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Test of Headed Reinforcement in Pullout

Dong-Uk Choi[1)*], **Sung-Gul Hong**[2)], **and Chin-Yong Lee**[3)]

[1)] *Dept. of Architecture Engineering, Hankyong National University, Korea*
[2)] *Department. of Architecture, Seoul National University, Korea*
[3)] *Technology & Research Institute, Conclinic Co. Ltd., Korea*

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Abstract

Results of an experimental study on the pullout behavior of the headed reinforcement are presented. A total of 48 pullout tests was performed to evaluate pullout strengths and load-displacement behaviors in pullout of the headed bars. The square steel heads had gross area of $4A_b$ and thickness of d_b. The test program consisted of three pullout test groups: Simple and Edge pullout tests using plain concrete slabs, comparison of pullout performances between the standard hooks and the headed reinforcement, and pullout tests of headed reinforcement using reinforced concrete columns. Test variables included concrete strengths ($f_c' = 27.1$MPa, 39.1MPa), reinforcing bar diameters (D16~D29), embedment depths ($6d_b$~$12d_b$), edge conditions, column reinforcement, and single-vs.-multiple bar pullout. Test results revealed that the heads effectively provided the pullout resistances of the deformed bars in tension. The load-displacement behaviors were similar between the 90-degree hooks and the headed reinforcement. When a multiple number of headed bars installed with small head-to-head spacings was pulled out, reinforcement designed to run across the concrete failure surface in a direction parallel to the headed bars helped improve the pullout performances of the headed reinforcement.

Keywords: headed reinforcement, beam-column joint, development, pullout, embedment depth, column ties

1. Introduction

The headed reinforcement is a mechanical device that consists of the steel head and the deformed reinforcing bar connected together using either bolting or welding technique. The headed reinforcement can replace standard hooks in the future in reinforced concrete construction. Constructability in the field improves significantly because the headed bars are straight and easy to install. Potential applications include exterior beam-column joints, knee joints, column-footing connections, and other innovative areas related to reinforced or precast concrete construction. In this study, the heads were designed, manufactured and tested with a goal of applying the headed reinforcement in the exterior beam-column joints where the reinforcement congestion is frequently encountered.

A total of 48 pullout (P/O) tests of headed bars was performed with results summarized in this study. The scope of this research included design of the heads and evaluation of the structural performances of the headed reinforcement.

2. Preparation for test

2.1 Head design

The geometry of the heads was determined as follows:

1) Since the headed bars were intended to be used in the beam-column joints in this study, heads as small as possible were desirable to minimize steel congestion;
2) the smallest heads found in literature had a net area of $4A_b$ (A_b = bar cross-sectional area).[1,2] The net areas of the heads were arbitrarily determined to be $3A_b$;
3) elastic F.E. analyses were then implemented to determine proper head thicknesses;
4) the F.E. analysis results revealed that by using the thicknesses equal to the bar diameters (d_b), the peak shear stresses developed in the heads were about the same as the flexural stresses as the bar is subjected to the yield load;
5) since the shear failure between the head and the bar

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* *Corresponding author*
Tel.: +82-31-670-5272; Fax.: +82-31-670-5015
E-mail address: choidu@hnu.hankyong.ac.kr

must be avoided, it seemed reasonable to accept this as the head design criteria.

Table 1 summarizes the head shape used in this study. The head thickness equals the bar diameter and the net area is $3A_b$ as described above. Fig. 1 shows a D19 deformed reinforcing bar and the head. Upset end was created at one end of the bar and then a bolted connection to the head was used.

2.2 Experimental program

The experimental program consisted of three different pullout test groups: (1) Simple and Edge pullout tests using plain concrete slabs, (2) comparison of pullout performances between 90-degree standard hooks and headed bars using reinforced concrete columns, and (3) pullout tests using reinforced concrete columns to evaluate the effect of column reinforcement on the pullout strengths of the headed reinforcement.

2.2.1 Concrete

Concrete was delivered in two different batches. The compressive strengths of cylinders were tested 28 and 56 days after casting with the results summarized in Table 2.

Table 1 Head geometry

Bar size	Cross section(mm x mm)	Thickness(mm)
D16	29 x 29	16
D19	32 x 32	19
D22	38 x 38	22
D25	45 x 45	25
D29	50 x 50	29

Table 2 Compressive strength development of concrete

Batch no.	f_c', MPa		Headed bars	Remarks
	f_{28}	f_{56}		
1	36.3	39.1	D16 D22 D25	- Simple & edge P/O tests - P/O tests using columns
2	24.1	27.1	D19 D29	- Simple & edge P/O tests - Hook vs. headed bars - P/O tests using columns

Table 3 Type-S and Type-E P/O test variables

Specimen index[1]	f_c', MPa	h_{ef}, mm	Specimen index[1]	f_c', MPa	h_{ef}, mm	C_1, mm
S16-7db.1	36.3	112	E16-7db.1	36.3	112	48
S16-7db.2	36.3	112	E16-7db.2	36.3	112	48
S19-7db.1	27.1	133	E19-7db.1	27.1	133	67
S19-7db.2	27.1	133	E19-7db.2	27.1	133	67
S25-7db.1	36.3	175	E19-7db.3	27.1	133	133
S25-7db.2	36.3	175	E19-7db.4	27.1	133	133
S29-12db.1	27.1	348	E25-7db.1	36.3	175	75
S29-12db.2	27.1	348	E25-7db.2	36.3	175	75

Note: 1. S = type-S, E = type-E; 16, 19, 25, 29 = D16, D19, D25, D29; 7db, 12db = hef; 1, 2, 3, 4 = replicate no.

All cylinders were cured in an environmental chamber where the temperature and the relative humidity were maintained at 21°C and 50%, respectively.

2.2.2 Steel

Grade SD40 reinforcing steel was delivered from one steel manufacturer. The coupon test results of D10 through D29 bars revealed that the yield strengths (f_y) were 420MPa or higher except for D19 bars (f_y was 360MPa for D19).

