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Seismic Performance Evaluation of Reinforced Concrete Pile-cap with a Pile, Exterior Column and Foundation Beam

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Abstract

Pile-cap is an important structural joint member. Its function is to transfer the stresses occurring on the columns through a group of piles to the ground, occurring on the complex stresses that occur under earthquake loading. It is difficult to identify if the pile-caps were damaged by the earthquake. It requires a complete excavation of the pile-caps. It's hard to observe the seismic behavior under earthquake loading.

It is very important to clarify pile-cap shear failure mechanism of reinforced concrete (RC) structures. However, shear failure mechanism of a pile, exterior column-beam pile-cap in RC structure is not resolved yet under bi-lateral loading. Currently, there is no research and few valid experiments, regarding the study of pile-caps. As a result, the stress mechanism has not been defined. Therefore, the pile-cap design has been left to the architect's discretion. Though performance-based design is applied to buildings as they become taller, in case of pile-caps, the lateral and vertical reinforcements is not considered and the pile-cap foundation is currently designed using methods prescribed by structural regulations. Most of the research in these studies has focused on the effects of vertical loading on structural performance and bar configurations in pile-caps. The performance was examined in cases of tension-only or compression-only loading, but the ultimate strength and deformation were not specified. In the previous report, we performed lateral load reversal tests of subassemblages with one pile, column, foundation beam and pile-cap. This report is a series study of grasping the seismic capacity of interior pile-caps, these specimens were carried out to investigate the pile-caps shear performance.

The specimens which were the exterior subassemblages of a precast pile, foundation beam and column, were half scale to actual frames. In this experimental study, five specimens were fabricated which can be divided into five types considering the arangement properties. The depth and width of the column and beam section were same, respectively. The length from the center of the column to the pin-roller support of a beam end was 1600mm. The height from the center of the beam to the loading point on the top of the column or to the bottom support was 1415mm, respectively. The shear span ratio was 4.16 in the column, 2.54 in the beam and 3.40 in the pile, respectively. Reversed lateral horizontal loads at the top of a column and constant axial load were applied to all specimens. Three configuration of D10 bars were used in the pile-cap. They were utilized as main reinforcement bars which were called a tie and lateral bar, respectively. Concrete compressive strength was 24MPa. All specimens were designed to fail in pile-cap.

The diagonal shear crack strength and ultimate shear strength can be estimated by the prediction method for usual RC beam-column joints to apply the vertical member section to the average between the pile, the column and the pile-cap section or that between column and pile-cap. But in this research, the small diameter pile was applied, which was smaller than the column section in case of the low buildings. Therefore, the quantification of the effective pile-cap section is not resolved in case of large diameter piles applied to high buildings. The shear strength of pile-caps was enhanced by confining effect due to the shear reinforcement amount and the transformation of the surrounding structural members were restrained by them. The difference in the positive and negative maximum strength was occurred by the strut mechanism in loading direction.

Keywords: pile cap, foundation beams, bar arrangement, pile cap seismic performance, maximum shear strength

1. Introduction

Pile-cap is an important structural joint member. Its function is to transfer the stresses occurring on the columns through a group of piles to the ground, taking place the complex stresses under earthquake loading. It is difficult to identify if the pile-caps were damaged by the earthquake. Because it requires a complete excavation of the pile-caps. It's hard to observe the seismic behavior under earthquake loading. It is very important to clarify pile-cap shear failure mechanism of reinforced concrete (RC) structures. However, shear failure mechanism of a pile, exterior column-beam pile-cap in RC structure is not resolved yet under bi-lateral loading.

Currently, there is no research and few valid experiments, regarding the study of pile-caps. As a result, the stress mechanism has not been defined. Therefore, the pile-cap design has been left to the architect's discretion. Though performance-based design is applied to buildings as they become taller, in case of pile-caps, the lateral and vertical reinforcements is not considered and the pile-cap foundation is currently designed using methods prescribed by structural regulations.

Most of the research in these studies has focused on the effects of vertical loading on structural performance and bar configurations in pile-caps. The performance was examined in cases of tension-only or compression-only loading, but the ultimate strength and deformation were not specified.

In the previous report, we performed lateral load reversal tests of subassemblages with one pile, column, foundation beam and pile-cap. This report is a series study of grasping the seismic capacity of interior pile-caps, these specimens were carried out to investigate the pile-caps shear performance.

2. Outline of Test

2.1. Specimens

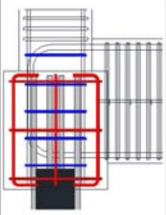
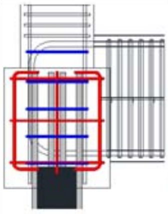
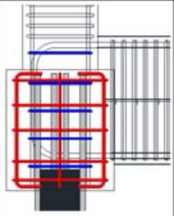
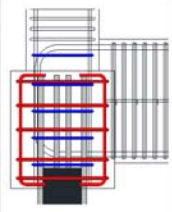
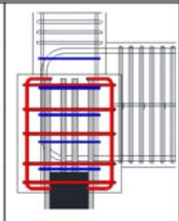
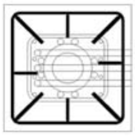
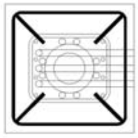
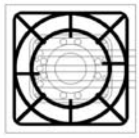
Five half-scale reinforced concrete pile-cap assembled a precast pile, an exterior column and a foundation beam, those specimen modeled actual middle-high buildings, were tested. A configuration of specimens, section dimensions and reinforcement details are shown in Figure 2.1 and each pile-cap details are shown in Table 2.1. Specific properties of specimens are summarized in Table 2.1. Material characteristics of concrete and steel are listed in Table 2.1and 2.2, respectively. Section dimensions and bar arrangements without the five pile-caps were common for all specimens.

The constant axial load in compression was applied at the top of the column for all specimens. The depth and width of the column section were 300mm and 350mm, respectively. 8-D13 were arranged in the column as longitudinal bar. The depth and width of the foundation beam section were 200mm and 600mm, respectively. 3-D22 were spread in the foundation beam as top and bottom longitudinal bar, respectively. The length from the center of the column to the loading point on a beam end was 1600mm. The height from the center of the beam to the supporting point on the top of the column or to the bottom support was 1415mm, respectively. The shear span ratio was 2.54 for the foundation beam, 4.16 for the column and 3.40 for the pile, respectively. Steel pile (Diameter is 190.7mm, thick is 45mm) was used as a precast pile, the embedment length was 100mm, 8-D22 bars were arranged as anchor dowel bars. The grout was filled into the hollow part of the steel pile for all specimens. All specimens were designed to form shear failure mechanism, so the column, the foundation beam and the steel pile were designed to higher strength than the usual on Design Guideline for Earthquake Resistant Reinforced Concrete Buildings Based on Inelastic Displacement Concept[1] and Recommendations for Design of Building Foundation[2].

