

## **FORMWORK DEVELOPMENT USING UHPFRC**

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### **Abstract**

This study investigates the structural performance of RC-UHPFRC composite slab structures to develop the permanent formwork system using UHPFRC. The flexure and bond performance are main interests for the composite behaviour of the slab structures. According to the preliminary test result in this study, the bond performance of the structure is deteriorated when using the heat treated UHPFRC plate for permanent formworks. The structural experiments are planned considering the result of preliminary test. Total eight specimens without heat treatments are made to evaluate the flexural performance of the composite structures. The main parameters of the experiments are the location and ratio of steel reinforcements. The experimental results show that the differences of reinforcement ratio between concrete and UHPFRC sections influence on both the failure mode (flexure or bond) and the post-peak behaviour of the composite structures.

### **Résumé**

Cette étude concerne les performances de dalles composites Béton Armés / BFUP, dans le but de développer des solutions de coffrage perdu. La résistance à la flexion et la tenue des liaisons sont les principaux points analysés. D'après les essais préliminaires conduits dans la présente étude, la liaison est détériorée lorsque les plaques en PFUP sont soumises à une cure thermique. Des essais supplémentaires sont prévus du fait des résultats de ces essais. Les éprouvettes sans cure thermique servent à analyser le comportement en flexion des structures composites BA/BFUP. Les principaux paramètres sont la localisation et le nombre de barres d'armature. Les résultats expérimentaux montrent que ces différences influent à la fois sur le mode de ruine et sur le comportement après rupture initiale.

## 1. INTRODUCTION

The Ultra High Performance Fibre Reinforced Concrete (UHPFRC) has provided new opportunities to advanced design technology of new concrete construction together with conventional concrete because of its outstanding mechanical properties. However, from the economic point of view it is necessary to overcome its high cost by finding new applications different from conventional concrete construction. We may maximize the material superior mechanical properties for the hybrid construction with other high-strength material and development of thin plate structures, formworks, and retrofit techniques. This paper presents experimental observation of the flexural behaviour of ordinary concrete slab with UHPFRC thin plate layers to investigate the possible utilization of UHPFRC formworks and retrofit. The primary objective of this study is to examine the structural behaviour of thin UHPFRC formwork panels with various steel ratios and construction methods.

## 2. UHPFRC IN CONCRETE SLAB STRUCTURE

The Ultra High Performance Fibre Reinforced Concrete (UHPFRC) is one of dependable materials to produce a thin plate utilizing its outstanding mechanical performance. In combination with conventional concrete construction, one of the promising utilization of UHPFRC thin layer structures is to provide permanent formworks for ordinary concrete slabs. These formworks have some advantages. First, the structural performances of the slabs are improved by tensile strength and stiffness of the UHPFRC layers (Fig. 1). Thus, the deflection of slab can be controlled and the ultimate strength is improved, respectively. Second, this construction may reduce costs and construction periods by reducing work force in construction site without removing the formwork after curing.

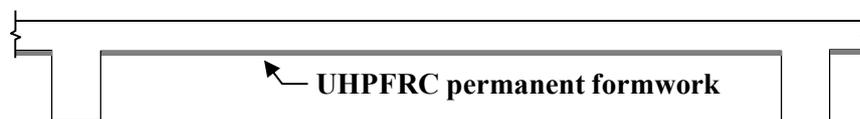


Figure 1 : UHPFRC Permanent formwork for RC slab

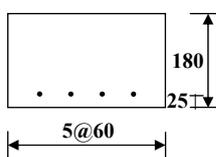
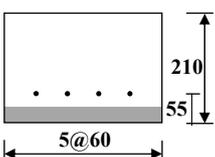
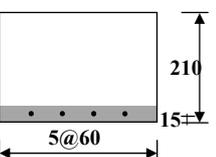
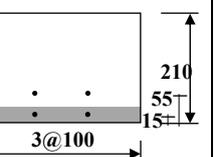
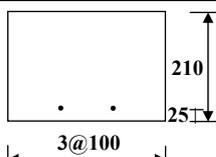
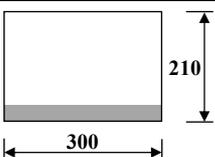
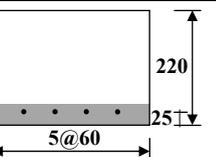
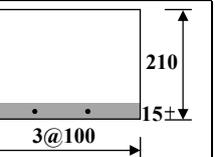
## 3. EXPERIMENTAL PROGRAM

The flexural behaviours of RC-UHPFRC composite beams are tested to investigate the structural performance of RC-UHPFRC composite slab system.

