- *Technical Paper* -

SHEAR RESISTANCE MECHANISMS OF PBL JOINT CONNECTION FOR UFC-PC HYBRID GIRDERS

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ABSTRACT

Shear resistance mechanism of Perfobond strip (PBL) joint with cast-in-place UFC connection for UFC-PC hybrid girders has been studied. Push out test of eight specimens was conducted. Experimental parameters were thickness and hole diameter of PBL and prestressing level on the connection. The experimental results showed that PBL with cast-in-place UFC connection is sufficient to transfer shear forces between segments. Shear resistance mechanisms were investigated. The shear capacity increased as the friction resistance by the prestressing stress on the connection.

Keywords: hybrid structure, UFC, connection, PBL, shear behavior

1. INTRODUCTION

During the last decade, the prestressed concrete (PC)-steel hybrid structure has been remarkably applied to the bridges in Japan such as cable-stayed and extradosed bridges due to their structural functional 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 examples of hybrid cable-stayed bridges [1]. However this type of structure has some drawback such as durability problems. UFC is an advanced cementitious composite material which has been rapidly developed for recent years and implemented through the infrastructure construction in the world. UFC has many advantages such as the mechanical characteristic values in excess of 150 MPa in the compressive strength with high bending toughness due to the existence of steel fibers. Furthermore, with close-packed micro-structures, UFC has excellent durability properties [2].

Thus, the advantages of UFC can be taken with remaining the benefits of steel by replacing the steel girder with the UFC segmental girder. Therefore, the authors propose to use UFC instead of the steel for central part of span in this study so called UFC-PC hybrid girder. The fundamental requirement in developing UFC-PC hybrid girders is to understand the behavior of joints and determine the joint type which locates at the end of PC girders in order to connect with a UFC girder. The connections should sufficiently transfer the shear force between UFC and PC parts. However, sufficient number of researches on joints for UFC-PC hybrid girder cannot be found. Therefore, the objective of this research is to propose and investigate a suitable joint type for UFC-PC hybrid girder.

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

2. EXPERIMENTAL PROGRAMS

2.1 Experimental parameters and specimens

Eight specimens were prepared and push-out tests were conducted in order to investigate the shear behavior of PBL joint filled with UFC. Table 1 lists the details of tested specimens and details of the specimens are provided in Fig. 1 and Fig. 2. The experimental

Table 1 Experimental cases

Name	t (mm)	d (mm)	σ'_c (MPa)	Series
PBL9	9	40	-	I
PBL16	16	40	-	I, II, III
PBL22	22	40	-	I
PBL-D30	16	30	-	II
PBL-D50	16	50	-	II
PBL-P5	16	40	5	III
PBL-P10	16	40	10	III
PBL-P15	16	40	15	III

t = Thickness of PBL, d = Hole diameter of PBL, σ'_c = Prestressing level on connection

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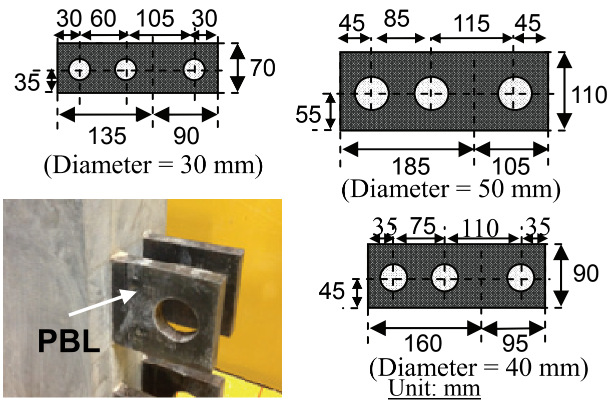


(a) Example of used PBL (b) Dimensions of used PBL

Fig. 1 Picture and dimensions of used PBLs

Table 2 Mix proportion of concrete

G_{max}	W/C	Unit weight (kg/m^3)					
[mm]	[%]	*W*	*C*	*S*	*G*	*SP*	*V*
15	57	165	292	718	857	4.38	0.25

W: Water, *C*: Cement, *S*: Fine Aggregate, *G*: Coarse Aggregate, *SP*: Superplasticizer, *V*: Viscosity improver

