Effect of pullout of longitudinal bar from footing in Full-scaled RC columns under E-Defense Excitation

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Displacement of RC column is strongly effected base rotation induced by pullout of longitudinal bar from footing. To evaluate the effect of pullout, experimental data of full-scale RC columns (C1-1 and C1-5) by shake table test is summarized. Pullout at base contributes about 30% to the column displacement. Analysis was conducted to make clear the mechanism of pullout, in which analysis considering bar-to-bar reduction with the redefined reduction coefficient on bond stress has well reappeared the experiment. It is clarified that tri-layer and bi-layer reinforcement of C1-1 and C1-5 contribute to the bar-to-bar reduction influence leading to greater strain of main bar and pullout.

Keywords: E-Defense excitation, pulling out, strain distribution, multi-layer, bar-to-bar reduction

1. INTRODUCTION

A 3D shake table experiment on a large-scale reinforced concrete bridge using E-Defense has been constructed by the National Research Institute for Earth Science and Disaster Prevention. With the facilities for E-Defense, a series of anti-seismic experiments of bridges has been conducted, among which full-scale RC columns named C1-1<sup>†</sup> and C1-5<sup>‡</sup> have been constructed shown in Fig. 1. Columns as the type of C1-1 built in the 1970s has been widely damaged during 1995 Kobe Earthquake. However, column C1-5 designed with 2002 JRA specification behaved satisfactorily under a near-field ground motion recorded during the 1995 Kobe Earthquake.

The objective specimens were designed for evaluating flexural failure. Response displacement of an RC column, which contributes to the development of lateral displacement of the deck, is not only caused by flexure but also rotation induced by the longitudinal bar pulling out from the inside footing. Our former research<sup>§</sup> has paid attention to the C1-1 specimens, and it is clarified that the pullout has contributed great (about 30%) to the column top displacement and tri-layer of C1-1 has contributed to the pullout with the bar-to-bar reduction influence. This paper will pay attention to the comparison between different reinforced C1-1 (tri-layer) and C1-5 (bi-layer) to evaluate their behavior in pullout.

The study flow can be shown as Fig. 2. In order to make clear the seismic behavior of C1-1 and C1-5, the experimental data including pullout displacement measured by both displacement

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Fig. 1 Shake Table Test Using E-Defense
meter and strain gauge are plotted firstly in Chapter 3. Moreover, in order to make clear the effect of pullout and reveal the contributed ratio of pullout to column displacement in different reinforced specimens, ratio of pullout-induced column displacement will be solved in Chapter 4 and comparison with other researches will be conducted. Analysis is conducted in Chapter 5 to make clear the mechanism of pullout and bar-to-bar reduction influence. Moreover, in order to make a definition for the bar-to-bar reduction influence in reinforcement of multi-layer, the reduction coefficient is evaluated in this chapter based on resistant area inside footing.

2. EXPERIMENTAL SETUP

2.1 Specimen C1-1

As Fig. 3 shows, the column was constructed by tri-layer of reinforcement of 29 mm diameter, 32, 32 and 16 bars at outer, middle and inner layers respectively. Deformed circular stirrups of 13 mm diameter are provided at 300 mm intervals. At the top zone of 1.15 m and at the base zone of 0.95 m length, outer ties are provided at 150mm intervals. Stirrups are lap spliced with 30 times of bar diameter (13 mm). The longitudinal reinforced ratio was 2.02%, and the tie volumetric reinforced ratio for the middle was 0.32% and for the top or base was 0.42%. The yield strength of the longitudinal bars, stirrups were measured as 366 MPa and 193 MPa respectively. Average strength of concrete based on the cylinder test reaches 33 MPa at the day of experiment.

Strain gauges (SG) were attached to the longitudinal bar shown in Fig. 3 and provided at 300 mm intervals. In both the transverse and bridge axis direction, the SG was attached to the outer, middle and inner bar. A series of displacement meter was set at the base by both sides of the transverse and bridge axis direction. The displacement meter are set from 80 mm height and provided at 200 mm intervals along the column body as Fig. 5 shows.