### 3.1 Test specimens and parameters

Total 8 beams are prepared for the experimental program. Two beams of them are RC beams and the other 6 beams are RC-UHPFRC composite beams. The dimensions and sizes of beam sections were determined by the prototype slab of typical residential buildings. The parameters and sections of the specimens are listed in Table. 1. The main parameters are the location and the ratio of steel reinforcements. The denotations of specimens in the table indicate the location and ratio of the rebar, for example the specimen C2U2 means that 2-D10 rebar reinforced in the concrete section and 2-D10 rebar reinforced in the UHPFRC layer. The thickness of the UFPFRC layers is 30mm except the specimen C0U4'. The specimen C0U4' is prepared for 10mm thicker than the specimen C0U4 to investigate the influence on stiffness of the UHPFRC layer.

Table 1. Beam sections and parameters

Specimen	C4	C4U0	C0U4	C2U2
Cross section				
a/d	4.84	3.85	3.85	3.85
Rebar	Concrete	4-D10	-	2-D10
	UHPFRC	-	4-D10	2-D10
Specimen	C2	C0U0	C0U4'	C0U2
Cross section				
a/d	4.05	3.85	3.85	3.85
Rebar	Concrete	2-D10	-	-
	UHPFRC	-	-	2-D10

### 3.2 Material properties

The mechanical properties of materials in this study are tested in the laboratory. The commercial ready-mixed concrete with the maximum aggregate size of 25 mm is used for the experimental program. The average compressive strength of the concrete is 18 MPa, which is lower than the concrete used for normal RC slab structures (24 MPa). However, the reinforcement ratio of the specimens is between 0.25 % and 0.62 %, which is slightly less or more than the minimum reinforcement ratio (0.3%) and adequately less than the balance reinforcement ratio (1.57 %). Thus, unless the bond failure occurs in the interface between concrete and UHPFRC, the tension controlled failures are expected in this experimental program in spite of the low concrete strength. The UHPFRC was made in the laboratory. The mix proportion and material properties of the UHPFRC are listed in Table 2 and Table 3, respectively. The properties of the steel reinforcements and steel fiber are listed in Table 4.

Table 2. Mix proportion of UHPFRC (weight ratio)

Cement	Silica fume	Quartz sand	Silica flour	Water	Super-plasticizer	Steel fiber*	W/C	W/B
1	0.25	1.1	0.35	0.22	0.03	2%	0.22	0.176

\* Volumetric ratio of UHPFRC

Table 3. Material performance of UHPFRC

Heat treatment	$f'_{u,c}$ (MPa)	$E_u$ (GPa)	$\sigma_{eq}$ (MPa)	Slump flow (mm)
Yes*	180	46	60	700±50
No**	143	43	45	

\* Temperature 80±2 °C, R.H 95±5% for 48 hours

\*\* Temperature 20±2 °C, R.H 60±5%

Table 4. Properties of rebar and steel fiber

Reinforcement steel (ribbed bar)			Steel fiber*			
$D_s$ (mm)	$f_y$ (MPa)	$f_u$ (MPa)	$f_{y,f}$ (MPa)	$L_f$ (mm)	$D_f$ (mm)	$L_f/d_f$
10	465	600	2,500	13	0.2	65

\* Data from manufacturer

### 3.3 Bond efficiency between UHPFRC and ordinary concrete

The preliminary tests were performed to investigate the bond performance between ordinary concrete and UHPFRC. The benefits in structural performance of RC-UHPFRC composite structures are made sure when UHPFRC is perfectly bonded on the concrete surface, if not, UHPFRC cannot show the better performance to the external loading.

Two types of specimens were prepared considering the general curing methods of UHPFRC. The hardened properties of the specimens are different according to the curing methods, as shown in Table 3. The specimen with heat treatments shows the final strength within 3 or 4 days after casting. The specimen without heat treatments, on the other hands, shows the final strength at 91 days after casting or later. Figure 2 (a) shows the general day-compressive strength relationship of the UHPFRC used in this study.

