International Journal of Concrete Structures and Materials
Vol.18, No.3E, pp.151~159, December 2006

Test of Headed Reinforcement in Pullout II: Deep Embedment

Dong-Uk Choi

(Received February 25, 2006, and Accepted August 30, 2006)

Abstract: A total of 32 pullout tests were performed for the multiple headed bars relatively deeply embedded in reinforced concrete column-like members. The objective was to determine the minimum embedment depth that was necessary to safely design exterior beam-column joints using headed bars. The variables for the experiment were embedment depth of headed bar, center-to-center distance between adjacent heads, and amount of supplementary reinforcement. Regular strength concrete and grade SD420 reinforcing steel were used. The results of the test the indicated that a headed bar embedment depth of $10d_b$ was not sufficient to have relatively closely installed headed bars develop the pullout strength corresponding to the yield strength. All the experimental variables, influenced the pullout strength. The pullout strength increased with increasing embedment depth and head-to-head distance. It also increased with increasing amount of supplementary reinforcement. For a group of closely-spaced headed bars installed in a beam-column joint, it is recommended to use column ties at least 0.6% by volume, 1% or greater amount of column main bars, and an embedment depth of $13d_b$ or greater simultaneously, to guarantee the pullout strength of individual headed bars over 125% of f_y and ductile load-displacement behavior.

Keywords: headed reinforcement, multiple headed bars, pullout, embedment depth, distance between heads, supplementary reinforcement.

1. Introduction

The headed reinforcement or a headed bar consists of a head and a deformed reinforcing bar. Simpler installation and less congestion of reinforcement, and more effective anchorage are the main advantages of using the headed bars over hooks.[1] Circular, rectangular, or square steel plate (head) is typically welded to the reinforcing bar using friction welding or general welding technique while the head can also be fastened to threaded end of the reinforcing bar.[2-4] Fig. 1 shows a headed bar embedded in concrete with an embedment depth of h_{ef} (distance between top of the head and the concrete face) subjected to a tensile force, P. As shown in Fig. 1 the head transfers the force primarily by bearing of the head on concrete. Additional force may be transferred along the stem. The stem yields and fractures in tension when the embedment depth and the cover thickness of concrete to the head are both sufficiently large. When the embedment depth is sufficiently large while the cover thickness is insufficient, the concrete adjacent to the head breaks out, resulting in a side-blowout failure. On the other hand, a headed bar with an insufficient embedment depth can abruptly fail resulting in a concrete breakout failure as indicated in Fig. 1.

In this study, the use of headed bars in the exterior beam-column joint was explored by testing multiple headed bars in pullout. As shown in Fig. 2 of the joint, while the embedment depth can be sufficiently large to make a single headed bar (a beam top bar) yield in tension, a group of closely spaced headed bars (multiple beam top bars) having the same embedment depth may create one large concrete breakout cone, resulting in a premature failure. Thus one practical drawback of headed bars can be the reduction in the pullout strength and a brittle failure of a group of closely spaced headed bars. It is noted that this study is the second of three technical papers prepared to explore the use of the headed bars in the exterior beam-column joints and deals with the pullout behavior of the headed bars only.[5]

A total of 32 pullout tests were completed on the multiple headed bars relatively deeply embedded in reinforced concrete columns of $h_{ef} = 10 - 15d_b$ (in which d_b is diameter of the stem). An experimental program was prepared to determine the minimum embedment depth that was necessary to safely design exterior beam-column joints using the headed bars. Throughout this

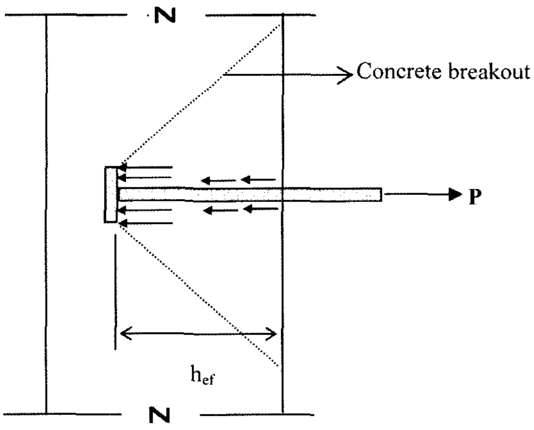

Fig. 1 Force transfer of headed bar.

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[1] KCI member, Dept. of Architectural Engineering, Hankyong National University, Anseong 456-240 Korea. *E-mail: choidu@hknu.ac.kr*

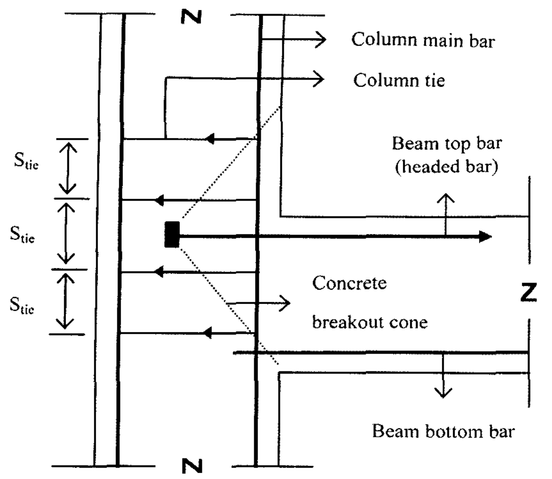


Fig. 2 External beam-column joint.

study, it is assumed that the headed bars are the main reinforcement of the beam and embedded in the column as shown in Fig. 2. As the beam is subjected to a negative moment, the headed bars become subjected to pullout. The pullout performance of the headed bars is likely dependant upon embedment depth, number of headed bars, cover thickness, distance between the adjacent headed bars, and amount of supplementary reinforcement, in this case, the supplementary reinforcement consists of existing column reinforcement such as column main bars and column ties. It is emphasized that, although many research results of headed reinforcement have been published, the study describing the pullout behavior of a group of headed bars is scarce in the literature.[6-11]

2. Preparation for test

2.1 Head

The bearing area of the head can significantly influence the anchorage capacity of the headed bar. ASTM A 970-98, for example, recommended a net head area of $10A_b$ (in which A_b is the cross-sectional area of the stem) for a welded head.[12] The same document, however, no longer specifies a head area but requires mechanical test of the head starting in 2004.[13] It is generally agreed among researchers that the head area should be large enough to provide a secure mechanical anchorage with negligible slip of the head. It is stressed that, in case of the beam-column joint where the reinforcing bars are typically congested, the use of very large head is unrealistic. In these applications, smaller heads can be used, and the anchorage relies on the bearing stress at the head combined with the bond stress over the development length.[8] Small heads were designed and used in this study to prevent the congestion of heads in the beam-column joint. The net bearing area of the head is only $3A_b$ as shown in Table 1. A square head was fastened to a threaded end of the reinforcing bar as shown in Fig. 3.

