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Pullout strength of high strength headed reinforcement vertically jointed to RC member

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ABSTRACT: Presented in this paper is a result of an experimental study for assessing the development performance of a high strength headed reinforcing bar which is vertically jointed along the axial direction to a reinforced concrete member, by assuming the development length of headed reinforcement, distance between the centers of each head, existence of hoop, etc. The result showed that the longer the development length, the higher the maximum strength, while the center-to-center distance between heads did not significantly affect the maximum strength. The maximum strength of a test subject which is equipped with hoops around the headed reinforcement is 86.0% higher than that of another subject which is not prepared with hoops, proving that the confinement details of the headed reinforcement are of paramount importance. While the theoretical strength derived from the CCD method underestimates the experimental strength, a theoretical strength estimated by using the ACI 318-11 development length formula assesses the experimental strength as unsafe.
KEYWORDS-headed reinforcement, development length, reinforced concrete, bond, high strength

I. INTRODUCTION

Generally, a standard hook rebar is used for the settlement design of the RC joint between the exterior column and girder. However, the standard hook rebar anchorage details become difficult in construction, including the placement of rebar and concrete, when the rebar is densely arranged on the column-beam joint. Since 2000, a mechanical anchorage design method has been suggested to resolve this.

The headed reinforcement comprises a circular or rectangular-cross sectional head with a predetermined thickness as a bearing plate on the end of the rebar and a deformed bar which is jointed with the head. The performance of anchorage regarding the headed reinforcement is influenced by the concrete strength, rebar strength, head shape, head area, edge distance, embedment length, etc.[2], [3], [4] The headed reinforcement must secure the embedment length which can demonstrate a sufficient tensile resistance above 125% the actual yield strength of the rebar, since it is a type of a mechanical contrivance. If a sufficient embedment length has been secured, it can demonstrate the stress exceeding the rebar yield strength. Otherwise, a concrete failure occurs.

Since the 1990s, the requirements for designs and experimental methods of headed reinforcement are being actively suggested, based on studies in the U.S., Japan, Canada, and Europe, including Germany. Also, various kinds of bar placement details which utilize the headed reinforcement are being suggested and utilized.

However, the results of these existing studies are mainly targeted for headed reinforcements with general strength of 400MPa yield strength, thus being difficult for their application to the high strength bar which is recently increasing in its uses. Especially, since more skyscrapers and large space structures are increasing the use of high strength bars for the reduction of concrete member cross section and enhancement of rebar construction, the needs for the settlement design of the high strength headed reinforcement are increasing.

In this study, for this matter, in order to use the high strength rebar for the anchorage details of headed reinforcement which is vertically jointed along the axial direction of reinforced concrete member, an experiment was conducted, in the purpose of assessing the bond performance of a headed reinforcement with the design yield strength of 600 MPa. In the experiment, a test subject, with its variables as the embedment length of headed reinforcement, distance between the centers of neighboring heads, the existence of hoop, etc., was manufactured, and was conducted with pullout test to assess the maximum strength and deformation performance. The result of the experiment was compared with the theoretical strength of the CCD method which is used for assessing the anchor strength of the existing mechanical anchoring steel. Also, the result was compared with the embedment length of ACI 318-11 headed reinforcement which is applied to the anchorage details of a headed reinforcement with general strength.

II. DEVELOPMENT STRENGTH AND LENGTH OF HEADED REINFORCEMENT

As of the existing standard regarding the headed reinforcement, a strength assessment formula using the CCD method, which is applied to the anchorage strength of a mechanically settled anchor, and ACI 318011 headed reinforcement embedment length calculation formula, which is based on the study of Thompson, were used.

