Evaluation for Punching Shear Strength of Slab-Column Connections with Ultra High Performance Fiber-Reinforced Concrete Overlay

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***Abstract*—**This paper presents the test results on 5 slab-column connection specimens with Ultra High Performance Fiber-Reinforced Concrete (UHPFRC) overlay including 1 control specimen to investigate retrofitting effect of UHPFRC overlay on the punching shear capacity. The test parameters were the thickness of the UHPFRC overlay and the amount of steel re-bars in it. All specimens failed in punching shear mode with abrupt failure aspect. The test results showed that by adding a thin layer of UHPFRC over the Reinforced Concrete (RC) substrates, considerable increases in global punching shear resistance up to 82% and structural rigidity were achieved. Furthermore, based on the cracking patterns the composite systems appeared to be governed by two failure modes: 1) diagonal shear failure in RC section and 2) debonding failure at the interface.

***Keywords*—**Punching shear strength, retrofit, slab-column connection, UHPFRC, UHPFRC overlay.

I. Introduction

THE flat plate system is subjected to the combination of locally high negative bending moments and shear forces around the columns, which increases the susceptibility of this zone to brittle punching shear failure [1], [3], [4], [6]. As can be seen in many collapse accidents, it may eventually lead to a hazardous progressive collapse of the entire structures, accompanied by a truncated cone above the column [5], [7], [8]. Additionally, many existing buildings constructed with flat plate systems are becoming obsolete. In this trend, it is significantly emphasized to investigate retrofitting the RC slab-column connections against punching shear failure.

To date, various methods have been proposed and used [6] for strengthening existing RC slab-column connections against punching shear failure; 1) enlargement of column section and slab thickness, or use of shear capital and drop panel, 2) post-installed shear reinforcement such as stirrups and shear bands, 3) pre-stressing, and 4) increasing of the amount of flexural reinforcement. This last method has been widely investigated to increase the punching shear resistance of deficient RC slab-column connections by attaching CFRP (Carbon Fiber-Reinforced Polymer), GFRP (Glass Fiber-Reinforced Polymer), and steel plate to the tensile surface. However, Much longer construction processes and a lot of labor have to be accompanied using the above mentioned methods. In addition, these methods are not capable of reducing permeability that causes corrosion of steel re-bars placed in RC section and cracking due to expansion [2]. Furthermore, the organic binder used for FRP attachment can significantly degrade the structural performance of the RC members through chemical reaction at the interface.

Alternatively, placing a thin layer of cementitious composite material on top surface of RC members can be the most efficient and practical method for field application among several retrofitting methods. However, in architectural point of view, the conventional NSC overlay method is actually inefficient. It is because not only several transverse reinforcements for shear connectors should be arranged in the enlarged section, which may cause additional damage to existing buildings, but also the existing buildings' self-weight considerably increases due to thick overlay thickness ranging from 100 mm to 500 mm to improve load carrying capacity of the slab-column connections. To resolve this problem, An innovative material comes to the fore: Ultra-High Performance Fiber-Reinforced Concrete (UHPFRC). Its high performance material properties can reduce the thickness of the retrofitting overlay, and be expected that the steel fibers mixed in the UHPFRC can play a significant role of the reinforcement.

To strengthen a RC slab-column connection with deficient resistance, it has been proposed to add on the surface a thin layer of UHPFRC with or without small diameter steel re-bars [9]. This technique modifies the slab into UHPFRC-RC composite slab. The UHPFRC overlay with steel re-bars acts as a two-dimensional tensile reinforcement and increases both bending and shear resistance of the system [2], [10]. The main purpose of this study, thus, is to evaluate the retrofitting effects of the UHPFRC overlay with or without steel re-bars on structural performance of UHPFRC-RC composite slab. Focus is placed on the behavior of RC slab-column connections without transverse reinforcement retrofitted by the UHPFRC overlay submitted to concentrated loading at center of column.