2.2 Materials

Normal strength concrete was used. Concrete compressive strengths of test cylinders were 30.7 MPa or 32.4 MPa as shown in Table 2. Grade SD420 (reinforing steel of which yield strength, f_y is 420 MPa) was used for headed bars, column main reinforcement, and column ties.

Table 1 Head geometry.

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

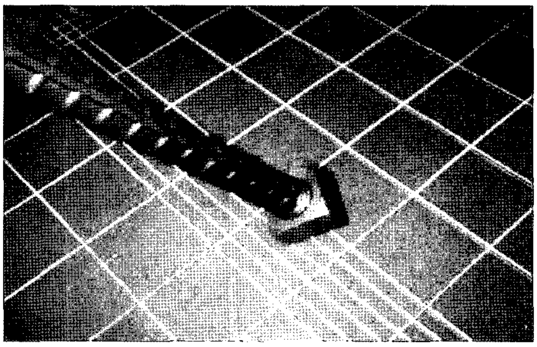


Fig. 3 Headed bar.

2.3 Test specimens

Researchers generally agree that an embedment depth of 8 to $10d_b$ is required for a single headed bar embedded in normal strength plain concrete to develop a pullout strength over f_y. Hence, in eight pullout specimens, two D29 headed bars were embedded in a reinforced concrete column-like members using an embedment depth of $10d_b$. Both headed bars were pulled out at once. Test objective was to determine if the two relatively closely spaced headed bars (center-to-center distance between adjacent heads, $s_{head} = 6d_b$) develop a pullout strength over f_y with an embedment depth of $10d_b$. Several different reinforcing schemes in the column-like members were used for the same set of eight pullout specimens. The center-to-center distances between column ties (S_{tie}) were $3d_b$, $6d_b$, $9d_b$, and none (for the case of no column ties). Also, two different main reinforcement ratios for the column (ρ_{st} = 0.56%, 1.13%) were used as summarized in Table 2 and Fig. 4. The objective was to determine if the pullout strengths and the load-displacement behaviors of the headed bars would change in relation to the different column reinforcement scheme.

Additional 24 pullout tests for D16, D22, D25, and D29 multiple headed bars were completed using deeper embedment depths of $13d_b$ and $15d_b$. The test variables other than the embedment depth were similar to the previous test sets as summarized in Table 2 and Fig. 4.

The notation for specimen index used in this study is shown as follows:

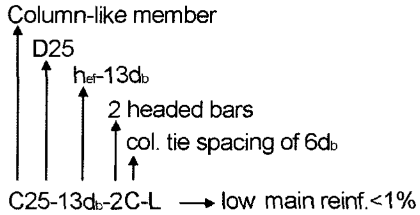


Table 2 Summary of pullout test variables and test results.

Specimen index	Headed bar	f_{ck} (MPa)	h_{ef} 1) (mm)	C 2) (mm)	S_{head} 3) (mm)	S_{tie} 4) (mm)	ρ_{st} 5) (%)	P_n 6) (kN)	$P_n/(A_b{*}f_y)$ 7) (%)	Remarks
C29-10db-2A-L	2D29	30.7	290 ($10d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	87 ($3d_b$)	0.56	457	84.7	strain gages
C29-10db-2C-L	2D29	30.7	290 ($10d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	174 ($6d_b$)	0.56	441	81.8	same as above
C29-10db-2D-L	2D29	30.7	290 ($10d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	261 ($9d_b$)	0.56	363	67.3	same as above
C29-10db-2E-L	2D29	30.7	290 ($10d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	-	0.56	348	64.5	same as above
C29-10db-2A-M	2D29	30.7	290 ($10d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	87 ($3\mathrm{d_b}$)	1.13	473	87.7	same as above
C29-10db-2C-M	2D29	30.7	290 ($10d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	174 ($6d_b$)	1.13	478	88.6	same as above
C29-10db-2D-M	2D29	30.7	290 ($10d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	261 ($9d_b$)	1.13	475	88.1	same as above
C29-10db-2E-M	2D29	30.7	290 ($10d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	-	1.13	442	82.0	same as above
C16-15db-3B-L	3D16	32.4	240 ($15d_b$)	56 ($3.5d_b$)	144 ($9d_b$)	72 ($4.5d_b$)	0.48	350	140	
C16-15db-3D-L	3D16	32.4	240 ($15d_b$)	56 ($3.5d_b$)	144 ($9d_b$)	144 ($9d_b$)	0.48	351	140	
C16-15db-3E-L	3D16	32.4	240 ($15d_b$)	56 ($3.5d_b$)	144 ($9d_b$)	-	0.48	258	103	
C16-15db-3B-M	3D16	32.4	240 ($15d_b$)	56 ($3.5d_b$)	144 ($9d_b$)	72 ($4.5d_b$)	0.96	376	150	bar fracture
C16-15db-3D-M	3D16	32.4	240 ($15d_b$)	56 ($3.5d_b$)	144 ($9d_b$)	144 ($9d_b$)	0.96	349	139	
C16-15db-3E-M	3D16	32.4	240 ($15d_b$)	56 ($3.5d_b$)	144 ($9d_b$)	-	0.96	303	121	
C22-15db-3B-L	3D22	32.4	330 ($15d_b$)	100 ($4.5d_b$)	100 ($4.5\mathrm{d_b}$)	100 ($4.5d_b$)	0.65	615	126	
C22-15db-3D-L	3D22	32.4	330 ($15d_b$)	100 ($4.5d_b$v)	100 ($4.5d_b$)	200 ($9d_b$)	0.65	548	112	
C22-15db-3E-L	3D22	32.4	330 ($15d_b$)	100 ($4.5d_b$)	100 ($4.5d_b$)	-	0.65	462	94.7	
C22-15db-3B-M	3D22	32.4	330 ($15d_b$)	100 ($4.5d_b$)	100 ($4.5d_b$)	100 ($4.5d_b$)	1.29	620	127	
C22-15db-3D-M	3D22	32.4	330 ($15d_b$)	100 ($4.5d_b$)	100 ($4.5d_b$)	200 ($9d_b$)	1.29	609	125	
C22-15db-3E-M	3D22	32.4	330 ($15d_b$)	100 ($4.5d_b$)	100 ($4.5d_b$)	-	1.29	581	119	
C25-13db-2B-L	2D25	32.4	330 ($13d_b$)	100 ($4d_b$)	200 ($8d_b$)	113 ($4.5d_b$)	0.65	562	132	
C25-13db-2C-L	2D25	32.4	330 ($13d_b$)	100 ($4d_b$)	200 ($8d_b$)	150 ($6d_b$)	0.65	550	129	
C25-13db-2E-L	2D25	32.4	330 ($13d_b$)	100 ($4d_b$)	200 ($8d_b$)	-	0.65	408	95.8	
C25-13db-2B-M	2D25	32.4	330 ($13d_b$)	100 ($4d_b$)	200 ($8d_b$)	113 ($4.5d_b$)	1.29	605	142	
C25-13db-2C-M	2D25	32.4	330 ($13d_b$)	100 ($4d_b$)	200 ($8d_b$)	150 ($6d_b$)	1.29	586	138	
C25-13db-2E-M	2D25	32.4	330 ($13d_b$)	100 ($4d_b$)	200 ($8d_b$)	-	1.29	480	113	
C29-15db-2C-L	2D29	32.4	435 ($15d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	174 ($6d_b$)	0.56	730	135	
C29-15db-2D-L	2D29	32.4	435 ($15d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	261 ($9d_b$)	0.56	636	118	
C29-15db-2E-L	2D29	32.4	435 ($15d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	-	0.56	664	123	
C29-15db-2C-M	2D29	32.4	435 ($15d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	174 ($6d_b$)	1.13	731	136	
C29-15db-2D-M	2D29	32.4	435 ($15d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	261 ($9d_b$)	1.13	772	143	
C29-15db-2E-M	2D29	32.4	435 ($15d_b$)	138 ($4.75d_b$)	174 ($6d_b$)	-	1.13	763	141	