Table 3 Mix proportion of UFC

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

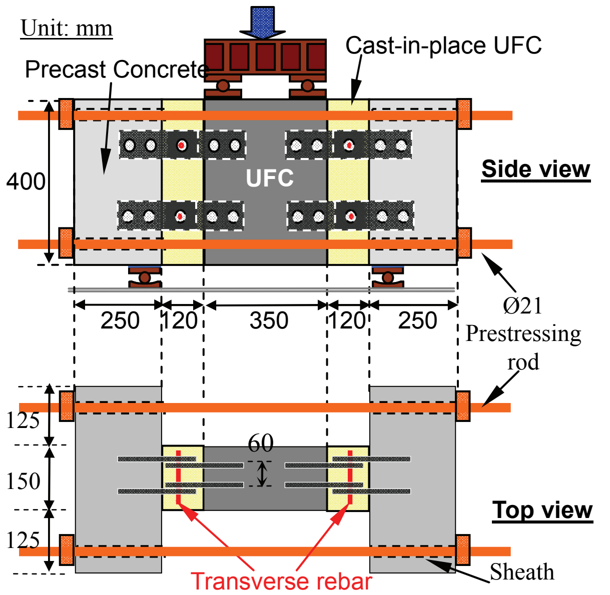


Fig. 2 Detail of specimens

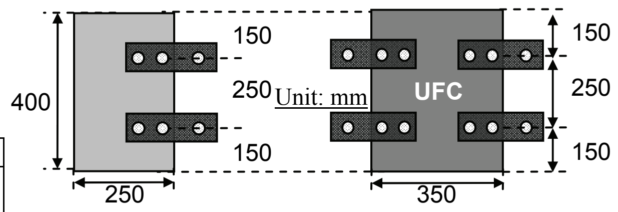


Fig. 3 Detail of RC and UFC segments (side view)

cases can be grouped into three different series, the effect of the thickness of PBL, the effect of diameter of PBL hole and prestressing level. Fig. 2 shows dimension and cross section of all specimens. Fig. 3 shows the details of RC and UFC segments. 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 9, 16 and 22 mm in PBL9, PBL16 and PBL22, respectively. Three specimens with the thickness of PBL was 16 mm in all specimens but the diameter of PBL hole was different were examined in Series-II. The original specimen was PBL16 with diameter of 40 mm. The 30 and 50 mm hole diameter were used in PBL-D30 and PBL-D50 specimens, respectively. Fig. 1(b) shows the dimension of all PBLs. For Series-III, by using the prestressing rods, the prestressing force was induced on the connection as shown in Fig. 2. The prestressing level can be calculated from the forces divided with the cross section area of connection which is equal to 400 mm height and 150 mm width in this study. The prestressing levels were 5, 10 and 15 MPa in PBL-P5, PBL-P10 and PBL-P15, respectively.

2.2 Materials

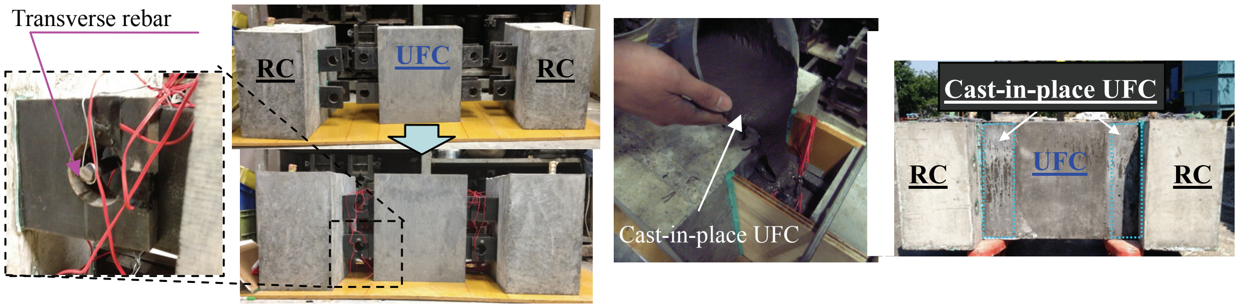
For UFC, the steel short fibers with 0.2 mm diameter and 15 mm length were used. Mix proportion of UFC is shown in Table 3. The volume fraction of steel fibers in all specimens was 2.0%. For the precast concrete part, the self-compacting concrete with the designed compressive strength of 7-day age concrete was 70 MPa was used. High-early strength cement, fine aggregates, coarse aggregates, viscosity improver and superplasticizer, which is high-performance air entraining (AE) water reducing agent were used in the concrete mixes. Mix proportion is summarized in Table 2. For the test, a SS400 steel grade (nominal yield strength of 240 MPa, tensile strength of 400-510 MPa) steel plate was used as PBL. The transverse reinforcement used in this research were deformed steel bar with the yield strength of 339 MPa with 9.53 mm nominal diameter.

