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Effect of Permanent Formwork using Ultra-High Performance Concrete on Structural Behaviour of Reinforced Concrete Beam Subjected to Bending as a Function of Reinforcement Parameter

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Abstract

In order to use ultra-high performance concrete (UHPC) as a permanent formworks for a reinforced concrete (RC) slab in a construction field, the structural performance of the RC-UHPC composite beams subjected to bending are experimentally investigated. The main parameters are the rebar location and the UHPC thickness. The experimental results show that the crack patterns of the composite specimen is different compared to the reference RC specimen, because of the crack localization phenomenon of UHPC. Within the post peak state of the load-deflection relationship, the composite specimen behaves similar to the RC specimen. However, the reinforcement of deformed bars in the UHPC section shows a synergy effect on structural performance; both load and deformation capacity is significantly increased. Nevertheless, it is required to reinforce the bars in normal concrete section for preventing debonding failure as well as for retaining the load resisting capacity at the post peak state. The best structural performance of the composite specimen is found when the reinforcement ratios are the same in the both normal concrete and UHPC sections. The results of this study help to apply and design the thin UHPC panel as a permanent formwork for retrofitting existing structures.

Keywords: Ultra-High Performance Concrete (UHPC); Permanent formwork; Composite beam

Introduction

Ultra-High Performance Concrete (UHPC) has outstanding mechanical properties (e.g., compressive strength>150 MPa) and durability, compared with conventional concrete [1,2]. This has provided new opportunities to develop new concrete technology. However, the unit cost of this material is very high [2,3]; thus, it should be carefully considered for the use of this material in practice. Utilizing a thin UHPC layer as a permanent formwork (Figure 1) for concrete slab or deck is a promising and effective method because it can improve structural performance (e.g., as crack-resisting capacity, reduction of deflection), durability and watertightness. As a first step, it is necessary to investigate the structural performance of a composite beam which is composed of thin UHPC and normal concrete. Therefore, this study experimentally investigated the flexural behaviour of the composite beam by varying reinforcing steel parameters: location and thickness of UHPC layer. In particular the significance of the location of the rebar (deformed bar) was discussed.

Experimental Procedure

Materials properties and mix proportions

The UHPC was prepared according to the mix proportion listed in Table 1 [4,5]. By using a pan type mixer, ordinary Portland cement type I, undensified silica fume, quartz sand and silica flour were firstly blended for 10 min, and then water and superplasticizer were added into the powder and mixed. Lastly, steel fiber was added and mixed for another 3 min. Once the mixing was finished, the slump flow was measured according to ASTM C1611 [6]. The slump flow value was determined as 700 ± 50 mm. Based on the ASTM C39 [7], the compressive strength was measured as 143 MPa at 28d. The specimen was cured under ambient curing condition of temperature of 20 ± 2°C and R.H of 60 ± 5% [8,9]. A commercial ready-mix concrete with the maximum aggregate size of 25 mm was used for the composite beam which was intended for a concrete slab production. The compressive strength of the concrete was 18 MPa, which was measured at 28d. As a main experimental parameter, deformed bar was used. Its diameter, yield strength and ultimate strength are 10 mm, 465 MPa and 600 MPa, respectively. The location and reinforce ratio are different per each specimen.

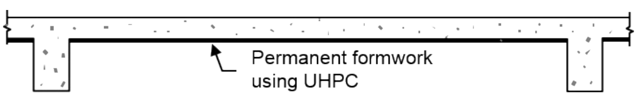

Figure 1: Example of permanent form-work using UHPC for RC slab.