Note: 1) h_{ef} = embedment depth, distance between the top of head and concrete face
2) C = edge distance, distance between the centers of head and edge
3) S_{head} = center-to-center distance between adjacent heads
4) S_{tie} = column tie spacing, A = $3d_b$, B = $4.5d_b$, C = $6d_b$, D = $9d_b$, E = *n/a* (no column ties)
5) ρ_{st} = $A_{st}/(b_{col} \times h_{col})$, column main reinforcement ratio
6) P_n = pullout strength determined from test
7) $P_n/(A_b{*}f_y)$ = (pullout strength determined from test) / (no. of bars * bar cross-sectional area * nominal yield strength) in %

It is noted that all column-like reinforced concrete members were cast and tested in the horizontal position, and no axial loads were applied during test for the cost concern. The test results, which is determined in the absence of axial load, should be on the conservative side compared to those determined with axial load application.

2.4 Test setup and instrumentation

The pullout test setup consisted of a reaction frame and a loading assembly as shown in Fig. 5. The loading assembly was composed of a steel box, high-strength steel rod, and 1,000 kN-capacity hydraulic cylinder as shown in Fig. 5(a). Predrilled holes in the 25-mm-thick steel plate located at the bottom side of the steel box allowed the threaded end of the headed bars to protrude inside the box so that a nut and a washer could be fastened to the bar as shown in Fig. 5(b). Multiple 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 bars using LVDTs as shown in Fig. 5(b). The applied force was measured using a pressure transducer. Signals from the LVDTs and the pressure transducer were recorded using an electronic data acquisition system with the sampling rate of ten data sets per second.

In eight pullout specimens, 5 mm strain gages were installed on headed bars, column main reinforcement, and column ties as shown in Fig. 6. Strain gauges on the column ties were installed assuming a 45° failure surface.[14] Three pairs of gauges were installed for the pullout specimens with S_{tie} of $3d_b$ as shown in Fig. 6(a). The strain gauges were named as "tie-1," "tie-2," and so on starting from the pair closest to the headed bar. Two pairs of strain

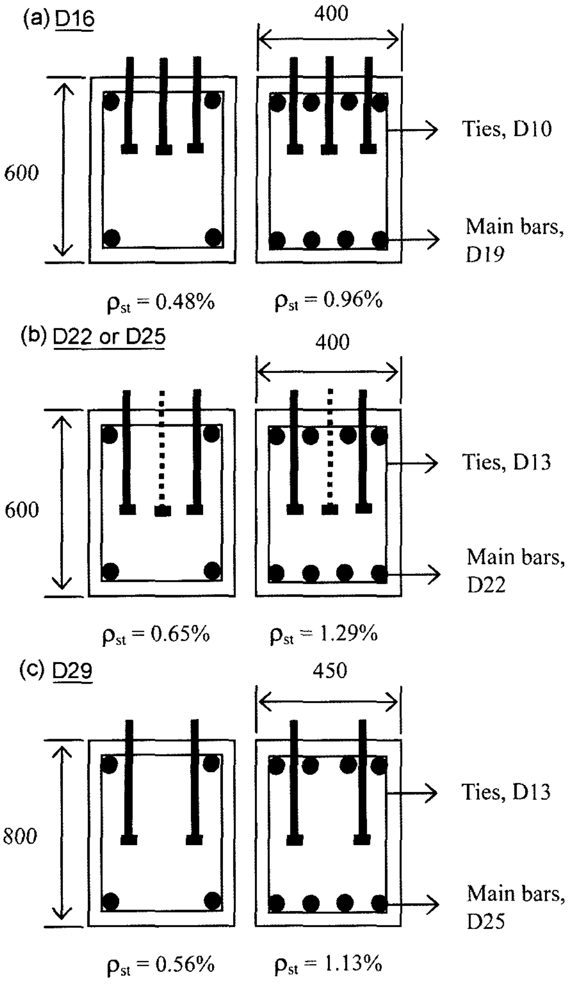


Fig. 4 Cross sections of reinforced concrete columns.

gauges were installed on the specimens with S_{tie} of $6d_b$, and one pair of strain gauges were installed on the specimen with S_{tie} of $9d_b$ as shown in Fig. 6(a). The position of strain gages installed on the column main reinforcement was 60 mm away from the headed bar while the three pairs of strain gages were installed on the stem as shown in Fig. 6(b); 'head-1' right above the head, 'head-3' right below the concrete face, and 'head-2' in the middle between 'head-1' and 'head-3.'