2.2.3 Fabrication of type-S, type-E P/O test specimens

Plain concrete slabs, 1.8m (W) x 1.8m (L) x 0.4m (H) typ., were used for the Simple (Type-S) and Edge (Type-E) pullout tests. Type-S test was defined as a test where a headed bar was installed in the middle so that the development of the concrete pullout cone was not influenced by boundaries. The edge distance, C_1, measured from the slab edge to the center of the head was greater than two times the bar embedment depth, h_{ef}, in all Type-S tests as shown in Fig. 2. In Type-E test, a headed bar was installed close to the slab boundary. The edge distance was less than the bar embedment depth in all Type-E tests. Sixteen Type-S and Type-E tests were completed using D16~D29 bars as summarized in Table 3. The embedment depths were $7d_b$ for D16~D25 bars and $12d_b$ for D29 bars. It is noted that the embedment depth was always less than one-half the slab height, an attempt to avoid development of cracking in the plain concrete slabs during test.$^{3)}$

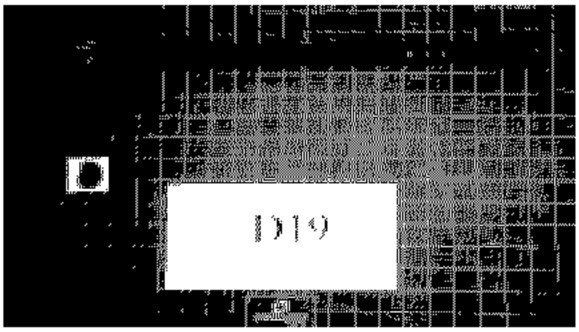


Fig. 1 Head and D19 deformed rebar

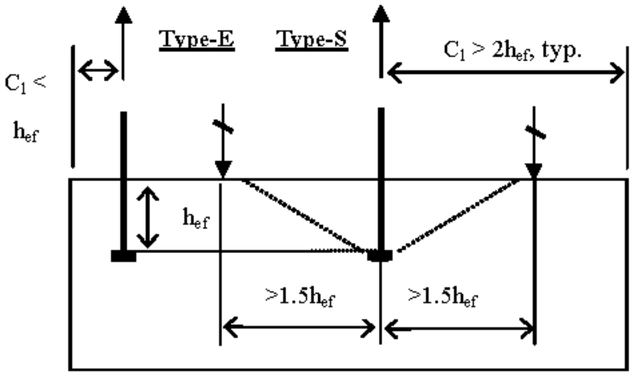


Fig. 2 Type-S and type-E P/O test schematics

2.2.4 Standard hook vs. headed reinforcement

It was important that a headed reinforcement develops pullout strength equivalent to that of a standard hook. Four reinforced concrete columns, 0.24m (W) x 1.8m (L) x 0.4m (H) each, were used to compare the structural performances between 90-degree standard hooks and headed bars in pullout. The hooks were fabricated as specified by the ACI Code.[4)] The hook development length, L_{dh}, required of D19 bars was 255mm (13.5d_b). Actual embedment depths used for test were 190mm (10d_b) and 305mm (16d_b) for the hooks. The embedment depth was 10d_b for the headed reinforcement. A couple of hooks or headed bars was pulled out at the same time as shown in Fig. 3. Table 4 summarizes the test variables.

It is noted that two different column tie spacings, S_{tie} = 3d_b and 6d_b, were used based on the following assumptions. In a beam-column joint shown in Fig. 4, as the top reinforcing bars of the beam are subjected to tension, the column ties crossing the concrete failure surface develop tensile resistances. The purpose of using the different tie spacings was to determine if larger pullout strengths could be determined with the use of smaller tie spacing.

2.2.5 Fabrication of type-C P/O test specimens

One serious drawback of headed bars can be reduction of pullout strengths as a group of closely spaced headed bars is subjected to pullout. Multiple bars together can create one large concrete failure cone and the individual headed bar may not reach the yield strength. The third test group, called Type-C pullout tests in this study, was needed to examine pullout behavior of the multiple headed bars. Twenty-four tests were completed using reinforced concrete columns: Six tests using D19 bars to evaluate the effect of column main reinforcement on the bar pullout strengths and 18 tests using D16 and D22 bars to evaluate the effect of column ties on the pullout strengths. The test variables are summarized in Table 5. The test schematics and the cross sections of the reinforced concrete columns are shown in Figs. 5 and 6, respectively.

Table 4 Test variables: hook vs. headed bar (2-D19)

Specimen index[1]	f_c', MPa	h_{ef}, mm	C_1, mm	S_{head}, mm	S_{tie}, mm	Cross section
Hook-10db-2A	27.1	190	63	114	57	b=240, h=400, re-inf.=8-D19, (D10)[2]
Hook-10db-2C	27.1	190	63	114	114	
Hook-16db-2A	27.1	304	63	114	57	
Hook-16db-2C	27.1	304	63	114	114	
HD-10db-2A.1	27.1	190	63	114	57	
HD-10db-2A.2	27.1	190	63	114	57	
HD-10db-2C.1	27.1	190	63	114	114	
HD-10db-2C.2	27.1	190	63	114	114	

Note: 1. hook = 90-degree hook, HD = headed reinf.; 10db, 16db = h_{ef}; 2 = 2 hooks or 2 headed bars; A = S_{tie} of 3d_b, C = S_{tie} of 6d_b; 1 or 2 = replicate no.; 2. (D10) = D10 used for column ties.

