# Experimental Study on Seismic Performance Evaluation of Reinforced Concrete Interior Pile Cap Joint with Precast Pile

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**SUMMARY:**
Pile cap is a very important member connecting the column, pile and foundation beams. There are two kinds of vertical members in a pile cap, column and pile. Therefore, the seismic behavior of a pile cap is more complicated than that of beam column joint. To examine the behavior of pile caps, the experiments on the reinforced concrete interior pile caps which were composed of one column, two footing beams and one pile were carried out under cyclic loadings.
In this study, the effects of axial force on the column and the volume of pile cap on the seismic behavior, e.g., the process of damages, failure mechanisms and the ultimate strength of pile caps, are investigated.

*Keywords: pile cap, foundation beams, reinforcing bars, pile cap seismic performance, joint*

## 1. INTRODUCTION

Pile cap is an important structural joint member. Its function is to transfer the stresses occurring on the superstructure through a group of piles to the ground. In particular, the complicated stress in pile cap occurs under earthquake loading. It is difficult to identify the pile cap condition 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 behaviour of pile cap under earthquake load.

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 later al and vertical reinforcements is not considered and the pile cap foundation is currently designed using methods prescribed by structural regulations[Architectural Institute of Japan(2001)]. Most of the research in these studies has focused on the effects of vertical loading on structural performance and bar configurations in pile caps, e.g. Tanabe[Tanabe, S., (1998)], Suzuki[Suzuki, K., (2005)] and Sakai[Sakai, S., (2007)]. The performance was examined in cases of tension-only or compression-only loading; Kobayashi[Kobayashi, K., (1998)] conducted tests in earthquake 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[Sakai, S., (2008)]. 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. TEST PROGRAM

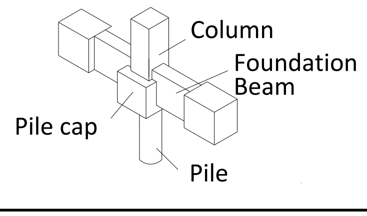
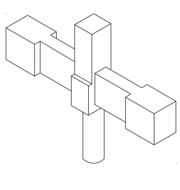
### 2.1. Specimens

Specific properties of specimens are summarized in Table 2.1. Material characteristics of concrete and steel are listed in Table 2.2 and 2.3, respectively. Section dimensions and reinforcement details are shown in Fig.1. The specimens which were the cruciform subassemblages of a precast pile, foundation beam and column, were quarter scale to actual frames. In this experimental study, three specimens were fabricated which can be divided into two types considering the cross section properties. Specimen RC-0-500 and RC-0.32-500, are named as Type A specimen with square pile caps which pile caps cross section was square with 500mm depth and width. Specimen RC-0.32-350 is Type B specimen with pile cap cross section smaller than Type A, and the pile cap depth is as same as the column depth. The constant axial load in compression was applied at the top of the column for specimen RC-0.32-500 and RC-0.32-350. Specimen RC-0-500 was not added to axial load. The depth and width of the column section were 300mm and 350mm, respectively. 12-D19 was arranged in the column as longitudinal bar. The depth and width of the foundation beam section were 200mm and 600mm, respectively. 3-D19 was spread in the 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 825mm. The height from the center of the beam to the supporting point on the top of the column or to the bottom support was 675mm and 975mm, respectively. The shear span ratio was 1.16 for the beam, 1.07 for the column and 3.54 for the pile, respectively. Three configuration of D10 bars were used in the pile cap. They were utilized as main reinforcement which were called a tie and lateral bar, respectively. Steel pile (t=35mm) was used as a precast pile, the embedment length was 50mm, 12-D22 bars were arranged as anchor dowel bars. The grout was filled into the hollow part of the steel pile for all specimens. Concrete compressive strength was 27MPa. Three specimens were designed to fail in pile cap.