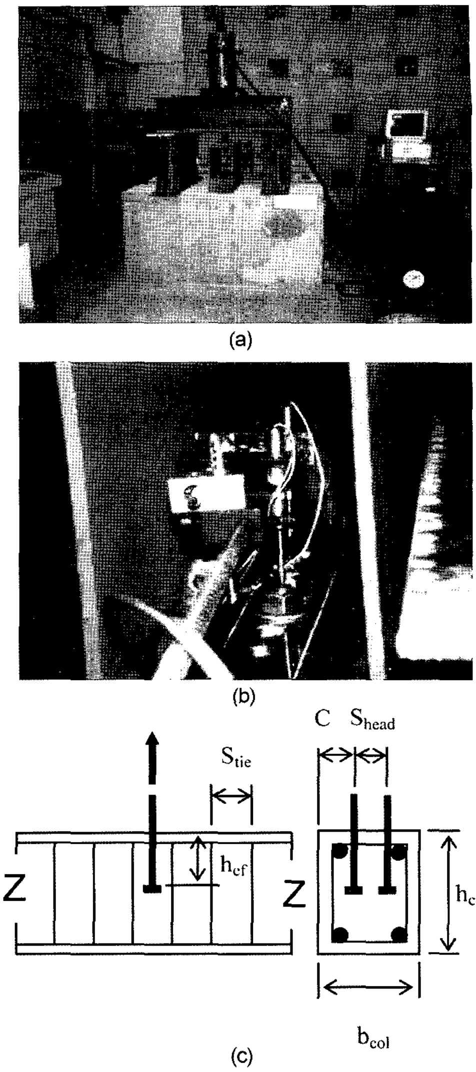


Fig. 5 Pullout test setup.

3. Test results

3.1 Pullout strength

3.1.1 Pullout tests: $h_{ef} = 10d_b$

The results of eight pullout tests for two of D29 headed bars

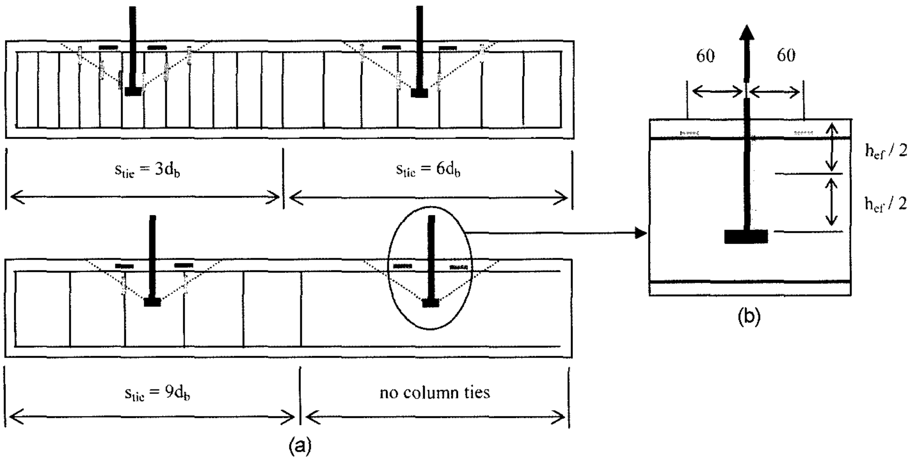


Fig. 6 Position of strain gauges.

with $h_{ef}= 10d_b$ (290 mm) as summarized in Table 2 reveal that the average pullout strength of two of D29 headed bars is 435 kN or 338 MPa for each headed bar, which is equivalent to 80.6% of f_y. Test results indicate that the embedment depth of $10d_b$ is not sufficient to make each of the relatively closely installed headed bars (S_{head}= 174 mm or $6d_b$) develop the strength equivalent to f_y.

In Table 2, the pullout strength (P_n) ranges between 348 kN and 478 kN (or 64.5% and 88.6% of f_y) showing wide variations of the pullout resistance as determined from the same two of D29 headed bars because the pullout strengths are influenced by supplementary reinforcement, i.e. existence of the column reinforcement. The pullout strength increases with decreasing column tiespacing (S_{tie}) as shown in Fig. 7. In Table 2 and Fig. 7, the average P_n of two of D29 headed bars with the smallest tie spacing ($S_{tie} = 3d_b$) is 465 kN while that of two of D29 headed bars with no column tie is 395 kN. The average P_n of the headed bars with the smallest tie spacing is 17.7% greater than the average P_n of those without any column ties.

The test results are consistent in that P_n keeps increasing with decreasing column tie spacing while this tendency is more conspicuous for the pullout specimens with column-like members of a lower main reinforcement ratio (ρ_{st}= 0.56%). Table 2 shows that, the pullout strengths of the two of D29 headed bars with two different column main reinforcement ratios are not the same. The average P_n of four tests with ρ_{st} = 0.56% is 402 kN while that of four tests with ρ_{st} = 1.13% is 467 kN, showing a difference of 16.2%. The test results indicate that P_n increases with increasing amount of main reinforcement as well as decreasing column tie spacing.

3.1.2 Pullout tests: $h_{ef}= 13d_b$

Table 2 shows that the average P_n determined from six tests of two of D25 headed bars with h_{ef} = $13d_b$ (330 mm) is 532 kN (or 525 MPa equivalent to 125% of f_y for each headed bar). Although the average pullout strength is 125% of f_y in all six completed pullout tests, the pullout strengths are smaller than 125% of f_y in at least two tests (C25-13db-2E-L and C25-13db-2E-M), indicating that the employed embedment depth of $13d_b$ is not large enough for the actual use of the headed bars in the field especially when the bars are installed closer than $8d_b$ (S_{head} is 200 mm or $8d_b$ for this set of six tests).

Table 2 and Fig. 8 show that P_n ranges between 408 kN and 605 kN again, showing wide variations in the pullout strengths. In Table 2, the average P_n of two of D25 headed bars with the smallest tie spacing (S_{tie} = $4.5d_b$) is 584 kN, and that for the specimens without any column ties is 444 kN. There is a significant 31.5% difference in the pullout strengths. Test results again reveal that P_n increases consistently with decreasing column tie spacing as shown in Table 2 and Fig. 8.