2.1 Tensile strength calculation using the anchor strength of CCD method.

Regarding an anchor with a head which undergoes a concrete break-out failure, the design formula using the Concrete Capacity Design (CCD) method is reported as most appropriate for the assessment of anchor strength.The concrete break-out withstand strength based on the CCD design formula of an anchor group being stressed is as shown in Formula (1).

$$N_{cbg} = \frac{A_N}{A_{NO}} \psi_1 \psi_2 \psi_3 N_b \quad (1)$$

2.2 Calculation of embedment depth using ACI 318-11 embedment length [4]

Based on the study of Thompson [1], regarding the headed reinforcement in ACI 318-11, the embedment length (l_{dt}) of a general headed reinforcement, and not an epoxy-coated steel reinforcement, is as shown in Formula (2).

$$l_{dt} = \frac{0.19 \times d_b \times f_y}{\sqrt{f_{ck}}} \geq Max[8d_b, 150mm] \quad (2)$$

III. TENSILE EXPERIMENT

For the tensile performance experiment, high strength rebars with the design yield strength of 500MPa and 600MPa, respectively, made of KS standard SD500 and SD600 materials with 22mm diameter were used. Fig. 1 shows the specifications of the head and headed reinforcement. By using the swaging method, the edge of the rebar was processed with screws for the joint with the head. Table 1 shows the physical properties including the yield strength, tensile strength, and percentage of elongation derived from the material test result of the rebar which is used for the test subject. The compression strength of the concrete was 25MPa.

Fig. 1 Details of headed bar

Table 1Mechanical properties of reinforcing bars

Type of reinforcing bars	Cross-sectional area, A_s(mm^2)	Grade (KS standard)	Yield strength by test, f_y (MPa)	Tensile strength by test, f_u (MPa)	Elongation (%)
D10 (stirrup)	71.3	SD400	478.1	704.2	17
D16 (main bar)	198.6	SD400	428.3	632.3	19
D19 (main bar)	286.5	SD400	434.1	611.0	19
D25 (main bar)	506.7	SD400	454.7	600.8	18
D22(headed bar)	386.7	SD600	705.1	862.4	41

Five test subjects were manufactured, as shown in Table 2, with the variables including the embedment length of headed reinforcement, distance between the centers of neighboring heads, and existence of hoop.

The embedment lengths of rebar were set as 13, 15, and 20 times the diameter of rebar (d_b). With the test subject SD6-15db-2H8 as the standard, one test subject was designed with hoop, and another was altered of its head center-to-center distance from 8d_b to 4db. The sizes of the test subject's cross section (B×H, width×height) were set as 400mm×600mm, 400mm×700mm, and 400mm×900mm, according to the embedment length as shown in the specifications of Fig. 2. The length of all the test subject was 2000mm, and the column-to-main rebar ratios depending on the changes in the size of cross sections range from 1.1 to 1.6%.

Table 2 List of specimens

Specimens	**Size: B×H×L(mm)**	**Development length,h_{ef}(mm)**	**Spacing of headed bars(mm)**	**Spacing of stirrups(mm)**	**Ratio of main bars (%)**
SD6-13db-2H8	400×600×2000	286	144(8d)	--	1.39
SD6-15db-2H4	400×700×2000	330	156(4d)	--	1.19
SD6-15db-2H8	400×700×2000	330	144(8d)	--	1.19
SD6-20db-2H8	400×900×2000	440	144(8d)	--	1.16
SD6-15db-2TH8	400×700×2000	330	144(8d)	130(6d)	1.19