Ready-mixed concrete was casted on the UHPFRC layer after 3 days from the casting day of UHPFRC. After 28 days, the flexural beam test was conducted. The dimension and test method are described in Figure 2 (b).

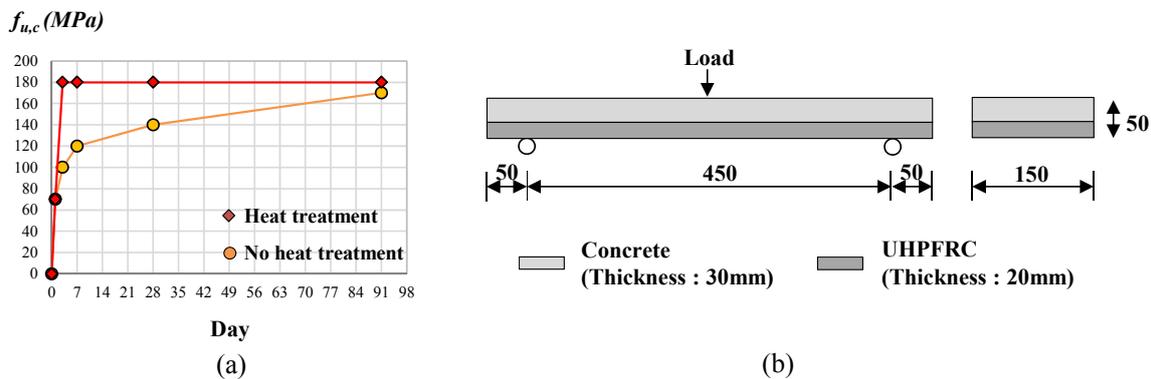


Figure 2. Day-compressive strength relationship of UHPFRC (a), and specimen dimension for bond performance between concrete and UHPFRC (b)

Figure 3 shows the load-deflection relationships and crack patterns of test specimens. In spite of the higher strength and stiffness (Table 3), it is observed the flexural performance of the specimen with heat treatments is not better than the specimen without heat treatment. High strength and stiffness of UHPFRC does not assure the high performance of the composite structures because the risk of bond failure between the concrete beam and UHPFRC layers increases when the stiffness between two cementitious materials is not compatible. Besides, the non-heat-treated UHPFRC harden steadily (Figure 2), i.e., the hydration reaction, closely linked to the development of compressive strength (Kamen, A., 2006), is progressed steadily. This fact has an advantage in bond performance of concrete-UHPFRC composite structures. When the fresh concrete is placed on the UHPFRC layer before the end of hydration reaction, the hydration reaction is progressed on the interface between two materials.

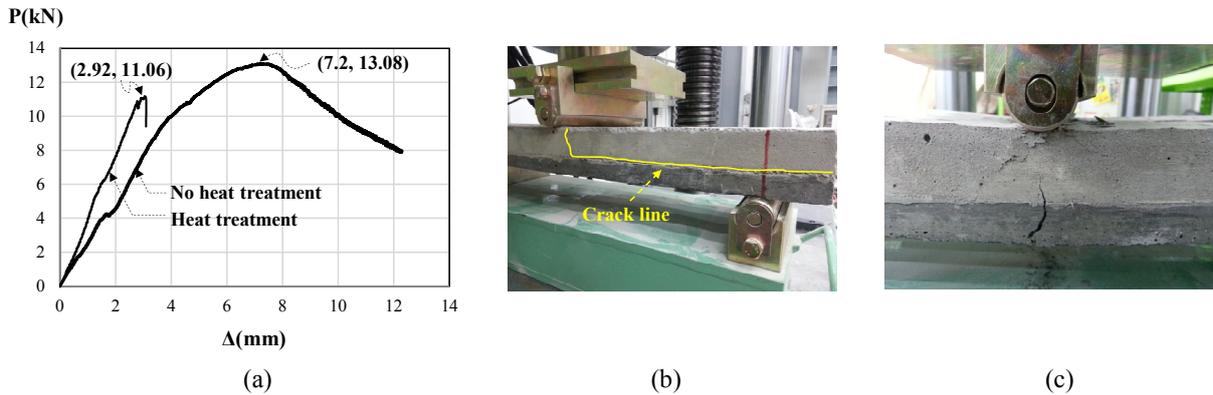


Figure 3. Result of preliminary test: (a) P- $\Delta$  relationship, (b) Failure of specimen with heat treatment, and (c) without heat treatment

Figure 4 shows the interface between concrete and UHPFRC. It can be seen that the surface of non-heat treated specimen is rougher than that of heat treated one. Thus, it is concluded that it is possible to improve the bond performance of the UHPFRC permanent formwork system by curing at room temperature and casting concrete at the initial curing period of UHPFRC.