## 2.2. Loading Method and Instrumentation

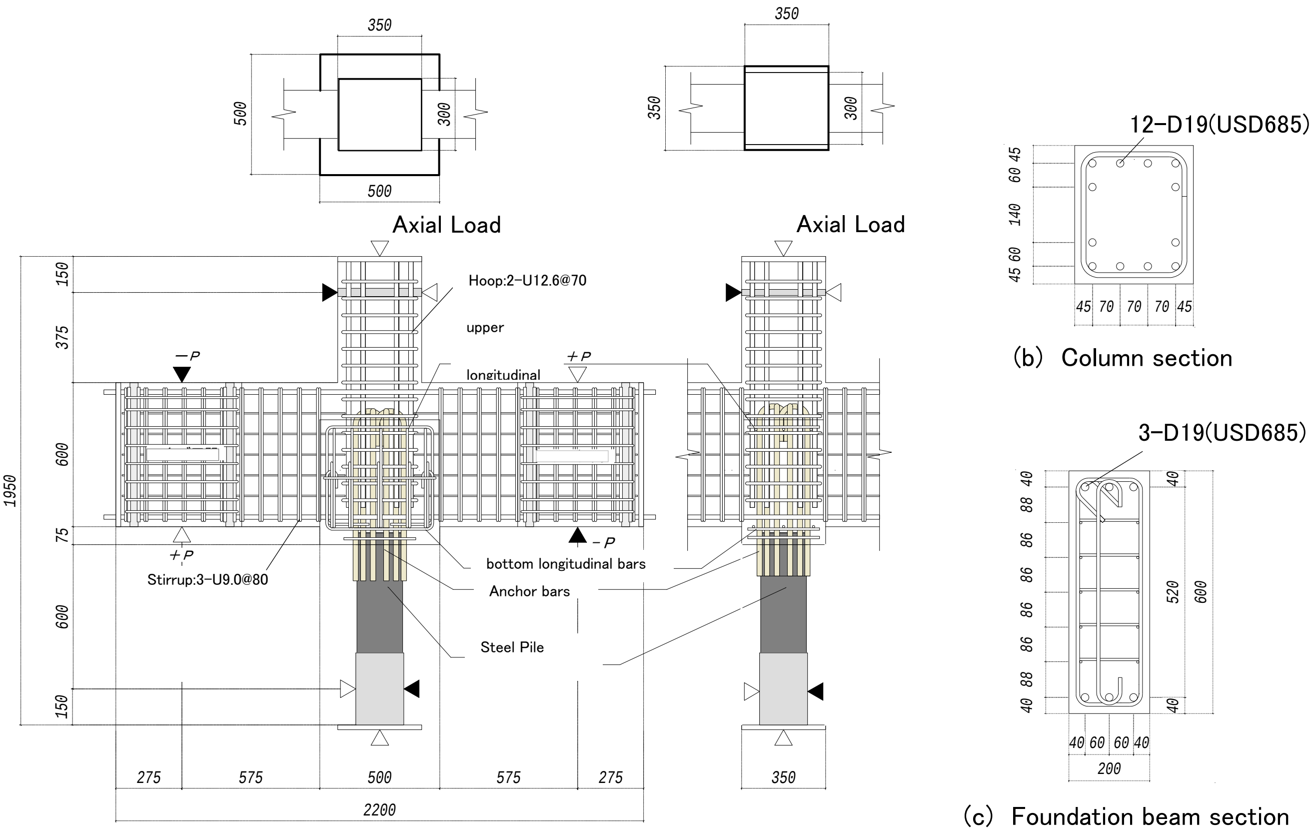
A loading apparatus is shown in Fig.2 and Photo.1. The top column end and bottom pile end were supported by hinges. The reversed vertical loads were applied at the tips of the foundation beams, and

Table 2.1. Properties of specimens

| Specimen | RC-0-500 | RC-0.32-500 | RC-0.32-350 |
|---|---|---|---|
| Shape |   | |  |
| | Type A | | Type B |
| Axial load ratio | 0 | 0.32 | |
| Pile cap | 500*500*520*1 | | 350*350*520*1 |
| | upper longitudinal bars :5-D10 | | :3-D10 |
| | bottom longitudinal bars :5-D10 | | :3-D10 |
| | tie :1-D10 | | : - |
| Column | longitudinal bars :12-D19(USD685) | | ,pt=1.88% |
| | hoop :U12.6@70 | | ,pw=1.19% |
| Foundation beam | longitudinal bars :3-D19(USD685) | | ,pt=0.74% |
| | stirrup :U9.0@80 | | ,pw=1.20% |
| Pile | steel pile : $\phi$ 190.7, t=35 | | |
| | anchor bar :12-D22(USD685) | | |