II. Test Program

A. Test Parameters and Details of Specimens

In order to evaluate the punching shear resistance of RC slab-column connections retrofitted by the UHPFRC overlay on the tension side, a series of punching shear test were planned by setting the UHPFRC overlay thickness (0 mm, 30 mm and 50 mm) and the steel reinforcement ratio (0, D10@180 mm and D10@90 mm) in the layer as test variables. Total of 5

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UHPFRC-RC composite slab-column connections without transverse reinforcement including 1 control specimen were fabricated as specified in Table I. The RC sections of all the specimens were casted with conventional NSC. Each RC substrate has a column as loading plate with a square cross section of 420 mm by 420 mm. The slab size is 2600 mm by 2600 mm with a total thickness of 150 mm, but the distance from the center of the column to each support was planned to be 1250 mm. Concrete cover was kept constant and equal to 20 mm for all specimens. All presented specimens had same orthogonal reinforcement layout and a standard longitudinal reinforcement ratio in RC section equal to 1.24% for tension steel reinforcement and 0.435% for compression side using 16 mm and 10 mm diameter re-bars equally spaced at 140 mm, respectively.

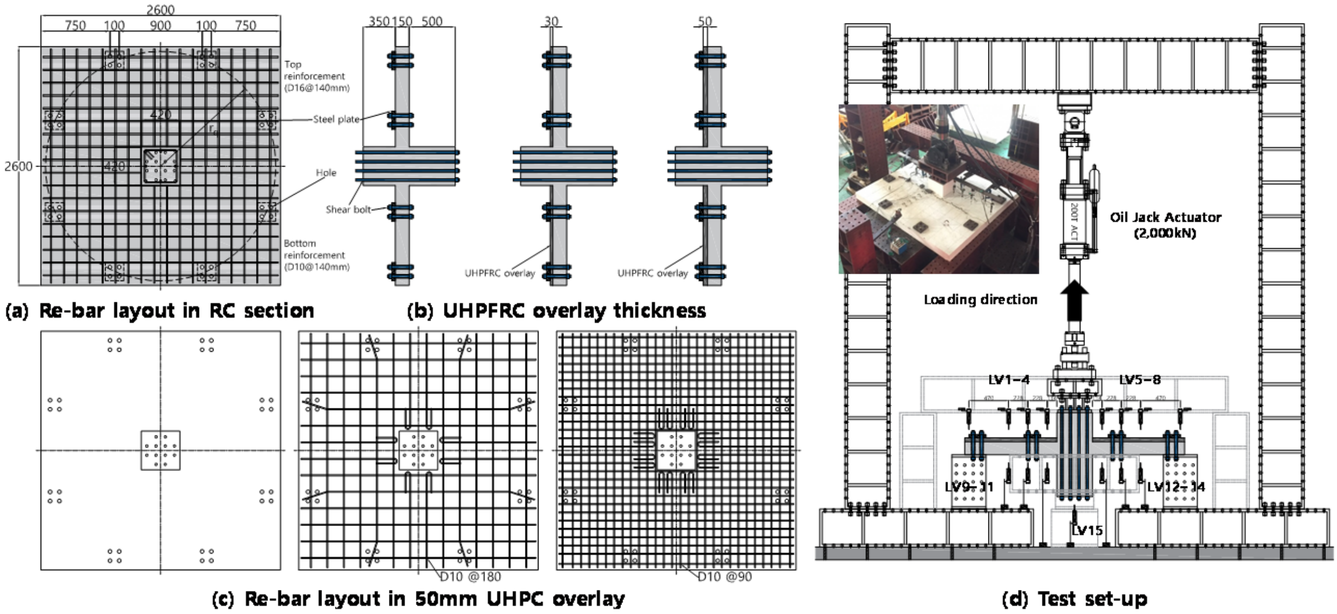

Fig. 1 Dimensions and reinforcement details of specimens (a), (b), (c) & Test setup (d)

TABLE I
DESIGN PARAMETERS OF TEST SPECIMENS

I.D.	Dimensions				Reinforcement			
					Steel in RC		Steel in UHPFRC	
	B (mm)	C (mm)	h_c (mm)	h_U (mm)	d_{sc} (mm)	ρ_{sc}	d_{sU} (mm)	ρ_{sU}
R				0			-	-
U30				30			-	-
U50	2600	420	150	50	114	1.24%	-	-
U50S				50			175	0.226%
U50L				50			175	0.452%

Note: B = side length of slab specimen, C = side length of column, h_c = thickness of RC section, h_U = thickness of UHPC overlay, d = effective depth from the extreme compression fiber to the centroid of tension steel re-bars, ρ = reinforcement ratio of tension steel re-bars.