Five configurations of D10 and D13 bars were used into the pile-cap. They were utilized as main reinforcement which were called a vertical and lateral bar, respectively. A combination between a kind and a number of a vertical and lateral bar were chosen as a test parameter. The bar arrangement in the pile-cap was used the "Type of basket" to examine the reasonable bar arrangement method in all specimens. "Type of basket" was arranged by some vertical and lateral bars to be provided by past experiment [3]. In all specimens the foundation beam was set above the normal position to interfere between the foundation beam bar and pile.

Specimen No.1 was called Standard Type, this specimen had two different vertical bars, i.e., 4-D10 and 4-D13. Specimen No.2 had a same amount of shear reinforcement, i.e., 3-D10 as Specimen No.1, and the vertical reinforcement was shorter than Specimen No.1 and No.3. Specimen No.3 had an increase shear reinforcements,

Table 2.1 – Properties of specimens

Specimen		No.1	No.2	No.3	No.4	No.5
Arrangement of Pile-cap						
Section of Pile-cap at bottom						
Axial load (Axial load ratio)		850kN (0.32)			890kN (0.32)	970kN (0.32)
Concrete	Compressive strength	25.4MPa			26.6 MPa	29.0 MPa
	Secant modulus	2.40GPa			2.36 GPa	2.40 GPa
	Strain at compressive strength	0.182%			0.213%	0.215%
	Tensile strength	1.77MPa			2.37 MPa	2.44 MPa
Pile-cap	High*Width*Depth	570mm*500mm*500 mm				
	Vertical reinforcement	4-D10^{*1} 4-D13^{*3}			4-D13^{*4}	4-D10^{*2} 4-D13^{*4}
	Shear reinforcement	5-D10^{*1}@235	5-D10^{*1}@200	5-D10^{*1}@120	5-D13^{*4}@120	
	Ring reinforcement bar	none				2-D13^{*4}
Column		Longitudinal bars: 8-D13^{*5} (USD785) Hoop: U9.0@50			8-D13^{*6}(USD785) U9.0@50	
Foundation beam		Longitudinal bars: 6-D22^{*7} (USD980) Stirrup: U9.0^{*9}@50			6-D22^{*8}(USD980) U9.0^{*10}@50	
Pile		Steel pile: ϕ 190.7mm, t=35mm Anchor bars: 8-D22^{*7} (USD980)			ϕ 190.7mm, t=35mm 8-D22^{*8}(USD980)	

i.e., 5-D10. Specimen No.4 had four vertical bars, i.e., 4-D10 and five lager diameter lateral bars, i.e., 5-D13. Specimen No.5 had same amount of vertical bars as Specimen No.3, i.e., 4-D10 and 4-D13, and had same amount of lateral bars as Specimen No.4, i.e., 5-D13, and had ring bars on the bottom of pile-cap. In all specimens, the anchor bars were used as anchorage bars with the steel pile.

2.2. Loading Apparatus and Instrumentation

A loading apparatus is shown in Figure 2.2. The foundation beam end was supported by horizontal roller, while the bottom of pile was supported by a universal joint. The reversed cyclic horizontal load and the constant axial load in compression (an axial load ratio of 0.32) were applied at the top of the column through a tri-directional joint by three oil jacks. This force represents the gravity load acting on the column having an axial load level of 0.32 $A_g f_c$, where A_g is the gross cross-sectional area and f_c is the concrete compressive strength. The jack orthogonal to a horizontal loading direction prevented an out-of-plane overturn for specimen.

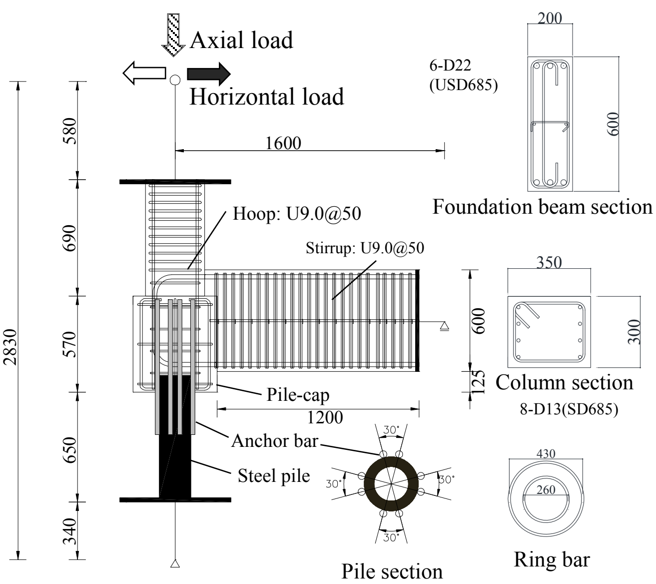


Figure 2.1 – Details of specimens

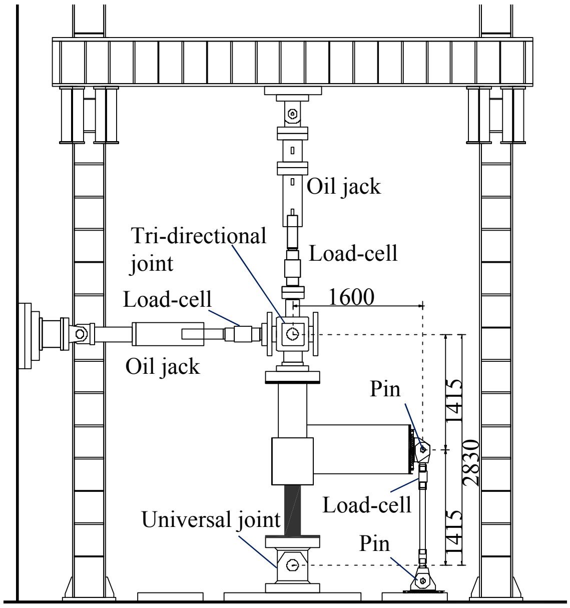


Figure 2.2 – Loading apparatus

All specimens were controlled by a story drift angle for one loading cycle of 0.25%, two cycle of 0.5%, 1%, 2%, one cycle of 3% respectively, and two cycle of 4%. The story drift angle was defined as a story drift divided by height of the column and pile; 2830mm. Lateral force, column axial load and foundation beam shear forces were measured by load-cells. Story drift, foundation beam and column deflections, and local displacement of a pile-cap panel were measured by displacement transducers. Strains of foundation beam bars, column bars and pile-cap bars, anchors and lateral reinforcements were measured by strain gauges.

