such as composite girder. So, the specimen is set on the roller supports so as to remove the frictional force perfectly, as shown in Figure 1 and 2. According to this measure, the confined condition in the push-out test will be able to correspond with that in actual structures.

3. RESULTS AND DISCUSSION

3.1 Ultimate Slip Strength

Every specimen was failed by the occurrence of concrete cracks at PBL hole and of concrete crack parallel to PBL plate in the concrete cover. Consequently, a concrete block sandwiching PBL plate was divided into two blocks and the concrete in the PBL hole remained, as shown in Figure 3.

Ultimate slip strength of PBL obtained from the push-out test is indicated in Table 2, also evaluated slip strengths obtained from three evaluation formulas, where the evaluation formula of Eq. (1), Eq. (2) and Eq. (3) in the table are Leonhardt et. al. [1], JSSHS (Japanese Standard Specifications for Hybrid Structures) [2] and Fujii et. al. [6], respectively.

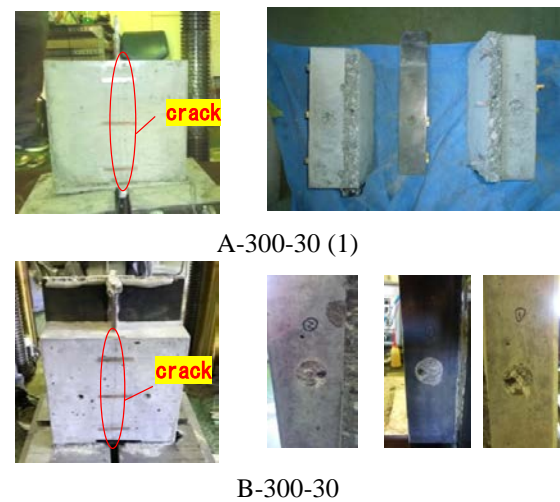


Fig.3 Specimen after loading

Table 2 Ultimate slip strength

Test Sample	[A] Test Result (kN)	Calculated Ultimate Slip Strength (Evaluation Formula)						Concrete Strength	
		Eq.(1)		Eq.(2)		Eq.(3)		Compre- ssive (MPa)	Tensile (MPa)
		Strength (kN)	$\frac{[A]}{Eq.(1)}$	Strength (kN)	$\frac{[A]}{Eq.(2)}$	Strength (kN)	$\frac{[A]}{Eq.(3)}$		
A-300-0 (1)	3.5	98.4	0.04	90.0	0.04	3.6	0.97	62.5	2.5
A-300-0 (2)	5.1	114.7	0.04	104.8	0.05	4.7	1.09	72.8	3.4
A-300-0 (3)	4.0	114.7	0.03	104.8	0.04	4.7	0.85	72.8	3.4
A-300-30 (1)	18.5	93.7	0.20	85.7	0.22	9.3	1.99	59.5	2.5
A-300-30 (2)	23.8	114.7	0.21	104.8	0.23	12.3	1.93	72.8	3.4
A-300-30 (3)	26.9	114.7	0.23	104.8	0.26	12.3	2.19	72.8	3.4
A-300-50	34.4	93.7	0.37	85.7	0.40	16.1	2.14	59.5	2.5
A-100-30	12.2	93.7	0.13	85.7	0.14	5.5	2.22	59.5	2.5
B-300-30	* 38.3	114.7	0.33	104.9	0.37	12.3	3.11	72.8	3.4
B-300-50	* 42.9	114.7	0.37	104.9	0.41	21.3	2.01	72.8	3.4
B-300-100	* 59.7	114.7	0.52	104.9	0.57	48.1	1.24	72.8	3.4
B-150-30	* 14.7	114.7	0.13	104.9	0.14	8.5	1.73	72.8	3.4

* Half of the loading load

Leonhardt et al. :

$$V = 1.4 \times d^2 \times \beta_{wn} \quad (1)$$

where, V: ultimate slip strength [N], d: diameter of PBL hole [mm], and β_{wn} : compressive strength obtained from cubic concrete specimen based on ISO 1920-3 [N/mm²]. Since the compressive strength f'_c is usually used based on the test result of the cylindrical specimen according to JIS A 1132 in Japan, the compressive strength β_{wn} is given by changing from cylindrical to cubic compressive strength using the relationship of $f'_c / \beta_{wn}=0.8$.