Test parameters

Total eight beams were prepared for the experiment. They are composed of two reinforced concrete beams and six composite beams as presented in Table 2. The dimensions were determined based on typical concrete slabs in residential buildings. As mentioned in the Section 1, the main parameters were set as the reinforcement ratio, location of rebar and UHPC thickness. The specimen names in Table 2 indicate the parameters. For instance, NC4+UC0 indicate that 4-D10 deformed bars are reinforced in the NC section of the specimen, but no bars are reinforced in the UHPC section. Basically, all UHPC sections were designed as thin as possible; thus, the thickness was determined

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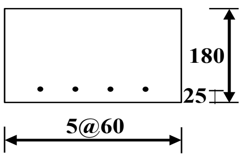
Cement	Silica fume	Quartz sand	Silica flour	Water	Super-plasticizer	Steel fiber*
1	0.25	1.1	0.35	0.22	0.03	2%
* Volumetric ratio of UHPC						

Table 1: Mix proportion of ultra-high performance concrete (by wt% of cement).

<table>
<tr><th colspan="2">Specimen</th><th>NC4</th><th>NC4+UC0</th><th>NC0+UC4</th><th>NC2+UC2</th></tr>
<tr><td colspan="2">Cross section</td>
<td>
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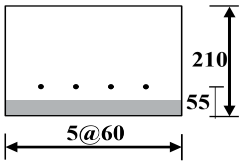
<td>
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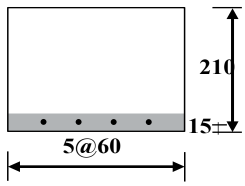
<td>
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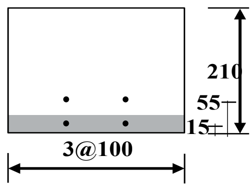
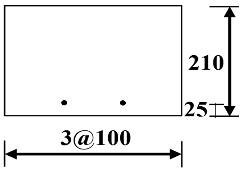
<td>
</td></tr>
<tr><td colspan="2">Sher span to depth ratio</td><td>4.84</td><td>3.85</td><td>3.85</td><td>3.85</td></tr>
<tr><td rowspan="2">Rebar in</td><td>Normal concrete</td><td>4-D10</td><td>4-D10</td><td>-</td><td>2-D10</td></tr>
<tr><td>UHPC</td><td>-</td><td>-</td><td>4-D10</td><td>2-D10</td></tr>
<tr><th colspan="2">Specimen</th><th>NC2</th><th>NC0+UC0</th><th>NC0+UC4*</th><th>NC0+UC2</th></tr>
<tr><td colspan="2">Cross section</td>
<td>
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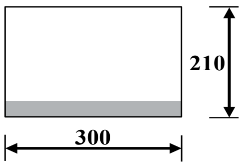
<td>
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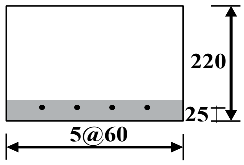
<td>
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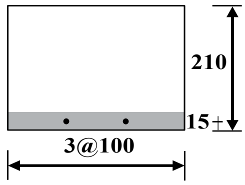
<td>
</td></tr>
<tr><td colspan="2">Sher span to depth ratio</td><td>4.05</td><td>3.85</td><td>3.85</td><td>3.85</td></tr>
<tr><td rowspan="2">Rebar in</td><td>Normal concrete</td><td>2-D10</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>UHPC</td><td>-</td><td>-</td><td>2-D10</td><td>4-D10</td></tr>
</table>

Table 2: Beam sections and parameters.

as 30 mm, considering the 10 mm of cover thickness of the UHPC layer. However, one specimen, NC0+UC4*, has 10 mm thicker UHPC section than NC0+UC4, to investigate the effect of the stiffness of the UHPC on the structural performance. All specimens were designed to show the tension control failures. In other words, the reinforcement ratios of the specimens are ranged between 0.25% and 0.62%, which are safely lower than the balance reinforcement ratio of 1.57%.