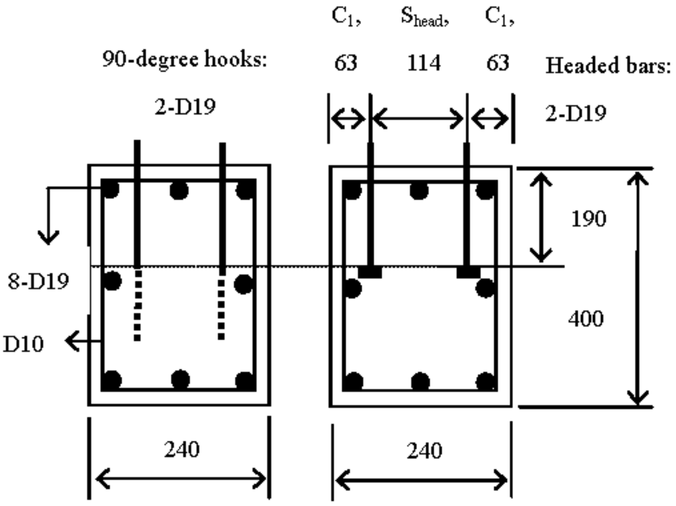


Fig. 3 Cross sections of reinforced concrete columns used to compare hooks and headed reinforcement

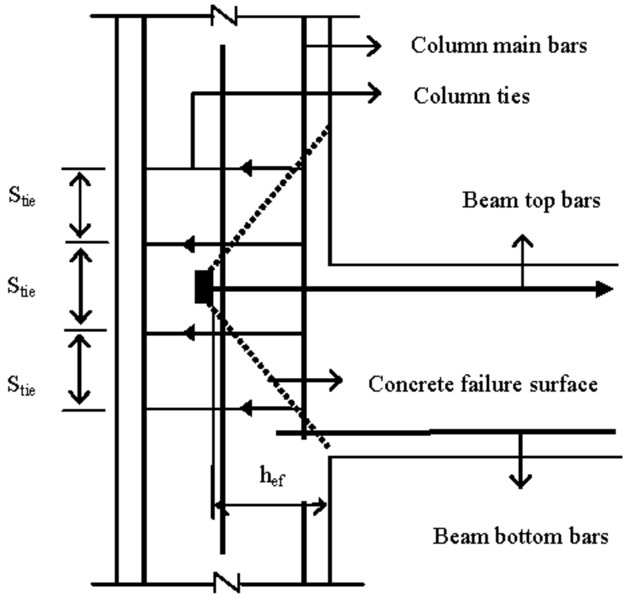


Fig. 4 External beam-column joint: contribution of column ties in developing P/O resistance

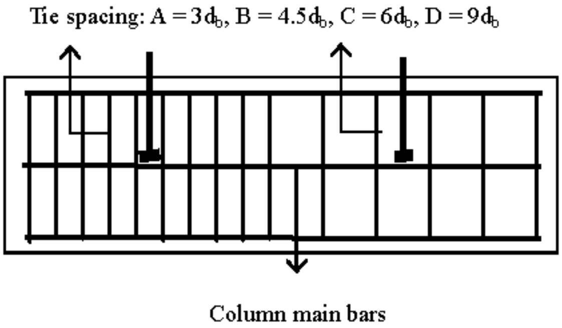


Fig. 5 Type-C P/O test schematics

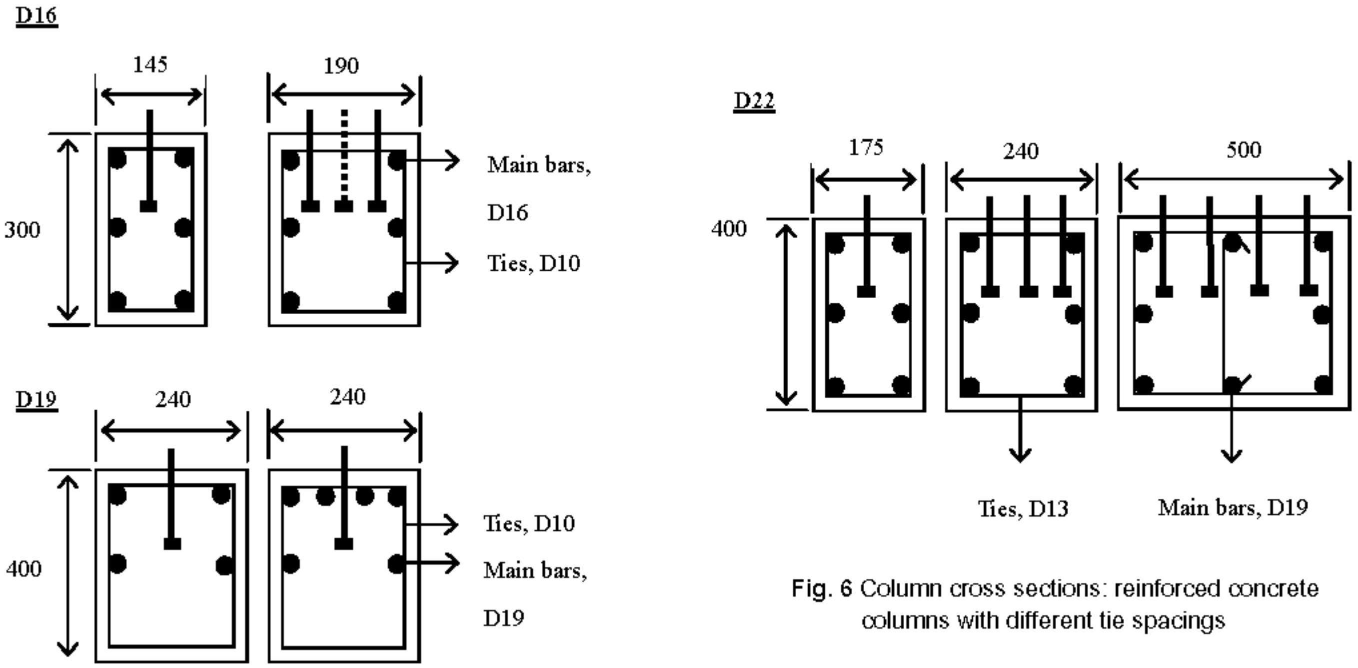


Fig. 6 Column cross sections: reinforced concrete columns with different tie spacings