It should be also notified that in the present study, since the basic concept of the retrofitting method using the UHPFRC overlay is to retrofit the existing RC structures rather than to newly design composite slabs consisting of Pre-Cast (PC) and Cast-In-Place (CIP) concrete structures, no dowel bars or shear connectors are considered whereas, the top surfaces of the RC substrates were roughened by means of sand-blasting method to adequately provide sufficient roughness and corresponding higher interfacial performance. In the present study, sand particles with size of 1.2~1.5 mm were sprayed using an engine type compressor with discharging pressure of about 0.88~0.98 MPa. According to worker, the surfaces were roughened by 0.5~1.0 mm as shown in Fig. 2. For appropriate load transfer at the interfaces, the sand-blasted surfaces were washed with water to prevent latency, and the UHPFRC was casted after removing residual dust on the surfaces by wind pressure. Since no additional shear connectors crosses the interface, shear transfer at the interface would be treated as relying solely on the concrete-to-UHPFRC interface's adhesion performance.

Fig. 2 Machine and comparison of surfaces before and after sand-blasting

To prevent segregation and sinking of the steel fiber attributed to the different density, no additional mechanical treatments such as vibrator were applied after pouring the UHPFRC. It also has to be mentioned that especially for the specimens with additional steel re-bars in the UHPFRC overlay with thickness of 50 mm, cover thickness of the UHPFRC overlay was planned to be 15 mm, which is smaller than that of ordinary RC slab structures. However, it is quite logical when considering the UHPFRC's homogeneous and tight material compositions.

B. Material Properties

Table II shows the material composition of normal strength concrete (NSC) with a nominal strength of 30 MPa used in fabricating the RC slab-column connections. The maximum aggregate size was 25 mm. Three cylinder type concrete specimens (100 mm x 200 mm) for each specimen were fabricated, and cured in the same conditions as that for the experimental specimens. A compressive strength test was manually conducted on the same day as the experiment date. The actual compressive strengths of NSC were measured based on the three cylinder coupon tests, mean values of which was measured to be about 41 MPa.

Three types of steel re-bars (SD400 D10, SD400 D16, and SD400 D22) were used for manufacturing the specimens. The mechanical properties of these re-bars were measured through direct tensile test of three coupon re-bars per each nominal size as summarized in Table III. The yield strengths were f_{sy} = 454MPa for SD400 D10, f_{sy} = 460MPa for SD400 D16, and f_{sy} = 544MPa for SD400 D22. The ultimate tensile strengths f_{su} were 584, 578, and 662 MPa, respectively.

TABLE II
MATERIAL COMPOSITION OF NSC

Nominal strength (MPa)	W/C (%)	Unit weight (kg/m^3)				
		W	C	S	G	A
30	43.1	169	392	825	952	2.74

Note: Maximum aggregate size = 25 mm, Slump = 120 mm.

TABLE III
MECHANICAL PROPERTIES OF STEEL RE-BARS

Steel grade	Type	f_{sy} (MPa)	ε_{sy}	f_{su} (MPa)	ε_{su}	E_s (GPa)
SD400	D10	454	0.00251	584	0.143	200
	D16	460	0.00233	578	0.248	200
	D22	544	0.00265	662	0.116	200

Note: D10 ($A_s = 71.26\,\text{mm}^2$); D16 ($A_s = 197.9\,\text{mm}^2$); D10 ($A_s = 387.9\,\text{mm}^2$).

TABLE IV
MATERIAL COMPOSITION OF UHPFRC

Nominal strength (MPa)	W/C (%)	Unit weight (kg/m^3)				
		W	P	F	SP	AE
180	0.2	197	1270	867	18.1	0.5

Note) P = premix binder = cement, Zr, Bs, filler, expansion agent, shrinkage reducing agent premix, F = fine aggregate, SP = super plasticizer, AE = air-entraining agent, Slump flow = 740 mm.