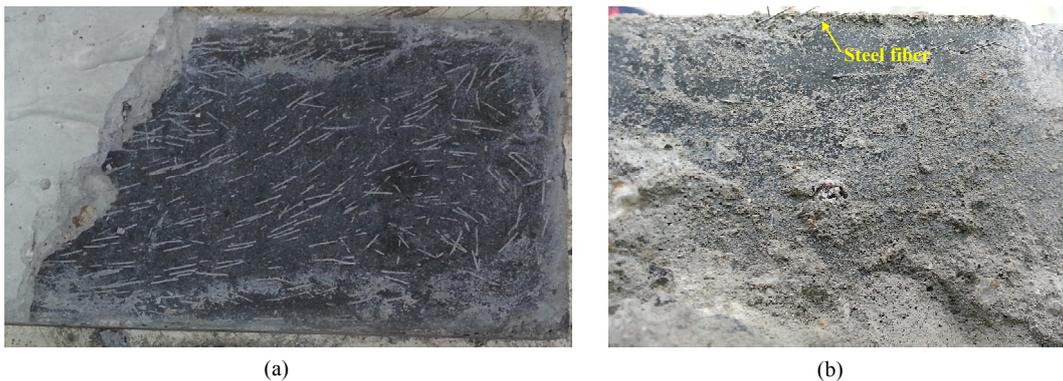


Figure 4. Interface between concrete and UHPFRC after test:  
 (a) with heat treatment, (b) without heat treatment

### 3.4 Fabrication of test specimens

The UHPFRC plates were made before casting the concrete. According to the results of the preliminary test, the concrete is poured at the initial stage of hydration reaction of UHPFRC to improve the bond performance. If the concrete is poured at the end of hydration reaction (after 91 days) or after heat treatment of UHPFRC, the brittle bond failure is obviously expected in the composite specimens. In this case, additional mechanical reinforcement is necessary to prevent the bond failure. Thus, when applying the non-heat-treated UHPFRC formworks in construction sites, additional mechanical reinforcement may be needed when the concrete is poured after initial period of the hydration reaction (about 7 days).

In this experimental program, the mould for UHPFRC plate was sloped at the start and then flattened at the end of the casting to keep the direction of the steel fiber (Figure 5). Two days later without heat treatment, the ordinary ready-mixed concrete was poured on the

UHPFRC plate. Then, RC-UHPFRC specimens were cured in a constant temperature and humidity room for another 28 days. The temperature and relative humidity in the room were set at  $20\pm 2^\circ\text{C}$ , R.H  $60\pm 5\%$  during all stages of this experimental program.

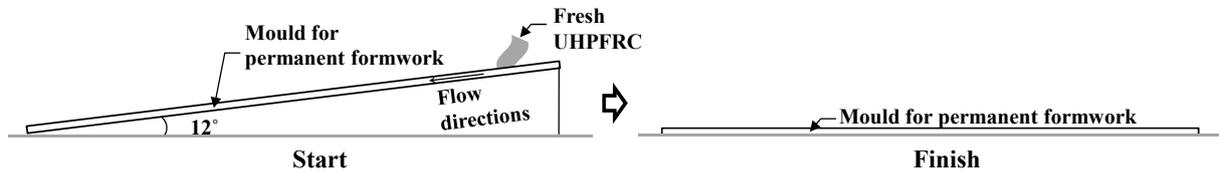


Figure 5. Pouring method of UHPFRC

### 3.5 Test setup and procedure

The test setup is prepared as shown in Figure 6. Four point bending tests were planned to investigate the flexural performance of the UHPFRC permanent formwork system. The displacement was increased at a speed of 1 mm/min. by hydraulic actuator. The load and deflection were measured by a load cell located between the actuator and the loading plate, and three LVDTs installed under the specimen, respectively. The strains in concrete and rebar were also measured by concrete gauges attached on the side of each specimen and steel gauges attached on the surface of each rebar, respectively.