Table 5 Type-C P/O test variables

Specimen index^1	f_c', MPa	h_{ef}, mm	C_1, mm	S_{head} mm	S_{tie} mm	Col. b*h	Re-^{2} bars	Specimen index^1	f_c', MPa	h_{ef}, mm	C_1, mm	S_{head} mm	S_{tie} mm	Col. b*h	Re-^{2} bars
C16-6db-1A	39.1	96	72.5	n/a	48	145 * 300	6-D16 (D10)	C19-10db-1AL	27.1	190	120	n/a	57	240 * 400	6-D19 (D10)
C16-6db-1C	39.1	96	72.5	n/a	96			C19-10db-1BL	27.1	190	120	n/a	86		
C16-6db-1D	39.1	96	72.5	n/a	144			C19-10db-1CL	27.1	190	120	n/a	114		
C16-6db-2A	39.1	96	47	96	48	190 * 300	6-D16 (D10)	C19-10db-1AH	27.1	190	120	n/a	57	240 * 400	10 D19 (D10)
C16-6db-2B	39.1	96	47	96	72			C19-10db-1BH	27.1	190	120	n/a	86		
C16-6db-2C	39.1	96	47	96	96			C19-10db-1CH	27.1	190	120	n/a	114		
C16-6db-2D	39.1	96	47	96	144			C22-6db-1A	39.1	132	87.5	n/a	66	175 * 400	6-D19 (D13)
C16-6db-3A	39.1	96	47	48	48	190 * 300	6-D16 (D10)	C22-6db-1B	39.1	132	87.5	n/a	99		
C16-6db-3B	39.1	96	47	48	72			C22-6db-1C	39.1	132	87.5	n/a	132		
C16-6db-3C	39.1	96	47	48	96			C22-6db-3A	39.1	132	54	66	66	240 * 400	6-D19 (D13)
C16-6db-3D	39.1	96	47	48	144			C22-6db-3B	39.1	132	54	66	99		
								C22-6db-4A	39.1	132	52	132	66	500 * 400	8-D19 (D13)
								C22-6db-4B	39.1	132	52	132	99		

Note: 1. C = Type-C; 16~22 = D16~D22; 6db, 10db = h_{ef}; 1~4 = no. of bars; A, B, C, D = S_{tie} of 3d_b, 4.5d_b, 6d_b, 9d_b; L or H = low or high percentage of col. main reinf.; 2. (D10), (D13) = col. ties.

Table 6 Test results: type-S and type-E P/O tests

Specimen index	f_c', MPa	h_{ef}, mm	C_1, mm	P_n, kN	P_n/F_y, %^{1}	P_n/CCD, %^{2}	Specimen index	f_c', MPa	h_{ef}, mm	C_1, mm	P_n, kN	P_n/F_y, %^{1}	P_n/CCD, %^{2}
S16-7db.1	36.3	112	n/a	73	87.5	60.1	E16-7db.1	36.3	112	48	47	56.3	76.6
S16-7db.2	36.3	112	n/a	80	95.9	65.9	E16-7db.2	36.3	112	48	47	56.3	76.6
S19-7db.1	27.1	133	n/a	132	110	97.2	E19-7db.1	27.1	133	67	52	43.2	71.8
S19-7db.2	27.1	133	n/a	104	86.4	76.6	E19-7db.2	27.1	133	67	48	39.9	66.3
S25-7db.1	36.3	175	n/a	160	75.2	67.4	E19-7db.3	27.1	133	133	78	64.8	76.6
S25-7db.2	36.3	175	n/a	151	71.0	63.7	E19-7db.4	27.1	133	133	75	62.3	73.7
S29-12db.1	27.1	348	n/a	360	134	62.7	E25-7db.1	36.3	175	75	87	40.9	72.6
S29-12db.2	27.1	348	n/a	392	145	68.2	E25-7db.2	36.3	175	75	92	43.2	76.8

Note: 1. P_n/F_y = test results divided by A_b*f_y where f_y = 420MPa (nominal yield strength of SD40 bars);
2. P_n/CCD = test results divided by CCD.

2.2.6 Test setup and instrumentation for measurement

The pullout test setup is shown in Fig. 7. The reaction frame consisted of steel supports, beams resting on the supports, and a base for load cell and hydraulic cylinder as shown in Fig. 7. The loading assembly, which consisted of a steel box and a high-strength steel rod, was used to connect vertically the headed bars and the 500kN-capacity hydraulic cylinder. Holes in the steel plate placed at bottom of the steel box allowed the threaded end of the test specimen to protrude inside so that nuts could be applied in the box. The high-strength steel rod then connected the steel box and the hydraulic cylinder. The headed bars were subjected to pullout as the force was slowly applied using the hydraulic cylinder operated by a hand pump. The displacement was measured on top of the headed bar using a LVDT. The applied force was measured using a load cell. Signals from the LVDT and the load cell were recorded using an electronic data acquisition system while the sampling rate was ten data sets per second. When more than one headed bar were tested at the same time, the displacements were measured using two LVDTs located on top of the outer most bars. When the displacement exceeded the bar diameter, it was assumed that the bar failed in pullout and the test was discontinued.

3. Test results

3.1 Simple and edge P/O test results

The results of Type-S and Type-E pullout tests are summarized in terms of the pullout strengths, P_n, in Table 6. The pullout strengths determined in Type-S tests are compared to the yield loads and the values predicted by the Concrete Capacity Design (CCD) method in Table 6 and Figs. 8 and 9, respectively.[5] Since the European standard cube (200 x 200 x 200mm) strengths are needed in the CCD equations, the cylinder strengths (f_c') presented in Table 2 were converted to cube strengths (f_{cc}') using 1/0.83 factor.

In Table 6 and Fig. 8, for D16 and D19 headed bars with $h_{ef} = 7d_b$, the pullout strengths range between 86.4% and 110% of the bar yield loads (A_b*f_y) although the embedment depths are much smaller than the development lengths required by the ACI Code (h_{ef}/L_d = 35.4%). For D25 headed bars with $h_{ef} = 7d_b$, the pullout strengths are 71% and 75.2% of the yield load while h_{ef}/L_d = 28.3%. For D29 bars with $h_{ef} = 12d_b$, the pullout strengths are 134% and 145% of the yield load (h_{ef}/L_d = 48.5%). In Fig. 9, where the test results are compared to the pullout strengths predicted by the CCD, the test results are lower than those of the CCD, probably because of the statistical scatter.