Table IV shows the material composition of UHPFRC with a nominal strength of 180 MPa used in fabricating the UHPFRC overlay on the tension side of the RC substrates. UHPFRC includes 2400 MPa high strength linear steel fibers with an aspect ratio, l_f / d_f = 13 mm/0.2 mm, in a volume of 2 % of the total mix volume. After curing period, the compressive and tensile strength tests were conducted as recommended in K-UHPC design guideline on the same day as experiment date. The actual compressive strength of UHPFRC was 196 MPa, and the actual tensile elastic strength and ultimate tensile strength were 7 MPa and 14.3 MPa, respectively.

C. Test Setup and Measurement Plans

Fig. 1 (d) shows the overall test setup used for the present study. A total of 12 shear bolts in size of diameter of 24 mm was installed at the bottom of an actuator with a capacity of 2000 kN and penetrated through the column of the test specimens and fixed to the lower part of the column. The specimens were designed to be fully fixed at 8 points equally spaced around circumference with radius of 1250 mm from the center of the column by steel plates. Each steel plate was fixed to the instrumented jig setting by tightening with four 24 mm diameter shear bolts.

The experiments were performed by applying a concentrated monotonic load to the column base, pulling up the column to the upward direction using the actuator. The direct punching load was applied until the test specimens reached their peak load. The tests were processed by displacement control at constant rate, 2 mm/min.

Linear Variable Displacement Transducers (LVDT) at top and bottom surfaces and concrete strain gauges at the bottom surface were installed to manually measure the displacement, slab rotation and strains at determined points. Steel strain gauges also were installed at tension steel re-bars in RC section before casting the concrete. During the test, variation of force, displacement at center and supports, and concrete and steel strains were automatically measured. In addition, for these test specimens, self-weight and weight of the test setup were deducted from the measured load.

III. TEST RESULTS

A. Cracking Pattern and Failure Mode

Fig. 3 shows the cracking pattern at top surfaces and cut sections adjacent to the column faces. Due to tangential bending efforts, many longitudinal micro-cracks were generated in the UHPFRC overlay, which tend to be more predominant as the reinforcement ratio in the UHPFRC overlay becomes increased (Figs. 3 (c)-(e)). In addition, the inclined diagonal shear cracks propagated from the RC section near the column turned out not to penetrate the UHPFRC overlay during the test. Therefore, the punching cone shaped cracks on the surface of the UHPFRC overlay can hardly be distinguished with naked eyes.

Based on the test results, two governing failure modes resulting from failure of each load transfer mechanism were observed at cut sections; (1) diagonal shear failure due to inclined shear cracks in the RC section, and (2) debonding failure at the interface due to NIC (Fig. 3 (f)). Although which load transfer mechanism dominantly acted is not determined, the two governing failure modes were recognized as major failure mechanisms of the composite slabs.

At cut sections, angle of the diagonal shear cracks tend to be

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smaller when retrofitted by the UHPFRC overlay in comparison with that of the control specimen R. In other words, the tip of the diagonal shear cracks generated in the RC section gets slightly farther away as retrofitted by the UHPFRC overlay. Thus, in the present study, the length from the column face to the tip of the diagonal shear cracks was estimated to be larger than twice the effective flexural depth ($2d_{sc}$) based on the observed cracking patterns.