2.3 Specimen fabrication

The specimen was combined of three parts which the both sides were reinforced concrete segments and UFC segment was in the center part. Fig. 4 shows the fabrication step of the specimens. All of segments were cast before in advanced with PBLs were embedded. Fig. 3 shows the detail of RC and UFC segments. After that all three segments were combined together with the designed position and 10 mm diameter transverse reinforcements were inserted into PBL holes. Afterwards, cast-in-place UFC was cast as shown in Fig. 4(b) and cured for about 7 days. The designed compressive strength of cast-in-place UFC was 100 MPa.

2.4 Loading method and measurement items

The load applied at the both end of precast UFC



(a) Setting of segments and transverse rebars (b) Casting of cast-in-place UFC (c) Completed specimen

Fig. 4 Fabrication of specimen

Table 4 Mechanical properties of concrete and UFC, and the result of loading tests.

Name	Mechanical properties of concrete		Mechanical properties of cast-in-place UFC		Mechanical properties of precast UFC		Results of loading test			Series
	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)	V_u (kN)	V_{UFC} (kN)	
PBL9	78.7	3.7	102.5	10.5			765.8	382.9		I
PBL16	84.3	3.3	123.8	11.2			789.4	394.7		I, II, III
PBL22	76.5	2.9	107.5	11.8	185.4	13.6	858.2	429.1		I
PBL-D30	74.6	3.0	112.4	11.5			701.8	350.9	374.5	II
PBL-D50	76.1	2.8	107.9	11.3			835.0	417.5		II
PBL-P5	75.3	3.1	108.5	11.6			1440.8	720.4		III
PBL-P10	74.1	3.4	107.4	10.5	187.5	12.8	1633.0	816.5		III
PBL-P15	72.5	2.9	113.5	11.1			2147.0	1073.5		III

f'_c: compressive strength of concrete, f_t : tensile strength of concrete, f'_{c_UFC} : compressive strength of cast-in-place UFC, f_{t_UFC} : tensile strength of cast-in-place UFC, $f'_{c\_UFC\_PC}$: compressive strength of UFC segment, $f_{t\_UFC\_PC}$: tensile strength of UFC segment, V_u : shear capacity of connection, V_{UFC} : shear capacity of UFC segment

segment and the support points were placed at the both end of RC part as shown in Fig. 2. 50 mm width steel plates were placed at the loading points on the top surface of the specimen. Steel rollers and a load distribution beam were placed. During the loading test, the applied load was measured. Transducers were used to measure the vertical displacements of all parts. 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. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Shear capacities

The result of loading tests and the mechanical properties of concrete, UFC and cast-in-place UFC are summarized in Table 4. From the JSCE recommendation, the shear capacity of UFC segment can be calculated by using Eqs. 1, 2 and 3 [3].

$$V_{UFC} = V_{rpcd} + V_{fd} \tag{1}$$

$$V_{rpcd} = 0.18\sqrt{f'_{c\_UFC\_PC}}\, b_w d \tag{2}$$

$$V_{fd} = (f_{vd} / \tan \beta_u) b_w z \tag{3}$$

where, V_{UFC} is shear capacity of UFC segment (kN), $f'_{c\_UFC\_PC}$ is compressive strength of UFC (MPa), b_w is width of web, d is effective depth (mm), f_{vd} is design average tensile strength of UFC (MPa), z is distance from the location of compressive stress resultant to the centroid of tension steel (mm), β_u is an angle between member axis and a diagonal crack (°).