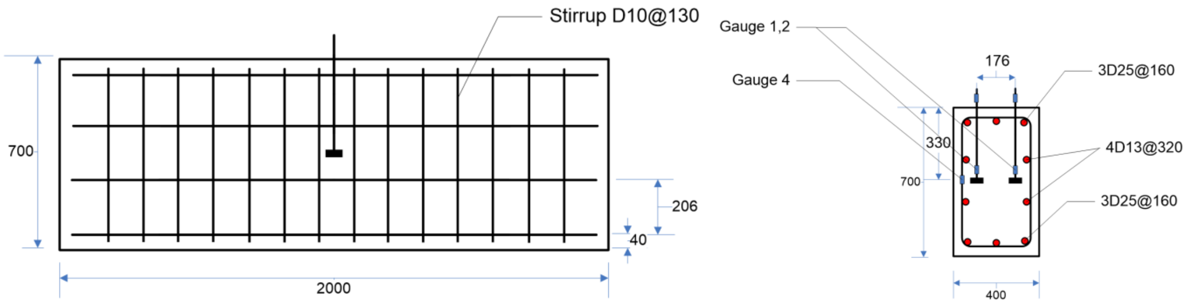

Fig. 2 Details of SD6-15db-2TH8 specimen (unit: mm)

Fig. 3 shows the test set-up subjects for pulling out the headed reinforcement. Two hollow hydraulic cylinders of 500kN were used to apply tensile force, and a load cell was used to measure the load. A linear variable differential transformer (LVDT) was installed to measure the tensile displacement, as shown in Figure 4. A rebar strain gauge was installed on the headed reinforcement, main rebar of the member, hoop, etc. to measure the strain rate.

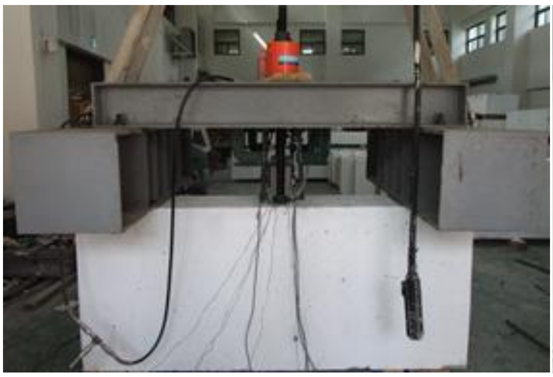

Fig. 3Test set-up

Fig. 4Setting of LVDT

IV. ANALYSIS OF THE RESULT

4.1 Aspect of crack and breakout failure

The shape and range of crack was similar across all the test subjects, and, as shown in Fig. 5, the crack led to the concrete breakout failure. No tensile rupture of the headed reinforcement occurred.

From the point where the head is embedded, an initial crack occurred along the vertical direction of the reinforced concrete member. After that, as the load increased, a crack occurred toward a direction 35～45°diagonal from the point where the head is receiving the bearing, eventually leading to failure, due to the increasing width of the crack.

4.2 Strength and load-displacement curves

Table 3 shows the maximum strength of the test subject, while Fig. 6 shows the test subject's load-displacement curve.

Compared to the test subject SD6-13db-2H8 with the embedment length of $13d_b$, the maximum strength of the test subjects which were altered of their embedment lengths to $15d_b$, and 20db were respectively increased by 28.7%, and 92.2%. The maximum strengths of the test subjects SD6-15db-2H8, and SD6-15db-2H4 which were set with the center-to-center distance as variable showed 3.0% difference, so the center-to-center distance did not influence the maximum strength significantly. The maximum strength of the test subject SD6-15db-2TH8, which was arranged with hoops around the headed reinforcement, was 86.0% higher than the test subject SD6-15db-2H8 which was not arranged with hoops. Also, the initial stiffness of the test subject SD6-15db-2TH8 was the highest among all the test subjects, its rebar showed a ductile behavior from the yielding to the final breakdown on the load-displacement curve.

