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Pullout Test of Headed Reinforcing Bar in RC or SFRC Members with Side-Face Blowout Failure

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Abstract In this study, side-face blowout failure strength of high strength headed reinforcing bar, which is vertically anchoring between RC or SFRC members, is evaluated throughout pullout test. The major test parameters are content ratio of high strength steel fibers, strength of rebar, length of anchorage, presence of shear reinforcement, and the side concrete cover thickness planned to be 1.3 times of the rebar. In pullout test, tensile force was applied to the headed reinforcing bar with the hinged supports positioned 1.5 and 0.7 times the anchorage length on both sides of the headed reinforcing bar. As a result, the cone-shaped crack occurred where the headed reinforcing bar embedded and finally side-face blowout failure caused by bearing pressure of the headed reinforcing bar. The tensile strength of specimens increased by 13.0 ~26.2% with shear reinforcement. The pullout strength of the specimens increased by 3.6 ~15.4% according to steel fiber reinforcement. Increasing the anchoring length and shear reinforcement were evaluated to reduce the stress bearing ration of the total stress.

Keywords: headed reinforcing bar, anchorage, bond, pullout test.

1. INTRODUCTION

The development of construction material technology rapidly progressed in the 20th century, therefore the demand for large structures such as high-rise building, long-range structures and nuclear power plant structures has been increasing. Consequently, the use of high strength reinforcing bars has increased significantly to improve constructability and structural safety in civil and building structures. High strength reinforcement has many advantages over the reduction of rebar usages compared to normal reinforcing bars. However, the anchorage length and lap splice length increment problem occur in terms of anchorage and lap splice design. Specially, joint design can be difficult due to limited space in the inter-member joints. Thus, using headed reinforcing bar with the mechanical anchorage detail can be effective solution. High strength rebar detail using mechanical anchorage may have the effect on the reduction of member and joint size, The shortening of construction time, the precise construction, and the labor cost reduction.

The current American Concrete Institute (ACI 318) and Korean Concrete Standard (KDS 14 20, KCI 12) specify the method of anchoring the headed reinforcing bar. Also, in ACI 318-14 and KCI 2012 state the yield strength of the headed reinforcing bar to 420 MPa and 400MPa.

Recently, KCI 2017 expanded the maximum yield strength of headed reinforcing bar to 600 MPa, but it is not yet applied as a national standard. Therefore, it is difficult to apply mechanical anchorage details to high strength rebars of 500 MPa or higher on-site.

Concrete has a disadvantage of having very little tensile resistance compared to compression. To compensate for this, the research and development of fiber reinforced concrete has been carried out since the 1970s, which improved the disadvantage of concrete by mixing the fibers into the concrete.

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In particular, the use of steel fiber reinforced concrete(SFRC) is increasing to induce ductile behavior of concrete and improve mechanical properties. Chun et al.(2016) have evaluated SFRC as contributing to the improvement of anchorage strength of headed reinforcing bar. Mechanical anchorage details for SFRC members and joints require design equations that are different from those of ordinary concrete.

The calculation of the anchorage performance of the headed reinforcing bar is highly influenced by the materials used, types of components and joints, working stress, and detail of anchoring reinforcement. Thus, much research is needed.

The purpose of this study was to investigate the detailed performance of mechanical anchorage of side fractured headed reinforcing bar in the vertical joint between RC members or SFRC members with high strength headed reinforcing bar. The test parameters are included content rate of steel fiber, strength of rebar, length of anchorage and presence of shear reinforcement.

2. EQUATIONS OF MECHANICAL ANCHORAGE

2.1 EQUATION OF ANCHORAGE LENGTH

In KCI 2012 and ACI 318-14, the anchorage length (l_dt) of the headed reinforcing bar is as shown in Eq. (1). In KCI 2017, the length of headed reinforcing bar is designed differently depending on the applied details, and the beam-column joint except for the uppermost floor is presented as Eq. (2). Considering the effect of thickness of concrete cover and reinforcing details.

$$l_{dt,KCI2012} = 0.19\frac{\beta f_y d_b}{\sqrt{f_{ck}}} \tag{1}$$

$$l_{dt,KCI2017} = 0.22\frac{\beta f_y d_b}{\psi\sqrt{f_{ck}}} \tag{2}$$

Where (1) and (2) describe the experiment parameter β for epoxy reinforcing bar 1.2, in other cases 1.0, f_y for design yield strength of the rebar in MPa, d_b is the diameter of the headed reinforcing bar, f_{ck} is the design compressive strength of concrete. ψ is influence coefficient due to side coating and transverse reinforcement.