The pullout strengths of the two of D25 headed bars with two different column main reinforcement ratios are not the same. The average P_n of three tests with ρ_{st} = 0.65% is 507 kN while that of three tests with ρ_{st} = 1.29% is 557 kN, showing a 9.9% difference. The test results again indicate that P_n increases with increasing amount of main reinforcement.

3.1.3 Pullout tests: $h_{ef}= 15d_b$

Although the headed bar embedment depth of $13d_b$ resulted in an average pullout strength of 125% of f_y as determined from the above six tests, the results obtained from the test of two headed bars that were as much as $8d_b$ apart from each other (S_{head} = $8d_b$). It is possible that multiple headed bars with smaller center-to-center distance between adjacent heads may result in pullout strengths less than that currently determined. Consequently, in the next three sets of pullout tests, an embedment depth of $15d_b$ was tried for 3 D16, 3 D22, and 2 D29 headed bars for pullout.

Table 2 shows that the average pullout strength determined from six tests of three of D16 headed bars with h_{ef} = $15d_b$ (240 mm) and S_{head} = $9d_b$ (144 mm) is 331 kN (or 555 MPa equivalent to 132% of f_y for each headed bar). The average pullout strength determined from six tests of two of D29 headed bars with h_{ef} = $15d_b$ (435 mm) and S_{head} = $6d_b$ (174 mm) is 716 kN (or 558 MPa equivalent to 133% of f_y for each headed bar). Also, Table 2 shows that the average pullout strength determined from six tests of three of D22 headed bars with h_{ef}= $15d_b$ (330 mm) and S_{head}= $4.5d_b$ (100 mm) is 573 kN (or 493 MPa equivalent to

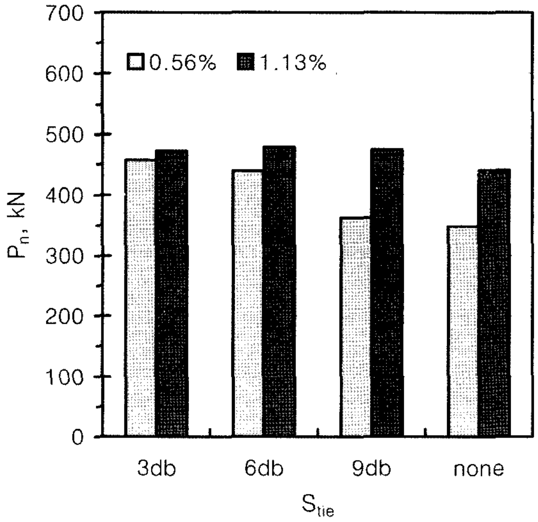


Fig. 7 Summary of pullout strength: two of D29 headed bars, h_{ef}= $10d_b$, S_{head}= $6d_b$, ρ_{st}= 0.56% or 1.13%.

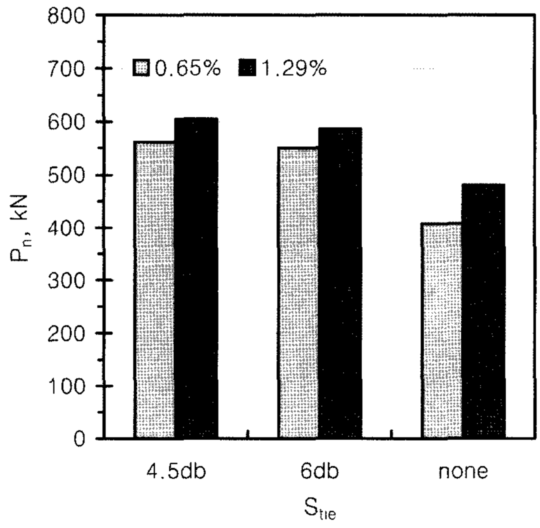
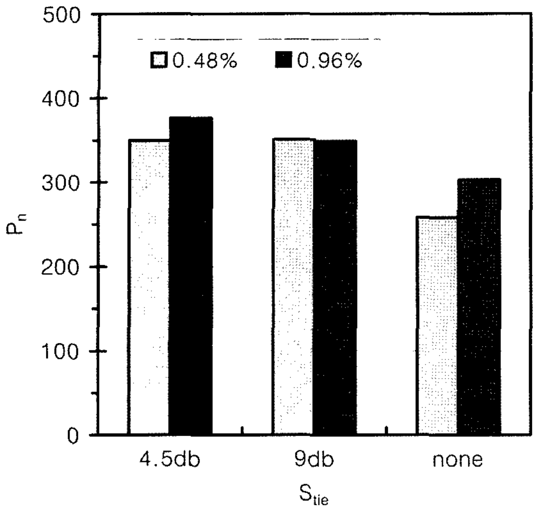
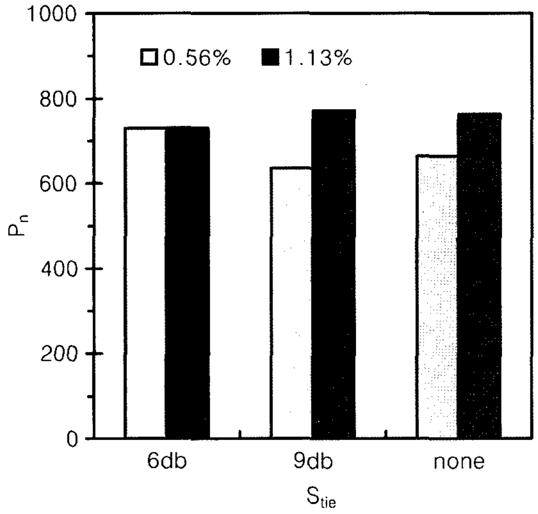


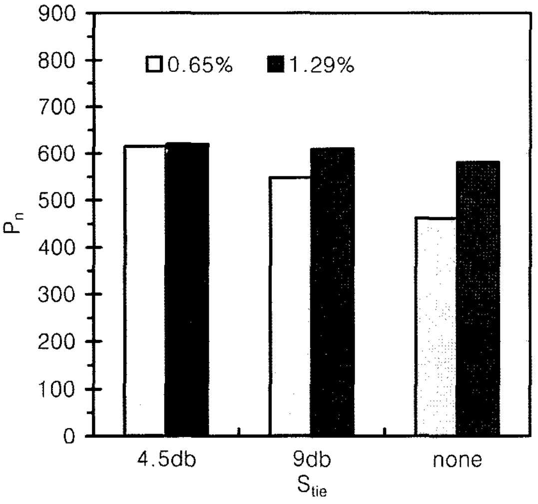
Fig. 8 Summary of pullout strength: 2D25 headed bars, h_{ef}= $13d_b$, S_{head}= $8d_b$, ρ_{st}= 0.65% or 1.29%.