From Table 4, the experimentally obtained shear capacities of PBL with cast-in-place UFC (V_u) in Series-I and II are higher than the calculated shear capacity of UFC segment (V_{UFC}) except in PBL-D30 specimen. It indicates that by using the PBL with cast-in-place UFC connection, the sufficient shear transfer forces between two girders can be made.

3.2 Load-deflection relationships and failure pattern

The load and the relative displacement relationships of Series I and II are shown in Fig. 5 and 6, respectively. The relative displacement was obtained by subtracting the displacements at the supporting points from the displacement at the middle point of the connection part.

Similar shear failure pattern was observed in all specimens. All specimens exhibited similar linear behavior from the initial loading up to the first separation crack at the interface between RC part and

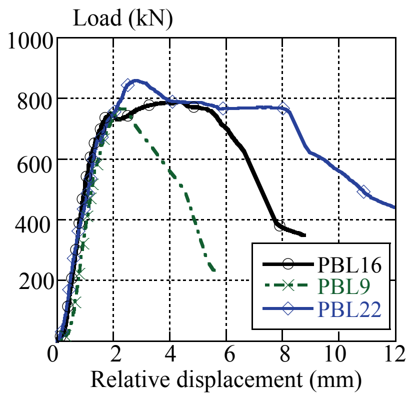


Fig. 5 Load-relative displacement in Series-I

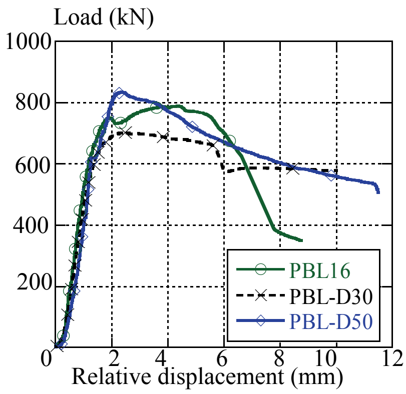


Fig. 6 Load-relative displacement in Series-II

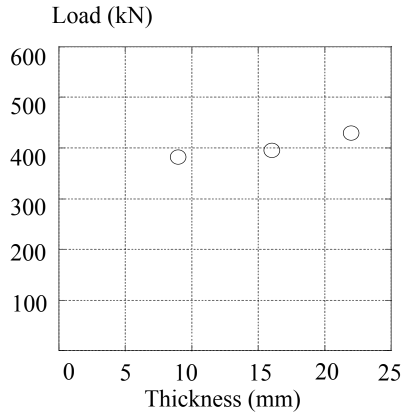


Fig. 8 Shear capacity - thickness of PBL relationship

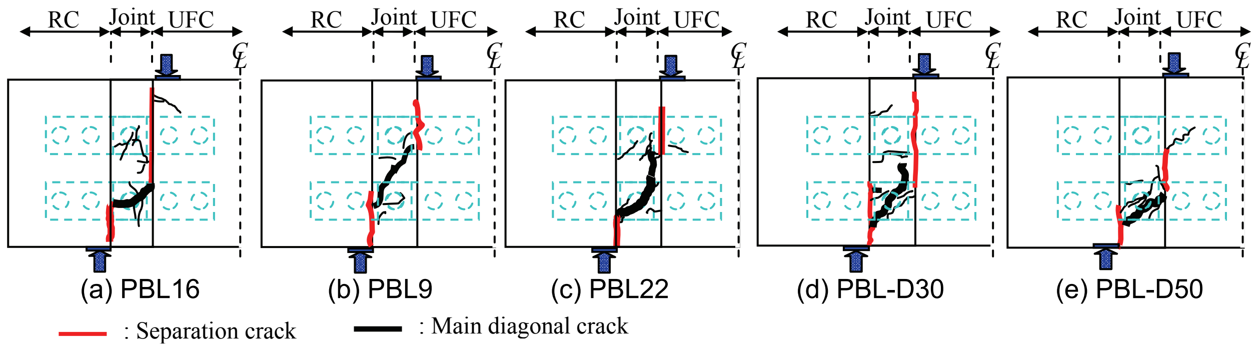


Fig. 7 Crack patterns of Series-I and II

cast-in-place UFC. The crack patterns observed at the peak loads in Sereis-I and II are illustrated in Fig. 7. From Fig. 7, it is clearly seen that there is only one remarkable crack in each specimen. Therefore, the failure mode was the shear failure at the connection in all specimens.