Load-displacement plots determined from three Type-S tests are shown in Fig. 10. The headed bars (S25-7db.1, 2) using the embedment depth not sufficient to develop the yield strength show rapidly decreasing pullout resistances as soon as the peaks are reached in Fig. 10. The headed bar (S29-12db.2) installed with an embedment depth sufficient to develop the bar yield load shows a ductile behavior.

The Type-S pullout test results reveal that (1) the heads effectively provide the pullout resistances of the deformed bars in tension, (2) embedment depths larger than $7d_b$ are needed to develop $1.25f_y$, while (3) $h_{ef} = 12d_b$ is

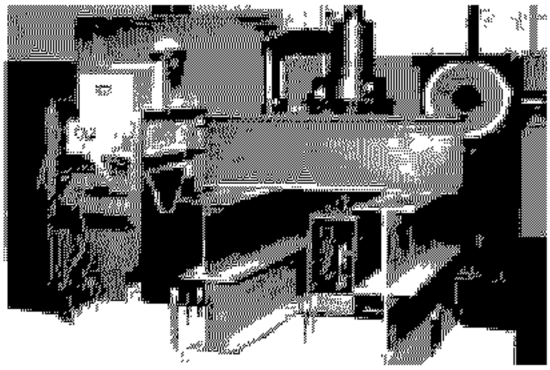


Fig. 7 Pullout test setup

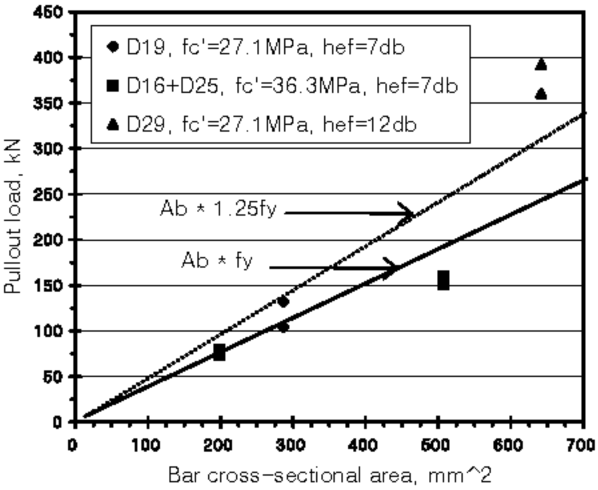


Fig. 8 Pullout strengths: test results vs. bar yield strengths (Type-S, D16~D29; $h_{ef} = 7d_b$ or $12d_b$)

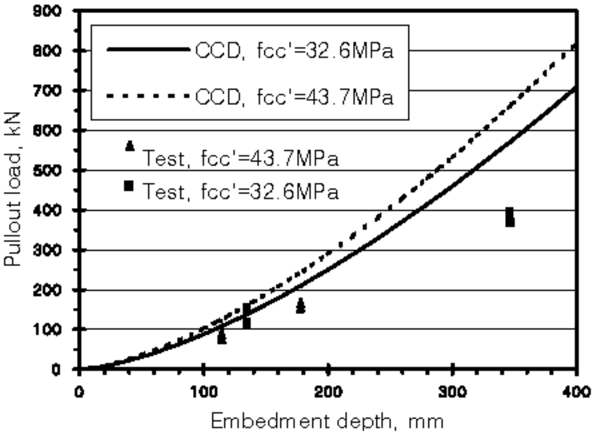


Fig. 9 Pullout strengths: test results vs. CCD (Type-S, D16~D29; $h_{ef} = 7d_b$ or $12d_b$)

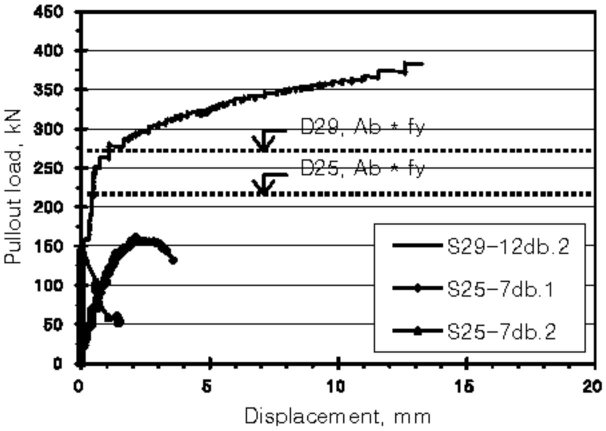
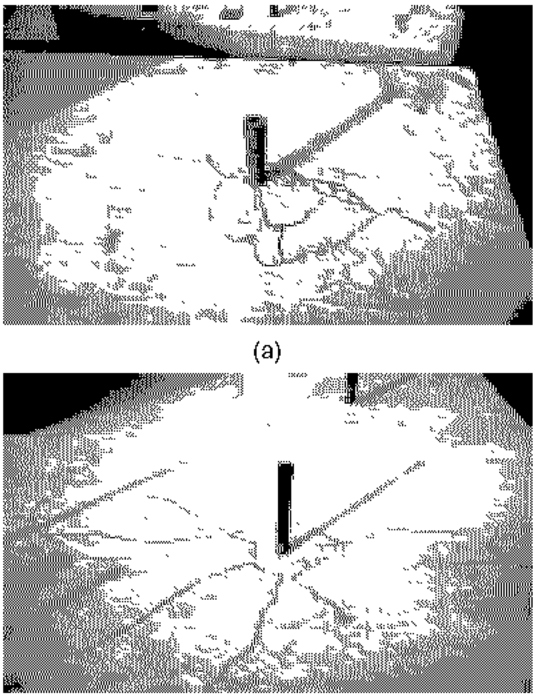


Fig. 10 Load vs. displacement: type-S; D25, D29; $h_{ef} = 7d_b$, $12d_b$; $f_c' = 36.3$MPa (D25), 27.1MPa (D29)