Fabrication of RC-UHPC composite specimen

To fabricate the composite specimen, thin UHPC panel was firstly prepared, and then normal concrete (NC) was casted on the panel after 2 days. All specimens were cured under ambient temperature of 20 ± 2°C and R.H of 60 ± 5%. It is common practice to apply heat treatment for precast UHPC production. However, in this study, heat was not applied because of the deterioration in the bond strength between the two different concretes and reflecting more realistic condition of retrofit application. Specifically, we conducted the preliminary test to investigate the effect of the heat treatment of the UHPC on the flexural behaviour of the composite beam (150 mm × 50 mm × 550 mm size). One of two UHPC panels (20 mm-thickness) was exposed to 80°C for 48 hrs (28 d compressive strength: 180 MPa), but the other one was cured at the ambient condition without the heat treatment. As shown in Figure 2, the 3-point bending test revealed that the brittle debonding failure occurred in the specimen only when the UHPC panel subjected to heat treatment before overlaid by NC. This is because the cement hydration reaction had almost terminated after the heat treatment, which makes impossible to gain chemical bond strength for a composite action.

Regarding structural performance of UHPC, fiber orientation in UHPC panel is a crucial factor [10]. To align their direction with the panel especially middle part of the specimen, fresh UHPC was firstly poured on the one sloped end of the mould; then, the mould filled with fresh UHPC was flatted and lastly the UHPC was flatten (Figure 3). At 2nd day, NC was cast on the UHPC panel and the composite specimens were cured until the test day.

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Test program

The test setup is presented in Figure 4. By using a hydraulic actuator (maximum capacity of 500 kN), displacement was controlled (1 mm/min) for static 4-point bending test. The load and deflection that are pointed at the Figure 4 were measured by load cells and linear variable differential transformers (LVDTs), respectively. In addition, the strains of concrete and rebar were measured by the attached strain gauges (orange lines).

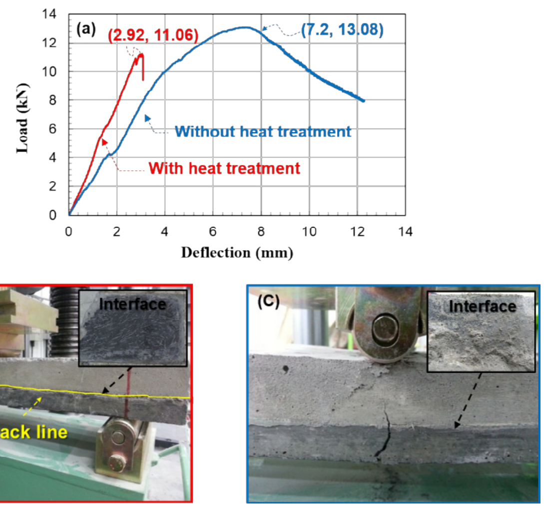

Figure 2: Effect of heat treatment of thin UHPC panel on flexural behaviour of NC-UHPC composite beam.

Results

Crack pattern and failure mode

Figure 5 shows the cracked specimens at the end of the test. Above of all, there are several flexural cracks in NC specimens between the loading points (Figures 5a and 5c). Moreover, these flexural cracks were localized in the composite specimens (NC2+UC2, NC4+UC0) as shown in Figures 5b and 5d. In other words, if the UC2 (or UC0) is used for the permanent formwork and NC2 (or NC4) is casted on to the formwork, crack pattern will be changed compared to a traditional formwork which has to be removed. This change can be explained by the crack localization phenomenon of the permanent UHPC panel, which was observed in this experiment. Multiple micro cracks simultaneously occurred in the UHPC that was subjected to tensile stress due to the loading; finally, one single crack expanded and the UHPC panel was detached. The detached both sides of panels retain straight shape, but the RC maintained curved shaped. After that, it was observed that the contribution of the panel to the structural performance was disappeared. As a result, the behaviour of the composite beams should be changed to that of RC beams. Thus, the localized crack was changed to several flexural cracks. These flexural cracks in the composite beam