2.2 Specimen C1-5

As Fig. 4 shows, C1-5 was constructed by bi-layer of reinforcement of 35 mm diameter, 36 and 36 bars at outer and inner layers respectively. Deformed circular stirrups of 13 mm diameter are provided at 150 mm intervals along the column body. Stirrups are lap spliced with 40 times of the bar diameter (22 mm). The longitudinal reinforced ratio was 2.19%. The yield strength of the longitudinal bars and stirrups were measured as 382 MPa and 345 MPa respectively. Average strength of concrete based on the cylinder test reaches 32.2 MPa at the day of experiment.

Strain gauges were attached to the longitudinal bar shown in Fig. 4, among which the first one in footing were located at -150mm from base and the others were provided at 300 mm intervals. The SG was only attached to outer bar as shown in Fig. 4(b). Displacement meter is set as same as C1-1 which has been described in Fig. 5.  

- 1995 Kobe Earthquake: extensive damage to RC column;
- Full-scale excision experiment: flexure failure type RC column (based on specification 1964 and 2002)

| BACKGROUND |
| Full-scale excision experiment: flexure failure type RC column (based on specification 1964 and 2002) |

| OBJECTIVE |
| To clarify the effect of pullout-induced column displacement |
| To evaluate the reduction influence on pullout from bar-to-bar |

| STUDY |
| Experiment |
| Case 1: Analysis considering single bar |
| Case 2: Analysis considering bar-to-bar reduction |
| Reduction coefficient |

| Fig. 2 Study flow |
| Fig. 3 C1-1 Column on E-Defense |
| Fig. 4 C1-5 Column on E-Defense |
| Fig. 5 Displacement Meter |
3. EXPERIMENTAL DATA OF PULLOUT

This chapter summarizes the general experimental data. The column top displacement was measured by three-dimensional displacement meter attached to the column top.

3.1 Experimental Response of Specimens

Experimental data based on the column top was plotted initially by the load-displacement (P-δ) relationship in Fig. 6. Among several applied loads, first load which leads to the main damage was used for the plot. As for C1-1 specimen, the maximum load was about 1660 kN and 1390 kN respectively in the bridge axis (East-West) and the transverse (North-South) direction. In bridge and transverse axis directions, column displacement have exceeded 0.1 m and 0.15 m respectively.

As for C1-5 specimen, the experimental response of C1-5 specimen was also plotted initially by the load-displacement (P-δ) relationship in Fig. 7. The maximum load in experiment of C1-5 has reached 2445 kN and 1682 kN respectively in the bridge axis (EW) and the transverse (NS). Column displacement, in bridge and transverse axis directions, has exceeded 0.107 m and 0.124 m respectively.

3.2 Measured Pullout

Both displacement meter at base and strain gauge being attached along the longitudinal bar are used to measure the pullout

\[ \delta_y = 0.049 \text{m} \] 
\[ \varepsilon_y = 1896 \mu \] 

Fig. 8 Definition of yield displacement

Fig. 9 Time history of measured pullout at north side in C1-1 and C1-5
displacement at base \( \delta \). At first, the pullout displacement can be measured directly by the displacement meter being attached at the base of column, shown in Fig. 5. Secondly, pullout displacement can be solved by integral on strain distribution, shown in Fig. 3 and Fig. 4. The measurement procedure will be evaluated in detail in Fig. 20 and Fig. 21 in Chapter 5, measured by strain gauges attached along the longitudinal bar (image in Fig. 9b)).

As the measured pullout displacement will be summarized by the special time point of column displacement at 1\( \delta \)y and 2\( \delta \)y, shown as Fig. 10 and Fig. 11. The definition of the time point at 1\( \delta \)y and 2\( \delta \)y of column displacement of C1-1 is explained by Fig. 8. Illustrated in Fig. 8, time history of column displacement and corresponded strain at base are plotted taking the north-south side of C1-1 as an example. Generally, the yield displacement (1\( \delta \)y) of column top is defined as the same time as the strain at base becomes yield (\( \delta_0 \)). Illustrated by Fig. 8, the strain of longitudinal bar at north side becomes yield (1896\( \mu \)) at 9.795s and at this moment the corresponding column displacement which reaches 0.049 m in south direction is defined as yield displacement (1\( \delta \)y, marked as N1). Column displacement of 2\( \delta \)y is twice of 1\( \delta \)y, which reaches 0.098 m at 12.515s marked as N2.

