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Punching Shear Strength of UHPC Slabs Dependent on Design Variables

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ABSTRACT

Case study on previous paper which investigated punching shear strength of UHPC slabs is presented. 4 design variables are chosen to analyze the effects of each variable to the punching shear strength(V_R); slab thickness(h), loading column dimension(c), steel fiber volume ratio(V_f) and reinforcement ratio(ρ). The effects of each varying parameter are studied by comparing all tested results. In conclusion, slab thickness and loading column dimension result in positive effects on increasing punching shear strength. However, in case of increasing the steel fiber and re-bar volume ratio, no outstanding phenomenon, even decrease in punching shear strength occurred.

1. INTRODUCTION

Ultra-High Performance Concrete(UHPC) is a new material which has higher mechanical properties and lower permeability than ordinary concrete. And thanks to their exclusive properties, effectively innovative design can be realized by using UHPC with lower material consumption. Nowadays, UHPC has been used to rehabilitate and retrofit existing structures. Among many methods to retrofit existing structures especially for slabs or decks, it is widely known that reinforced(R-) UHPC overlay method is one of the most popular and effective method. However in such cases, punching shear failure is usually the governing failure mode. Such failures can occur without noticeable warning, which can lead to significant damages to a structure or even collapse. So, it is strongly required to pay attention to punching shear strength of UHPC slabs. In this paper, aspect of punching shear strength of UHPC slab depending on the design variables will be checked by case study.

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2. DESIGN VARIABLES

There are a lot of variables which already have been experimentally proved to be related to the punching shear strength of UHPC slab. Variables mainly considered in many previous studies can be classified under 3 heads, which correspond to concrete matrix, steel fiber and reinforcement steel bar, respectively. Actually UHPC consists of these 3 things and therefore variables with respect to those have larger impact on the punching shear strength of UHPC slab than other things. Fig. 1 shows composition of UHPC and variables for each component.

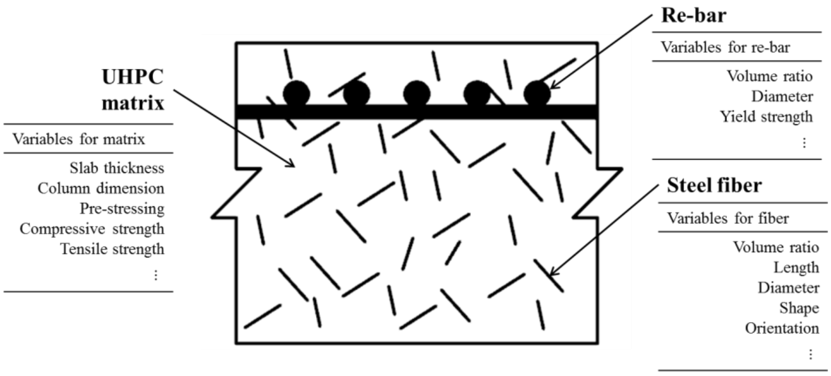

Fig. 1 Composition of R-UHPC and variables for each component

The higher total number of test results exist, the more accurate case study can be performed. So, it does make sense to take dominant variables into account for confirming and summarizing contribution to the punching shear strength of UHPC slab. As a result, for UHPC matrix, slab thickness and loading column dimension are selected, which is directly related to effective depth and control perimeter. Control perimeter means critical shear perimeter, and is assumed to be located at a distance $\mathrm{d_{eff}}/2$ from the column faces according to the ACI 318M-11 Code provisions. Fig. 2 shows control perimeter criteria for rectangular and circular column.

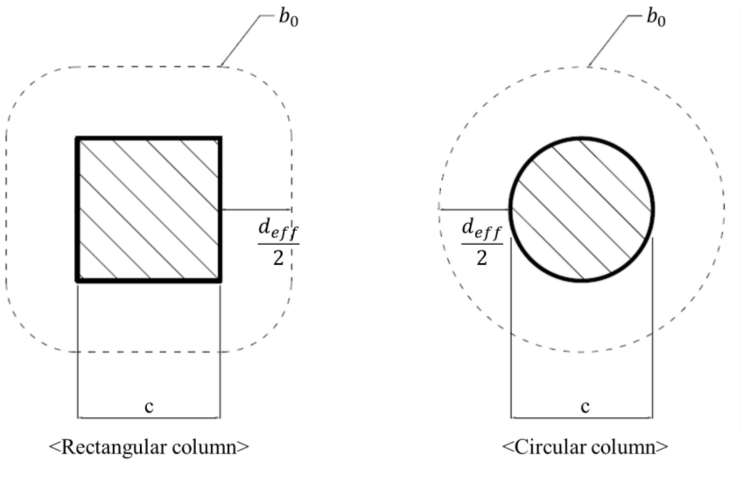

Fig. 2 Control perimeter(b_0) criteria depending on column shape

Additionally, volume ratio for reinforcement and steel fiber are also selected. Even though other options such as length, diameter and orientation of re-bar and fiber are considerably influential as well, only volume ratio would be treated in this case study. Variables and corresponding symbols to be used are summarized in Table. 1.