(a) 3D16 headed bars, $S_{head} = 9d_b$, ρ_{st} = 0.48% or 0.96%



(b) 2D29 headed bars, $S_{head} = 6d_b$, ρ_{st} = 0.56% or 1.13%



(c) 3D22 headed bars, $S_{head} = 4.5d_b$, ρ_{st} = 0.65% or 1.29%

Fig. 9 Summary of pullout strength: $h_{ef} = 15d_b$.

117% of f_y for each headed bar).

Fig. 9 shows the influence of existing column reinforcements, both main reinforcement and ties, on the pullout strength of the headed bars. The pullout strengths increase with decreasing column tie spacing. The test results are consistent as shown in Figs. 9(a) and (c), and the deviation from this trend for the case of two of D29 is probably an outlier in the test data in Fig. 9(b). Also, Table 2 and Fig. 9 show that the pullout strengths of the headed bars installed in column-like members with greater amount of main reinforcement are consistently higher than those installed in column-like members with smaller amount of the main reinforcement. The difference is 7.2%, 11.3%, and 11.5% for three of D16, 3D22, and two of D29 headed bars, respectively.

3.2 Pullout load vs. displacement

The existing column reinforcements, both main bars and column ties, contribute not only to increase the pullout strength of the headed bars but also to improve the ductile behavior in pullout as shown in Fig. 10. Fig. 10 shows the load-displacement plots of three of D22 headed bars (a test set with the smallest center-to-center distance between adjacent heads). In Fig. 10(a), only one specimen named "C22-15db-3B-L" develops the pullout strength equivalent to 125% of f_y. Two other specimens develop strength smaller than 125% of f_y and also show less ductile behaviors than "C22-15db-3B-L". On the other hand, Fig. 10(b) shows that the pullout strengths practically equivalent to 125% of f_y are attained in all three specimens. All specimens also show ductile behaviors. The column main reinforcement must have influenced the pullout behaviors because, between the two different sets of the pullout tests, only ρ_{st} was changed from 0.65% to 1.29%. The load-displacement plots clearly reveal that column reinforcement is important in improving the strength and the ductile pullout behavior of the headed bars.

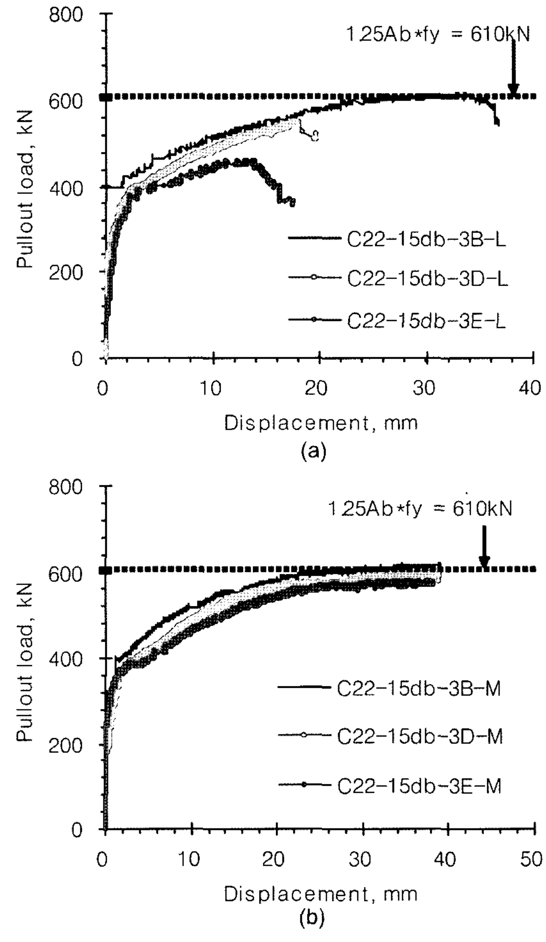


Fig. 10 Pullout load vs. displacement: 3D22, $h_{ef} = 15d_b$.

3.3 Failure mode

In all pullout tests, the headed bars were typically pulled out very slowly as the load was increased. A brittle concrete breakout was not observed. No bar fractures were encountered neither except for one test of D16 bars where one of three headed bars fractured in tension. Fig. 11 shows a crack pattern obtained from a pullout test specimen after the completion of test (two of D29). The first cracks developed at the head location and progressed upward at an inclination approximately between 35° and 45°. As the load was further increased, splitting along the stem appeared. The splitting crack sometimes extended below the head position at a load close to the ultimate as shown in Fig. 11.

3.4 Strain gauge readings

The strain gauges were installed on the headed bar stem, column main reinforcement, and column ties for a set of eight pullout specimens as described previously. Readings from the strain gauges are shown in Figs. 12 and 13. The x-axis represents the strains developed in the column ties for Fig. 12(a) and stem for Fig. 12(b), while the y-axis represents the stresses developed in the stem in Fig. 12. All column ties do not exhibit large strains until about 70% of the peak stress is reached as shown in Fig. 12(a). Column ties close to the headed bar (tie-1, tie-2) develop large strains and contribute to increase P_n while a column tie far away from the headed bar (tie-3) develops very small strains and hence provides no contribution to P_n. In Fig. 12(b), strains developed in the upper part of the stem (close to the applied force) are larger than those developed in the lower part (close to head). The differences in the strain values indicate that the bond between concrete and stem is not broken even at the peak load, and the anchorage relies on the bearing stress at the small head combined with the bond stress over the stem.

In Fig. 13, the x-axis represents the strains developed in the column ties while the y-axis represents the stresses developed in the stem. The stress-strain plots determined from the three tests again show that column ties close to the headed bar develop large strains and contribute to increase P_n.