*1:depth×width×height

the constant axial load in compression (an axial load ratio of 0.32) was applied at the top of the column during the experiment. All specimens were subjected to cyclic load (vertical displacements at beam ends were both at opposite directions and having the same value) at the tip of foundation beam. A reversed quasi-static cyclic load was applied at the tip of the foundation beam using 1000kN hydraulic jacks. The load was measured using a load-cell. The loading routine was controlled by a force. A force of 50kN was applied in the first cycle and 100kN load was applied in the following two cycles until the maximum strength was reached, but the second loading was controlled to first displacement. The axial load was kept constant using another 2000kN hydraulic jack provided with a load cell to measure the applied load. This force represents the gravity load acting on the column



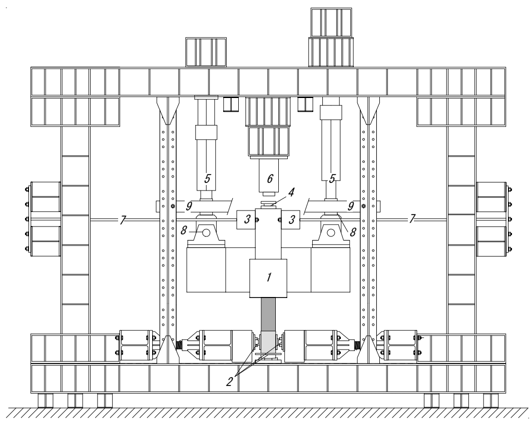

*Type A (RC-0-500, RC-0.32-500)* *Type B ( RC-0.32-350 )*

(a) Detail of specimen

unit(mm)

Figure 1 Section dimensions and reinforcement details


Photo 1. Loading apparatus




1.specimen, 2.pin, 3.column confined system, 4.pin, 5.1000kN oil jack 6.2000kN oil jack, 7.PC steel, 8.load cell, 9. torsion prevention system

Figure 2. Loading apparatus

Table 2.2. Material properties of concrete

| Compressive strength, MPa | Secant modulus*1, GPa | Strain at compressive strength, % | Tnsile strength, MPa |
|---|---|---|---|
| 30.2 | 23.9 | 0.21 | 2.8 |

*1: Secant modulus at one-quarter of compressive strength

Table 2.3. Material properties of steel bars

| Diameter | Yield strength MPa | Nomonal Young's modulus, MPa | Yield strain % |
|---|---|---|---|
| D6 | 334 | 189 | 0.21 |
| D10 | 340 | 187 | 0.19 |
| D19 | 697 | 185 | 0.49 |
| D22 | 694 | 182 | 0.49 |
| φ9.0 | 1407 | 189 | 0.89 |
| φ12.6 | 1413 | 201 | 0.88 |
| STKM13A-SH | 423* | - | - |

having an axial load level of $0.32A_gf_c$, where $A_g$ is the gross cross-sectional area and $f_c$ is the concrete compressive strength. Story drift, the foundation beam, the column and the pile lateral deflections, and local displacement of a pile cap panel were measured by the displacement transducers. The displacement of the column above and below the joint was measured using two displacement transducers attached to the top and bottom of the foundation beam. Strains of foundation beam bars, column bars, pile cap bars, anchors and lateral reinforcement were measured by strain gauges. Vertical force and column axial load were measured by load-cells.

