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EXPERIMENTAL STUDY ON SHEAR-SLIPPING BEHAVIOR OF PBL JOINT CONNECTION BETWEEN CONCRETE AND UFC HYBRID GIRDER

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ABSTRACT

In this study, Perfobond (PBL) strip which is flat plate containing a number of holes filled with cast in placed UFC is proposed to connect between UFC and concrete girder components. Push-out test of four specimens were conducted. The specimens consisted of middle UFC part and concrete parts at the both side which were connected by proposed connection. The experimental parameters are thickness and the hole's diameters of PBL. The experimental results indicated that shear capacity of PBL joint increases with increase in thickness and the hole's diameter of PBL. Furthermore, the experimental results were compared with existing shear-capacity equations for PBL shear connector. It showed that the calculated values overestimate the experimental values.

Keywords: UFC, PBL, Joint, Hybrid girder, Shear

1. INTRODUCTION

Nowadays, the prestressed concrete (PC)-steel hybrid structure has been applied to long-span bridges in Japan such as cable-stayed and extradosed bridges due to their structural economical and constructional advantages. The steel girder is employed at the central part of middle spans; in order to reduce the self weight of bridges and the span can be longer. The Ibigawa and Kisogawa bridges, which are the longest extradosed bridges in the world, are the one of example of hybrid cable-stayed bridges (Kurita and Ohyama 2003). However this type of structure has some drawback such as durability problems. This lacking can be solved by the application of developed Ultra High Strength Fiber Reinforced Concrete (UFC). UFC is an advanced cementitious composite material which has been rapidly developed for recent years and implemented through the bridge construction in the world. Through the proper "Ultra High" strength parameters, UFC provides with characteristic values in excess of 150 MPa and 5 MPa in the compressive and tensile strengths with

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Table 1: List of the experimental cases

No.	Name	Thickness of PBL (mm)	Diameter of PBL's hole, Ø (mm)	Diameter of rebar, *r* (mm)	Series
1	PBL16	16	40	10	I, II
2	PBL22	22	40		I
3	PBL-Ø30	16	30		II
4	PBL-Ø50	16	50		



Figure 1: Perfobond (PBL) strip.

Table 2: Mix proportion of UFC

Flow (mm)	Unit weight (kg/m^3)			
	Water	Premix binder	Steel fiber	Water reducing agent
260±20	180	2254	157	24

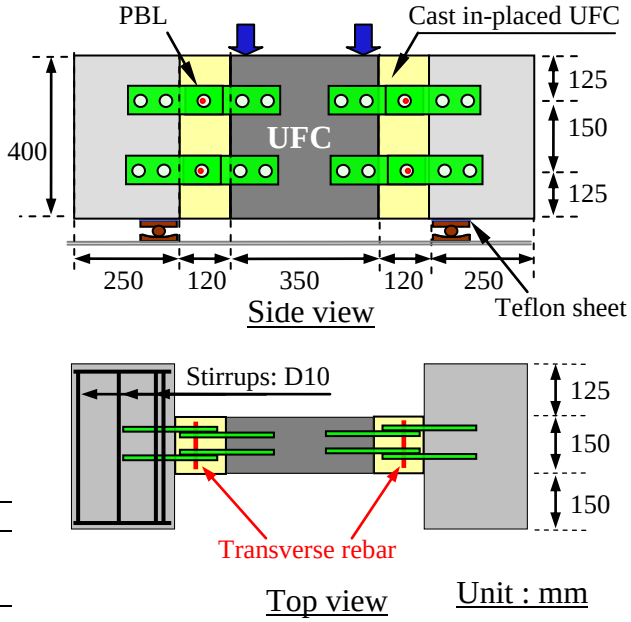

Figure 2: Details of specimen.

high bending toughness due to the existence of steel fibers (Katagiri et al. 2002). Furthermore, with close-packed micro-structures, UFC has excellent durability properties. Following the aforementioned point of view, PC-UFC hybrid bridges are started to be developed. The fundamental requirement in developing PC-UFC hybrid girders is to understand the behavior of joints and determine the joint type. However, sufficient number of researches on joints for PC-UFC hybrid girder cannot be found. Therefore, the objective of this research is to propose and investigate a suitable joint type for PC-UFC hybrid girder.