As for the pullout displacement has been measured by both displacement meter and strain gauge, time history of measured pullout at north side in C1-1 and C1-5 is plotted for an example in Fig. 9 (a) and (b) respectively. Illustrated by Fig. 9, the pullout displacement measured by displacement meter and strain gauge has been plotted for comparison. Shown in Fig. 9 (a) for north side of C1-1, the measured pullout by displacement meter and strain gauge has not been accord with each other and measured data by strain gauge is relative smaller. However, as shown in the Fig. 9 (b) for north side of C1-5, the measured data by both displacement meter and strain gauge have accorded with each other well.

Based on the defined yield displacement of column top in Fig. 8 and time history of measured pullout in Fig. 9, the summary of measured pullout at column displacement of 1\( \delta \)y and 2\( \delta \)y is plotted in Fig. 10 and Fig. 11 for C1-1 and C1-5 respectively. The displacement meter set at the height of 80 mm from the base. It includes the elongation between the point of base and the point at 80 mm height. Compared with plastic hinge length (about 1300 mm), elongation length (80 mm) is so small that he effect of elongation length the can be neglectable.

Fig. 10 makes a general summary of measured pullout by both displacement meter and strain gauge in C1-1. Illustrated in Fig. 10, pullout displacement by displacement meter is measured at 1.1 ~ 1.7 mm at 1\( \delta \)y and 2.8 ~ 5.0 mm at 2\( \delta \)y. Pullout displacement by strain gauge is measured at 0.9 ~ 1.1 mm at 1\( \delta \)y and 1.1 ~ 4.1 mm at 2\( \delta \)y. Similar to the time history of measured data at north side in Fig. 9 (a), the measured data by strain gauge is not accord with that by displacement meter and seems to be varied for C1-1 specimen.

Fig. 11 also makes a general summary of measured pullout by both displacement meter and strain gauge in C1-5. Illustrated by the Fig. 11, pullout displacement by displacement meter is measured at 1.3 ~ 1.8 mm at 1\( \delta \)y and 3.6 ~ 4.8 mm at 2\( \delta \)y. Pullout displacement by strain gauge is measured at 1.1 ~ 1.3 mm at 1\( \delta \)y and 2.5 ~ 3.7 mm at 2\( \delta \)y. Moreover, similar to the statement in Fig. 9 (b), the measured data in C1-5 by both displacement meter and strain gauge seems to be accord with each other well compared with that in C1-1, and the measured data does not vary obviously.

It is considered that the different behavior of measured pullout in C1-1 and C1-5 can be explained by the measured strain distribution shown in Fig. 21 and Fig. 22 which will be evaluated in detail in Chapter 5. Paying attention to the set of strain gauge, three strain gauges has been set within the area of 0 ~ 0.3 m in C1-5, however, only two strain gauges has been set within this area in C1-1. Measured data in C1-1 at area of 0 ~ 0.3m is one less than that in C1-5 so that the integral calculation on strain distribution in C1-1 is considered as inexact. With the insufficient measured data in the area of 0 ~ 0.3 m in C1-1, integral based on this group of data seems to be inexact and the measured pullout appears varied in Fig. 10 being not accord with the data measured by displacement meter.
4. EVALUATION ON THE PULLOUT-INDUCED COLUMN DISPLACEMENT

4.1 Response Column Displacement

Column top displacement is not only caused by flexure but also rotation induced by the longitudinal bar pulling out from the inside footing. Orbit of column top has been plotted in Fig. 12 and Fig. 13 respectively.

Illustrated by Fig. 12, column top is located at different place of yield displacement for each direction. However, paying attention to the west direction, marked as W1 for 1δy and W2 for 2δy, the location of column top has not displaced obviously so that it is undependable to use this group of data to evaluate the pullout-induced column displacement during 1δy ~ 2δy. For the evaluation on pullout-induced column displacement in NS and EW direction, the component value of column top displacement in corresponded direction is used as the NS and EW direction has been evaluated separately. Illustrated by Fig. 12, taking the north as an example, when the column displacement reaches yield (1δy, marked as N1 in Fig. 8) the column top is located closely to the NS axe and the component value of N1 in NS direction is marked on the NS axe, among which the pullout-induced column displacement in this direction will be solved by the pullout measured at south.