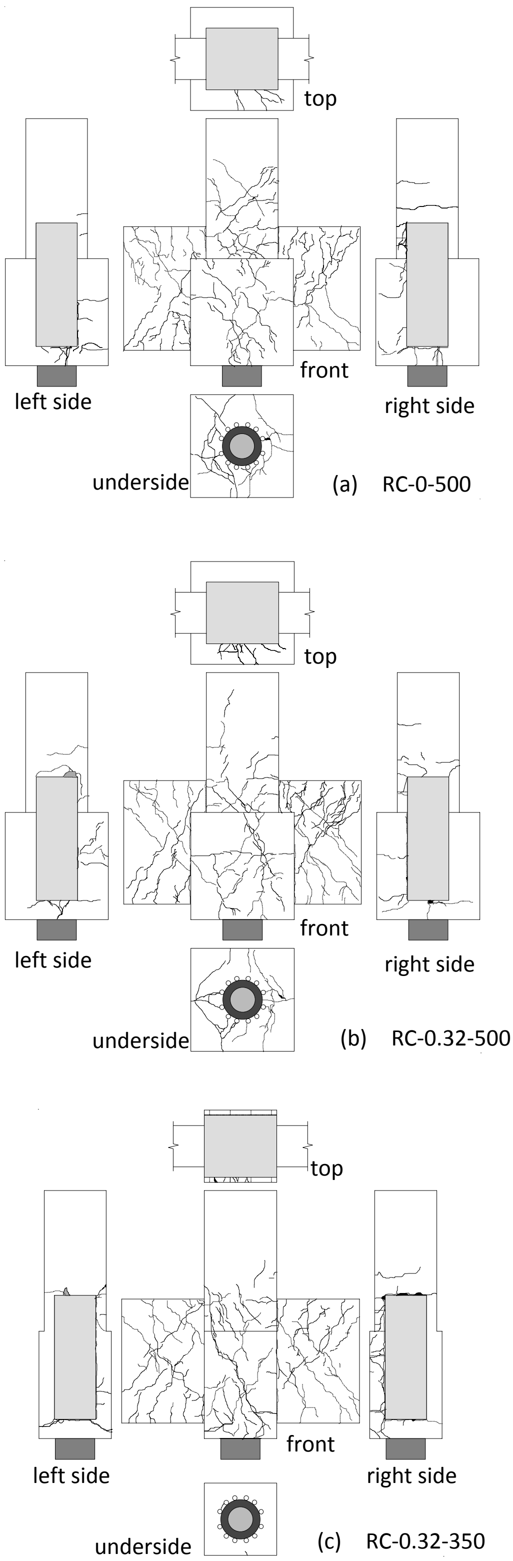



Figure 3. Crack patterns

## 3. TEST RESULTS AND DISCUSSION

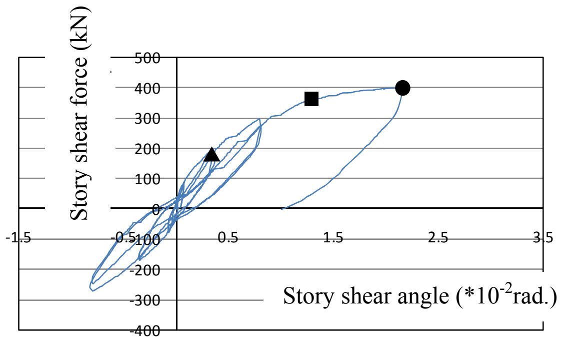
### 3.1. General Observations

Crack patterns at the maximum displacement are shown in Fig.3. Many diagonal shear cracks occurred in the foundation beam for all specimens after the flexural cracks in foundation beam critical section. The story shear reached the maximum force after the diagonal cracks occurred in the column and pile cap. For specimen RC-0-500 and RC-0.32-500, the crack at the bottom of the pile cap due to the slip from pile cap with the increase in story drift. The crack occurred at the column end did not expanded into the face of pile cap immediately, gradually spread with the increase in story shear. Because the pile cap section is larger than the column section. These cracks closed at the load decrease, but the strain of lateral reinforcement in pile cap was kept tension. On the other hand, for specimen RC-0.32-350, the crack and damage at the bottom of the pile cap did not occurred, the story shear reached maximum force when the shear crack at the pile cap expanded. Main crack occurred across the pile cap form the main longitudinal bar in the foundation beam at the bottom of pile cap to upper critical section of the column and the foundation beam.