Table 2.2 – Material properties of steel

Diameter	Yield strength MPa	Nominal Young's modulus, GPa	Yield strain %
D10*1	366	185	0.201
D10*2	362	175	0.207
D13*3	347	178	0.196
D13*4	356	176	0.222
D13*5	791	191	0.615
D13*6	766	185	0.431
D22*7	1044	177	0.778
D22*8	1015	193	0.727
U9.0*9	1386	198	0.858
U9.0*10	1313	181	0.926
steel pile	346**	Tensile strength : 665MPa	

**: Yield strength and strain were determined by 0.2% offset method.
*1~*10: corresponding to Table 1

3. TEST RESULTS

3.1. Story Shear – Drift Relationships

Relationships between the story shear force and the story drift angle are shown in Figure 3.1. The story shear force was obtained from moment equilibrium between measured beam shear forces and the horizontal force at a loading point on the top of the column. Yielding of anchor bars of pile-cap and a peak of shear the story shear force is indicated by an open triangle and a solid circle symbol respectively. The theoretical ultimate flexural capacity of the foundation beam is shown by a horizontal dashed line, which was computed by a section analysis assuming that a plane section remains plane. The positive story shear force and negative shear force had different peak story shear for all specimens, the positive peak story shear force was 25% approximately as large as the negative peak story shear force. It appears that the resisting mechanism of pile-cap varies according to the tension either in the top or the bottom foundation beam reinforcement.

The peak story shear force was attained at a story drift angle of 2% for all specimens in the positive loading. In the negative loading, the peak story shear force was attained at a story drift angle of 1% for Specimen No.1 and 2% for other specimens. It appears that the story shear force was not enhanced because the pullout deformation of pile at a story drift angle of 2% in Specimen No.1 was larger than other specimens. The peak story shear forces were almost equal between Specimen No.1 and No.2, but the story shear force decreased abruptly after the peak for Specimen No.2, Specimen No.2 had shorter vertical bars in the pile-cap than Specimen No.1. For specimen No.3, the peak shear force in positive loading or negative loading were 6.8% or 11.3%, respectively, as large as that for Specimen No.1. This indicates that the shear force was enhanced by the increasing tie bars in pile-cap.