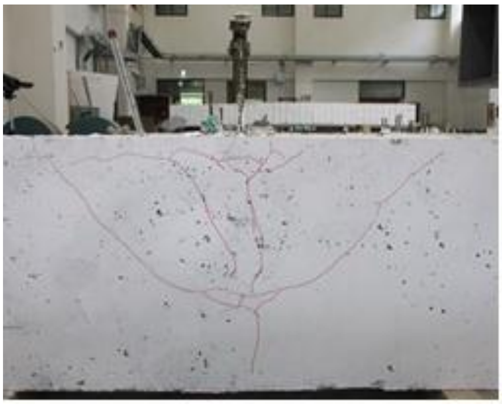

Fig. 5Typical failure mode

Table 3Test results

Specimens	P_{TEST} (kN)	f_{TEST} (MPa)	P_{CCD} (kN)	P_{TEST}/P_{CCD}	f_{ACI} (MPa)	f_{TEST}/f_{ACI}
SD6-13d-2H8	208.64	269.56	87.8	2.38	418.4	0.64
SD6-15d-2H4	260.88	337.05	95.3	2.74	482.8	0.70
SD6-15d-2H8	268.62	347.05	95.3	2.82	482.8	0.72
SD6-20d-2H8	400.92	517.98	112.9	3.55	643.7	0.80
SD6-15d-2TH8	485.2	626.87	95.3	5.09	482.8	1.30

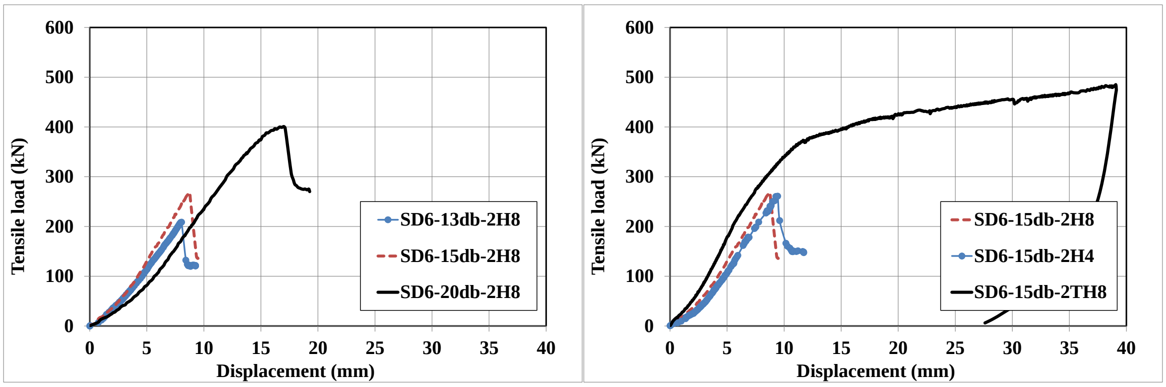

Fig. 6 Tensile load-displacement curves

4.3 Load-strain curves

Fig. 7 shows the relationship between the load and strain rate measured by the rebar strain gauge attached to the headed reinforcement. All the subjects showed insignificant deformation of the headed reinforcement until 60% of the maximum load, and the strain rate tremendously increased henceforth. While the test subject SD6-15db-2TH8 arranged with hoops experienced the deformation of headed reinforcement exceeding the yield strain rate, all the other test subjects which were not arranged with hoops did not undergo the yielding of headed reinforcements. Since the hoop confines the concrete around the headed reinforcement, it increases the bearing stress surrounding the head and significantly influences the increase of strength and ductile behavior.

Although the column main rebar shows a constantly increasing strain rate, drawing a parabola, due to the increase of tensile stress caused by the pullout, it did not undergo yielding.