2.2 Side-face blowout strength equation

Chun et al. (2016) presented the side-face blowout strength ($f_{p, Chun}$) through regression analysis based on the experiment of the headed reinforcing bar applied to the beam-column joint for SUPER Concrete as shown in Eq. (3). The headed reinforcing bar used in the experiment was a high strength reinforcement of SD600.

$$f_{p,Chun} = (3\frac{l_{dt}}{d_b} + 31)(0.75 + 0.25\frac{c_{so}}{d_b})\sqrt{f_{ck}} \tag{3}$$

Where c_{so} is the side coating thickness(mm), l_{dt} is the embedment depth of the high strength headed reinforcing bar, f_{ck} is the design compressive strength of concrete, and d_b is the diameter of high strength headed reinforcing bar.

3. TEST OF ANCHORAGE PERFORMANCE

3.1 TEST PLAN

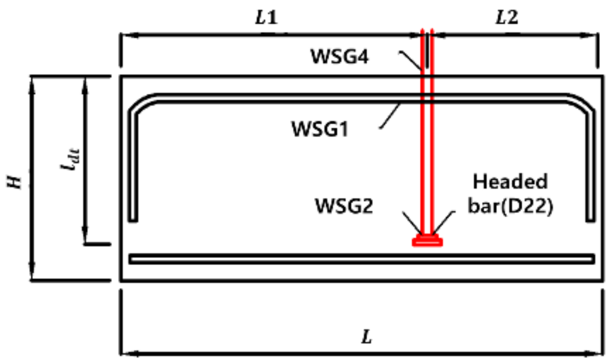
In this study, a simplified test specimen was planned which the tensile force was applied directly to the headed reinforcing bar without making the horizontal member used as the main reinforcement at the connections between RC member and SFRC members, and the compressive force was carried out at a point considering the effective depth.

A total of 10 specimens were produced as shown in Table 1 The experiment parameters include steel fiber mixing rate (NC: 0%, SC: SFRC 1%), design compressive strength of concrete (24: C24, 40: C40), strength of reinforcement (S5: SD500, S6: SD600), length of anchorage (H350: 270mm, H450: 370mm), shear reinforcement (C0: no-details, C1: D10@80). Figure.1 shows the details of specimens with or without shear reinforcement.

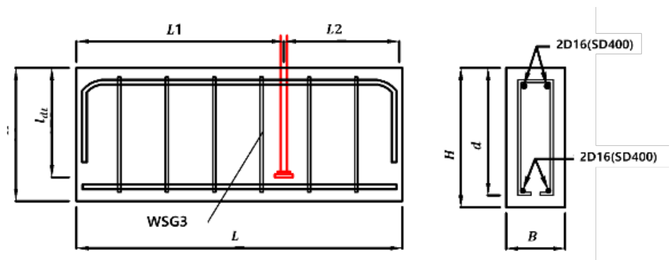
Table 1. Test matrix

Specimen	Volume ratio of steel fiber (%)	f_{ck} (MPa)	Headed bar	l_{dt} (mm)
NC24-S5-H450-C0	0 %	24	SD500	370
NC24-S6-H450-C0	0 %	24	SD600	370
NC40-S6-H350-C0	0 %	40	SD600	270
NC24-S5-H450-C1	0 %	24	SD500	370
NC24-S6-H350-C1	0 %	24	SD600	270
NC24-S6-H450-C1	0 %	24	SD600	370
NC40-S5-H350-C1	0 %	40	SD500	270
NC40-S6-H350-C1	0 %	40	SD600	270
SC24-S6-H350-C1	1.0 %	24	SD600	270
SC24-S6-H450-C1	1.0 %	24	SD600	370

The diameter of the high strength headed reinforcing bar was planned to be D22. The height of test specimen was set-upped by adding 80 mm to the anchorage length of the headed reinforcing bar. The upper and lower reinforcing bars used two D16 of SD400. To induce side-face blowout failure, the side concrete cover thickness (c_{so}) of all the specimens was equally designed to be $1.3d_b$.



(a) C0 series specimens



(b) C1 series specimens

Figure 1. Detailed view of the specimens

3.2 TEST PROCEDURE AND INSTRUMENTATION

Figure 2. Test setup

Figure 2 shows the details of specimen installation. The hinge was positioned at $1.5l_{dt}$ to one side the vertically reinforced high strength headed reinforcing bar. It is considered that the concrete breakout failure occurs when the point is set at 1.5 times or more of the anchorage length. Also, on the other side of the headed reinforcing bar, in consideration of the effective depth of the member joint to the point, the steel plate was formed by assuming a compressive stress block to receive a compressive stress of $0.7l_{dt}$.