Table. 1 Design variables and corresponding symbols

Type	Variables	Symbols
UHPC matrix	Thickness	h
	Loading column dimension	c
Reinforcement steel	Volume ratio	ρ
Steel fiber	Volume ratio	V_f

3. CASE STUDY

UHPC slab test results done by previous researchers were checked. In order to verify tendencies of each design variable's effect, punching shear strength versus 4 design variables graphs will be plotted. Exactly, two terms about punching shear strength would be taken into account, which is equal to V_R and $\frac{V_R}{b_0 d_{eff}\sqrt{f_c}}$. The reason why the second term is additionally used is that the term is widely applied form to analyze structural behavior of UHPC about punching shear. Furthermore, when comparing the several results related to the re-bar and fiber volume ratio, other unnecessary effect due to the variation of thickness and column dimension could be ignored. Therefore, V_R values for slab thickness and loading column dimension, $\frac{V_R}{b_0 d_{eff}\sqrt{f_c}}$ values for re-bar and fiber volume ratio will be checked.

3.1 Results by Hussein Abbas Azzez Al-Quraishi(2014)

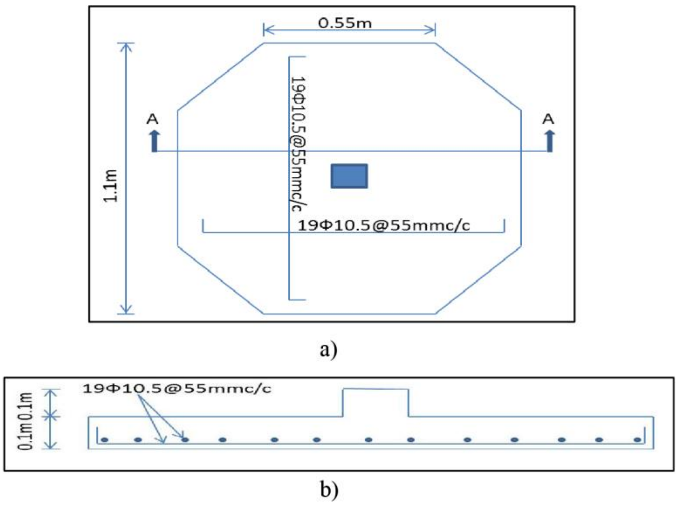

Fig 3. UHPC slab and section geometry (by Hussein A.)

Fig. 3 shows geometry of tested specimens. Hussein tested 7 UHPC slabs in total. All tested slabs had an octagonal shape with 550mm long sides. The slabs were simply supported along four edges and had a square shaped loading column. And steel fibers which have a length of 20mm, diameter of 0.25mm, aspect ratio of 80 were used. The variables chosen were compressive strength, re-bar yield strength, re-bar and fiber volume ratio. 5 slabs of all are selected to be investigated because only the latter two variables are involved in this study, which were tested with 5 UHPC slabs. Table. 2 shows UHPC test specimen's properties.

Table. 2 UHPC slab test dimensions and results (by Hussein A.)

Specimen	V_f (%)	ρ (%)	f_c (MPa)	h (mm)	d_{eff} (mm)	b_0 (mm)	c (mm)	V_{Rtest} (kN)
G1Ufib0	0	2	198.5	100	80	651.3	100	210.6
G1Ufib0.5	0.5	2	198.9	100	80	651.3	100	268.6
G1Ufib1.1	1.1	2	208.2	100	80	651.3	100	384.5
G3Uρ1%	0.5	1	198.9	100	80	651.3	100	248
G4Ut55	0.5	2	199.2	55	44	538.2	100	124

As shown in the Table. 2, main variables are fiber volume ratio and re-bar volume ratio. In fact, G1Ufib1.1 specimen has a little bit different compressive strength from other specimens. However, because same materials, proportion and mixing skills were used, this can be just attributed to the higher fiber volume ratio. Fig. 4 shows the relationship between fiber volume ratio and re-bar volume ratio and load.