In Fig. 14, the positions of the column ties, that developed large strains and hence were effective in increasing P_n are shown. Fig. 14

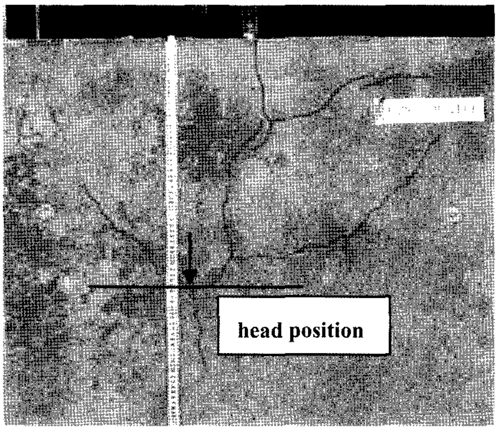
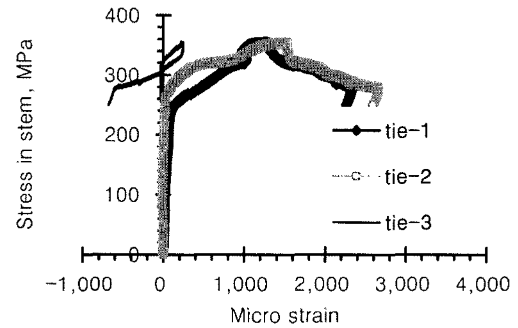
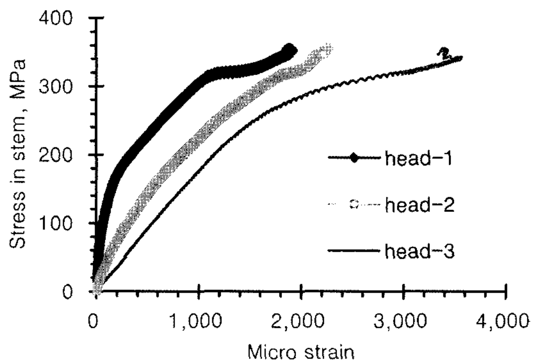


Fig. 11 A Pullout test specimen after the completion of the test.

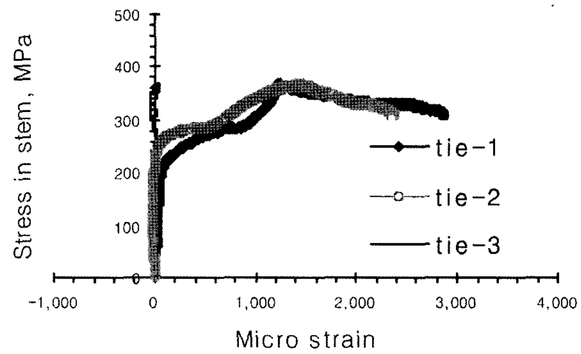


(a) Column ties

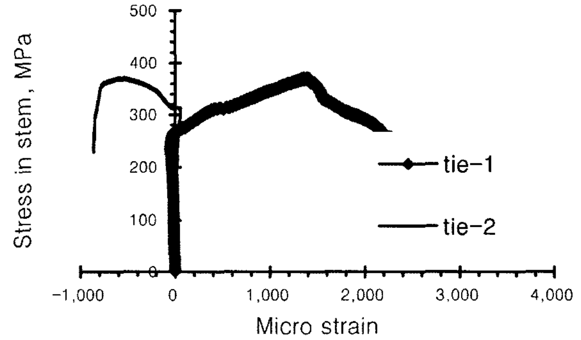


(b) Headed bar

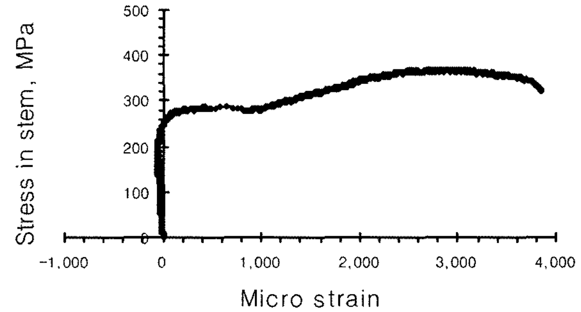
Fig. 12 Stress in stem vs. strains in col. ties and headed bar: C29-10db-2A-L.



(a) C29-10db-2A-M



(b) C29-10db-2C-M



(c) C29-10db-2D-M

Fig. 13 Stress of stem vs. strain in column ties.

reveals that the column ties that are located within a distance equal to 0.45 * h_{ef} from the headed bar contribute to P_n.

3.5 Analysis of test results

Fig. 15 shows a relationship between the column ties and the pullout strength of the headed bars. Fig. 15(a) shows the results of eight tests of two of D29 headed bars with an embedment depth of 10d_b; x-axis represents the volumetric ratio of the column ties to concrete. The pullout strength increases with the use of increasing amount of column ties as shown in Fig. 15(a). Fig. 15(b) shows the results of 24 tests with an embedment depth of 13d_b (2D25) and 15d_b (3D16, 3D22, and two of D29). The pullout strengths again increase with the use of increasing amount of column ties as shown in Fig. 15(b). In Fig. 15(b), a dashed line indicates that the pullout strengths are always over 125% of f_y when the volumetric ratio of the column ties to concrete is 0.6% or greater. Test results reveal that by employing an embedment depth of 13d_b or greater and, at the same time, using the column ties with a volumetric ratio of 0.6% and greater, the headed bars develop pullout strength over 125% of f_y, the minimum strength specified by the ACI code.[15]