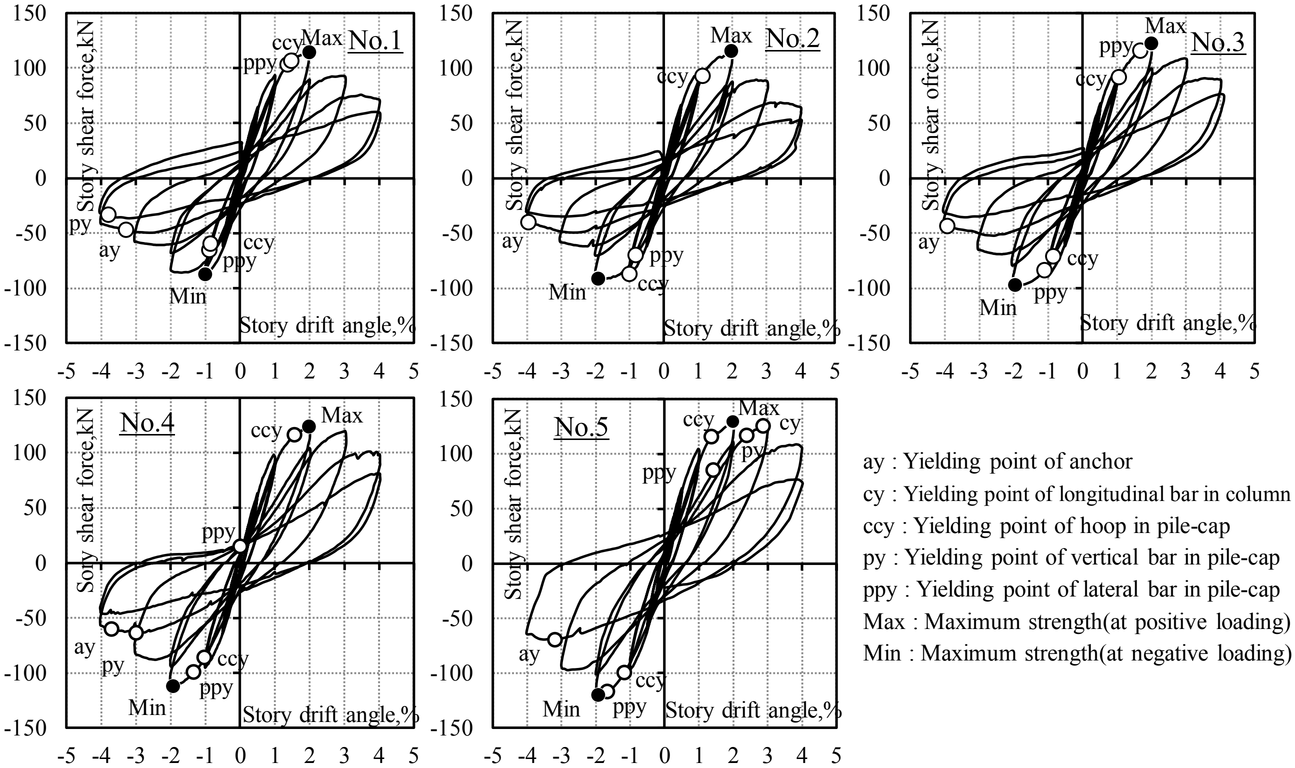


Figure 3.1 – Story shear – story drift angle relationships

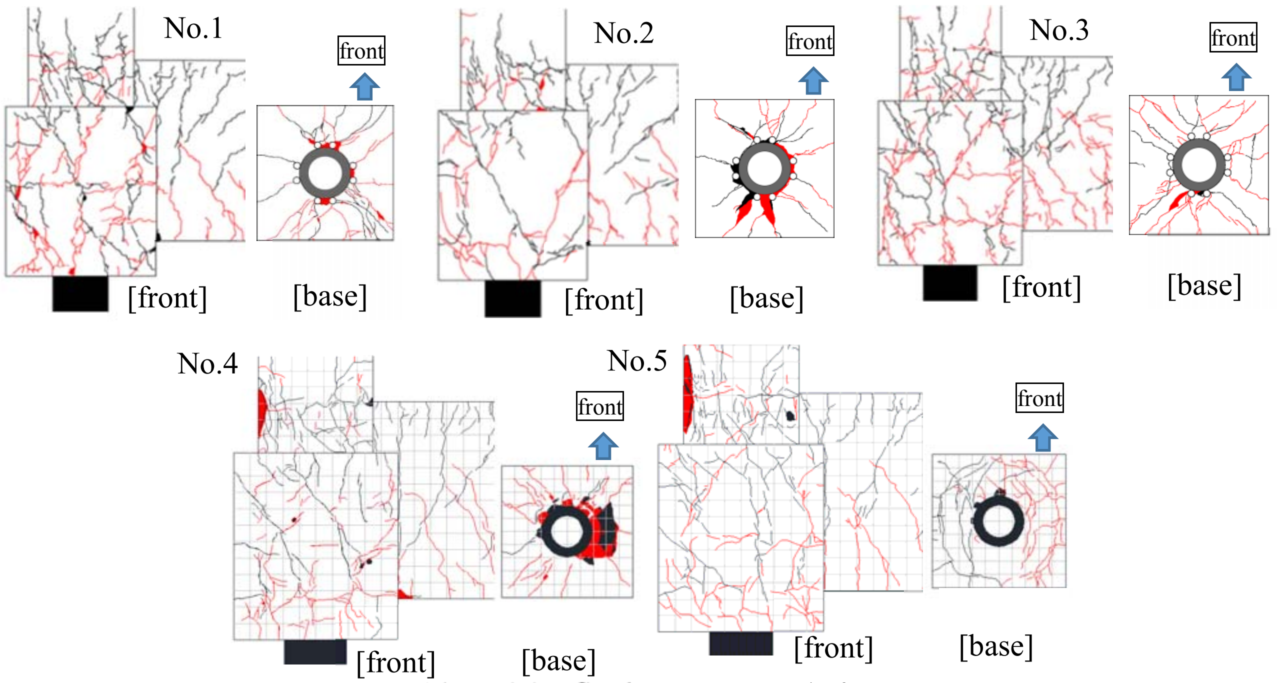


Figure 3.2 – Crack patterns at end of test

For Specimen No.4 or No.5, the peak story shear force in the positive loading was 10% or 7.7%, respectively, as large as that in the negative loading. This indicates that the shear force in the negative loading was enhanced by the increasing tie bars in pile-cap. For all specimens, the story shear force decreased gradually after peak in the positive loading, to the contrary, it decreased drastically in the negative loading. It appears that the compression strut mechanism was different in positive loading and negative loading, the crack pattern was different, too.

3.2. Crack Patterns

Crack patterns at the end of test are shown in Figure 3.2. Peak story shear forces and story drift angle, initial shear crack at pile-caps and yielding of the pile anchors obtained by the tests are summarized in Table 3.1, respectively. For all specimens, the column flexural cracks occurred in positive loading after the foundation beam flexural cracks and shear cracks occurred. After that diagonal shear cracks occurred in foundation beam–column joint with the increase in the deformation. After these cracks grew into diagonal shear cracks in pile-cap, the maximum story shear force was attained. For all specimens, the pile-cap tie bars and the column reinforcement bars in pile-cap yielded at the peak story shear force, after that the story shear force decreased to increase the shear cracks and to expand the shear crack width. For all specimens, the column flexural cracks occurred in negative loading after the foundation beam flexural cracks and shear cracks occurred, too. After that diagonal shear cracks occurred in pile-cap, then the diagonal shear cracks occurred in foundation beam–column joint.

At the end of test, the concrete in the foundation beam-column joint for Specimen No.1 and No.2 expanded to the direction orthogonal to the loading direction.

Table 3.1 – Test results

	No.1		No.2		No.3		No.4		No.5	
	Q	R	Q	R	Q	R	Q	R	Q	R
	kN	%	kN	%	kN	%	kN	%	kN	%
Flexural carck in foundation beam	21.6 -13.9	0.11 -0.07	25.9 -22.3	0.13 -0.15	19.4 -18.7	0.07 -0.10	21.3 -25.8	0.13 -0.15	20.4 -29.8	0.07 -0.25
Shear crack at pile cap	84.3 -73.7	0.78 -0.64	94.8 -76.3	1.00 -0.73	96.4 -83.1	0.93 -0.86	96.8 -91.0	0.98 -0.90	102.8 -96.4	1.01 -1.00
Yielding of the pile anchor bars	-46.7	-3.34	-41.4	-3.83	-45.3	-3.77	-60.8	-3.69	-69.6	-3.19
Maximun story shear	114.0 -87.9	2.00 -1.00	115.4 -91.8	2.00 -1.78	121.8 -97.4	2.00 -1.91	123.9 -112.2	1.99 -1.93	129.3 -120.0	2.01 -1.93

Q:Story shear force, R:Story drift angle

upper stage in cell:positive loading, lower stage: negative loading

3.3 Failure Mode

The crack around the anchor occurred in the bottom of pile-cap in the both loadings for all specimens, after that these cracks grew into the upward. The damage developed in the bottom of pile-cap with the increase in the deformation, there was a space between pile-cap and pile in the negative loading by the pile pulled out pile-cap. From the above results, pile-cap shear failure occurred for all specimens.

3.4 Story Drift Contribution

The contribution of deformation of a foundation beam, a column, a pile-cap and a pile to the story drift was calculated and shown in Figure 3.3. The deformation of the pile which is a rigid body was treated as slipping pile out of a pile-cap. The deflection component in positive and negative loadings were different. In the positive loading, the deformation of the pile-cap was large when a story shear was peak, the slipping out of a pile-cap increased after peak story shear. On the other hand, in the negative loading, the deformation of a pile-cap and pile were almost equal when a story shear was peak. After peak story shear, the slipping out of a pile-cap increased, but the deformation of a pile-cap decreased. The reason for increase extraction in the negative loading includes the deterioration of the bond with the anchor bar. The weakening of a restricting force at the lower part of pile-cap occurred because of the foundation beam position was set up.

3.5 Strain Distribution

The locations of gauges in foundation beam, column hoop and pile-cap hoop are shown in Figure 3.4.1 and 3.4.2, respectively. The strain gauges were stuck on the foundation beam longitudinal bar and column hoop in the same position at the all specimens.