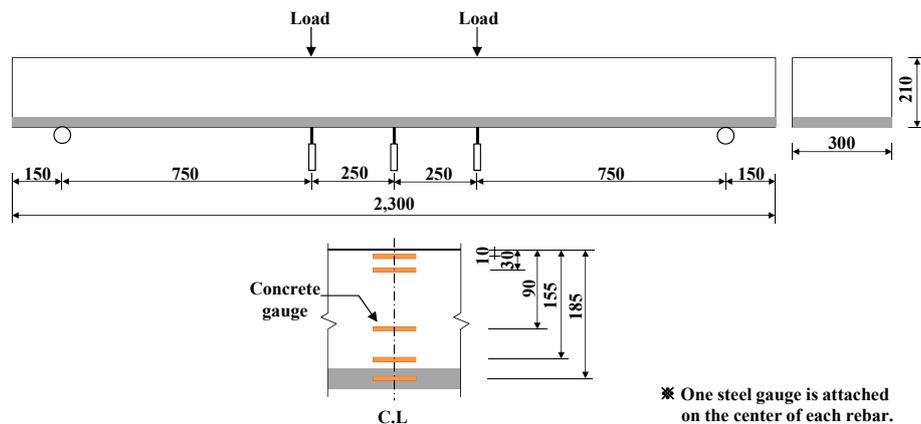


Figure 6. Test setup and instrumentation of typical specimen

## 4. EXPERIMENTAL RESULT DISCUSSION

### 4.1 Crack patterns and failure modes

Figure 7 shows the crack pattern of the specimens at the end of the test. Two RC specimens (C2 and C4) show several flexural cracks between two loading points. However, flexural cracks are localized in RC-UHPFRC composite specimens (C2U2, C4U0, C0U0 and C0U2). One large crack is formed from micro cracks in the UHPFRC layer. Then, the localized cracks are propagated from the interface between RC and UHPFRC to the top of the specimen because cracked interfaces are weak compared with other parts (uncracked section) of the specimen. In particular, the localized crack formed in the interface is spread when rebar is placed in the concrete section (C2U2 and C4U0). In the case of composite specimens without reinforcement in the concrete section (C0U0 and C0U2), one crack propagates

vertically regardless of steel reinforcement in UHPFRC section. The specimen C0U0 reinforced just 30mm of the UHPFRC, shows a brittle flexural failure.

The composite specimens with 4-D10 rebar in the UHPFRC section and without reinforcement in the concrete section (C0U4 and C0U4') are showed brittle bond-failure. Near the peak load, a part of concrete suddenly slipped through the upper surface of UHPFRC.