As for C1-5 specimen, the pullout displacement measured by both displacement meter and strain are accords with each other shown in Fig. 11. Illustrated by Fig. 13, the column top towards each side at 1δy has located closely to the corresponding axe so that the measured pullout has not been affected by the column displacement towards other direction. Moreover, the location of column top at 1δy and 2δy are not so close with each other as W1 and W2 shows so that the pullout of displacement at corresponding side keeps increasing shown in Fig. 11.

To sum it up, location of column top has measured in both NS and EW direction. For evaluation of pullout-induced column displacement, measured column top displacement in NS and EW direction has been evaluated separately by the measured pullout displacement at opposite side. For example, pullout-induced column displacement in south direction is evaluated by the pullout measured at north side and corresponded component value of column displacement in south direction.

4.2 Ratio of Pullout-induced Column Displacement

Based on the orbit of column top plotted in Fig. 12 and Fig. 13, yield displacement towards each side can be summarized in Fig. 15 and Fig. 16 for C1-1 and C1-5 respectively, among which the pullout-induced column displacement can be solved.

As for the procedure of solving pullout-induced column displacement shown in Fig. 14. Firstly, taking NS direction as an example, the measured pullout (un) of C1-1 and C1-5 is solved as Fig. 10 and Fig. 11 shows respectively. Secondly, the neutral axis of based section (X0) is solved by the cross-section calculation6.
Thirdly, with the measured pullout ($u_0$) and neutral axis ($X_0$), base rotation can be solved ($\tan \theta = u_0 / X_0$). Finally, the pullout-induced column displacement can be solved by the base rotation and height of column ($\delta_{\text{pullout}} = u / X_0 \times 7.5$ m) which is plotted in Fig. 15 and Fig. 16 for C1-1 and C1-5 respectively.

Illustrated by Fig. 15 for C1-1, column displacement of $1\delta y$ and $2\delta y$ and pullout-induced column displacement has been plotted. Taking the column displacement towards south as an example, the yield displacement reaches 0.049 m and the displacement of $2\delta y$ is solved as twice of yield displacement reaching 0.098 m. Based on the measured pullout and solution procedure stated above, pullout-induced column displacement is solved as 0.013 m at displacement of $1\delta y$ and 0.027 m at displacement of $2\delta y$.

Similar to C1-1, illustrated by Fig. 16 for C1-5, column displacement of $1\delta y$ and $2\delta y$ and the pullout-induced column displacement also has been plotted. Different from that of C1-1, the experimental data in C1-5 seems to be steady in different direction. Taking the column displacement towards south as an example, it can be seen that the yield displacement reaches 0.038 m and the displacement of $2\delta y$ is solved as twice of yield displacement reaching 0.076 m. Pullout-induced column displacement is solved as 0.009 m at displacement of $1\delta y$ and 0.021 m at displacement of $2\delta y$.

Based on the column displacement at $1\delta y$ and $2\delta y$ and the pullout-induced column displacement summarized in Fig. 15 for C1-1, the ratio of pullout-induced column displacement can be plotted in Fig. 17 by the solution procedure stated above. Illustrated by Fig. 17, as the pullout-induced column displacement at $1\delta y$ is solved as 0.013 m, it takes 26.5% in the corresponding column displacement reaching 0.049 m. At column displacement of $2\delta y$ reaching 0.098 m, among which the pullout-induced column displacement reaches 0.027 m and takes 27.6%. As shown in Fig. 17, pullout at base has contributed 28% to the top displacement in average.