The 2000kN Universal Transverse Mercator coordinate system (UTM) was used to apply the pullout load to the headed reinforcing bar, and the displacement was measured as the relative displacement between the draw grip positions holding the headed reinforcing bar from the point.

In order to evaluate the bearing stress acting on the headed reinforcing bar and the tensile stress acting on the rebar, strain gauges (WSG) were attached to the positions of WSG2 and WSG4 (Figure 1).

4. ANALYSIS OF TEST RESULT

4.1 The result of material test

A cylindrical standard specimen of 100 x 200 mm was fabricated to test the concrete compressive strength (f_{ck}). Compressive strength test was performed using Universal Testing Machine (UTM) according to KS F 2405. The concrete compressive strength test was carried out after 28 days of casting, and the test results are shown in Table 2.

Table 2. Test results of concrete materials

Series	f_{ck} (MPa)			
	1	2	3	Mean
NC24	34.5	35.8	36.8	35.70
NC40	49.9	51.8	54.3	52.00
SC24	36.6	36.6	36.8	36.67

The result of tensile strength of rebar is shown in Table 3. The tensile force velocity is applied as standard with a rate of change of 3MPa/sec of rebar stress in accordance with KS B 0802(KSA 2003).

Table 3. Results of tensile test of headed reinforcing bar

Series	f_y (MPa)	f_u (MPa)	f_y/f_u (%)	E_s (GPa)	ε_{elo} (%)
D22 (SD500)	514	642	80	181	38
D22 (SD600)	639	784	82	190	17
D16 (SD400)	428	585	73	198	16
D10 (SD400)	501	611	82	184	15

Notation: f_y means a yield strength, and f_u means a tensile strength, E_s means a modulus of resilience, ε_{elo} mean a extensibility

4.2 Damages and Failure Modes

The final failure mode of the specimen is shown in Fig 3. Every specimen showed similar failure mode. As pullout load began to increase, the cone-shaped crack started from the anchorage initiated headed reinforcing bar, spreading out to the top edged of the specimens. Subsequently, not only the cone-shaped crack occurred in the part of the concrete where the headed reinforcing bar was embedded, and the side fracture caused by the bearing stress of the headed reinforcing bar appeared, resulting in final failure.

(a) NC24-S5-H450-C0

(b) NC24-S5-H450-C1

(c) NC24-S6-H450-C1

(d) SC24-S6-H450-C1

(e) NC40-S5-H350-C1

(f) NC40-S6-H350-C1

(g) NC24-S6-H350-C1

(h) SC24-S6-H350-C1

Figure 3. Typical specimen failures

4.3 Load-Displacement Curve and Test Bearing Strength Relationship

Table 4 shows the maximum bearing strength (P_{max}), of each specimen, the maximum stress $f_{T,max}$ of the reinforcing bars at the maximum bearing strength, and the final failure mode (SF: side-face splitting fracture) of the specimen. Figure 4 shows the comparison of the Load-Displacement curves between the pullout loads and the displacements of the specimens. According to the Figure 4, the initial stiffness at 4 is similar for all the specimens.

The pullout strength of the NC system without reinforcing steel fiber was analyzed by increasing strength of concrete. The pullout strength of the NC40-S6-H350-C1 specimen was increased by 17.3% compared to the NC24-S6-H350-C1 specimen. In chapter 2, the existing equation is computed to be proportional to the square root of concrete strength. Among the concrete used in specimen, the increase rate for square root of concrete in compression is 20.7% and the increase rate of 17.3% is similar to that of conventional methods.