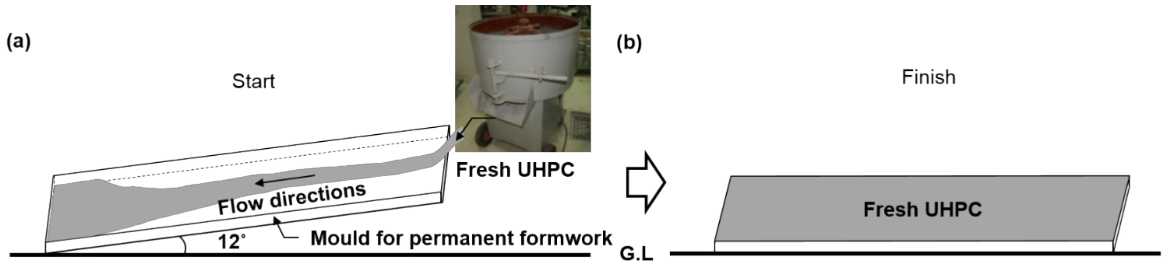

Figure 3: Preparation of thin UHPC permanent formwork considering uniform fiber orientation (i.e., horizontal direction to the surface).

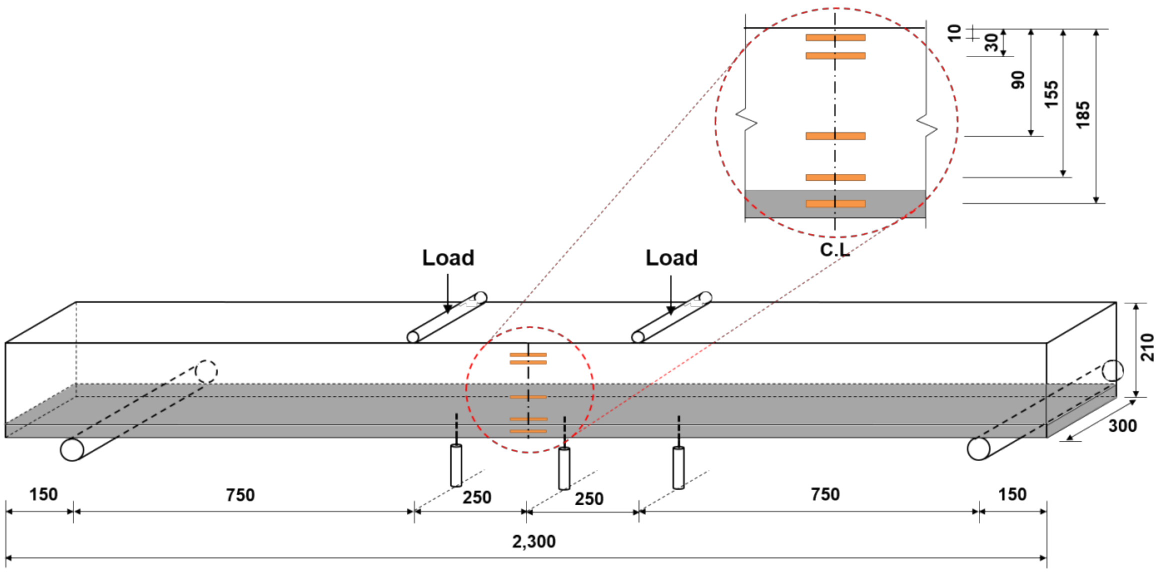

Figure 4: Setup for 4-point bending test.