As for C1-5 specimen, response column displacement at $1\delta y$ ~ $2\delta y$ and pullout-induced column displacement is summarized in Fig. 16, the ratio of pullout-induced column displacement can be plotted in Fig. 18 by the solution procedure stated above. Illustrated by Fig. 18, as the pullout-induced column displacement at $1\delta y$ is solved as 0.009 m, it takes 23.6% in the corresponding column displacement reaching 0.021 m. At column displacement of $2\delta y$ reaching 0.076 m, among which the pullout-induced column displacement reaches 0.021 m and takes 27.6%. As shown in Fig. 18 pullout at base has contributed 30% to the top displacement in average during $1\delta y$ ~ $2\delta y$.

To sum it up, although C1-1 and C1-5 have been reinforced differently based by different code, they seem to have similar behavior on the pullout and it-induced column top displacement. Pullout in C1-5 seems greater than C1-1. However, as the C1-5 (diameter of 2 m) has a larger scale than C1-1 (diameter of 1.8 m), the natural axle...
of C1-5 (1δy: 1.16 m; 2δy: 1.36 m) is also bigger than that of C1-1 (1δy: 0.97 m; 2δy: 1.3 m). Consequently, the base rotation and it-induced column displacement in both C1-1 and C1-5 is also same with each other. Moreover, according to the yield displacement shown in Fig. 15 and Fig. 16, both of C1-1 and C1-5 have reached 0.038 m averagely. The ratio of displacement due to the pullout of longitudinal bar was 30 %, and this value is not much difference with other specimens.

4.3 Comparison with the Former Researches

Effect of pullout-induced column displacement was clarified by Kosa et al. (1996) and Hoshikuma et al. (2001). Kosa et al. (1996) conducted cyclic loading experiments of 4.3 m tall square column with section size of 1 m × 1.167 m, which the section view can be shown as K-(1) in Table 1. It is found that the column displacement due to pullout was 25% in the ultimate displacement in the full-scaled column shown as the comparison in Fig. 19. Hoshikuma, Unjoh and Nagaya conducted a 9.6 m tall 2.4 m width square column being reinforced by bars of 35 mm diameter with 122 mm bar-to-bar spacing, which the section can be shown as H-(1) in Table 1, and its 1/4 scaled models, which is a 2.4 m tall and 0.6 m width square column being reinforced by bars of 10 mm diameter with 15 mm bar-to-bar spacing, is marked as H-(2) in Table 1 is established. Column displacement due to pullout in the full-scaled model (H-(1)) was 20% of the total column displacement while the column displacement due to pullout in the 1/4 scaled model (H-(2)) was 15% ~ 35% of the total column displacement shown in Fig. 19.

Table 1 makes a general comparison between the four specimens by different institute. They has different scale and is reinforced differently. It is considered that different bar-to-bar influence exists in different reinforcement. Bar-to-bar influence can be expressed by the reduction coefficient defined as follows:

\[ K_i = 0.4 + 0.03D_i/\phi \]  

(1)

Here, \( K_i \) is the reduction coefficient for bond stress, \( D_i \) is the distance between two adjacent bars and \( \phi \) is the diameter of longitudinal bar.

As the four specimens has been reinforced differently, the authors take the single outer layer as an example to explain the reduction coefficient. As for C1-1, the reduction coefficient of outer layer has been calculated as 0.56 with the bar-to-bar distance of 156 mm (D) and bar diameter of 29 mm (ϕ). Similarly, reduction coefficient for outer layer in specimen C1-5, K-(1), H-(1) and H-(2) can be calculated as 0.53, 0.52, 0.50 and 0.45 respectively. However, the C1-1 and C1-5 has been reinforced by multi-layer, the actual reduction coefficient has been solved by both lapped direction and layer direction reaching about 0.4, which will be explained in detail in Chapter 5. Consequently, the pullout-induced column displacement in C1-1 and C1-5 takes a relative high ratio shown as Fig. 19 with the relative greater bar-to-bar reduction influence.

5. Evaluation of the Influenced Factor on Pullout

5.1 Analysis Based on Strain Distribution

Based on the measured pullout displacement by displacement meter and strain gauge in Chapter 4, pullout contributed to the response column displacement by about 30% which seems to be great. In this chapter, the mechanism of pullout is evaluated based on experimental data and corresponded analysis.