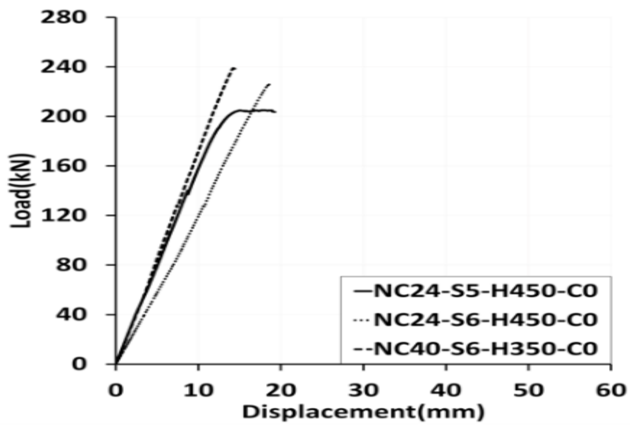
Table 4. Test result

Specimens	P_{max} (kN)	$f_{T,max}$ (MPa)	Failure Mode
NC24-S5-H450-C0	205.3	529.8	SF
NC24-S6-H450-C0	226.1	583.5	SF
NC40-S6-H350-C0	239.3	617.5	SF
NC24-S5-H450-C1	259.1	668.6	SF
NC24-S6-H350-C1	233.7	603.1	SF
NC24-S6-H450-C1	255.5	659.4	SF
NC40-S5-H350-C1	252.8	652.4	SF
NC40-S6-H350-C1	274.1	707.4	SF
SC24-S6-H350-C1	269.6	695.7	SF
SC24-S6-H450-C1	264.6	682.8	SF

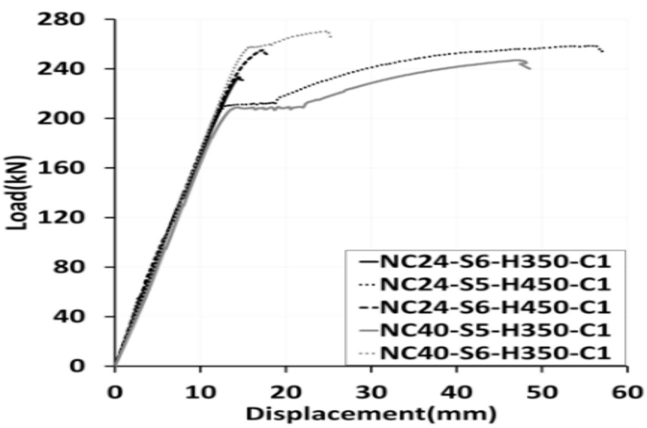
In comparison of pullout strength according to the reinforcement of steel fiber in figure 5(a), 3.6 to 15.4% strength was increased when it was reinforced with steel fiber. And the effect on steel fiber reinforcement was found to be greater when the length of anchorage was smaller. Considering the 1.3% increase in the square root of concrete compressive strength due to steel fiber reinforcement, the effect of increasing the pullout strength of steel fiber reinforcement is expected to be significant.

Comparing the pull-out strength according to reinforcement of shear in Figure 5(b) shows that C1 series of experiments with shear reinforcement placed at 80 mm intervals increased the pullout strength by 13.0% to 26.2% compared to those of C0 series without shear reinforcement.

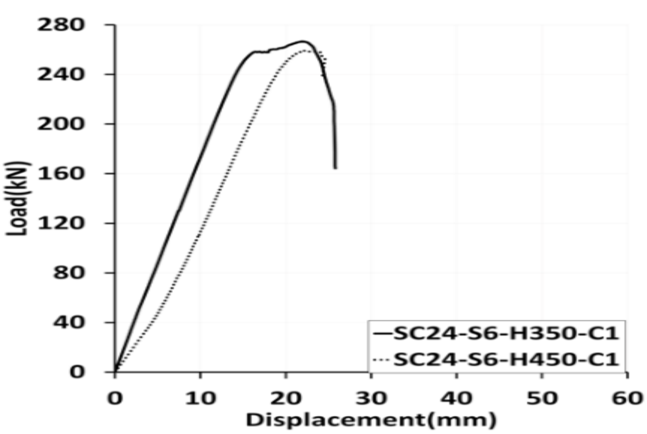
In comparison of pullout strength according to the anchorage length of Figure 5(c), the NC series tests showed a 9.3% increase in pullout strength. However, the SC series tests showed a 1.9% decrease in pullout strength. It is considered that the