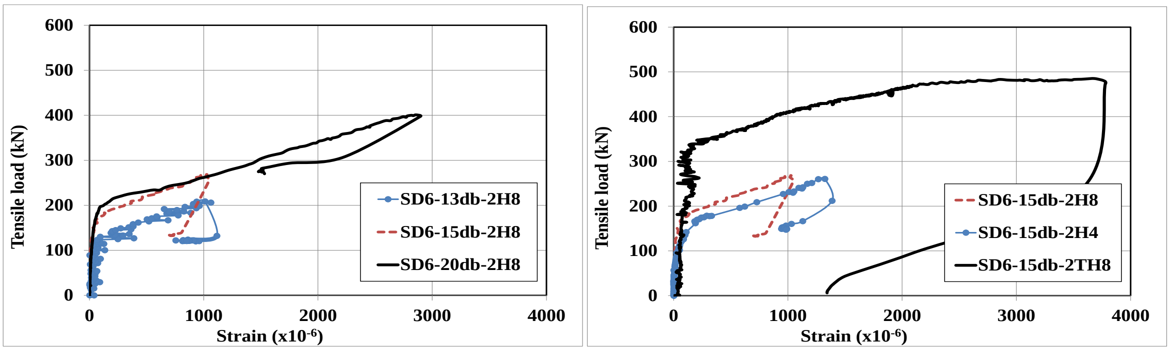

Fig. 7Tensile load-strain curves

4.4 Comparison between the theoretical strength and experimental strength

Ignoring the adhesive force of the headed reinforcement and assuming that the maximum force can be calculated by the concrete breakout failure resistance performance due to the bearing of the head, the theoretical strength was assessed, as shown in Table 3, by using Formula (1) of the CCD method.

The result of experimental maximum tensile force (P_{TEST}) / theoretical maximum tensile force (P_{CCD}) in Table 3 ranged from 2.38 to 5.09, showing that the theoretical force calculated by the CCD design method is being seriously underestimated. This may be due to inconsideration of the anchorage capacity due to the adhesion of the headed reinforcement, and to the introduction of safety factor of the CCD assessment formula based on the 5% probability of failure.

By using the embedment length calculation formula of general strength headed reinforcement, which yield strength is limited to 420MPa in ACI 318-11, in order to apply the actual material test strength, the embedment length of the test subjects resulted in 589.5mm. The embedment length by ACI 318-11 formula was assumed as having secured 1.25 times the yield strength or the strength in which the rebar undergoes the tensile rupture. The theoretical strength was estimated based on this, and is shown in Table 3.

In Table 3, the test subjects which are not arranged with hoops show the experimental tensile strength (f_{TEST}) / theoretical tensile strength (f_{ACI}) ranging from 0.64 to 0.80, stating that the ACI design formula assesses the experimental strength as unsafe. However, the test subject SD6-15db-2TH8 arranged with hoops shows 30% increased tensile strength of 626.9MPa, compared with the theoretical tensile strength of 482.8MPa, verifying that the confinement details of the headed reinforcement are of paramount importance.

V. CONCLUSION

In this study, in order to assess the anchorage capacity of a high strength headed reinforcement which is vertically jointed to the reinforcement concrete member along the axial direction, a tensile experiment was conducted. The results of the experiment can be arranged as the following.

1) All the test subjects experienced cracks 35～45°diagonal from the point where the head receives bearing, leading to the concrete breakout failure, with no tensile rupture of the headed reinforcement.

2) The longer the embedment length, the higher the maximum strength. The increment of the maximum strength of the test subjects was greater than the increment of the embedment length.

3) The distance between the centers of neighboring heads did not significantly influence the maximum strength. The maximum strength of the test subject arranged with hoops around the headed reinforcement showed 86.0% increase in strength, compared to the test subject not arranged with hoops, verifying that the confinement details of the headed reinforcement are very important.

4) The comparison between the theoretical force by using the CCD method (P_{CCD}), and the experimental force (P_{TEST}) showed the ratio of P_{TEST}/P_{CCD} ranging from 2.38 to 5.09, implying that the theoretical strength calculated by the CCD design method overly underestimates the experimental strength.

5) The comparison between the theoretical strength estimated by using ACI 318-11 embedment length calculation formula (f_{TEST}) and the experimental strength (f_{ACI}) showed that the ratio f_{TEST}/f_{ACI} of the test subject not arranged with hoops was 0.64 to 0.80, stating unsafety, whereas the test subject arranged with hoops showed that ratio f_{TEST}/f_{ACI} as 1.30.

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