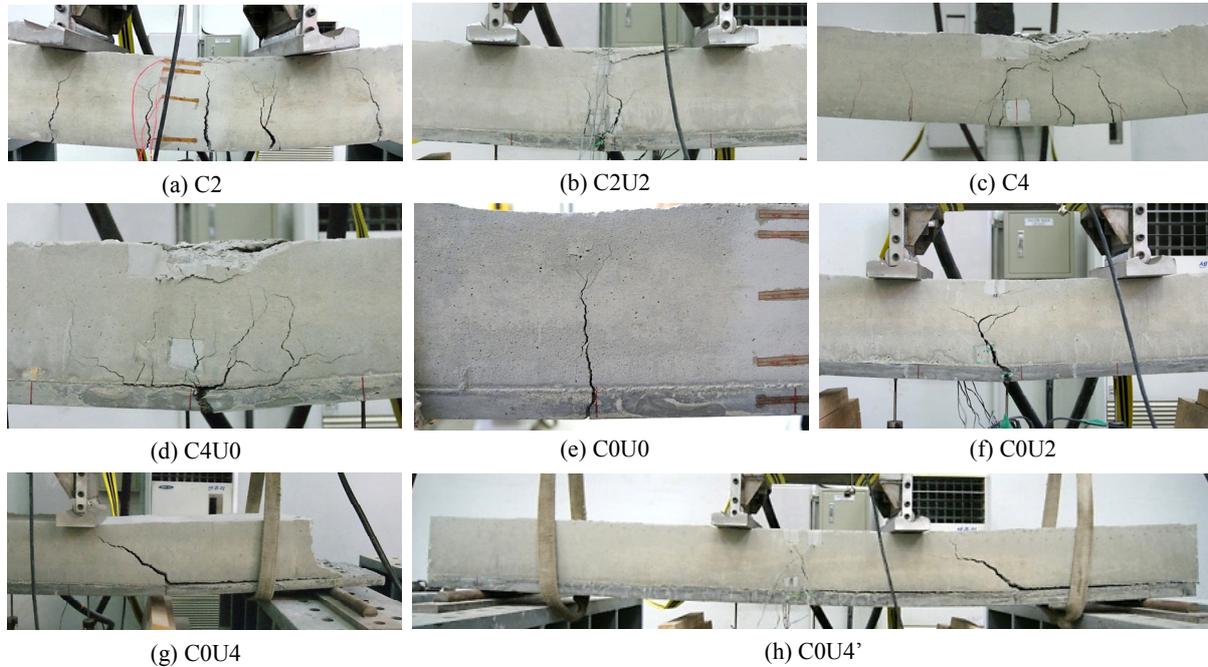


Figure 7. Crack pattern at ultimate state

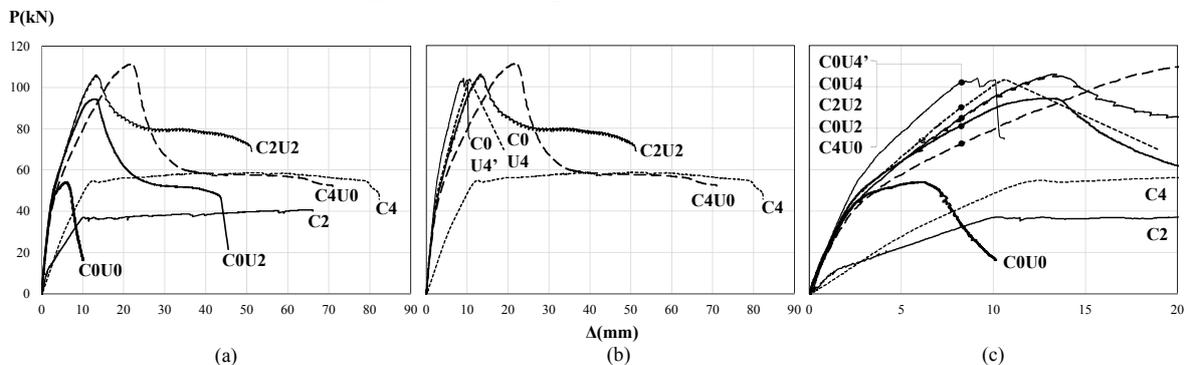


Figure 8. Load-midspan deflection relationship: (a) flexure failure, (b) specimens with 4-D10 rebar, (c) stiffness of specimens

#### 4.2 Load-deflection relationship and stiffness

Figure 8 shows the load-mid span deflection relationships of 8 different specimens. Compared with two RC specimens (C2 and C4), the load of all concrete-UHPFRC composite specimens increased sharply in the pre-peak state. However, the load of the composite specimens sharply dropped immediately after the peak load. Two composite specimens with no reinforcement in concrete section and 4-D10 rebar in UHPFRC section (C0U4 and C0U4'), show the brittle bond failure even before the macro cracks are developed in UHPFRC as well

as the rebar yields. In spite of no reinforcement in concrete section, the specimen C0U2 showed flexural failure and the load dropped slowly than C0U4 and C0U4', after tensile strength is reached in UHPFRC and rebar yields. This specimen has the residual resistances to the load after the failure of UHPFRC because the rebar resist the load until the fracture. The composite specimen without any reinforcements (C0U0) lost its load resistance capacity due to the failure of UHPFRC. The maximum load of this specimen is 35% higher than that of the RC specimen C2. However, no residual resistance is expected when tension rebar is neglected in a concrete-UHPFRC composite structure. The results of the test are summarized in Table 5.