(a) NC-C0 series specimens

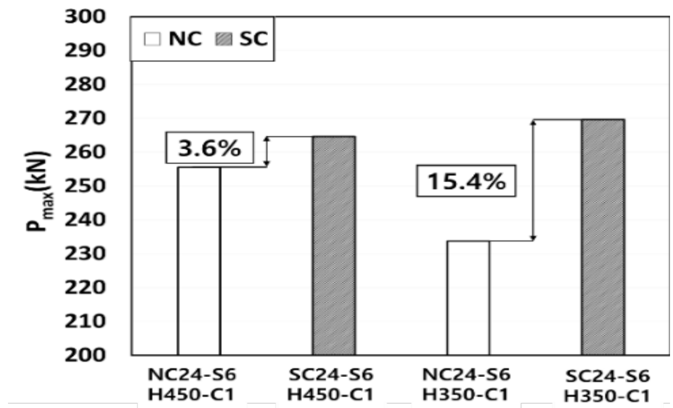


(c) NC-C1 series specimens

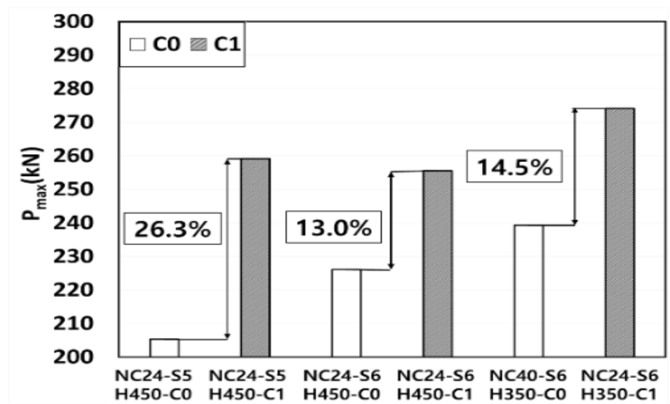


(d) SC-C1 series specimens

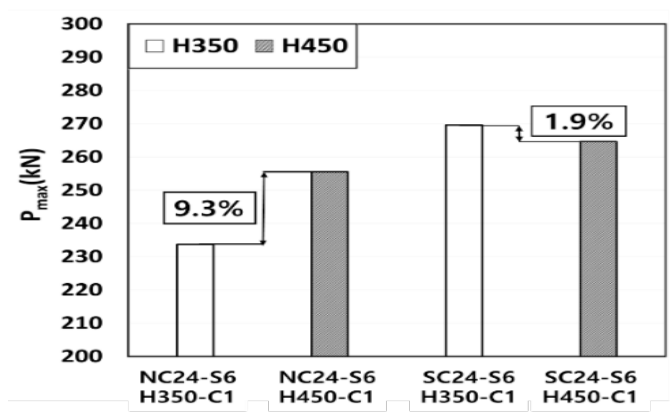
Figure 4. Comparison of load-displacement curves



(a) Volume ratio of steel fiber



(b) Shear reinforcement



(c) Anchorage length

Figure 5. Comparison of P_{max}

strength of side-face blowout strength increases with steel fiber reinforcement, which is relatively less affected by the anchorage length.

The average pullout strength of the specimens using SD600 rebar was 5.7% higher than that of the SD500 rebar.

4.4 Strain Curve of Rebar

The stress of headed reinforcing bar (f_T) is expressed as the sum of the adhesion stress between the concrete and the surface of reinforcing bar and the bearing stress (f_B) of the headed reinforcing bar. The bearing stress shown in Figure 1, was calculated from the strain measured from the strain gauge (WSG2) attached to the reinforcing bar, and the stress-strain curve evaluated from the material test. In Figure 6, calculation for f_B/ f_T which acts on 25%, 50%, 75%, and 100% of maximum pullout load is computed by analyzed ratio of bearing stress to total stress.

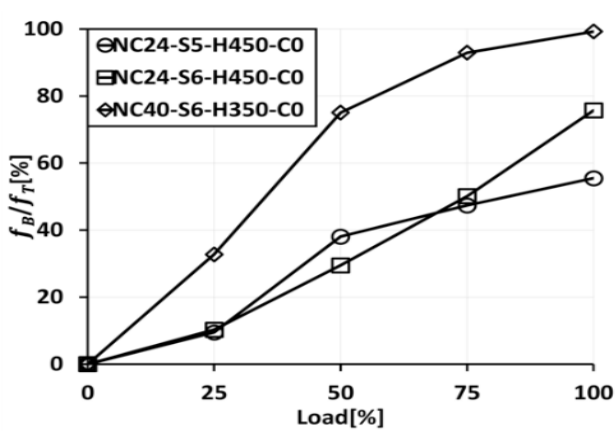
In figure 6, H350 series specimens (l_{dt}=270mm) with small anchorage length were generally found to have greater f_B/ f_T than H450 series specimens (l_{dt}=370mm). This is because the adhesion performance was reduced due to decreased anchorage length, which led to an increase in the bearing stress and ratio.

The C1 series specimens with shear reinforcement spacing at 80 mm intervals reduced the overall bearing stress rate compared to the C0 series specimens without shear reinforcement. This is due to the fact that the shear reinforcement contributed to the increase of bond stress while suppressing the expansion of cone-shape crack width.