(a)

(b)

Fig. 11 Test photo: Type-S

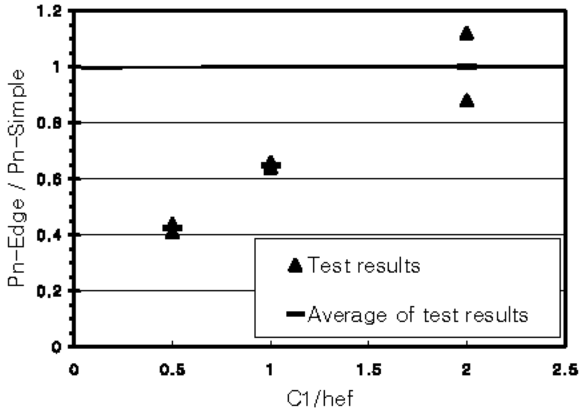


Fig. 12 Influence of edge distance on pullout strength: type-E, D19 , $h_{ef} = 7d_b$, $f_c' = 27.1$Mpa

sufficient for the single D29 bar to develop over 1.25 f_y strength when using normal strength concrete.

The only failure mode observed in the Type-S tests was the bar pullout. The headed bars were pulled out slowly typically creating a small concrete cone shown in Fig. 11(a). In some tests, cracks also appeared in the radial direction starting from perimeter of the cone as shown in Fig. 11(b).

The results of Type-E pullout tests are also summarized in Table 6 and Fig. 12. Fig. 12 shows the influence of existing edges on the pullout strengths where, for D19 bars with $h_{ef} = 7d_b$, the pullout strengths consistently decrease with decreasing edge distances.

3.2 Test results: hook vs. headed reinforcement

Test results of eight specimens where the pullout performances between the 90-degree standard hooks and the headed bars were compared are summarized in Table 7 and Fig. 13. The peak values for 2-D19 bars with $h_{ef} = 10d_b$ and $h_{ef} = 16d_b$ range between 118%~125% and 129%~133% of the bar yield strength, respectively, in Table 7. The peaks are reached with relatively large 10~15mm displacements, probably because of confining effect provided by column reinforcement. Load-displacement plots for three tests (Hook-10db-2A, HD-10db-2A.2, HD-10db-2C.2) shown in

Table 7 Test results: hook vs. headed bar (2-D19)

Specimen index	f_c', MPa	h_{ef}, mm	S_{tie}, mm	P_n, kN	P_n/F_y, %^{1,2}
Hook-10db-2A	27.1	190	57	285	118
Hook-10db-2C	27.1	190	114	270	112
Hook-16db-2A	27.1	304	57	320	133
Hook-16db-2C	27.1	304	114	311	129
HD-10db-2A.1	27.1	190	57	290	121
HD-10db-2A.2	27.1	190	57	302	125
HD-10db-2C.1	27.1	190	114	284	118
HD-10db-2C.2	27.1	190	114	287	119

Note: 1. $f_y = 420$MPa; 2. P_n/F_y = test results divided by A_b*f_y.

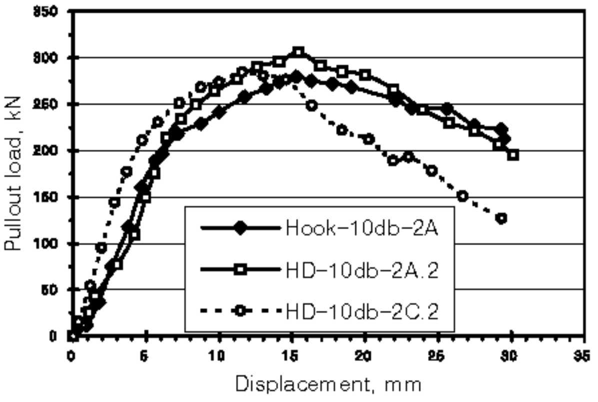


Fig. 13 Load vs. displacement: comparison between standard Hook and Headed Reinforcement (2-D19, $h_{ef} = 10d_b$, $S_{tie} = 3d_b$ or $6d_b$, $f_c' = 27.1$MPa)

Fig. 13 reveal that the pullout stiffnesses, strengths, and post-peak behaviors are similar between the hook and the headed bars.

3.3 Effect of column reinforcement on P/O strength

3.3.1 Effect of column tie spacing on P/O strength

The D16 and D22 bars were used to investigate the influence of different column tie spacings on the multiple bar pullout strengths. Up to four headed bars were pulled out at the same time. Also four different column tie spacings and the relatively small embedment depth ($h_{ef} = 6d_b$) were used.

The pullout strengths increased with decreasing tie spacings as shown in Table 8 and Figs. 13 and 14. The pullout strengths of 2-D16 and 3-D16 bars with $S_{tie} = 6d_b$ are 76.8% and 82.9% of those with $S_{tie} = 3d_b$, respectively in Table 8. The pullout strengths of 2-D16 and 3-D16 bars with $S_{tie} = 9d_b$ are only 51.2% and 53.7% of those with $S_{tie} = 3d_b$. The test results are consistent as shown in Fig. 14. In Fig. 14, the pullout strengths of the headed bars increase as the tie spacings decrease for D22 and D16 bars. In Fig. 15, the results of three tests using 2-D16 bars are shown. The pullout strength is highest when $S_{tie} = 3d_b$ is used (C16-6db-2A). The pullout strength is reduced with $S_{tie} = 4.5d_b$ (C16-6db-2B) and the strength is lowest with $S_{tie} = 6d_b$ (C16-6db-2C).

In addition, the contribution of individual bar in pullout decreased with the use of smaller head-to-head spacings, or S_{head}, as shown in Table 8 and Fig. 16. The pullout test results, four tests each using 2-D16 (C16-6db-2A through 2D) and 3-D16 bars (C16-6db-3A through 3D) are compared in Fig. 16. In Fig. 16, the pullout resistances of individual bars (P_n / number of bars tested) in the 3-bar pullout tests range between 67.1% and 82.4% of those in the 2-bar pullout. The Type-C pullout test results strongly indicate that (1) the column ties influence the pullout strengths of the headed bars with small embedment depths, (2) the pullout strengths increase with smaller tie spacings, and (3) the contributions of the individual bars in multiple bar pullout decrease with the use of smaller head-to-head spacings.