JSSHS :

$$V = \frac{1.6 \times d^2 \times f'_c}{\gamma_b} \quad (2)$$

where f'_c : compressive strength of a cylindrical specimen [N/mm²], and γ_b : member factor (=1.0).

Fujii et al. :

$$V = V_{int} + 2.5 \times T_c \quad (3a)$$

$$V_{int} = 2 \times \left\{ \pi \times \frac{d^2}{4} + (n - 1) \times A_s \right\} \times \tau_s \quad (3b)$$

$$T_c = \frac{f_{ct}}{e \times \frac{y}{I} + \frac{1}{A}} \quad (3c)$$

$$I = \frac{b \times h^3}{12} \quad (3d)$$

$$A = b \times h \quad (3e)$$

where V_{int} : the pure shear strength under the condition without concrete confinement [N], this condition corresponds to the specimen without concrete cover. T_c : the maximum confined force caused by the concrete cover, that is the maximum resistance force resisting the splitting force which makes concrete block divide into two blocks. n: the ratio of the elastic modulus E_s / E_c for concrete E_c and rebar E_s , A_s : the cross-sectional area of rebar set through PBL hole [mm²] (=0 in this paper), and τ_s : shear strength of concrete, which Fujii et al. [6] adopts tensile strength of concrete [N/mm²], e: distance from the neutral axis of the concrete cover to the tip of the PBL plate [mm] (see Figure 4), y: distance from the center of the PBL hole to the neutral axis of the concrete cover [mm](see Figure 4), I: moment of inertia of concrete cover [mm⁴], A: cross-sectional area of concrete cover [mm²].

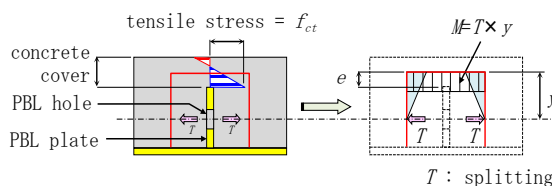


Fig.4 PBL model used by Fujii et al.

Exactly speaking, Fujii et al. [6] indicated confinement factors not only the cover but also other factors in the case of push-out test, that is: rebar set through PBL hole, rebar set perpendicular to PBL plate in the cover, and the friction force along the boundary between block and test bed at the bottom, all of which will resist the splitting force passively, different from active confinement such like prestressing force. Then, the evaluation formula Eq. (3) can be derived from the following assumptions:

(1) When slip load (shear force) V is subjected to PBL, the slip load will produce a splitting force T at the hole as shown in Figure 4, as well as shear stress parallel to the PBL plate surface at both sides of the hole. Then, the splitting force and the shear stress will be larger as the slip load increases.

(2) The concrete sandwiching the PBL plate can be regarded as a rigid frame consisted of the concrete cover and both sides concrete, as shown in Figure 4.

(3) The splitting force T will cause a bending moment $M(=Ty)$ and an axial tensile force $N(=T)$ in the concrete cover. The concrete cover will crack when the tensile extreme fiber stress reaches the tensile strength of concrete, then the concrete will be divided into two blocks. Consequently, the concrete cover will resist the splitting force until the occurrence of the crack in the concrete cover.

(4) By using beam theory, the maximum confinement force T_c due to the concrete cover can be calculated under the condition when the fiber stress of the concrete cover is the tensile strength of concrete f_{ct} at the top of PBL plate, as indicated in Eq.(3c).