Table 5. Summary of test results

Specimen	Steel yielding		Peak load					Ultimate state	Failure mode
	$P_y$ (kN)	$\Delta_y$ (mm)	$P_{max}$ (kN)	$\Delta_{pmax}$ (mm)	$\epsilon_s$	$\epsilon_c$	$\epsilon_u$		
C4	54.8	12.3	58.6	38.6	$\epsilon_s > \epsilon_v$	$\epsilon_c < \epsilon_o$	-	Rebar fracture	Flexure
C4U0	102.2	16.4	111.2(1.90 <sup>*</sup> )	21.5	$\epsilon_s > \epsilon_v$	$\epsilon_o < \epsilon_c < \epsilon_{cu}$	$\epsilon_u > \epsilon_{u,t}$	Concrete crushing	Flexure
C0U4	-	-	103.5(1.77 <sup>*</sup> )	10.6	$\epsilon_s = \epsilon_v$	$\epsilon_c < \epsilon_o$	$\epsilon_u < \epsilon_{u,t}$	Slip of interface	Debonding
C0U4'	-	-	103.3(1.76 <sup>*</sup> )	10.1	$\epsilon_s < \epsilon_v$	$\epsilon_c < \epsilon_o$	$\epsilon_u < \epsilon_{u,t}$	Slip of interface	Debonding
C2U2	104.4	12.7	106.1(1.81 <sup>*</sup> )	13.1	$\epsilon_s > \epsilon_v$	$\epsilon_c < \epsilon_o$	$\epsilon_u = \epsilon_{u,t}$	Rebar fracture	Flexure
C2	36.8	9.9	40	66	$\epsilon_s > \epsilon_v$	$\epsilon_c < \epsilon_o$	-	Rebar fracture	Flexure
C0U0	-	-	54(1.35 <sup>**</sup> )	6.3	-	$\epsilon_c < \epsilon_o$	$\epsilon_u = \epsilon_{u,t}$	UHPFRC fracture	Flexure
C0U2	90.47	10.23	94.3(2.36 <sup>**</sup> )	12.4	$\epsilon_s > \epsilon_v$	$\epsilon_c < \epsilon_o$	$\epsilon_u > \epsilon_{u,t}$	Rebar fracture	Flexure

\* Peak load ratio to specimen C4

\*\* Peak load ratio to specimen C2

Table 6. Reinforcement ratio and stiffness

Specimen		C4	C4U0	C0U4	C2U2	C2	C0U0	C0U2	C0U4'
$\rho_s$ (%)	in concrete	0.62	0.52	-	0.25	0.26	-	-	-
	in UHPFRC	-	-	0.5	0.25	-	-	0.25	0.5
$h_u$ (mm)		-	30	30	30	-	30	30	40
$\rho_u$ (%)		-	0.29	0.29	0.29	-	0.29	0.29	0.36
$K_e$ (kN/mm)		5.55	19.39	23.01	20.15	8.41	21.62	24.94	22.76
$K_h$ (kN/mm)		4.56	5.06	7.34	6.93	3.14	1.98	6.06	7.66

In the composite specimens, two specimens (C4U0 and C2U2) show the best structural performance. These specimens satisfy the conditions that rebar is reinforced in the beam section and the reinforcement ratio of concrete section is no less than that of UHPFRC section. These conditions are related to the failure mode of the composite beams subjected to bending. For example, C0U4 and C0U4' showed the brittle bond failure because the ratio of  $\rho_s$  in UHPFRC to  $\rho_s$  in concrete is high compared with the Specimen, C4U0. This ratio is related to the difference between stiffness of concrete section and UHPFRC layer. The reinforcement ratio and stiffness of the specimen is listed in Table 6.

The specimen C4U0 presented the highest peak load among all specimens. After cracking in UHPFRC, several cracks are developed in concrete section due to the local bond failure near the localized crack in UHPFRC layer, which lead to the reduction of flexural stiffness. The load of this specimen increases until the peak load, and post-peak behaviour begins due

to the failure of the UHPFRC layer. After the failure of UHPFRC, the specimen behaves like the RC specimen C4. There was no residual resistance in UHPFRC layer of the specimen C4U0 because the layer had no steel reinforcement. The specimen C2U2, on the other hands, showed the residual resistance to the load after the failure of UHPFRC layer because the rebar in the layer resists load even after yielding. In the pre-peak stage of this specimen, relatively small number of cracks was observed compared with the specimen C4U0, reinforced 4-D10 rebar in the concrete section. Compared with other composite specimens, the structural performance of C2U2 is excellent because not only the reduction of the stiffness was relatively less in the pre-peak stage, but also the degradation of load resistance capacity is slow in the post-peak stage.