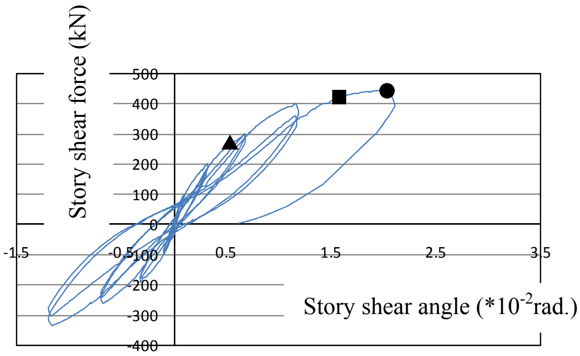
Table 3.1. Test results

| Specimen | RC-0-500 | | RC-0.32-500 | | RC-0.32-350 | |
|---|---|---|---|---|---|---|
| | Q kN | R % | Q kN | R % | Q kN | R % |
| Flexural carck in foundation beam | 84.6 | 0.07 | 92.0 | 0.08 | 75.0 | 0.1 |
| Shear crack at pile cap | 188.5 | 0.32 | 276.1 | 0.58 | 196.0 | 0.46 |
| Yielding of the pile anchor bars | 342.0 | 1.15 | 421.5 | 1.58 | - | - |
| Maximun story shear | 399.6 | 2.15 | 445.7 | 2.04 | 387.2 | 2.96 |

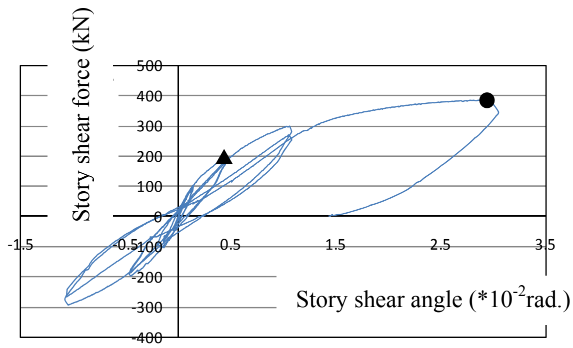
Q:Story shear force, R:Story drift angle




(a)RC-0-500




(b)RC-0.32-500




(c)RC-0.32-350

●: maximum strength, ■: anchor bars of pile cap yielded , ▲: pile cap shear cracks

Figure 4. Story shear force - Story drift angle relations

### 3.2. Failure Mode

It was concluded that specimens RC-0-500 and RC-0.32-500 failed by yielding of the pile anchors, Specimen RC-0.32-350 failed in pile cap shear.

### 3.3. Story Shear – Drift Relations

Peak story shear forces, flexural crack in foundation beam, shear crack at pile cap and yielding of the pile anchors obtained by the tests are summarized in Table 3.1, respectively. Diagonal shear crack strength in pile cap was observed. The story shear force – story drift relationships are shown in Fig.4. In this experiment, so the supported span and the loading span were same, the shear force was averaged the both shear force of foundation beams which measured by load cell. The story drift angle was ratio of the vertical displacement at both foundation beams to loading span. Shear crack point of pile cap, yielding point of anchor bars in pile cap and peak point of the story shear force are shown by solid triangles, solid squares and solid circles in Fig.4, respectively.

The peak story shear force was attained at a story drift angle of about 2% and 3% for Type A specimens and Type B specimen, respectively. For all specimens, the restoring force characteristics showed spindle-shaped curves. For specimens RC-0-500 and RC-0.32-500, the story shear force decreased gradually after yielding the pile anchors, and finally, the only story drift increased after the pile was slipped from the pile cap. For specimen RC-0.32-500 which was applied axial load, the peak story shear force was 10 percent as large as that for specimen RC-0-500 which was not applied axial load. For specimen RC-0.32-350, the diagonal shear crack expanded and the shear force did not increase before yielding the pile anchors.