The load linearly increased after the first separation crack. Then, the main crack occurred on the cast-in-place UFC. After that, the main diagonal crack initiated continued from the surface of RC side to the surface UFC side as the load increased. As a result from the appearance of the main diagonal crack, the increment of load-displacement relationship of the specimens was reduced. From this stage, the load-displacement relationship showed nonlinear behavior. After that, the separation crack between precast and cast-in-place UFC propagated. Finally, the separation crack between precast and cast-in-place UFC propagated and widened. Therefore, the load reached to the peak and dropped.

3.3 Effect of thickness of PBL

PBL9, PBL16 and PBL22 specimens were used to investigate the effect of thickness of PBL in Series-I. The shear capacity of PBL joint filled with cast in-place UFC increases with the increase in thickness of PBL as the specimens can be arranged as PBL9, PBL16 and PBL22 in order of the shear capacity of connection with 382.9, 394.7 and 429.1 kN, respectively as shown in Table 4 and Fig. 8. Furthermore, the crushing of cast-in-place UFC at the end of PBLs cloud not observed in the experiment.

3.4 Effect of hole diameter of PBL

The influence of hole diameter of PBL is discussed from the results of PBL16, PBL-D30 and PBL-D50 specimens in Series-II. Fig. 9 draws the relationship between shear capacities and the hole diameter of PBL. From Table 4 and Fig. 9, it indicated that, the shear capacity shows gradual increase by the increase in diameter of PBL hole.

3.5 Effect of prestressing forces

The shear capacity and mechanical properties of concrete, UFC and cast-in-place UFC are shown in Table 4. In Series-III, the confining forces were induced on the cross section of connection area in order to simulate the effect of prestressing force of segmental girder. The influence of prestressing force was determined by the experimental result of PBL16, PBL-P5, PBL-P10 and PBL-P15 specimens, in which the prestressing stress was varying from 0, 5, 10 and 15 MPa, respectively.

Fig. 10 shows the relationship between the load and relative displacement in Series-III. PBL-P5 and PBL-P10 failed in shear at the joint as the crack patterns shown in Fig. 11(a) and (b). However, PBL-P15 specimen failed in flexural failure of UFC segment as the flexural cracks shown in Fig. 11(c). It can be said that the failure mode changed when the prestressing stress reached 15 MPa.