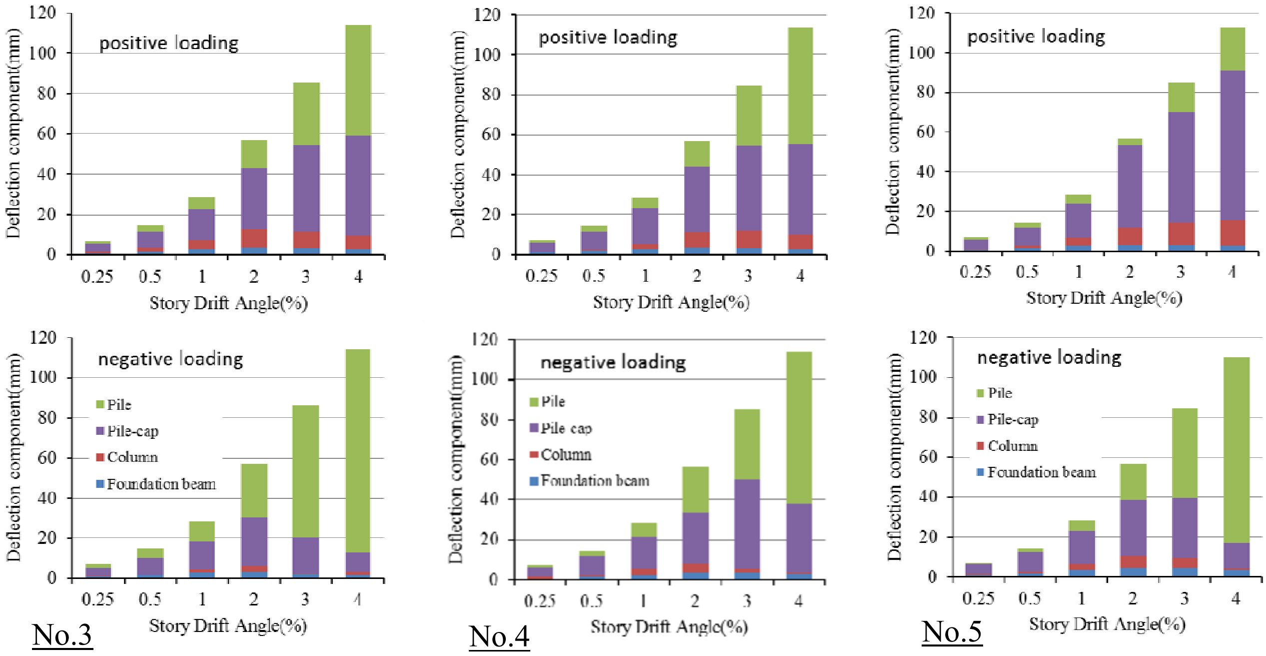
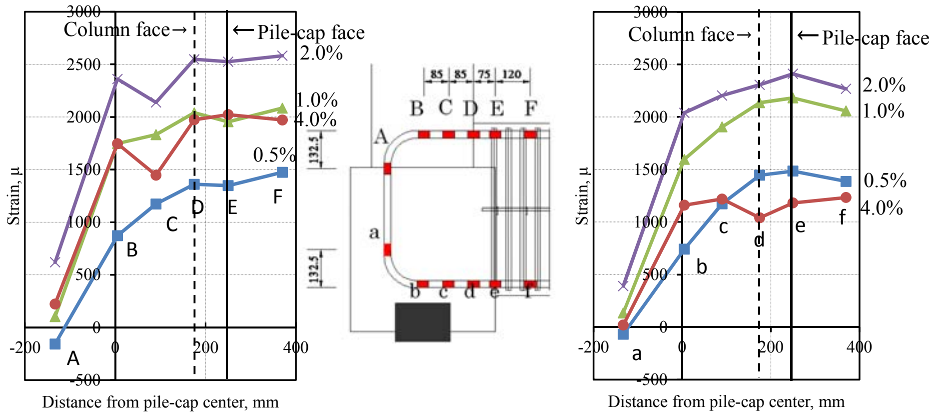
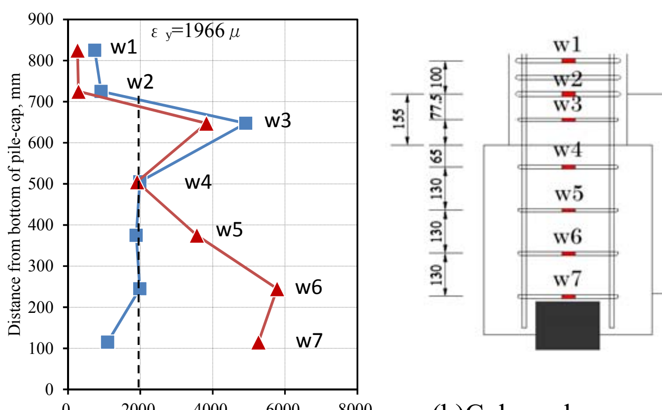


Figure 3.3 – Deflection components of stroy drift

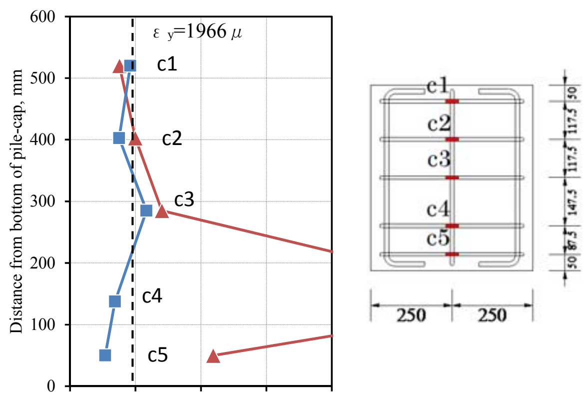


(a)Foundation beam longitudinal bar

Figure 3.4.1 – Strain distributions along longitudinal bars in pile-cap



(b)Column hoop



(c)Pile-cap hoop

Figure 3.4.2 – Strain distributions along hoop in column and pile-cap

3.5.1 Foundation Beam Longitudinal Bar

Strain distributions along a foundation beam upper and bottom longitudinal bars at tension side are shown in Figure 3.4.1. The column critical section and the pile-cap critical section are also shown by dotted and black thick line, respectively. The maximum tension strain of an upper longitudinal bar was occurred at the column critical section, the tension strain outside of this section decrease. On the other hand, the maximum tension strain of a bottom longitudinal bar was occurred at the pile-cap critical section, the tension strain outside of this section decrease. From the above results, the critical section was different from each loading. The bond performance long the foundation beam bottom longitudinal bar between the column critical section and the face of pile becomes deteriorative in accompany with large drift angle. This indicates that the bond deterioration is affected by the tension force of anchor. At the peak story angle, the anchorage of bent-up bar covered the most tensile force of the bottom longitudinal bar.

3.5.2 Column Hoop

Strain distributions of a column hoop at the peak story shear are shown in Figure 3.4.2. The positive and negative loadings are also shown by blue and red marks, respectively. In this figure, the yield strain is illustrated by dotted line, the different kind of hoop strength was arranged under and below the column critical section. The strain of hoop in pile-cap and foundation beam–column joint yielded for all specimens in both loadings. The strain value peaked in the foundation beam-column joint region and reduced downward within the pile-cap in positive loading. But the strain value increased within the foundation beam-column joint region and at the bottom of pile-cap in negative loading. This indicates that the strain distribution of hoop corresponds to the different properties of the shear crack in positive and negative loading.