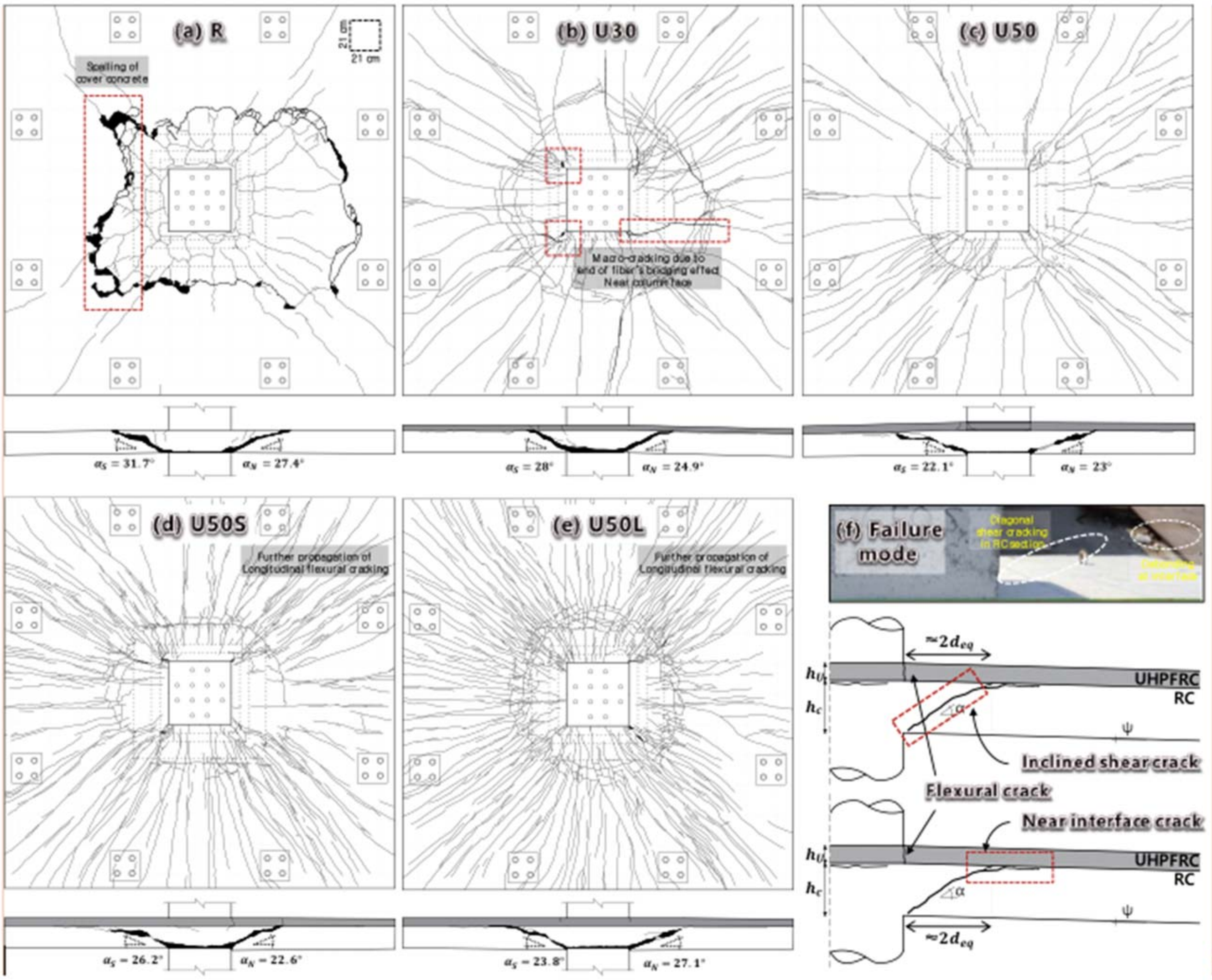

Fig. 3 Cracking pattern at top tensile surfaces and cut sections

B. Load-Displacement Relationship

Fig. 4 shows altogether the load-displacement relationships of the test specimens. On the basis of comparison of the load-displacement behaviors, it can be concluded that the layer of UHPFRC significantly increased the flexural rigidity of a RC slab and provided additional punching shear resistance to the RC slab-column connection. An overview of the main test results are summarized in Table V.

For the control specimen R, stiffness deterioration was observed at around 126 kN due to the initial longitudinal flexural cracks, and an almost proportional relation between displacement and shear force was then maintained before it reached its maximum load. At around 500 kN, one of the longitudinal reinforcing bar in the RC section located at d_{sc} from the column face has reached the yield strain ε_{sy} , but without big difference in the load-displacement behavior. After reaching its maximum shear force at around 644 kN, the conical shaped concrete cover at the top surface was spalled out by punching shear, causing subsequent substantial strength deterioration. Thus, the measured maximum load V_u was determined by flexure-shear failure mode.

For all retrofitted specimens, consistently, stiffness deterioration was observed at around 200~270 kN due to the initial longitudinal flexural cracks, and then an almost proportional relation between displacement and axial load was maintained before it reached its maximum load. In addition, no reinforcing bars experienced yielding for all retrofitted

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specimens, which indicates that the measured maximum loads V_u are determined by punching shear failure, causing subsequent substantial strength deterioration. When the retrofitted specimens reached their maximum load carrying capacity, in contrast to the control specimen R, the bridging effect of the embedded short fibers in the overlay prevented the concrete cover from being spalled out, which was distinguished as an another advantage of the retrofitting method.