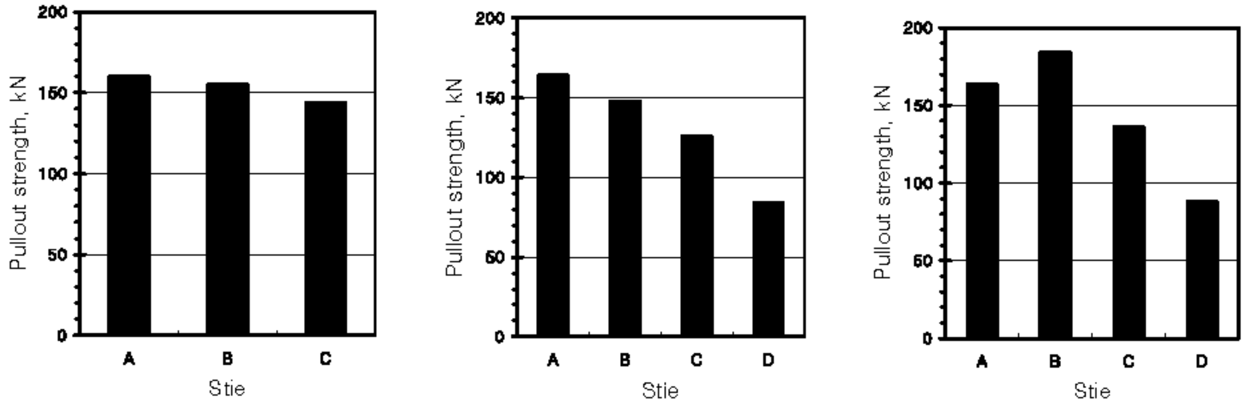
3.3.2 Effect of column main bars on P/O strength

Six pullout tests using single D19 bars with $h_{ef} = 10d_b$

Table 8 Test results: type-C P/O tests

Specimen index	f_c' MPa	h_{ef} mm	S_{tie} mm	ρ_{st} %^{1}	P_n kN	P_n/F_y %^{2,3}	P_n/N_{bar}^{4}	Specimen index	f_c' MPa	h_{ef} mm	S_{tie} mm	ρ_{st} %^{1}	P_n kN	P_n/F_y %^{2,3}	P_n/N_{bar}^{4}
C16-6db-1A	39.1	96	48	2.74	84	101	84	C19-10db-1BL	27.1	190	86	1.79	158	131	158
C16-6db-1C	39.1	96	96	2.74	80	96	80	C19-10db-1CL	27.1	190	114	1.79	160	133	160
C16-6db-1D	39.1	96	144	2.74	78	94	78	C19-10db-1AH	27.1	190	57	2.98	157	130	157
C16-6db-2A	39.1	96	48	2.09	164	98	82	C19-10db-1BH	27.1	190	86	2.98	156	129	156
C16-6db-2B	39.1	96	72	2.09	148	89	74	C19-10db-1CH	27.1	190	114	2.98	155	129	155
C16-6db-2C	39.1	96	96	2.09	126	76	63	C22-6db-1A	39.1	132	66	2.46	160	98	160
C16-6db-2D	39.1	96	144	2.09	84	50	42	C22-6db-1B	39.1	132	99	2.46	155	95	155
C16-6db-3A	39.1	96	48	2.09	164	66	55	C22-6db-1C	39.1	132	132	2.46	144	89	144
C16-6db-3B	39.1	96	72	2.09	184	74	61	C22-6db-3A	39.1	132	66	1.79	330	68	110
C16-6db-3C	39.1	96	96	2.09	136	54	45	C22-6db-3B	39.1	132	99	1.79	230	47	77
C16-6db-3D	39.1	96	144	2.09	88	35	29	C22-6db-4A	39.1	132	66	1.15	395	61	99
C19-10db-1AL	27.1	190	57	1.79	160	133	160	C22-6db-4B	39.1	132	99	1.15	430	66	108

Note: 1. ρ_{st} = column main reinforcement ratio = $A_{st}/(b_{col.}*h_{col.})$; 2. f_y = 420MPa; 3. P_n/F_y = test results divided by A_b*f_y; 4. test results divided by number of bars pulled out at the same time in kN.



(a) D22 (b) 2-D16 (c) 3-D16

Fig. 14 Pullout strength vs. tie spacing (S_{tie}): type-C; D16, D22; $h_{ef} = 6d_b$; $S_{tie} = 3d_b$ (A), $4.5d_b$ (B), $6d_b$(C), $9d_b$(D)

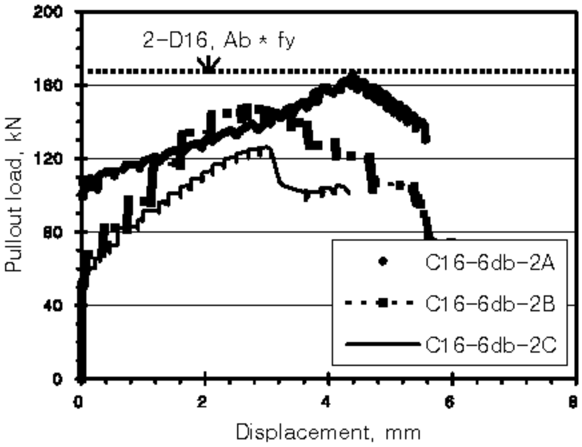


Fig. 15 Load vs. displacement: type-C; 2-D16; $h_{ef} = 6d_b$; $f_c' = 39.1MPa$; $S_{tie} = 3d_b$ (A), $4.5d_b$ (B), $6d_b$ (C)