3.5.3 Pile-Cap Hoop (lateral bar in pile-cap)

Strain distributions of a pile-cap hoop at the peak story shear are shown in Figure 3.4.2. The positive and negative loadings are also shown by blue and red marks, respectively, the yield strain is illustrated by dotted line. In this figure, the strain of hoops yielded in all specimens, and the strain distribution of pile-cap hoop exhibits a similar tendency.

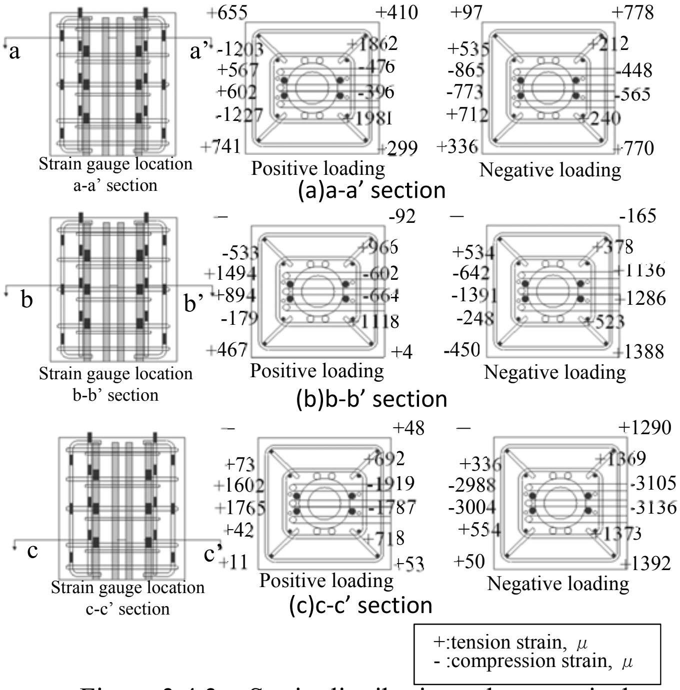


Figure 3.4.3 – Strain distributions along vertical longitudinal bars in pile-cap

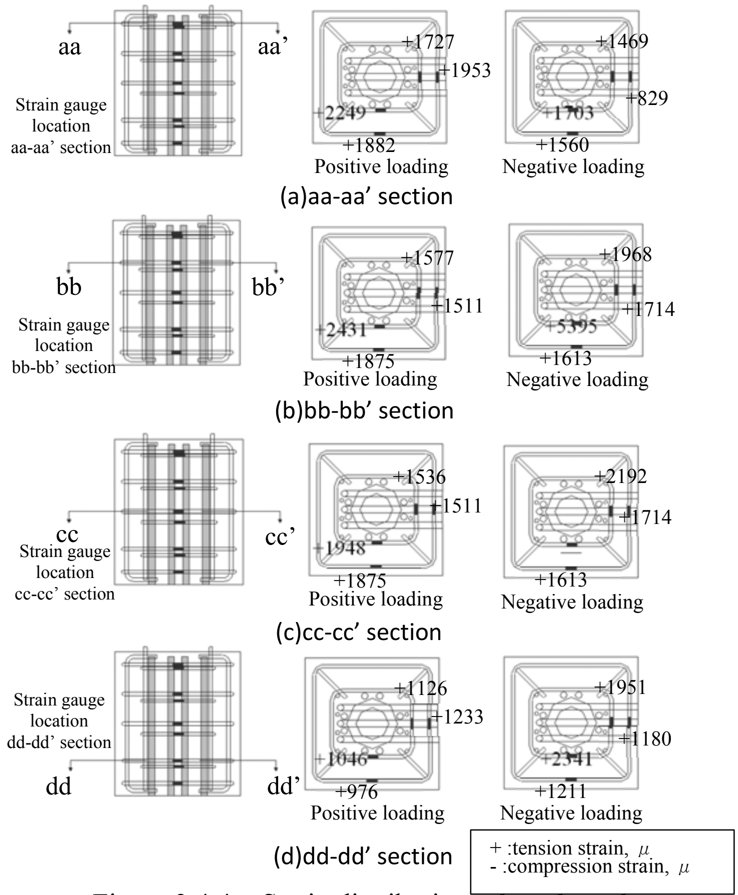


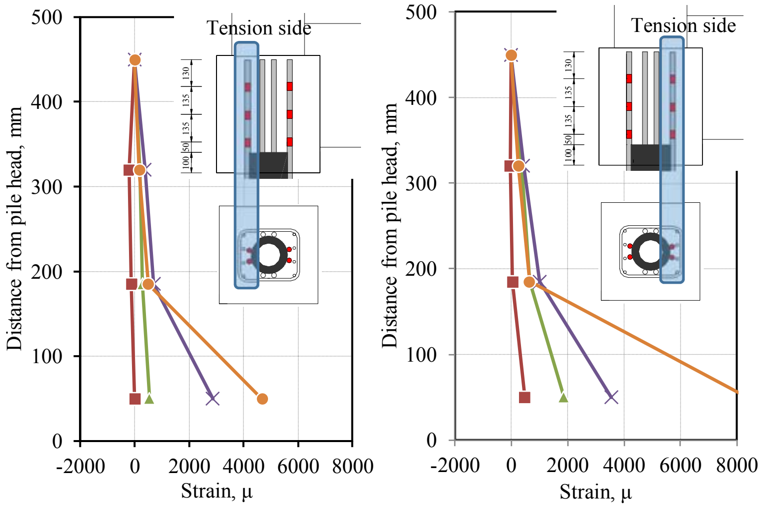
Figure 3.4.4 – Strain distributions along lateral longitudinal bars in pile-cap

3.5.4 Vertical Bar in Pile-cap

Each strain value of a pile-cap vertical bar at the peak story shear for specimen No.4 are shown in Figure 3.4.3 The strain value of the inner vertical bar arranged at the bottom of pile-cap, that is anchor, was bigger than the outer, which is vertical bar, in the both loadings.

3.5.5 Lateral Bar in Pile-cap and Hoop

Each strain value of a pile-cap hoop and lateral bar at the peak story shear for specimen No.4 are shown in and Figure 3.4.4, respectively. The strain value of the inner lateral bar arranged at the upper of pile-cap, that is hoop, was bigger than the outer, which is lateral bar, in the both loadings, too. This indicates that the inner stress in the pile-cap contributes intensively on the inward side.