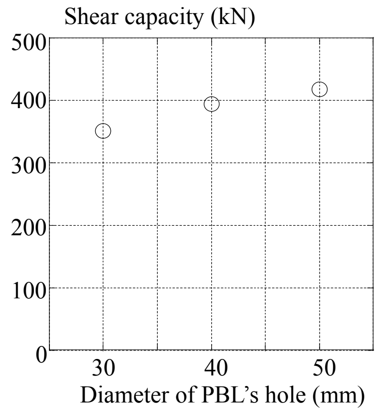


Fig. 9 Shear capacity-hole diameter of PBL relationship

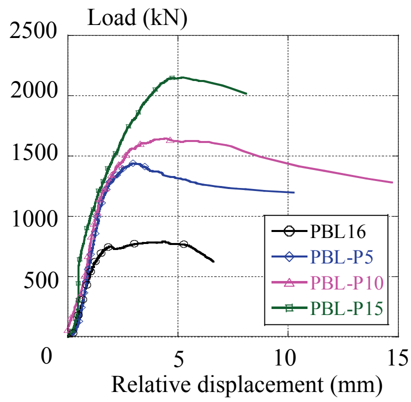


Fig. 10 Load-relative displacement in Series-III

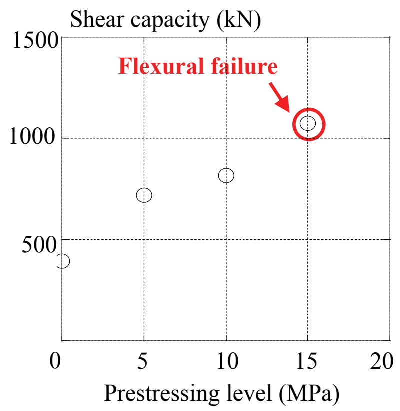


Fig. 12 Shear capacity-prestressing stress relationship

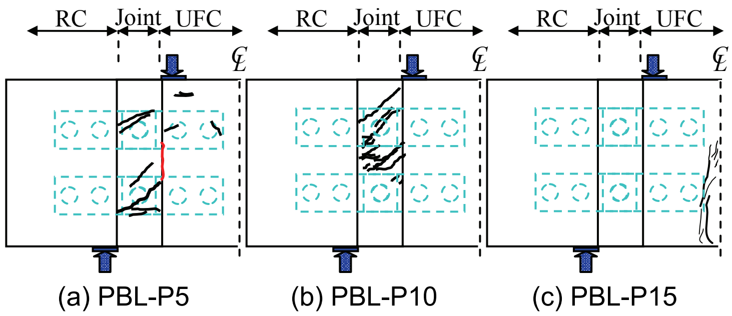


Fig. 11 Crack patterns of Series-III

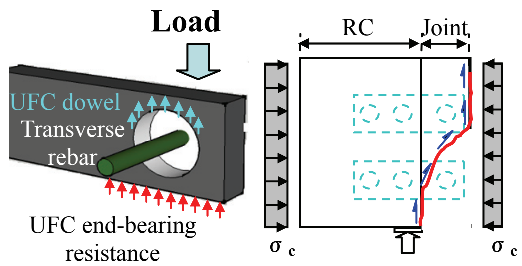


Fig. 13 Resistance mechanism of connection and contribution of PBL

From Table 4 and Fig. 12, specimens can be ordered as PBL16, PBL-P5 and PBL-P10 according to shear capacity of connection which the shear capacityies were 394.7, 720.4 and 816.5 kN, respectively. It is clearly seen that by induced prestressing force, the greatly affects on the shear capacity of connection is obvious. Therefore, shear capacity drastically increased with increase in the prestressing stress. Moreover, due to the confining stress, the separation crack could not be observed. In addition, the crack pattern of both specimens looked different from previous specimens which the number of crack on cast-in-place UFC increased.

The flexural failure was occurred in PBL-P15 specimen which the main diagonal crack on connection part and the separation crack could not be observed. The flexural crack occurred on the middle part of UFC segment at the load of 2035 kN. Afterwards, the load reached to the peak at 2147 kN.

3.6 Resisting mechanism of PBL connection

The shear resistance of PBL with cast-in-place UFC connection was investigated. The contribution on shear resistance mechanisms of PBL with cast-in-place UFC connection is categorized into four contributions, the resistance of UFC dowel in the hole of PBL, the end bearing resistance between PBL and UFC, the contribution of prestressing stress and the resistance from the transverse reinforcement. The mechanical resistance characteristics of a PBL with cast-in-place UFC connection and all of the contributions in PBL as illustrated in Fig. 13.

First is the dowel action of cast-in-place UFC in the hole of PBL. With the increase in diameter of hole of PBL, the dowel resistance of cast-in-place UFC increased. Consequently, the shear capacity of PBL with cast-in-place UFC connection increased.

As discussed in session 3.3, with increase in thickness of PBL, the shear capacity of connection increased. Therefore, the second contribution is the end-bearing resistance of PBL and cast-in-place UFC. The end-bearing resistance comes from the resisting forces of cast-in-place UFC which the contact area is under the PBL rib. It should be noted that the high compressive strength of cast-in-place UFC with over than 100 MPa used in the connection part, the shear capacity can be significantly increased.

The influence of prestressing stresses on the connection part is taken into consideration as the third contribution. The contribution of prestressing force majorly affects the shear capacity of the connection. As the results reported above, the shear capacity is significantly increased and the crack width drastically closed by the inducing of the prestressing forces on the connection part. Due to the confining force on the cross section of connection, the crack on the connection can be closed, therefore, the friction resistance of connection and other part increased. Thus, the shear capacity of the connection increased.

The last resistance contribution is the dowel resistance of the transverse reinforcement in the PBL hole.