## 5. CONCLUSIONS

The permanent formworks using UHPFRC have advantages of reduction in construction period and cost. However, the structural performance of the RC-UHPFRC composite structures is necessary to check prior to practical use. This study investigates the flexural performance of the composite concrete slab structures with UHPFRC. The following conclusions are reached.

In the preliminary test, the heat treated UHPFRC and concrete composite beam showed the brittle bond failure, while the non-heat treated composite beam showed the typical flexural failure. Thus the heat treatment of UHPFRC deteriorates the bond efficiency of the composite structures. The peak load is increased when the RC specimens is strengthened with UHPFRC layer. The brittle bond failure happened in the specimens, reinforced 4-D10 rebar in the UHPFRC layer and no rebar in the concrete section.

In the RC-UHPFRC composite specimens, the peak load is reached at the maximum tensile stress in UHPFRC and yielding of rebar. However, the load decreases immediately after the peak load because the fracture of UHPFRC is earlier than that of rebar. In the composite specimen without any rebar, the fracture of UHPFRC layer leads to the failure of the specimen. The specimens reinforced rebar just in concrete section behave like RC specimens after the peak load because UHPFRC layer loss its load resistance capacity after the failure of UHPFRC. The specimen reinforced rebar in both the concrete and the UHPFRC, shows the residual resistance to the load after the peak load because rebar in UHPFRC resists load despite the failure of UHPFRC.

It is possible to control the failure mode and post-peak behaviour of RC-UHPFRC composite structures subjected to bending by reinforcing rebar in concrete and UHPFRC properly. No more reinforcement ratio is allowed in the UHPFRC section than the concrete section according to the result of this study.

This research program focuses on the bond performance, ductile behaviour, fire resistance capacity and economic reinforcement detail of the composite slab structures. The next step of the program is to find the available period of non-heat treated UHPFRC formwork without mechanical reinforcement for bond performance. The main variables are the time interval between casting days of concrete and UHPFRC. Then, rational mechanical reinforcement and cross section are determined to prevent the brittle bond failures for the both heat treated and non-heat treated formwork. Finally, the fire resistance capacity of the formwork is evaluated to prevent the spalling and strength degradation of the structures during fires.

## NOTATIONS

- $a/d$  = shear span to depth ratio  
 $D_s$  = diameter of rebar  
 $D_f$  = diameter of steel fiber  
 $E_u$  = elastic modulus of UHPFRC  
 $f_{u,c}$  = compressive stress of UHPFRC  
 $f'_{u,c}$  = compressive strength of UHPFRC  
 $f_y$  = yield strength of rebar  
 $f_{y,f}$  = tensile strength of steel fiber  
 $f_u$  = ultimate strength of rebar  
 $h_u$  = thickness of UHPFRC  
 $K_e$  = initial stiffness of beam (uncracked stage)  
 $K_h$  = hardening stiffness of beam (cracked stage before peak load)  
 $L_f$  = length of steel fiber  
 $P$  = load  
 $P_y$  = load when reinforcements yields  
 $P_{max}$  = Peak load  
 $V_f$  = Volumetric ratio of fiber in UHPFRC  
 $\Delta$  = mid span deflection  
 $\Delta_y$  = mid span deflection at  $P_y$   
 $\Delta_{pmax}$  = mid span deflection at  $P_{max}$   
 $\epsilon_c$  = strain of concrete  
 $\epsilon_{cu}$  = ultimate strain of concrete  
 $\epsilon_o$  = strain of concrete at maximum stress  
 $\epsilon_s$  = tensile strain of steel  
 $\epsilon_u$  = tensile strain of UHPFRC  
 $\epsilon_{u,t}$  = tensile strain of UHPFRC at maximum stress  
 $\epsilon_y$  = strain of steel at yield stress  
 $\sigma_{eq}$  = equivalent tensile strength of UHPFRC,  $\sigma_{eq} = 3P_{max}L / 2bh^2$   
 $\rho_s$  = reinforcement ratio  
 $\rho_u$  = equivalent reinforcement ratio of UHPFRC,  $\rho_u = (\text{section area of UHPFRC}) \times (V_f)$

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