Strain distribution of C1-1 at 1δy along the longitudinal bar inside the footing (from -1.5 m to 0 m) and strain distribution (from -1.35 m to 0 m) of C1-5 has been plotted in the Fig. 20. At the yield point, behavior of
longitudinal bar in different side has accords with each other in both C1-1 and C1-5. However, shown in Fig. 21, at the time of 2δy strain distribution of direction becomes different as the longitudinal bar has exceed yield. Shown in Fig. 21 (a), the strain at base (0m) in C1-1 has reached about 17826μ and 20643μ in west and south side respectively. Moreover, as shown in Fig. 21 (b), the strain at base of C1-5 has reached 13736μ and 15540μ in south and east side respectively.

Analysis is conducted based on the calculated methods reported in the literature 9). The following theoretical equation shows the relationship of bond stress, steel stress and slip (τ-s and σ-τ):

\[
\frac{\tau}{f_{ck}'} = 0.73(\ln(1 + 5000S / \phi))^{3/2} (1 + \varepsilon \times 10^5) \tag{2}
\]

\[
\Delta \sigma = \pi \cdot \phi \cdot \Delta x \cdot \tau / A_i \tag{3}
\]

Here, \(\tau\) is the bond stress between concrete and steel bars for single bar; \(f_{ck}'\) is compressive strength of concrete; \(S\) is bond slip; \(\phi\) is the diameter of longitudinal bar; \(\varepsilon\) is strain of the longitudinal bar; \(\Delta \sigma\) is the increment of stress in interval of \(\Delta x\).

Based on the equations listed above, analysis based on the strain distribution is conducted. As for the analytical procedure, firstly, the strain of longitudinal bar at base (0m) is defined by the yield strain of main bar (1896μ). Secondly, assume a certain value for the bond slip (S) at base (0m). With the defined yield strain and bond slip at base, the bond stress at 0m can be solved by Eq. (2) and then the increment of stress (\(\Delta \sigma\)) can be solved by Eq. (3). The analysis results in a series of stress and strain value along the longitudinal bar by interval of \(\Delta x\) inside footing by the equations. Thirdly, judgment is made on the bond slip at the end of steel. The analysis can come to an end until the bond slip at the bottom of longitudinal bar in analysis is zero.

5.2 Reduction Influence from Bar-to-bar

The kind of analysis by Eq. (2) and (3), defined hereinafter as Case 1, has been conducted by considering single bar. However, C1-1 and C1-5 has been reinforced by plural bars and the resistant capacity will be reduced due to close reinforced spacing. The reduction on bond stress is described by certain reduction coefficient on bond stress, and analysis considering this bar-to-bar reduction based on the defined reduction coefficient, named hereinafter as Case 2, is conducted by:

\[
\frac{\tau}{f_{ck}'} = 0.73(\ln(1 + 5000S / \phi))^{3/2} (1 + \varepsilon \times 10^5) \tag{4}
\]

\[
\tau' = K \cdot \tau \tag{5}
\]

Here, \(\tau'\) is the bond stress between concrete and steel bars for reinforcement of plural bar; \(K\) is the defined reduction coefficient.

![Fig.20 Strain Distribution at 1δy](image)

![Fig.21 Strain Distribution at 2δy](image)

![Fig.22 Mechanism of Bar-to-bar Reduction](image)
As it is stated above, the reduction coefficient for bond stress has been defined as Eq. (1), which has considered the reinforcement of single layer only. Since C1-1 and C1-5 have been reinforced by multi-layer, the definition of reduction coefficient needs to consider the surrounded bars in both lapped and layered direction.

The mechanism of bar-to-bar reduction is explained by Fig. 22, in which the reduction influence from bar-to-bar has been expressed by the resistant area of concrete around the main bar. As for reinforcement of single bar, shown in Fig. 22 (a), the resistant area is set as \( A_0 \) (cone-shape area) and the bonding length has been determined as 32\( \phi \) based on JRA specifications (2002) \(^{10}\). Similarly, resistant area of reinforcement by double bars is set as \( A_0' \) (intersect cone-shape) shown in Fig. 22 (b). Based on the relationship between resistant area, force and stress shown in the figure, the resistant stress \( \tau \) of each bar in reinforcement of double bars becomes greater than that in single bar being calculated as 1.905 times of the resistant stress in reinforcement by single bar.