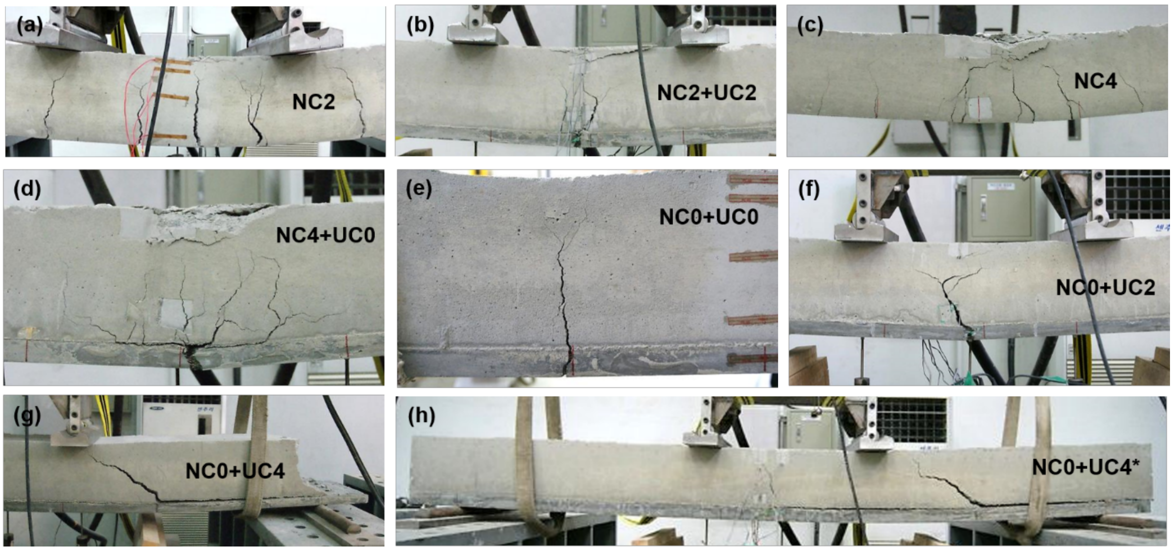

Figure 5: Cracked specimens after test.

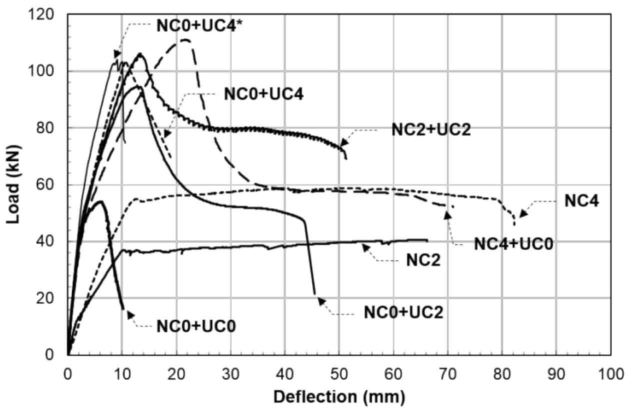

Figure 6: Load-midspan deflection relationship.

occurred when rebar was reinforced. On the other hand, brittle flexural failure occurred in other case as shown in Figures 5e and 5f.

On the other hand, two composite specimens which have 4-D10 deformed bars in UHPC section showed brittle debonding failure (Figures 5g and 5h); the upper part of the interface between NC and UHPC was suddenly detached and slipped.

Load-deflection relationship

The relationships between load and mid-span deflection are presented in Figure 6. Within the pre peak state, the load-deflection curve of the composite specimens sharply increased than that of RC specimens. This indicates significantly increased initial stiffness due to the contribution of the UHPC. However, the increased load in the composite specimen steadily drop again after once peak load reached; the decrease rate depended on the location of rebar and thickness of the UHPC section.

Table 3 summarizes the test results including the data and information obtained from load cell, LVDT and strain gauges. The peak load of the specimen NC0+UC0 was 35% higher than that of NC2. Although this composite specimen showed pseudo strain hardening behaviour by the fiber bridging action in the UHPC panel, the specimen suddenly collapsed. In other word, since all UHPC section was cracked after peak load, the entire load resistance capacity disappeared without leaving residual resistance. This brittle failure was also observed during the tests of NC0+UC4 and NC0+UC4*, in which deformed bars were reinforced. In these specimens, the debonding failure which was explained in Section 3.1 occurred even before the macro cracks were developed in a concrete and the bars yielded. Moreover, increasing the thickness of UHPC by 10 mm accelerated the debonding failure (compare NC0+UC4 and NC0+UC4*). Rather, reducing reinforcement ratio by 50% led to certainly better result in this case, i.e., the specimen NC0+UC2 showed ductile flexural failure, and UHPC and rebar reached their tensile strength. After the failure of UHPC, the specimen still had the residual resistance due to the embedded rebar.