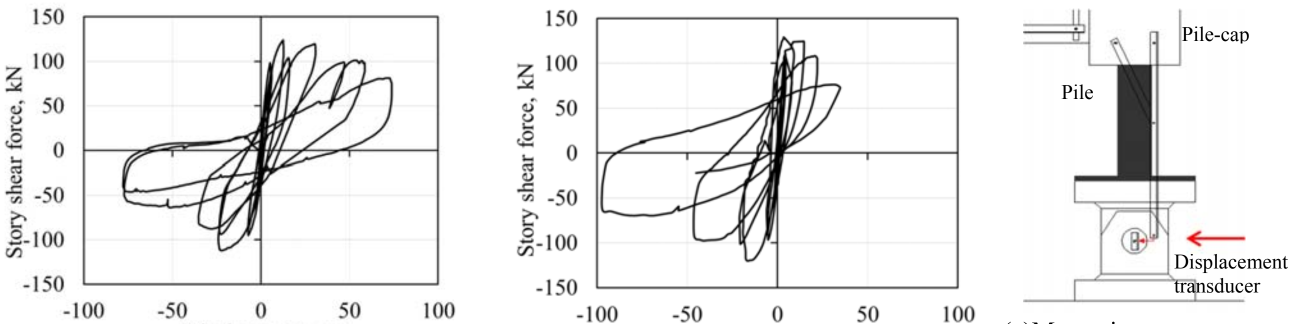


(a)positive loading (b)negative loading

Figure 3.5 – Strain distributions along anchor bars in pile

3.5.6 Anchor Property of Anchor Bar

The position of gauges in anchor and the strain distribution along the anchor are shown in Figure 3.5 and the yield strain is illustrated by dotted line. The length of anchor is about 20d (d is a reinforcement diameter). The strain value increased linearly from the end of anchor to the pile head until a story drift angle of 2% with both loadings. The tension force was not shared from the end of anchor to the pile head and the local bond stress along the anchor bar at the pile head sharply increased with the increase in the deformation.



(a)Specimen No.4 (b)Specimen No.5 (c)Measuring system at pile

Figure 3.6 – Relationships between the story shear force and the pile deformation

Specimen No.4 Specimen No.5 Specimen No.4 Specimen No.5

(a) maximum story shear [R=2.0%] (b) miximum story drift angle [R=4.0%]

Photo3.1– Crack pattern of pile-cap bottom

In this experiment, the anchor bars were arranged within the column hoop, according to the bond contribution of the column hoop, the tensile force was held by the column hoop. And the anchor property was affected by the tension force of the foundation beam bottom longitudinal bar, too.

3.5.7 Pile Deformation effected by Ring Bar Effects

Relationships between the story shear force and the pile deformation are shown in Figure 3.6, and failure conditions of the pile-cap bottom at the peak story shear are shown in Photo 3.1. The deformation with the positive loading for specimen No.4 was larger than that for specimen No.5. This indicates that the surrounding pile head was confined by the ring bars arranged around the pile head for the specimen No.5.

For specimen No.5, the deformation at the peak story shear(at a story drift angle of 2%) with the positive or negative loading was 72% or 27%, respectively, as small as that for specimen No.4, and then the deformation at a story drift angle of 4% with the positive or negative loading was 62% as small as that for specimen No.4, but with negative loading, the deformation was 27% as large as that for specimen No.4. This indicates that at the peak story shear, the deformation for specimen No.5 is suppressed small by the ring bars arranged around the pile head. But the crack around the pile head became prominent at the peak story drift angle, such effects could not be achieved and then the deformation increased.

4. DISCUSSION

4.1 Consideration of the Compressive Strut Mechanism

(1) Expected resistance mechanism

With the positive loading, the struts were formed in two directions, that is to say, from foundation beam to column and from pile to column, as a result, the compressive force of column was dispersed. On the other hand, with the negative loading, the struts overlapped and were formed in one direction, the compressive force of the column and foundation beam were different. The maximum strength shows a difference with both loadings because that the column compressive force coincides with the foundation beam compressive force.

(2) Stress Transfer Condition

The stress transfer conditions of specimen No.5 in pile-cap are shown in Figure 4.1. Each stresses and the compression depth were calculated by the strain of the longitudinal reinforcements considering each members dimension. The column reinforcing bar which arranged the pile-cap upper bar vicinity with the positive loading and the pile head vicinity with the negative loading in the pile-cap yielded at the peak story shear. On the other hand, the pile-cap reinforcing bar yielded at the peak story shear but the value of strain was smaller than that of the column reinforcing bar. From this, the strut receiving a compressive force gets more compressive resultant force at the place overlapping strut, the strut resistant mechanism was not formed the same along the depth.

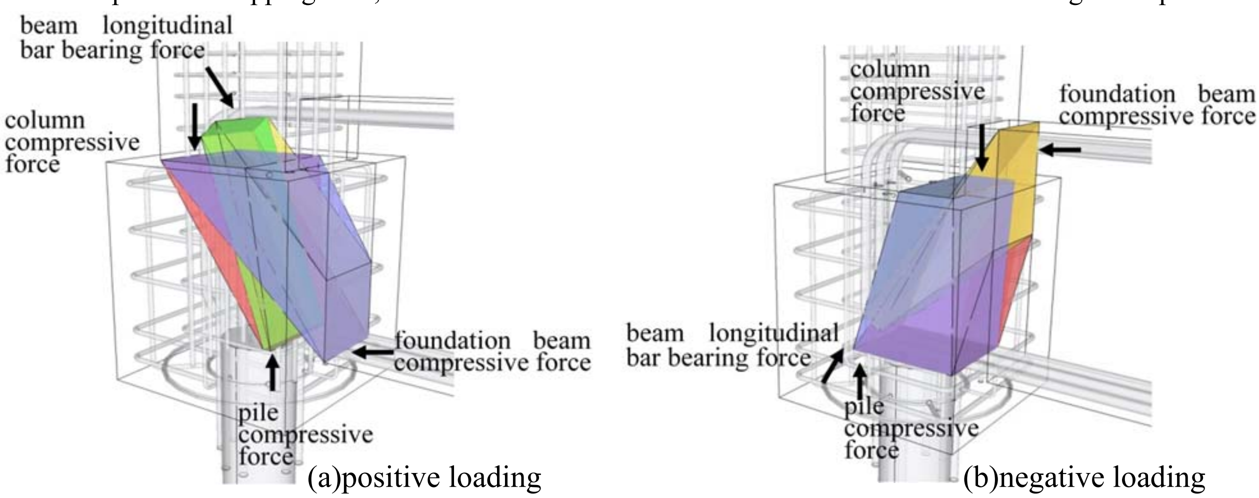


Figure 4.1 – The stress transfer conditions in pile-cap (Specimen No.5)

4.2 Evaluation of Pile-cap Join Shear Strength

The relationship the pile-cap joint shear strength and the ratio of the joint shear reinforcing bar are shown in Figure 4.2. The test results reported according to Reference [3], [4] are shown by solid symbols in Figure 4.2 and Table 4.1. The pile-cap joint input shear force was computed as Equation (1).