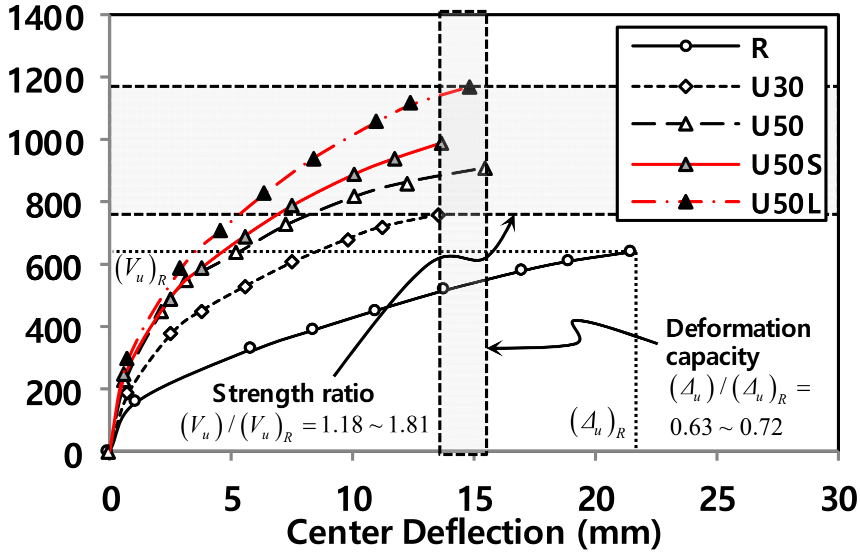

Fig. 4 Load-displacement relationship

Regarding to the deformability, the deformation capacity of the retrofitted slab-column connections turned out to be maintained above a certain level even though the retrofitting level increased, which is unmatched with the conventional sense. To identify this trend of the structural behavior of the UHPFRC-RC composite slab, cracking patterns, strains and thickness variations adjacent to the slab-column connection should be investigated.

TABLE V
EXPERIMENTAL TEST RESULTS

I.D.	Failure mode	Inclined shear crack (°)	Load stage (mm, kN)					
			At initial cracking		At ultimate		At failure	
			Δ_{cr}	V_{cr}	Δ_u	V_u	$\Delta_{failure}$	$V_{failure}$
R	FS	29.6	0.785	126.1	21.64	644.4	21.98	636.1
U30	S/DB	26.5	0.867	200.7	13.63	758.4	14.18	707.7
U50	S/DB	22.6	0.713	235.4	15.57	908.9	16.53	855.1
U50S	S/DB	24.4	0.638	259.4	13.7	984.5	14.53	879.1
U50L	S/DB	25.5	0.675	278.2	14.86	1170.6	15.21	1157

Note: FS=Flexural shear failure, S=Shear failure, DB=Debonding at the top of the diagonal shear crack. V_{flex} is the calculated flexural strength based on yield line theory. α_N and α_S are the measured diagonal shear crack angle from north and south direction, and α is the average value of α_N and α_S. V_{cr}, V_u and $V_{failure}$ are the initial cracking strength, the ultimate strength and the strength at failure, respectively. Δ_{cr}, Δ_u and $\Delta_{failure}$ are the measured displacement at center of the column corresponding to each strength.

IV. Discussion of Test Results

A. Effects of Test Parameters

By increasing the thickness of the UHPFRC overlay from 30 mm to 50 mm, the punching shear resistance of the UHPFRC-RC composite slab increases at least 22% for specimen U30 with 30 mm UHPFRC overlay and up to 41% for specimen U50 with 50 mm UHPFRC overlay. This confirms that the UHPFRC overlay directly contributes to improving the global punching shear resistance by acting as a two-dimensional reinforcement.

In comparison of the test results of U50, U50S and U50L, the use of steel re-bars in the UHPFRC overlay has a significant influence on the maximum shear resistance and deformation capacity of the UHPFRC-RC composite slab. These experimental results are quite different from that of previous research performed by Bastien-Masse and Brühwiler [2]. In the research, the use of steel re-bars in the UHPFRC overlay did not have a significant influence on the maximum resistance and deformation of the composite slab. This experimental result directly implies that the load transfer mechanism of the UHPFRC-RC composite slab should be re-considered from a slightly different point of view from the previous study.