Among the eight specimens, the best performance regarding both the load and deformation capacity was shown in NC4+UC0 and NC2+UC2. They satisfied the condition that rebar is reinforced in the NC section and its reinforcement ratio is higher than the UHPC section. The specimen NC4+UC0 marked the highest peak load among the all specimens. However, after the peak load its behaviour was almost identical to that of NC4 due to the failure of UHPC. On the other hands, NC2+UC2 retained residual load resistance after the peak load, which can be apparent by comparing with NC2. Especially, the structural performance of NC2+UC2 is outstanding in both pre and post peak load in terms of the initial stiffness as well as the residual load resistance.

Discussion

Figure 7 explains the effect of each parameter of this study on the structural behavior of the composite beam. By reinforcing small portion of rebar (close to the minimum reinforcement ratio of concrete slab) in the UHPC section, the structural performance of the beam was significantly increased in terms of both the load and deformation capacity (Figure 7a). These remarkable increases were possible due to the intensified tension stiffening effect in the UHPC section which was caused by the fiber bridging action [11]. Thus, it is reasonable to use

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Specimen	At rebar yield		At peak load					Failure mode	Note
	P_y (kN)	Δ_y (mm)	P_{max} (kN)	Δ_{pmax} (mm)	ε_s	ε_c	ε_u		
NC4	55	12.3	59	37	$\varepsilon_s>\varepsilon_y$	$\varepsilon_c<\varepsilon_o$	-	Flexure	Rebar fracture
NC4+UC0	102	16.4	111	22	$\varepsilon_s>\varepsilon_y$	$\varepsilon_o<\varepsilon_c<\varepsilon_{cu}$	$\varepsilon_u>\varepsilon_{u,t}$	Flexure	Concrete crushing
NC0+UC4	-	-	104	11	$\varepsilon_s=\varepsilon_y$	$\varepsilon_c<\varepsilon_o$	$\varepsilon_u<\varepsilon_{u,t}$	Debonding	Slip of interface
NC0+U4C'	-	-	103	10	$\varepsilon_s<\varepsilon_y$	$\varepsilon_c<\varepsilon_o$	$\varepsilon_u<\varepsilon_{u,t}$	Debonding	Slip of interface
NC2+UC2	104	12.7	106	13	$\varepsilon_s>\varepsilon_y$	$\varepsilon_c<\varepsilon_o$	$\varepsilon_u=\varepsilon_{u,t}$	Flexure	Rebar fracture
NC2	37	9.9	40	66	$\varepsilon_s>\varepsilon_y$	$\varepsilon_c<\varepsilon_o$	-	Flexure	Rebar fracture
NC0+UC0	-	-	54	6	-	$\varepsilon_c<\varepsilon_o$	$\varepsilon_u=\varepsilon_{u,t}$	Flexure	UHPFRC fracture
NC0+UC2	90	10.23	94	12	$\varepsilon_s>\varepsilon_y$	$\varepsilon_c<\varepsilon_o$	$\varepsilon_u>\varepsilon_{u,t}$	Flexure	Rebar fracture

P_y = Load when reinforcements yields.
P_{max} = Peak load.
Δ_y = Mid span deflection at P_y
Δ_{pmax} = Mid span deflection at $P_{max.}$
ε_c = Strain of concrete.
ε_{cu} = Ultimate strain of concrete.
ε_o = Strain of concrete at maximum stress.
ε_s = Tensile strain of steel.
ε_u = Tensile strain of UHPC.
$\varepsilon_{u,t}$ = Tensile strain of UHPC at maximum stress.
ε_y = Strain of steel at yield stress.

Table 3: Summary of test results.