The proposed joint consisted of Perfobond (PBL) strip which is flat steel plate containing a number of holes filled with cast in placed UFC as shown in Figure 1. The specimens consisted of middle UFC part and concrete parts at the both side which were connected by the proposed joint. The experimental parameters were thickness and the hole's diameters of PBL. The shear-slipping behavior is investigated and the shear capacity is compared with the calculated shear capacity of the girder part.

2. EXPERIMENTAL PROGRAM

2.1. Experimental parameters and specimens

To investigate the shear behavior of PBL joint filled with UFC, four specimens were prepared. Push-out tests were conducted. The summary of test variables and details of specimens are provided in Table 1 and Figure 2. The experimental cases can be classified into two different series, the effect of the thickness of PBL, and the effect of the hole diameter of PBL. Figure 2 shows dimension, arrangement of reinforcing steel bars and cross section of all specimens. In the series I, the effect of the thickness of PBL was considered. The dimension of the specimens was same, but the thicknesses of PBL were 16 and 22 mm in PBL-16 and PBL-22, respectively. Series II consisted of three specimens, the thickness of PBL was 16 mm in all specimens but the diameter of PBL hole was different. The original specimen was PBL16 with diameter of 40 mm. The hole diameter of PBL-Ø30 and PBL-Ø50 were 30 and 50 mm, respectively.

2.2. Materials

The self-compacting concrete was used in this experiment. The materials used in the concrete mixes were high-early strength cement, fine aggregates, coarse aggregates, viscosity improver and superplasticizer, which was high-performance air entrained (AE) water reducing agent. The designed compressive strength of 7-day age concrete was 70 MPa. For UFC, The steel short fibers with 0.2 mm diameter and 15 mm length were used. Mix proportion of UFC is shown in Table 2. The volume fraction of steel fibers in all specimens was 2.0%. For the test, a SS400 steel grade (nominal yield strength of 240 MPa, tensile strength of 400-510 MPa) rib was used as PBL. The longitudinal reinforcing bars used in this research were deformed steel bar with the yield strength of 339 MPa.

2.3. Fabrication process of the specimens

Figure 3 shows the fabrication step of the specimens. The specimen consisted of three parts. The middle was UFC segment which had been fabricated in advance. The both sides were reinforced concrete segments which were also cast in advance. After that all three segments were set into the



(a) Setting of all segments (b) Casting of cast in-placed UFC (c) Completed specimen

Figure 3: Fabrication process of the specimens.

Table 3: Mechanical properties of concrete and UFC, and the results of loading tests

Name	Mechanical properties of concrete		Mechanical properties Of cast in placed UFC		Mechanical properties of precast UFC		Results of loading test	
	f'_c (MPa)	f_t (MPa)	f'_{c_UFC} (MPa)	f_{t_UFC} (MPa)	$f'_{c_UFC_pc}$ (MPa)	$f_{t_UFC_pc}$ (MPa)	Peak load (kN)	*Shear* Capacity (kN)
PBL16	84.3	3.3	123.8	11.2	205.4	13.6	789.3	394.7
PBL9	78.7	3.7	102.5	10.5			765.8	382.9
PBL22	76.5	2.9	107.5	11.8			858.2	429.1
PBL-Ø30	74.6	3.0	112.4	11.5			701.8	350.9
PBL-Ø50	76.1	2.8	107.9	11.3			835.0	417.5

f'_c: compressive strength of concrete, f_t: tensile strength of concrete, f'_{c_UFC}: compressive strength of cast in placed UFC, f_{t_UFC}: tensile strength of cast in placed UFC, $f'_{c_UFC_pc}$: compressive strength of precast UFC, $f_{t_UFC_pc}$: tensile strength of precast UFC

position and steel rebars were inserted into PBL holes. Then, cast in-placed UFC was cast and cured for about 7 days. The target strength of cast in-placed UFC was 100 MPa.