B. Deformation Capacity

The deformation capacity of the retrofitted specimens turned out to be maintained above a certain level even though the retrofitting level increased, which is unmatched with the conventional sense. Considering the cracking pattern, the out-of-plane bending in the UHPFRC overlay probably allows the RC section to deform further, leading to comparatively larger deformation and crack opening of the RC section. This implies the additional contribution of the UHPFR overlay to the total punching shear resistance.

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V. CONCLUSION

To verify the contribution of the UHPFRC overlay to global punching shear resistance of the UHPFRC-RC composite slab, five slab-column connections with varying UHPFRC thickness with or without steel re-bars in it were tested under displacement controlled concentric loading. The major findings of this report are summarized as follows.

1) By adding a thin layer of UHPFRC, the normalized punching shear resistance increases at least 22% for 30 mm UHPFRC overlay and up to 82% for 50 mm UHPFRC overlay with steel in it. This confirms that the UHPFRC overlay acts as two-dimensional reinforcement.
2) The use of steel re-bars in the UHPFRC overlay has a significant influence on the resistance and deformation of the composite slabs, which is different outcome from that of previous research performed by Bastien-Masse and Brühwiler [2]. These experimental results directly imply that the load transfer mechanism of the UHPFRC-RC composite slab should be reconsidered from a slightly different point of view compared to the previous study.
3) Due to bending efforts, many longitudinal flexural cracking occurred in the UHPFRC overlay, which tended to be more predominant as the thickness and reinforcement ratio of the layer become increased.
4) At cut sections, angle of the diagonal shear cracks tend to be smaller when retrofitted by the UHPFRC overlay in comparison with that of the reference slab. In other words, the tip of the diagonal shear cracks get farther away as retrofitted by the UHPFRC overlay. Thus, in the present study, the length from the column face to the tip of the cracks was estimated to be larger than twice the flexural depth d_{sc} .
5) The deformation capacity of the retrofitted specimens turned out to be maintained above a certain level even though the retrofitting level increased, which is unmatched with the conventional sense.

REFERENCES

[1] ACI Committee 318. (2011). Building Code Requirements for Structural Concrete (ACI 318-11) and Commentary (pp. 503). Farmington Hill, MI: American Concrete Institute.
[2] Bastien-Masse, M., and Brühwiler, E. (2016). Experimental investigation on punching resistance of R-UHPFRC-RC composite slabs. *Materials and Structures*, 49(5), 1573-1590.
[3] British Standards Institution. (2004). Eurocode 2: Design of Concrete Structures – Part 1-1: General Rules and Rules for Building (pp. 225). Bruxelles, Belgium: European Standard EN-1992-1-1: 2004:E, European Committee for Standardization.
[4] Japan Society of Civil Engineers. (2010). Standard Specifications for Concrete Structures-2007 'Design' (pp. 469). Tokyo, Japan: Japan Society of Civil Engineers.
[5] Kinnunen, S., and Nylander, H. (1960). *Punching of concrete slabs without shear reinforcement* (p.112). Elander
[6] Korea Concrete Institute. (2012). Korean Structural Design Code (KCI 2012) (pp. 342). Seoul, Korea. (in Korean).
[7] Muttoni, A. (2008). Punching shear strength of reinforced concrete slabs without transverse reinforcement. *ACI structural Journal*, 105(EPFL-ARTICLE-116123), 440-450.
[8] Muttoni, A., and Schwartz, J. (1991). Behavior of beams and punching in slabs without shear reinforcement. In *IABSE colloquium* (Vol. 62, No. EPFL-CONF-111612, pp. 703-708). IABSE Colloquium.
[9] Noshiravani, T., and Brühwiler, E. (2013). Experimental investigation on reinforced ultra-high performance fiber-reinforced concrete composite beams subjected to combined bending and shear. *ACI Structural Journal, 110*(2), 251.
[10] Wuest, J (2007) *Comportement structural des bétons de fibres ultra performants en traction dans des éléments composes* (Doctoral dissertation, Ecole Polytechnique Fédérale de Lausanne). (in French)

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