(5) For the relationship between the slip load and the splitting force, Fujii et al. gave the coefficient=2.5 as in Eq.(3a) from their experimental result which includes effects of the frictional force at the bottom of the specimen.

(6) Moreover, for Eq.(3b) means the shear resistance at both ends of the hole when the concrete remains in the hole at the failure as shown in Figure 3.

According to Eq.(3), it will be noticed that ultimate strength of PBL becomes higher as the concrete cover becomes thicker and as the concrete height becomes higher because the inertial moment and cross-sectional area of the concrete cover become larger.

Relationship between the ultimate slip strength and the thickness of the concrete cover is illustrated in Figure 5. From Figure 5 and Table 2,

it can be noticed that the test results show that ultimate strength of PBL becomes higher as the concrete cover becomes thicker and that when the concrete cover exists, the higher height of the concrete block gives larger ultimate slip strength. These phenomena are obviously caused by the confined effect depending on the concrete cover. Thus, confined force effects largely on the ultimate slip strength of PBL, for example, the ultimate slip strength of the specimen A-300-50 (cover-thickness=50 mm) was approximately 10 times higher than that of A-300-0 (without cover). Consequently, the confined effect should be taken into account correctly in the evaluation of PBL slip strength.

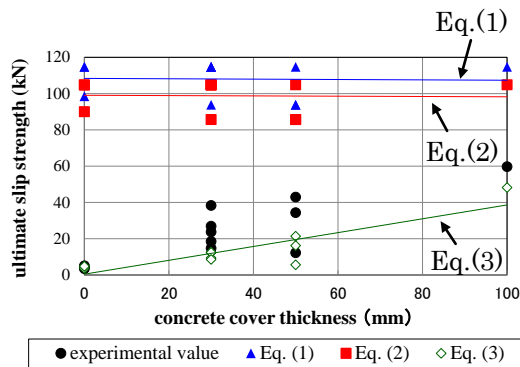


Fig.5 Relationship between concrete cover thickness and ultimate slip strength

On the other hand, as for Eq. (1) and Eq. (2), the ultimate slip strength is decided by the only a diameter of PBL and compressive strength of concrete. Therefore, the ultimate slip strength becomes consequently the same value for each series in Table 2, because these equations do not take the confinement effect into account. Adding to this, it is also noticed that the ultimate slip strengths based on both equations are significantly larger than test results. This reason is probably that these evaluation equations were built by regression analysis based on the experimental data which must have contained several confinement effects such as frictional force at the bottom.

In contrast, it can be noticed that Eq. (3) can express the tendency of the phenomena due to the confined effect of the cover, as indicated in Table 2. However, the ultimate slip strength evaluated by Eq. (3) is remarkably smaller than the test results. In Eq.(3), Fujii et al.[6] gave the coefficient of T_c as 2.5, which was decided according to the relationship between the slip load V and the splitting force T obtained from the push-out test

with the frictional force at the bottom of concrete, namely, mortar was laid on the testbed firstly and then the specimen was set on the mortar layer before loading. In this case, because the splitting force will be only frictional force small, the coefficient will be larger than 2.5 really when removing the frictional force such as the tests in this paper. Consequently, the ultimate slip strength obtained by Eq.(3) will be smaller than the test results.

Jyengar [4] gave the coefficient=4 theoretically in his research for post-tensioned prestressed concrete beams. In accordance with Jyengar, the ultimate slip strengths at the coefficient=4 instead of 2.5 in Eq.(3) are illustrated in Figure 6 as well as test results. It can be noticed that the slip strengths when the coefficient=4 are more coincident with the test results though almost of test results are still higher than the evaluated slip strength. So, judging from test results in this paper, the following evaluation formula would be more appropriate for rating the slip strength of PBL with concrete cover, though there are not so many data of which frictional force at the bottom is removed completely.