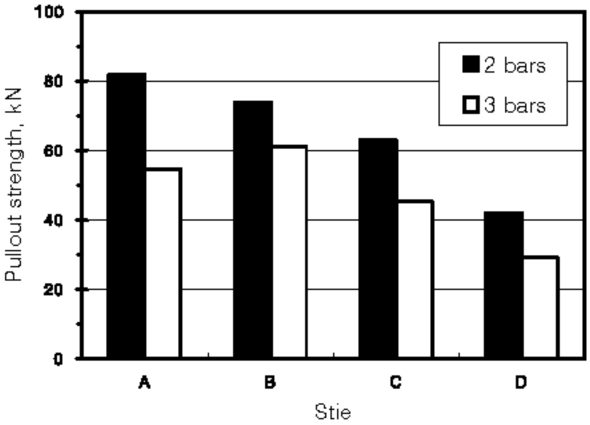
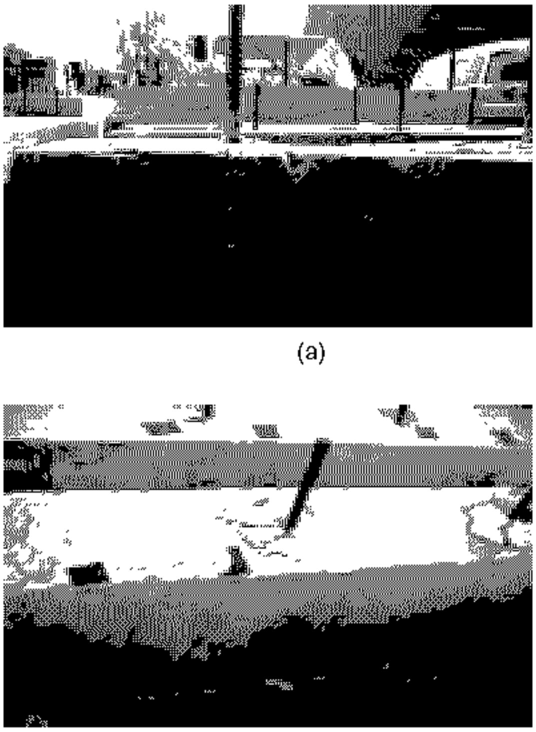


Fig. 16 Pullout strength / bar vs. head spacing (S_{head}): type-C; D16; $h_{ef} = 6d_b$; S_{head} = 96mm (2 bars), or 48mm (3 bars)

were performed to investigate the effect of column main reinforcement on the pullout strengths of the headed reinforcement. In a set of three tests (C19-10db-1AL through CL), the reinforcement ratio, ρ_{st}, of the reinforced concrete column sections used for tests was 1.79% while in another set of three tests (C19-10db-1AH through CH), the reinforcement ratio was 2.98% as shown in Table 8. The concrete strength was 27.1MPa and three different tie spacings were also tested in each test groups.

The amount of column main reinforcement did not affect the pullout strengths. As summarized in Table 8, the average pullout strength of the three tests with ρ_{st} = 1.79% is 159kN and the average of the other three tests with ρ_{st} = 2.98% is 156kN. It is noted that in all tests the ratios of the pullout strengths over the bar yield loads, P_n/F_y, are over 125%. The fact that the bars have yielded probably explains the test results that the tie spacings did not influenced the pullout strengths in these tests as shown in Table 8.


(a)

(b)

Fig. 17 Test photo : type-C

3.3.3 Failure modes

When multiple headed bars were pulled out at the same time, cracks appeared on the column side faces starting from the head location and progressed upward typically creating an angle between 35° and 45° as shown in Fig. 17(a). When single headed bar was pulled out, cracks did not appear on the column side faces and small concrete cone was created around the headed bar as shown in Fig. 17(b). No bar fractures were observed in the Type-C P/O tests.

4. Discussion of test results

In the Type-S tests, where the single D29 headed bars were installed in the plain concrete slabs using $h_{ef} = 12d_b$, the load-displacement plots indicated a ductile pullout failure as shown in Fig. 10. It was because the pullout load exceeded the bar yield load and the plot shows the tensile behavior of a reinforcing bar beyond the yield strength. However, if multiple D29 bars with small head-to-head spacing were pulled out using the same embedment depth of $12d_b$, the individual bars could not have reached the yield strengths. This implies that, in real beam-column joints, there exists problems in the pullout behavior of multiple headed bars and the problem can be improved by proper use of column reinforcement.

On the other hand, in the Type-C tests of single D19 bars with $h_{ef} = 10d_b$, the pullout strengths exceeded the bar yield load and the tie spacings did not influence the pullout strengths. This suggests a possibility that for the multiple headed bars that are installed with sufficiently large head-to-head spacings and embedment depths, the use of ties will not be necessary.

The Type-C pullout test results also seems to indicate that the column main bars do not significantly affect the headed bar pullout strengths. This results are consistent with test data published else where.[6,7)]

5. Conclusions

This experimental study was implemented for the purpose of applying the headed reinforcement in the exterior beam-column joints. The heads were designed to have a very small bearing area ($3A_b$) considering the typical congestion of reinforcing steel of the beam-column joints. Findings from this study are summarized as follows:

1) The heads effectively provided the pullout resistances of the deformed bars in tension.
2) For single D16 and D19 headed bars with embedment depths of $7d_b$, the pullout strengths were over 86% of the bar yield loads.
3) For single D29 bars with embedment depths of $12d_b$, the pullout strengths were over 125% of the bar yield load.
4) The development of single D16~D29 bars is expected with the embedment depths of $8d_b$~$12d_b$ depending on the bar diameters in normal strength concrete.
5) Use of column ties significantly influenced the pullout strengths of the multiple headed bars with small embedment depths and the pullout strengths increased with smaller tie spacings.
6) Reinforcement designed to run across the concrete failure surface in a direction parallel to the headed such as column ties in this study, was necessary to help bars, improve the pullout resistances of a multiple number of closely spaced headed bars.
7) Column main bars did not significantly affect the pullout strengths of the headed reinforcement.
8) The pullout stiffnesses, pullout strengths, and load-displacement behaviors were similar between the standard hooks and the headed reinforcement.

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