As for the condition of bar-to-bar reduction in the reinforced type of C1-1 and C1-5, section view of C1-1 and C1-5 is plotted in Fig. 23 (a) and (b) respectively. C1-1 specimen is reinforced by tri-layer with bars of 29 mm diameter, and C1-5 specimen is reinforced by bi-layer with bars of 35 mm diameter. As the C1-5 has been reinforced one layer less than C1-1, the definition of reduction coefficient in C1-5 is explained by Fig. 23 (c) firstly.

In lapped direction, with the bar-to-bar distance of 148 mm, the resistant area which is reset as \( A_1 \) has been calculated as 1.07 times of \( A_0 \) so that the resistant area for each bar decreases to 0.535 times of \( A_0 \). Similarly, in layered direction, the resistant area \( A_2 \) with bar-to-bar distance of 100 mm is calculated as 1.05 times of \( A_0 \) and the resistant area for each bar becomes 0.525 times of \( A_0 \).

When considering the lapped direction and layered direction together, shown as Fig. 23 (c), the resistant area of the three bars in tri-angle area, marked as \( A_3 \), roughly equals to \( (A_1+A_2-A_0) \) as both \( A_1 \) and \( A_2 \) has included a resistant area of single bar \( A \) (\( A_0 \)). Consequently, the resistant area of the three bars is calculated as 1.13\( A_0 \) so that resistant area for each bar decreases to 0.377\( A_0 \) (1.13\( A_0/3 \)).

Fig. 23 (d) is plotted to explain the reduction coefficient of C1-1 with tri-layer. The reinforcement of C1-1 can be regarded as two groups of tri-bar which has been explained by C1-5 in Fig. 23 (c). The resistant area \( A_3 \) roughly equals to \( (A_1'+A_2'-A_0) \), among which the \( A_1' \) (1.15\( A_0 \)) and \( A_2' \) (1.14\( A_0 \)) can be solved by example in Fig. 23 (c). The resistant area of the five bars is calculated as 1.29\( A_0 \) so that resistant area for each bar becomes 0.26 times of \( A_0 \).

Relationship between reduction coefficient \( K \) and relative bar-to-bar spacing (D/\( \phi \)) is established by Fig. 24. The \( D \) includes both bar-to-bar space in lapping and layer direction. The value of D/\( \phi \) is defined as the average valued in this two directions by the corresponded bar-to-bar space. Illustrated by Fig. 24, the solved reduction coefficient of C1-1 and C1-5 has been marked. Moreover, when the bar-to-bar distance is large enough, bar-to-bar
influence will fade away (K=1) so that this extreme condition is also marked. Fig. 24 also makes a comparison with the referenced relationship of Eq. (1) by Mr. Ishibashi which considers the single layer. C1-1 and C1-5 are reinforced by multi-layer, the actual reduction coefficient becomes smaller than single layer considered by Mr. Ishibashi.

5.3 Analytical Result vs. Experimental Data

The analytical results are plotted in Fig. 25 and Fig. 26 for C1-1 and C1-5 respectively based on the analytical model for Case 1 and Case 2 analysis explained in Section 5.1 and 5.2. C1-1 is illustrated by Fig. 25 in which the (a) and (b) illustrate the state of 1δy and 2δy. C1-5 specimen is illustrated by the Fig. 26 in which the (a) and (b) illustrate the state of 1δy and 2δy.

Illustrated in Fig. 25, for C1-1 specimen, the analytical result of strain distribution in analysis of Case 2 has reappeared the experiment better than the analysis of Case 1 without considering the bar-to-bar reduction. The strain of main bar in analysis Case 2 becomes greater than that in single bar, which causes the measured pullout displacement by strain gauge becomes greater.

Similarly, shown in Fig. 26, for C1-5 specimen, the analytical result of strain distribution in analysis of Case 2 has reappeared the experiment better than the analysis of Case 1 without considering the bar-to-bar reduction at both 1δy and 2δy. The strain of main bar in analysis Case 2 also becomes greater compared with the analytical result in single bar, which causes the pullout at base in bi-layered C1-5 becomes greater.