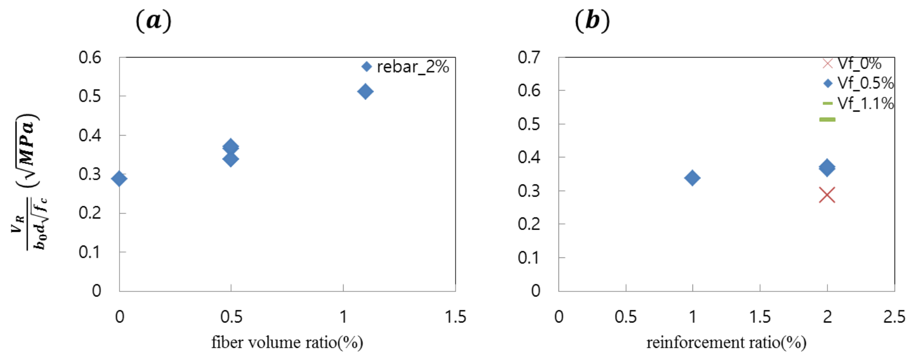

Fig. 4 Relationship between (a)V_f, (b)ρ with load

As expected, steel fiber and re-bar volume ratios have positive effect on the punching shear strength. However, test results are quite insufficient to experimentally analyze the phenomenon. Therefore, to confirm this phenomenon, more data results would be obtained from more punching shear tests.

3.2 Results by Lionel Moreillon

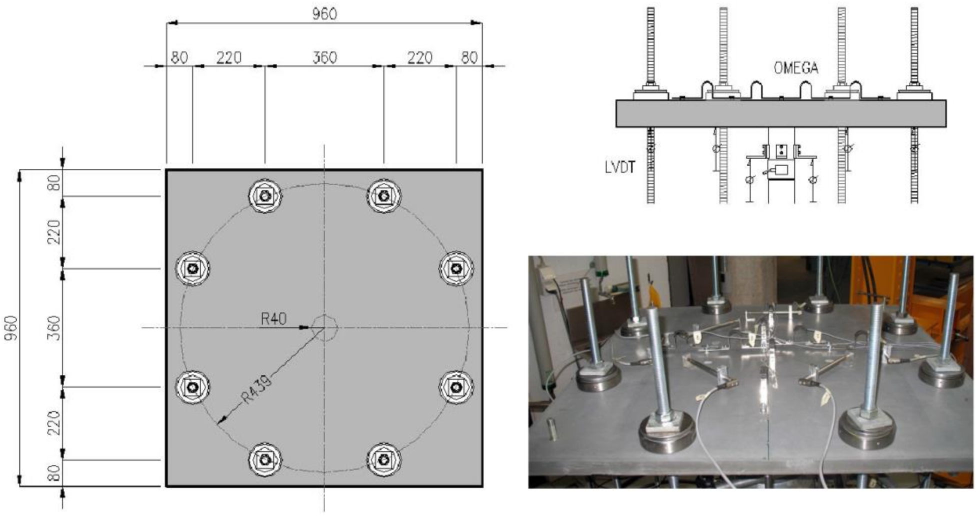

Fig. 5 UHPC slab and section geometry (by Lionel M.)

Lionel M. tested 18 UHPC slabs in total. Fig. 5 shows tested UHPC slab's geometry. All slabs had square shape with a 960mm side. The slabs were supported by eight steel rods, anchored to a steel frame. And two types of steel fiber were used. One has a length of 12.7mm, diameter of 0.175mm and aspect ratio of 72.5, and the other has a length of 20mm, diameter of 0.3mm and aspect ratio of 66.7. And a circular shaped loading column was used. The varying parameters were slab thickness, steel fiber and re-bar volume ratio. Some properties for UHPC slabs can be seen in Table. 3.

Table. 3 UHPC slab test dimensions and results (by Lionel M.)