$$V_{ju} = T - V_c \tag{1}$$

Where T is measured tensile force of the foundation beam longitudinal bar on a beam critical section, V_c is the measured story shear force. The vertical line in Figure 4.2 is displayed the pile-cap joint shear strength(V_{jh}) divided by the join shear strength(${}_jV_{ju}$) computed according to Reference [1], because each specimen was not different from the concrete compressive strength. The joint shear strength is computed by Equation (2).

$${}_jV_{ju} = \kappa\ \phi\ F_j b_j D_j \tag{2}$$

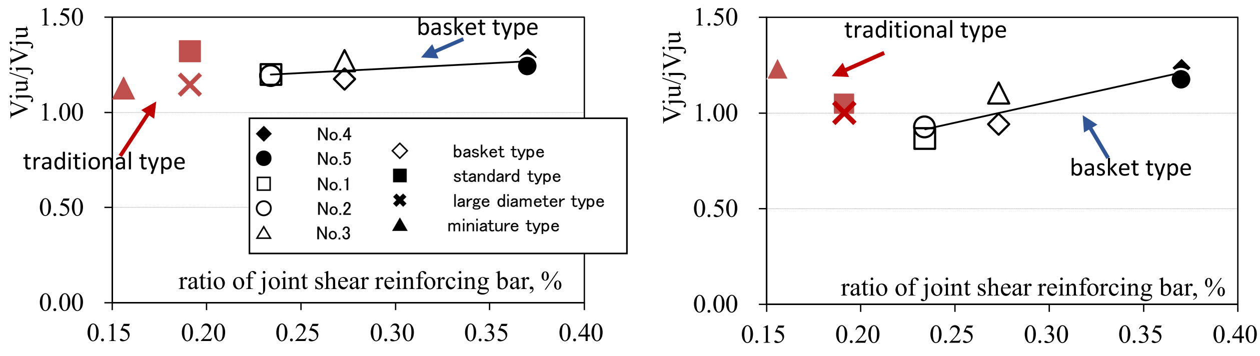
Where κ is a coefficient of joint shape, ϕ is a correction factor with the presence or absence of the transverse beam, b_j is a joint effective width(mm), D_j is an anchorage length of foundation beam longitudinal bar(mm), F_j is a reference value of joint shear strength ($=0.8\,\sigma_B^{0.7}$).

$$P_{jw} = \frac{\sum A_{jw}}{b_c \cdot j} \tag{3}$$

Where j is a center of gravity length between an upper longitudinal bar and a bottom bar(mm), b_c is a column width(mm), $\sum A_{jw}$ is a total cross-sectional area of a shear reinforcing bar on column and pile-cap between an upper longitudinal bar and a bottom bar(mm^2).

Table 4.1 – Test results of joint shear force in pile-cap

Specimen		positive loading		negative loading		ratio of joint shear reinforcing bar
		joint shear force	Lower strength by AIJ provision	joint shear force	Lower strength by AIJ provision	
		V_{ju}[kN]	${}_jV_{ju}$[kN]	V_{ju}[kN]	${}_jV_{ju}$[kN]	[%]
2013	No.4	479.8	371.6	459.7	371.6	0.37
	No.5	490.3	394.8	463.2	394.8	0.37
2012[4]	No.1	431.6	360.2	312.1	360.2	0.23
	No.2	430.1	360.2	334.1	360.2	0.23
	No.3	458.5	360.2	398.3	360.2	0.27
2010[3]	basket type	487.1	414.8	390.3	414.8	0.27
	standard type	547.7	414.8	434.4	414.8	0.19
	large diameter type	575.4	502.3	502.7	502.3	0.19
	miniature type	379.1	336.2	413.8	336.2	0.16



(a)positive loading (b)negative loading

Figure 4.2 – Relationships pile-cap joint shear strength and ratio of joint shear reinforcing bar

At the positive loading, the pile-cap join shear strength increased slightly with the ratio of the shear reinforcing bar. Conversely, at the negative loading, the pile-cap join shear strength increased greatly with the ratio of the shear reinforcing bar. In the future, we consider that it is necessary to quantitatively evaluate the effect of pile-cap shear reinforcement.

5. Conclusions

Concluding remarks drawn by this study are as follows.

(1) Due to the effect of raising the foundation beam position, the confined force of the bottom pile-cap was reduced by the foundation beam. Especially, with the negative loading, the anchor bar was affected by tensile force of the foundation beam bottom longitudinal bar, the pile deformation of slipping out of the pile-cap was increased.

(2) The maximum story shear strength was improved and the around member deformations were controlled by the increasing the pile-cap shear reinforcing bars.

(3) The maximum story shear force differed with the negative loading and the positive loading on the relationship between story shear force and story drift. This indicates that the resistance mechanism was different in the loading direction, and the failure caused by the influence of foundation beam at the bottom of pile-cap has progressed.

(4) According to the strain results, the strut receiving a compressive force got more compressive resultant force at the place overlapping strut, the strut resistant mechanism was not formed the same along the depth. From the above, the maximum story shear force was different in the loading direction.

(5) With the negative loading, the pile-cap joint shear strength was effected significantly by the ratio of shear reinforcement. The stress transfer mechanism was different with the positive and the negative loadings, respectively.

(6) There was no striking difference between the maximum strength for Specimen No.1 and No.2, not arranging the tie and lateral bars around the pile head. But the story shear force decreased gradually after story shear force reached the maximum value and the damage of the bottom of pile-cap was remarkable.

(7) The pile deformation for Specimen No.5 arranged the ring bar around the pile head, was suppressed, but that increased because the crack on the bottom pie-cap occurred in a ring shape around the pile head at the peak story drift angle (corresponding to the story drift angle is 4%).

6. Acknowledgements

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7. References

[1] Architectural Institute of Japan (2001): Design Guideline for Earthquake Resistant Reinforced Concrete Buildings Based on Inelastic Displacement Concept.

[2] Architectural Institute of Japan(2002): Recommendations for Design of Building Foundation

[3] Matsumoto G, Hirabayashi Y, Hayashi S, Ishikawa K, Ogura H, Kishida, S, (2010) : Estimation of Earthquake Resistance of Pile Caps combined with structural members, *Summaries of Technical Papers of Annual Meeting*, AIJ, 445-446, (in Japanese).

[4] Owaku T, Tomiyama Z, Uesaka Y, Kishida S, Hayashi S, (2013): Experimental Study on Seismic Performance of Pile caps on the Exterior frame : No.1 Outline of experiment and Experimental results, No.2 Experimental results and Conclusions, *Summaries of Technical Papers of Annual Meeting*, AIJ, 695-698, (in Japanese).