Table 5 Experimentally observed and calculation results.

	t (mm)	h (mm)	d (mm)	$ø_{st}$ (mm)	f'_{c_UFC} (MPa)	σ'_c (MPa)	V_{exp} (kN)	V_{joint} (kN)	V_{exp} $/V_{joint}$
PBL16	16	92.5	40	9.53	123.8	-	394.7	1157.8	0.34
PBL9	9	92.5	40	9.53	102.5	-	382.9	971.4	0.39
PBL22	22	92.5	40	9.53	107.5	-	429.1	1015.2	0.42
PBL-D30	16	90.0	30	9.53	112.4	-	350.9	601.7	0.58
PBL-D50	16	95.0	50	9.53	107.9	-	417.5	1581.9	0.26
PBL-P5	16	92.5	40	9.53	108.5	5	720.4	-	-
PBL-P10	16	92.5	40	9.53	107.4	10	816.5	-	-
PBL-P15	16	92.5	40	9.53	113.5	15	1073.5	-	-

t: thickness of PBL (mm), h : length of PBL in connection part (mm), d : the hole diameter of PBL (mm), $ø_{st}$: Diameter of transverse reinforment (mm), f'_{c_UFC} : compressive strength of cast-in-place UFC (MPa), σ'_c: prestressing stress on connection part (MPa), V_{exp} : shear capacity from experiment (kN), V_{ud} : shear capacity calculated from JSCE equation (kN)

3.7 Comparison with the existing shear capacity equation of PBL

In this section, the experimental results of all specimens were compared with the calculation results calculated from the equations by JSCE Standard specifications for hybrid structures. The shear carried by each PBL connection for steel girder and RC slab at the hole of PBL in which the hole of PBL contains a transverse reinforcement (V_{ud}) can be determined by using Eq. 4 [4]. As Eq. (4) was empirically developed for application of steel girder with RC slab, the applicable range is set as shown in Eq. 5. Therefore, shear capacity of joints can be calculated by Eq. 6

$$V_{ud} = 1.45 \times ((d^2 - \phi_{st}^2) \times f_c^{'} + \phi_{st}^2 \times f_{st}) - 26.1 \times 10^3 \quad (4)$$

$$51.0 \times 10^3 < (d^2 - \phi_{st}^2) \times f_c^{'} + \phi_{st}^2 \times f_{st} < 488.0 \times 10^3 \quad (5)$$

$$V_{joint} = \Sigma V_{ud} \quad (6)$$

where, V_{ud} is shear carried by each PBL (N), d is diameter of the PBL hole (mm), $ø_{st}$ is diameter of transverse reinforcement (mm), f'_c is compressive strength of concrete (MPa) and f_{st} is tensile strength of transverse reinforcement (MPa), t is thickness of PBL (mm), V_{joint} is shear capacity of joints (N), ∑ is number of PBLs.

The results of shear capacity from the experimental investigation and the obtained shear capacity by Eq. 4 are shown in Table 5. In all specimens, the shear capacity observed in the experiment became smaller than that obtained by Eq. 4. It is indicated that Eq. 4 overestimates the experimental results. This can be explained as the applicable range of the equation was determined for the normal concrete only. However, UFC with compressive strength over 100 MPa were used in this experiment. Moreover, the influences of thickness of PBL and prestressing stress on the connection were not considered in this equation. Consequently, in order to use for PBL with cast-in-place UFC connection, the modification of the appropriate equation should be made.

4. CONCLUSIONS

(1) By comparing shear capacity of connection with shear capacity of UFC segment, the results showed that the efficiently transferring of shear forces between UFC and concrete segments can be ensured.
(2) The contribution on shear resistance characteristics of PBL with cast-in-place UFC connection comes from, first, end-bearing resistance of UFC. Second is the dowel action of UFC in the hole of PBL together with shear resistance of transverse reinforcement in third term. The last contribution comes from the prestressing stress on the connection part.
(3) From comparisons of the calculation results from JSCE equation with the experimental observations, the calculation values were overestimated in all cases. This is because the effect of thickness of PBL does not take into account in this equation and the applicable range was determined for the normal concrete only.

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