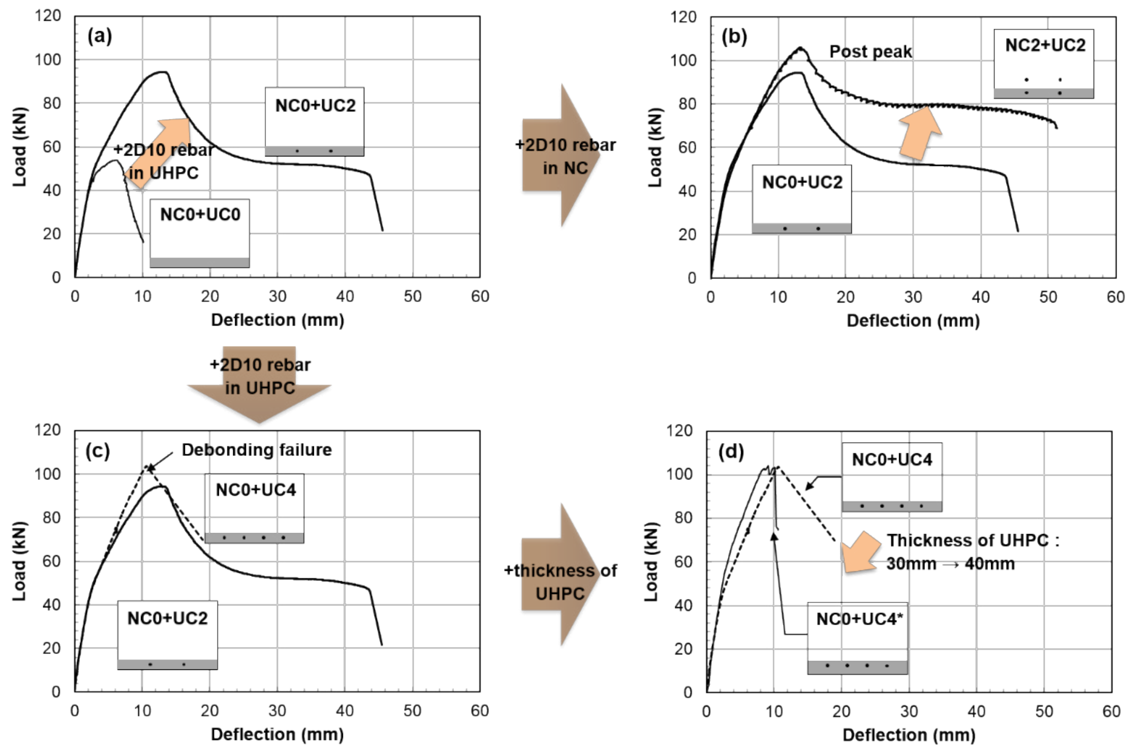

Figure 7: Structural behavior of tested composite beams.

deformed bars for structural UHPC, because of the intensified tension stiffening effect as well as fiber bridging action.

When the same ratio of rebar was additionally reinforced in the concrete section, the post peak load was maintained highly (Figure 7b). Thus, it is recommended to use additional rebar in concrete section for structural safety. In addition, it is interesting to note that the fibers in UHPC contributed to increase of the safety, because the teeth shape in the load-deflection curve can be formed when the fibers pull out from the matrix of UHPC while resisting against loading.

However, when the same rebar was additionally reinforced in the UHPC section, the failure mode was changed negatively (Figure 7c). As the gap of stiffness between NC and UHPC increased, relatively weak part of concrete suddenly failed. Figure 7d also evidently shows the same trend of the result. It reveals the importance of the balance in the stiffness when designing the permanent formwork of UHPC.

Conclusion

This study investigated the structural performance of the RC-UHPC composite beam subjected to bending, in order to utilize the

UHPC panel as a permanent formwork for concrete slab or deck. In particular, the load-deflection behavior of the beam was observed based on reinforcement ratio, location of rebar and thickness of UHPC.

The load resisting capacity of the RC beam could be significantly increased by using the UHPC permanent formwork. When rebar was not included in the UHPC section, the behavior of this composite beam was almost identical to that of the RC beam because the resisting capacity of UHPC disappeared after the peak load. The reinforcement of rebar in UHPC section can further increase the structural behavior because of the intensified tension stiffening effect. However, in this case, there is a prerequisite for the structural safety of balancing the stiffness between the two concretes. If not, the interfacial bond failure can occur. Therefore, the same reinforcement ratios of rebar in concrete and UHPC sections marked the best result in terms of both load and deformation capacity.

Acknowledgment

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