Specimen	V_f (%)	ρ (%)	f_c (MPa)	h (mm)	d_{eff} (mm)	b_0 (mm)	c (mm)	V_{Rtest} (kN)
BCV_1%_30_0	1	0	150	30	15	298.5	80	21.5
BCV_1%_30_1.31	1	1.31	150	30	15	298.5	80	18.2
BCV_1%_30_2.57	1	2.57	150	30	15	298.5	80	54
BCV_2%_30_0	2	0	150	30	15	298.5	80	22.5
BCV_2%_30_2.57	2	2.57	150	30	15	298.5	80	42
BCV_1%_40_0.98	1	0.98	150	40	20	314.2	80	31
BCV_1%_40_1.92	1	1.92	150	40	20	314.2	80	49
BCV_2%_40_0	2	0	150	40	20	314.2	80	35
BCV_2%_40_1.92	2	1.92	150	40	20	314.2	80	48
BCV_1%_60_0.96	1	0.96	150	60	40	377	80	75
BCV_1%_60_1.96	1	1.96	150	60	40	377	80	130
BCV_2%_60_0	2	0	150	60	40	377	80	81
BCV_2%_60_0.96	2	0.96	150	60	40	377	80	120
BCV_1%_80_1.06	1	1.06	150	80	60	439.8	80	180
BCV_1%_80_1.31	1	1.31	150	80	60	439.8	80	220
BCV_1%_80_1.88	1	1.88	150	80	60	439.8	80	270
BCV_2%_80_0	2	0	150	80	60	439.8	80	135
BCV_2%_80_1.88	2	1.88	150	80	60	439.8	80	274

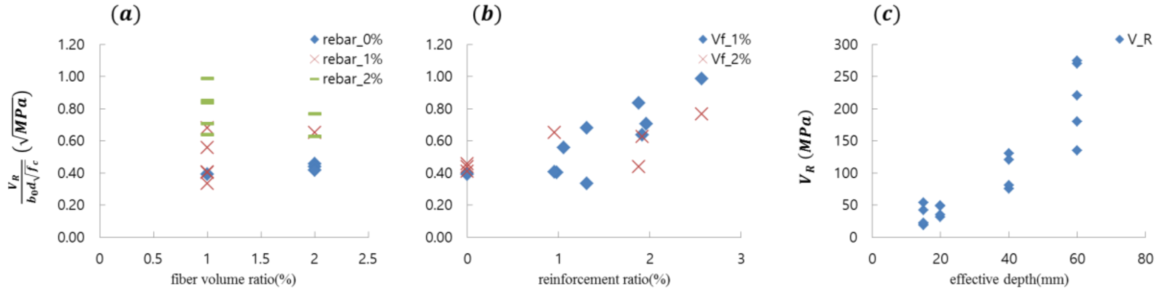

Fig. 6 Relationship between (a)V_f, (b)ρ, (c)slab thickness with load

Fig. 6 shows the relationship between fiber volume ratio, re-bar volume ratio and slab thickness with punching shear strength. As shown in Fig. 6, punching shear strengths become increased proportionally to slab thickness increases. However when it comes to steel fiber and re-bar volume ratios, strangely no outstanding tendency can be found. On the contrary, decreases rather than increases in punching shear strength with higher horizontal axis value are observed. It seems like an undesirable situation. In case of ordinary reinforced concrete, increasing re-bar ratio generally improves punching shear strength, although leads to decrease in deflection capacity. But when considering the steel fiber effect, this aspect can be explained by concentration of stress due to the steel fiber. Under external tensile forces, a lot of micro cracks are generated throughout the whole part of UHPC. And after a macro crack appears, strain becomes larger only at the location of macro crack section because at the other section steel fibers strongly resist the external forces. This phenomenon rather decreases the punching shear strength of UHPC slabs.

3.3 Results by Devin K. Harris

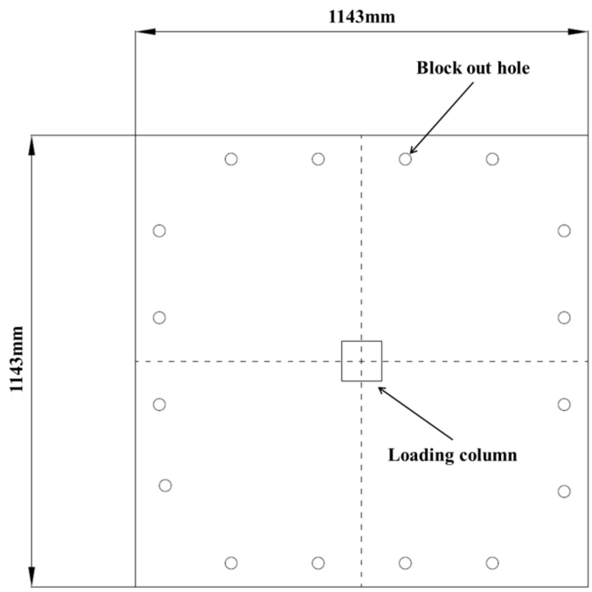

Fig. 7 UHPC slab specimen geometry (by Devin K. H.)