$$V = V_{int} + 4.0 \times T_c \quad (4)$$

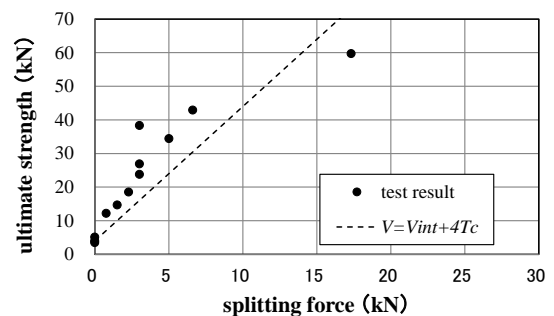


Fig.6 Relationship between splitting force and ultimate slip strength

3.2 Strain Of Concrete Cover

Relationship between slip load and surface strain of the concrete cover is illustrated in Figure 7. The slip load V in the figure shows the force carried by one PBL hole, namely V of B series is a half of slip load by the reason of two holes, as shown in Figure 2. The direction of the strain is perpendicular to PBL plate. Though the specimen of B series has two concrete covers, the strain in Figure 7 is indicated only on one side because both strains are almost the same.

Comparing inside strain and outside strain of concrete cover in Figure 7, it can be noticed that

the outside strain is in compression and the inside in tension before the maximum load, but as the slip load becomes near the maximum load the outside strain changes from compression to tension rapidly. These phenomena can be explained by the PBL model indicated by Fujii et al., namely the bending moment in the concrete cover appears due to the splitting force as shown in Figure 4, then once the crack by the splitting force initiates in the concrete cover, the inside strain changes to tensile strain.

Furthermore, comparing the upper surface and the lower surface of the concrete, the absolute value of the strain of the upper surface is remarkably smaller than the lower surface, as also shown in Figure 7. This shows the bending moment with orthogonal direction as shown in Figure 8(b) will be produced by the slip load as well as the bending moment as Figure 8(a) simultaneously. Figure 9 shows the crack of the concrete cover at the PBL failure. The crack width

at the bottom is always wider than that at upper side in all specimens as shown in Figure 9, though this phenomenon of the crack width is not sure in the conventional push-out tests which the specimen is set on the mortar or gypsum. Anyway, this orthogonal bending moment will not appear in a lot of actual composite structures except push-out test, then the orthogonal bending moment occurred in push-out test may effect something as confined force on the slip strength of PBL. However, we could not clarify whether the orthogonal bending moment effects on the slip strength or not.

In this paper, when a crack occurs over the entire height of the concrete cover, the slip load decreases suddenly by the reason of without rebars, because the confinement effect is not expected any longer. Incidentally, if a rebar is placed through the PBL hole, the slip strength decreases very slowly after the maximum load, then the slip can grow far larger, for example more than 10mm.