2.4. Loading method and measurement items

Specimens were subjected to a push-out loading with the load applied at the end of precast UFC segment. At the loading points on the top surface of the specimen, steel plates with 50 mm width, steel rollers and load distribution beam were placed. Moreover, Teflon sheets were inserted between specimen and supports. During the loading test, the applied load was measured. Vertical displacements of precast concrete, UFC and joint parts were measured by using transducers. To check the initial crack and their propagation, pictures of side surface were taken and all cracks on the surface were marked with loading increments.

3. RESULTS AND DISCUSSIONS

3.1. Load-displacement relationships, failure mode and crack patterns

Table 3 shows the mechanical properties of concrete and UFC, and the result of loading tests. Figure 4 and 5 show the relationships between the load and the relative displacement of series I and II, respectively. The relative displacement was obtained by subtracting the displacements at the supporting points from the displacement at the middle point of the joint part.

Figure 6 shows the crack patterns observed after the loading tests. The failure modes of all specimens with PBL connections were determined. It is obvious that only one critical crack was remarkable in each specimen. The mode of failure of all specimens was shear failure at the joint.

All specimens exhibited similar linear behavior from the initial loading up to the first separation crack between concrete and cast in-placed UFC interface. After the first separation crack, the load still increased linearly until the initiation of the main crack occurred in a joint part. The main crack initiated continued from first separation crack. After the initiation of main crack, the main crack propagated to the interface of precast and cast in-placed UFC. In addition, the appearance of the diagonal crack reduced the slope of load-displacement relationship of specimens. From this stage, the rate of load increment became slight and the load-displacement relationship showed nonlinear