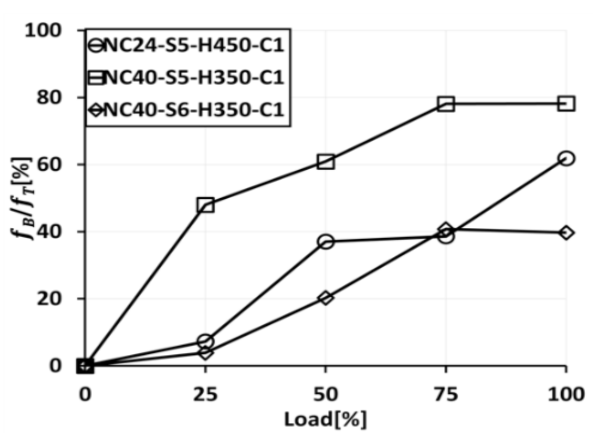
4.5 Comparison of Theoretical Strength and Experimental Strength

Using the equation (3) on the side-face blowout failure strength of the headed reinforcing bar described in Chapter 2, the theoretical bearing strength ($P_{p,Chun}$) was calculated by multiplying the cross-sectional area to the $f_{p,\ Chun}$. Table 5 shows the theoretical and bearing strength (P_{max}) of each specimen.

The average $P_{max}/P_{p,Chun}$ of all specimens was 0.59, indicating that the existing equation was evaluated as unstable by estimating the actual side-face blowout failure strength. The standard deviation was estimated to be 0.078.



(a) NC-C0 series specimens



(b) NC-C1 series specimens

Figure. 6 Bearing stress

According to the presence of shear reinforcement for NC-type specimens without steel fiber reinforcement, the average values of $P_{max}/P_{p,Chun}$ of C0 and C1 specimens were founded to be 0.51 and 0.62, respectively. Therefore, the specimens with shear reinforcement was evaluated as much close to

Whether the shear reinforcement present or not for the NC series specimens which are without the steel fiber reinforcement, the average $P_{max}/P_{p,Chun}$ of C0 and C1 found to be 0.51 and 0.62. Therefore, the specimen with shear reinforcement evaluated as much closer to the side-face blowout strength. Meanwhile, the average $P_{max}/P_{p,Chun}$ of SC series specimens with steel fiber reinforcement computed as 0.69, representing as the biggest average values.

Table 5. Comparison of Theoretical Strength and Experimental Strength

Specimens	P_{max} (kN)	$P_{p,Chun}$ (kN)	$\frac{P_{max}}{P_{p,Chun}}$
NC24-S5-H450- C0	205.3	429.0	0.48
NC24-S6-H450- C0	226.1	429.0	0.53
NC40-S6-H350- C0	239.3	461.1	0.52
NC24-S5-H450- C1	259.1	429.0	0.60
NC24-S6-H350- C1	233.7	357.2	0.65
NC24-S6-H450- C1	255.5	429.0	0.60
NC40-S5-H350- C1	252.8	461.1	0.55
NC40-S6-H350- C1	274.1	461.1	0.59
SC24-S6-H350- C1	269.6	357.2	0.75
SC24-S6-H450- C1	264.6	429.0	0.62

Notations: P_maxis a means maximum load; P_(p,Chun) is a means side-face blowout

5. CONCLUSION

In this study, pullout test was performed to evaluate the side-face blowout failure strength of high strength headed reinforcing bar used for mechanical anchorage between RC or SFRC members. The results are summarized as follows:

(1) The cone-shaped cracks start from the anchorage initiated headed reinforcing bar gradually spread the concrete fracture as pullout loads increase on every specimen, resulting in side-face blowout failure.

(2) Pullout strength with shear reinforcement of the C1 series specimens increased by 13.0 ~ 26.2% compared to the C0 series specimens. The SC series with steel fiber increased the pullout strength by 3.6 ~15.4% compared to the NC series. And The smaller the anchorage length, the greater the effect of increasing pullout strength by reinforcing steel fibers.

(3) The smaller the anchorage length, the lower the adhesion stress, and the higher the bearing stress ratio for every total stress. The shear reinforcement contributes to the increase of crack width and adhesion stress, thereby reducing the bearing stress ratio of the specimens with shear

reinforcement.

(4) The result of the ratio of test strength to side-face blowout failure strength of Chun at al. was estimated to be 0.59 on average and 0.078 on the standard deviation. From this, it can be seen that the equation of Chun at al evaluated the actual side-face blowout failure as unstable.

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