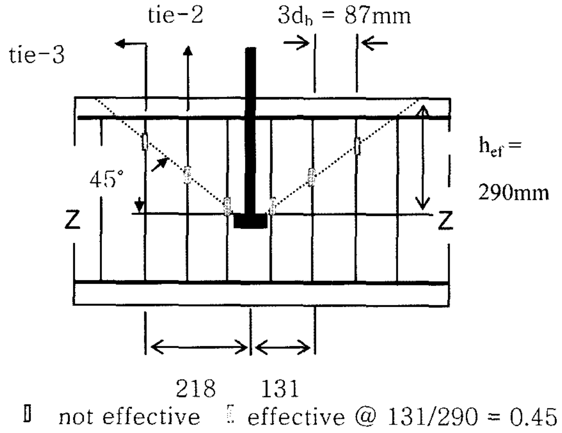
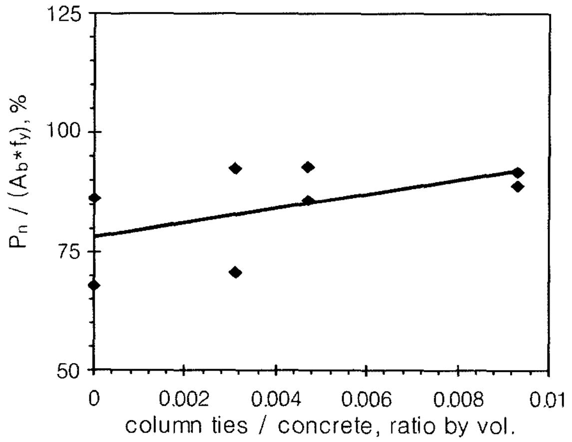
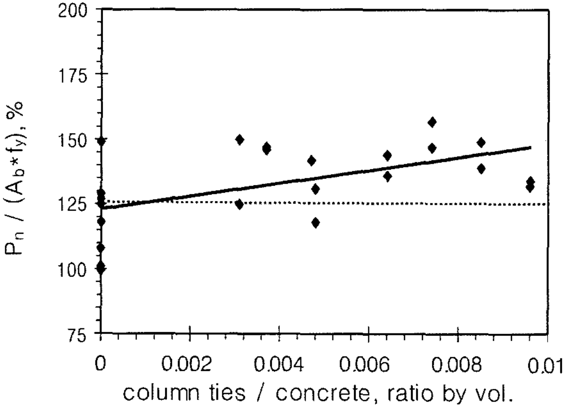


Fig. 14 Position of effective column ties: C29-10db-2A.



(a) 2D29 (h_{ef} = 10d_b)



(b) 2D25(h_{ef} = 13d_b), 3D16, 3D22, 2D29 (h_{ef} = 15d_b)

Fig. 15 Influence of column ties on pullout strength.

It should be noted that, in Fig. 15(b) there are scatters in the pullout strengths when the volumetric ratio is null. The strengths vary because they must rely on less predictable behaviors of concrete only when no column ties are used.

It is noted that the current conclusion is applicable only to headed bars installed in normal strength concrete when the center-to-center distance between adjacent heads is 4.5d_b and greater. The pullout behavior of a group of headed bars with smaller center-to-center distance between adjacent heads must be investigated in the follow-up research.

Fig. 16 shows a relationship between the column main reinforcement and the pullout strength of the headed bars. The pullout strengths consistently increase with increasing main reinforcement ratios as shown in Fig. 16. The average slope of the linear regression lines in Fig. 16 is 21.3 MPa/% of main bars while the minimum is 18.2 MPa/% of main bars. Test results suggest that the pullout strength of the headed bars can increase by about 18 MPa for one percent increment of column main bars. It should be noted here that the main reinforcement ratio up to 1.29% was tested in the current study.

Finally, Table 2 shows that, for the specimens with an embedment depth of 13d_b or 15d_b and with both column ties and a column main reinforcement ratio of 0.96% and greater, the pullout strength is always over 125% of f_y. Consequently, It is recommended to use at least 0.6% of column ties by volume, 1% or greater amount of column main bars, and an embedment depth of 13d_b or greater to guarantee the pullout strength of individual headed bars over 125% of f_y and the ductile behavior of multiple headed bars.

4. Conclusions

Pullout tests were performed on the multiple headed bars rela-

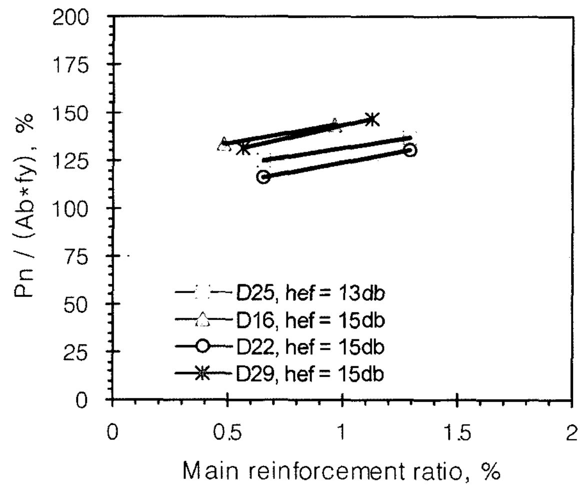


Fig. 16 Influence of the main reinforcement on pullout strength.

tively deeply embedded in reinforced concrete columns with an objective to determine the minimum embedment depth that was necessary to safely design exterior beam-column joints using headed bars. It was assumed that the headed bars were the main reinforcement of the beam and embedded in the column as shown in Fig. 2. The pullout test variables were embedment depth, center-to-center distance between adjacent heads, column tie spacing, and main reinforcement ratio. Pullout test results of headed bars installed in normal strength concrete revealed the followings:

1) The embedment depth of $10d_b$ is not sufficient to have the relatively closely installed headed bars develop the strength corresponding to f_y.

2) The pullout strength of individual headed bars is reduced when a closely spaced headed bar group is subjected to pullout.

3) The pullout strengths of headed bars increase with the use of supplementary reinforcement. In this study, the pullout strengths increased with increasing amount of column ties (or reinforcement designed to run in a direction parallel to the headed bars, refer to Fig. 2).

4) The pullout strengths of headed bars also increase with increasing amount of main reinforcement (or reinforcement designed to run perpendicular to the headed bars, refer to Fig. 2).

5) For a group of closely-spaced headed bars, it is recommended to use at least 0.6% of column ties by volume, 1% or greater amount of column main bars, and an embedment depth of $13d_b$ or greater simultaneously to guarantee the pullout strength of individual headed bars over 125% of f_y and the ductile load-displacement behavior.

6) The above conclusion is applicable when the center-to-center distance between adjacent heads is $4.5d_b$ or greater. The pullout behavior of a group of headed bars with smaller center-to-center distance between adjacent heads should be investigated in the follow-up research.

In addition, readings obtained from the strain gauges installed on the headed bar stem, column main reinforcement, and column ties reveal the followings:

1) The bond between concrete and stem was not broken at the peak load, and the anchorage can rely on the bearing stress at the small head combined with the bond stress over the stem.

2) Most column ties do not exhibit large strains until about 70% of the peak stress is reached. Thus, column ties are likely to contribute to increasing the ultimate strength of the headed bars and do not play a significant role in the service stage.

3) Only those column ties that are located within a distance of 0.45 times the embedment depth from the headed bar contribute to increase the pullout strength.

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