Devin K. Harris tested 12 small, fiber reinforced UHPC slabs to characterize punching shear strength. Fig. 7 shows tested UHPC slab's geometry. All slabs had square shape with a 1143mm side. All edges of the slabs were fully restrained to 16 supports to yield the highest probability of a punching shear failure prior to a flexural failure. Steel fibers which have a length of 13mm, diameter of 0.2mm and aspect ratio of 65 were added at a ratio of 2%. And square shaped loading column was used. The varying parameters were slab thickness and loading column plate dimensions. Some properties for slabs are listed in Table. 4. As specimen's names were not indicated, all specimen name sheets are left as voids.

Table. 4 UHPC slab test dimensions and results (by Devin K. H.)

Specimen	V_f (%)	ρ (%)	f_c (MPa)	h (mm)	d_{eff} (mm)	b_0 (mm)	c (mm)	V_{Rtest} (kN)	Failure mode
-	2	0	220	55.1	55.1	325.1	38	104	P
-	2	0	220	58.9	58.9	389	51	121	P
-	2	0	220	53.8	53.8	269	25	101	P
-	2	0	220	66.2	66.2	412	51	147	P
-	2	0	220	65.5	65.5	509.8	76	160	F
-	2	0	220	64.5	64.5	354.6	38	136	P
-	2	0	220	70.1	70.1	476.2	64	152	F
-	2	0	220	78.7	78.7	503.2	64	173	F
-	2	0	220	71.8	71.8	377.6	38	157	P
-	2	0	220	76.9	76.9	341.6	25	148	P
-	2	0	220	72.3	72.3	431.1	51	171	F
-	2	0	220	83.1	83.1	438.7	44.4	175	F

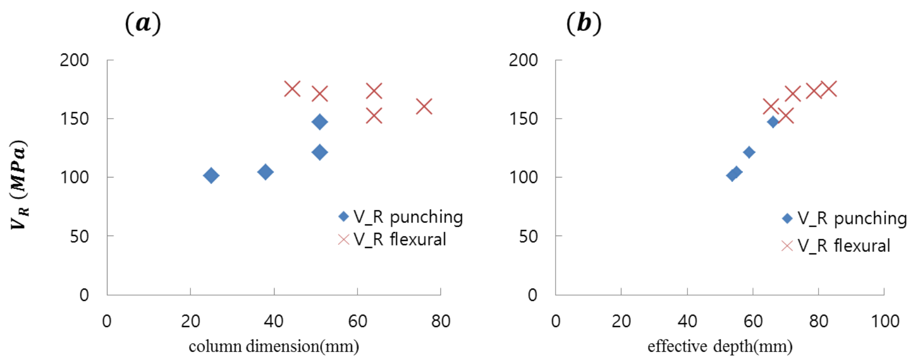

Fig. 8 Relationship between (a)loading column dimension, (b)slab thickness with load

Fig. 8 shows the relationship between loading column dimensions and slab thickness with punching shear strength. Especially for this set of tests, almost half of all UHPC slabs were failed by flexural failure rather than by punching shear failure. If all the results were considered together regardless of the failure mode, it would be hard and even irrelevant to verify punching shear strength. Therefore, all the results are divided into two groups, punching shear failure group and flexural failure group. The two groups are presented in Fig. 8 as trapezoidal shaped points and X-shaped points, respectively.

As seen, increasing loading column dimension and slab thickness can lead to increase in punching shear strength. The results are quite well matched with an intuition. Punching shear strength is essentially related to the control perimeter, which is assumed by using two parameters, loading column dimension and slab thickness as shown in Fig. 2. As a result, larger loading column dimension and slab thickness lead to increase in control perimeter section, then punching shear strength becomes larger than before. And it finally surpasses flexural strength of the slab. In this way, flexural failures occurred at higher range of varying parameters.

4. CONCLUSIONS

In this paper, the effects of design variables to the punching shear strength of UHPC slabs are studied by analyzing the 3 previous researches. Among many options, the 4 design variables, which mean slab thickness, loading column dimension, steel fiber volume ratio and reinforcement ratio are adopted. In summary, by increasing the slab thickness and loading column dimension, the punching shear strength of the UHPC slabs can be increased as well as the control perimeter sections become larger. However, contrary to expectations, increasing fiber volume ratio and re-bar volume ratio even can decrease the punching shear capacity due to the concentration of the stresses.

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