Case 2 analysis has taken the bar-to-bar reduction influence into consideration with the redefined reduction coefficient on bond stress for specimens with reinforcement of multi-layer. Based on the analytical result illustrated in Fig. 25 and Fig. 26 for C1-1 and C1-5 respectively, Case 2 analysis has well reappeared the experimental data of strain distribution. Consequently, the redefinition of reduction coefficient for specimens with reinforcement of multi-layer is feasible. Moreover, based on the analysis, it is clarified that tri-layer reinforcement of C1-1 and bi-layer reinforcement of C1-5 contributes to the bar-to-bar reduction influence leading the strain of main bar becomes greater, which causes the pullout of longitudinal bar in C1-1 and C1-5 becomes greater.

6. CONCLUSIONS

Based on the experiment and analysis on C1-1 and C1-5, following conclusions have been drawn:

(1) In C1-1 specimen, which conducted in Edefense, pullout displacement by displacement meter is measured at 1.1 ~ 1.7 mm at 1δy and 2.8 ~ 5.0 mm at 2δy. Pullout displacement by strain gauge is measured at 0.9 ~ 1.1 mm at 1δy and 1.1 ~ 4.1 mm at 2δy. In C1-5 specimen, pullout displacement by displacement meter is measured at 1.3 ~ 1.8 mm at 1δy and 3.6 ~ 4.8 mm at 2δy. Pullout displacement by strain gauge is measured at 1.1 ~ 1.3 mm at 1δy and 2.5 ~ 3.7 mm at 2δy. Measured pullout in C1-5 by both displacement meter and strain gauge has been accord with each other well. However, with the insufficient measured point in 0 ~ -0.3m area from base, measured pullout in C1-1 by strain gauge has not been accord with the measured pullout by displacement meter well. Based on measured pullout by displacement meter, ratio of pullout-induced displacement in the response column displacement is solved as 28% and 30% in C1-1 and C1-5 respectively.

(2) C1-1 has been reinforced by tri-layer with bar of 29 mm diameter, and C1-5 has been reinforced by bi-layer with bar of 35 mm diameter. In response column displacement, the ratio of pullout-induced column displacement in C1-1 and C1-5 is relative greater than the specimens established by Kosa et al. (1996) and Hoshikuma et al. (2001). C1-1 and C1-5 has been reinforced by more layers and closer bar-to-bar
spacing than the referenced specimens. Based on the calculated reduction coefficient on bond stress for each specimens, it is clarified that tri-layer reinforcement of C1-1 and bi-layer reinforcement of C1-5 has contributed to the bar-to-bar reduction and pullout of longitudinal bar inside footing, which causes higher ratio and greater effect of pullout-induced column displacement than other specimens.

(3) Reduction influence from bar-to-bar has been expressed by the reduction coefficient on bond stress. It is considered that the resistant area of concrete around the main bar determines the bar-to-bar reduction. With the relative closed bar-to-bar spacing, the resistant stress for each bar in the reinforcement of double bar is reduced by about 50% of than in single bar reinforcement (47.6% for bar-to-bar spacing of 100mm). As for tri-layered C1-1 and bi-layered C1-5, the reduction coefficient has been solved as 0.26 and 0.377 respectively. As the C1-1 and C1-5 are reinforced by multi-layer, the redefined reduction coefficient by resistant area becomes smaller than that in single layer considered by Mr. Ishibashi.

(4) Analysis considering the bar-to-bar reduction is based on the redefined reduction coefficient on bond stress for specimens with reinforcement of multi-layer (tri-layer in C1-1 and bi-layer in C1-5). The analysis has well reappeared the experiment of both C1-1 and C1-5 so that the redefinition of reduction coefficient for specimens with reinforcement of multi-layer is feasible. It is clarified in analysis that tri-layer reinforcement of C1-1 and bi-layer reinforcement of C1-5 contribute to the bar-to-bar reduction influence leading the strain of main bar becomes greater, which causes the pullout of longitudinal bar in C1-1 and C1-5 becomes greater.

References

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