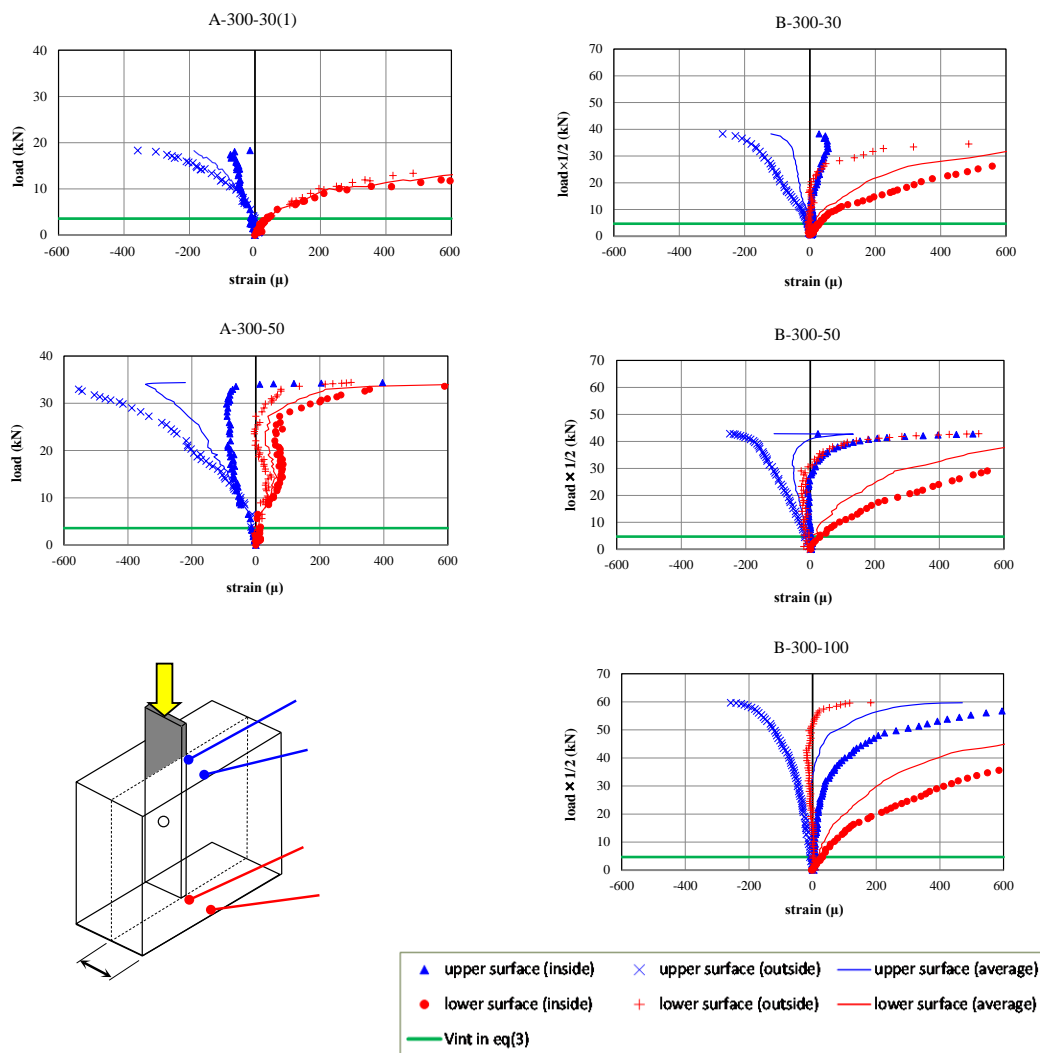


Fig.7 strain of the concrete cover measured during loading in the push-out test

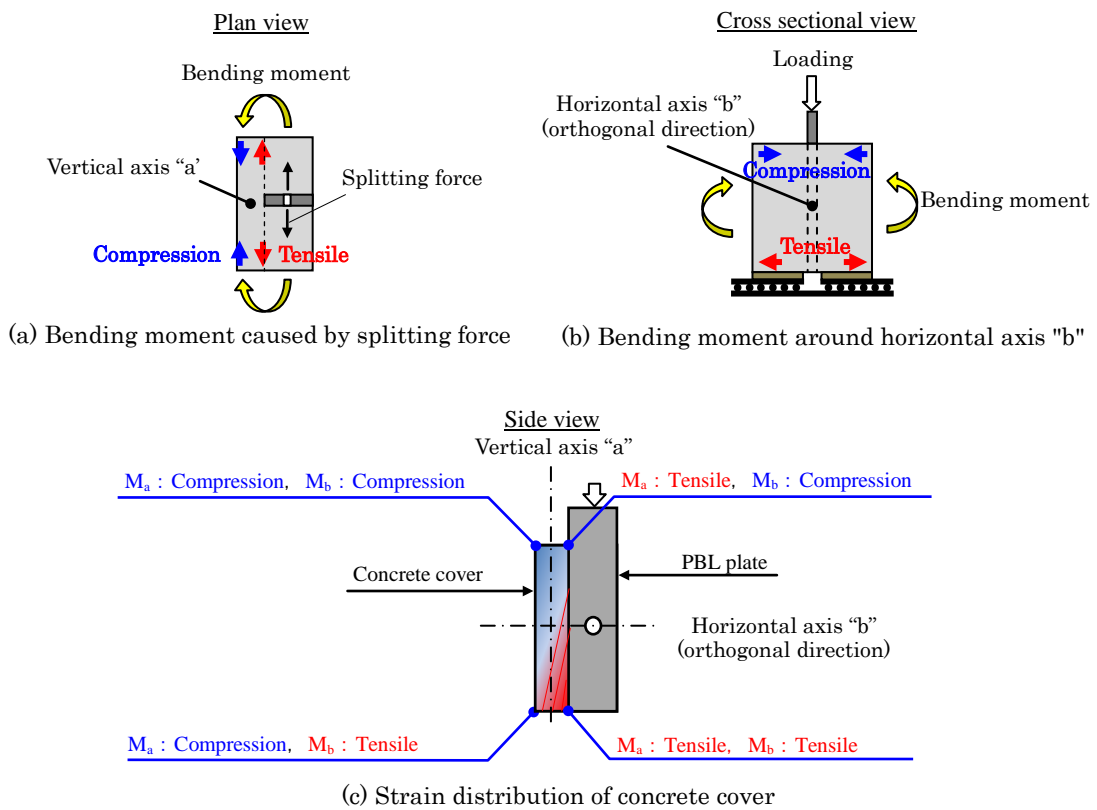


Fig.8 Schematic diagram of strain distribution of concrete cover

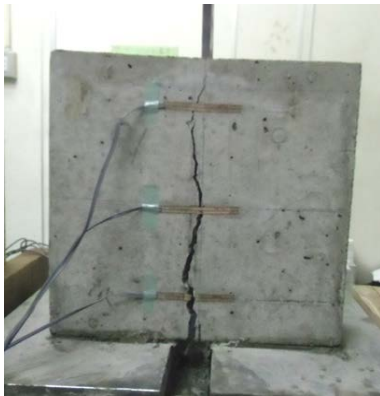


Fig.9 Crack of concrete cover in push-out test

4. CONCLUSION

Focusing on the confined effect due to concrete cover, the ultimate slip strength of PBL with a small hole was investigated by conducting push-out tests. In this paper, the frictional force at the bottom of a specimen was removed perfectly, because the frictional force, which acts as a confinement factor, will make the ultimate slip

strength of PBL enhance significantly. Test results were compared with three evaluation formulas having been proposed. It can be concluded from the test results as below:

- (1) Ultimate slip strength becomes larger as concrete cover becomes thicker. This fact is clearly due to the confined effect caused by the cover. When the cover is 50 mm, the slip strength (34.4 kN) is about 10 times of that without cover (3.5 kN). Thus, ultimate slip strength is significantly affected by concrete confinement.
- (2) For ultimate slip strength, test results are far smaller than that obtained by both Leonhardt et al. and Japanese Standard Specifications for Hybrid Structures. Especially in the case without concrete cover, the test result is about 1/25 of them. This reason may be that their evaluation formulas are tacitly taken confined effects into account because they are derived from regression analysis based on test results, many of which contain several concrete confinements.
- (3) Ultimate slip strength increased as the concrete height of specimen becomes larger. This phenomenon is also caused by the concrete confinement of the cover and can be explained also by the concept of Fujii et al.[6].

(4) Two kinds of bending moment appear in concrete cover in the push-out test. One makes concrete divide mainly into two blocks and another is similar to the bending moment of simple beam which is induced by slip load. Though the latter bending moment will not appear in an ordinary composite structure, the crack width of concrete at failure in the push-out test is larger at the bottom than at the top.

(5) An evaluation formula of the slip strength of PBL is proposed by revising the evaluation formula of Fujii et al. Comparing with test results, this formula can evaluate the slip strength well.

5. ACKNOWLEDGMENTS

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