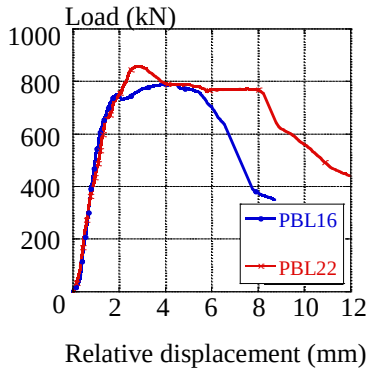

Figure 4: Load-relative displacement relationship in series I

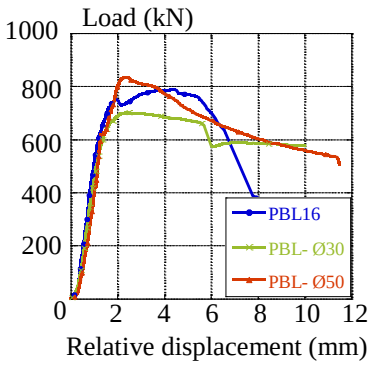

Figure 5: Load-relative displacement relationship in series II

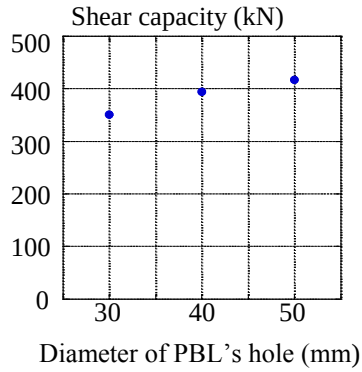

Figure 7: Shear capacity-diameter of PBL's hole relationship

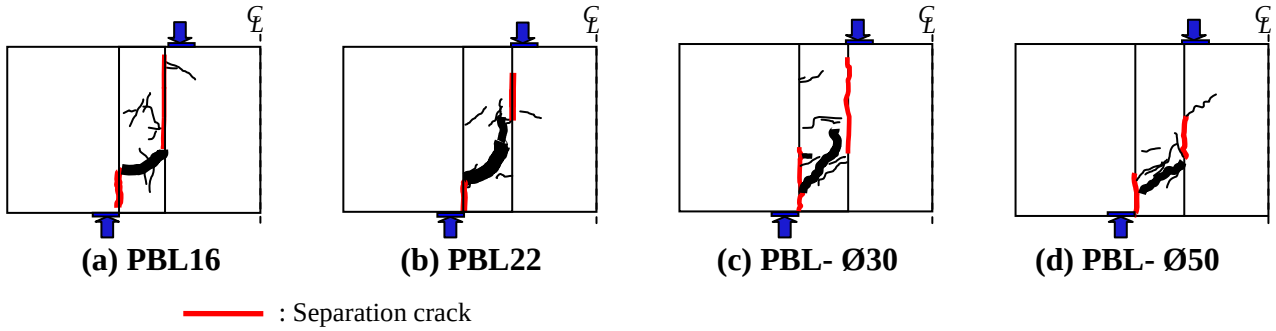

Figure 6: Crack patterns

behavior. Then, the separation crack between precast and cast in-placed UFC propagated, the load reached to the peak and dropped due to the separation crack between precast and cast in-placed UFC propagated pass through the interface. Similar process of shear failure was observed in all specimens.

3.2. Effect of the thickness of PBL

The influence of thickness of PBL is discussed based on the experimental results of PBL16 and PBL22 specimens in Series I. From Table 3 and Figure 4, specimens can be arranged as PBL16 and PBL22 in order of shear capacity of connection. It is indicated that the shear capacity of PBL joint filled with cast in-placed UFC increases with increase in thickness of PBL. It is because the end-bearing resistance increases with increase of thickness of PBL.

3.3. Effect of the hole's diameter of PBL

Series II comprises of three specimens (PBL16, PBL-Ø30 and PBL-Ø50). The relationship between shear capacities against hole's diameter of PBL is drawn in Figure 7. It can be seen that with the increasing of diameter of PBL's hole, the shear capacity shows gradually increased. This is because the shear resistance of characteristic PBL is mainly affected by the dowel effect of the UFC in the rib hole.

Table 4: Experimentally observed and calculation obtained shear capacity of PBL joint

Number	Name	Thickness of PBL (mm)	Diameter of PBL's hole, Ø (mm)	V_{ud} (kN)	V_{exp} (kN)	V_{exp}/V_{ud}
1	PBL16	16	40	968.6	394.6	0.41
2	PBL22	22	40	968.6	429.1	0.44
3	PBL-Ø30	16	30	562.6	350.9	0.62
4	PBL-Ø50	16	50	1490.6	417.5	0.28

V_{exp}: experimental values

3.4. Comparison with shear-capacity equations of PBL

According to JSCE standard specifications for hybrid structures (JSCE 2009), the shear capacity of PBL at rib hole (V_{ud}) can be calculated by using Eq. (1)

$$V_{ud} = 1.45 \times ((d^2 - \varphi_{st}^2) \times f_c^{'} + \varphi_{st}^2 \times f_{st}) - 26.1 \times 10^3 \quad (1)$$

where, d is diameter of the PBL hole (mm), $ø$ is diameter of transverse rebar (mm), $f_c^{'}$ is compressive strength of concrete (MPa) and f_{st} is tensile strength of transverse rebar (MPa).

The shear-capacity results of the PBL joint determined in this experiment are compared with values derived from shear-capacity equations from JSCE. Table 4 summarizes the results of experimentally observed and computationally obtained shear capacity of PBL by Eq. (1). From Table 4, the calculation results in all cases are higher than the observed push-out test results. This is because the equation did not consider the effect of thickness of PBL and also the applicable range was derived for the normal concrete only. Moreover, it should be noted that in this experiment, the supporting points could be rotate and slide which is difference from equations from JSCE. Therefore, the equation should be modified in order to use for PBL joint with cast in placed UFC.

4. CONCLUSIONS

1. With increasing in the thickness and hole's diameter of PBL, the shear capacity of PBL increased. This is because the end-bearing and dowel effect of PBL increased from increasing of thickness and hole's diameter of PBL.

2. Through comparisons of the experimental results with the calculation results from JSCE equation, the derived values were overestimated in all cases. From such comparison, improved equation should be established.

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