### 3.4. Strain Distribution

The positions of gauges in foundation beam and column are shown in Fig.5. The value of the strain

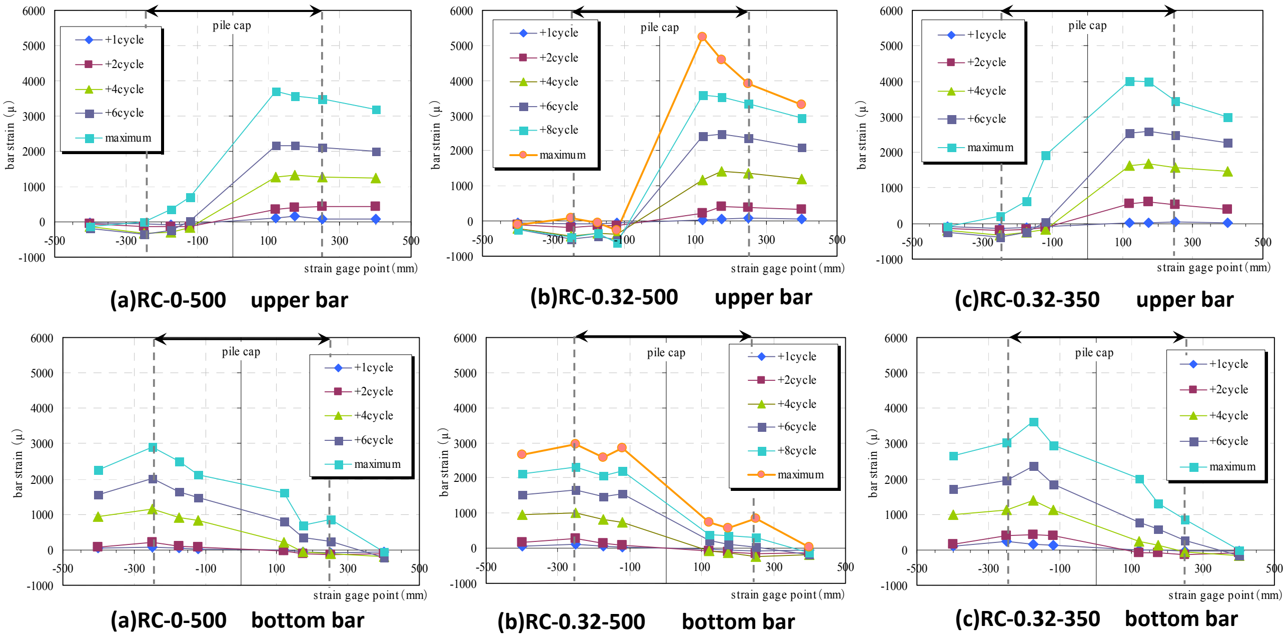


Figure 5. Strain distributions along foundation beam longitudinal bars

gauge stuck on the steel bar in the same position of the front and the back was averaged. Strains of beam and column longitudinal bars were measured by strain gauges.

*3.4.1. Effect of Foundation Beam Longitudinal Bar*

Strain distributions along a foundation beam upper and bottom longitudinal bars at positive loading are shown in Fig.5. The maximum strain was at the column critical section, because the upper longitudinal bars were arranged over the depth of pile cap. The bond deterioration along the foundation beam upper longitudinal bar occurred and the strain was switched from compression to tension in the pile cap for specimens RC-0-500 and RC-0.32-350. The bottom longitudinal bar tension strain was peak at the end of pile cap for all specimens. The bond deterioration along the foundation beam bottom longitudinal bar was larger than that along the foundation beam upper longitudinal bar. Strain distribution for specimen RC-0.32-350 and that along the beam longitudinal bars in beam-column joint for superstructure were almost same.

*3.4.2. Effect of Column Longitudinal Bar*

The strain distribution of column longitudinal bars at the positive loading is illustrated in Fig.6. All strain values of column longitudinal bars became tensile strain. All strain values in the upper face of the foundation beam became the maximum. It is probable that the upper face of the foundation beam for all specimens was a critical section.In the case of the negative loading, the critical section was a same position, too. The strain values of column longitudinal bars above the critical section became the compression, and the strain of values below the critical section became the tension. Because, the tensile stress of the anchor bars were transferred to column longitudinal bars which were arranged side the anchor.

*3.4.3. Effect of Hoop*

The strain distribution of the hoop at the positive loading is illustrated in Fig.7. In this figure, the strain did not yield. The strain value at the center of the pile cap for all specimens was biggest in other strains, the strain value decreased gradually as it separates from this hoop. In specimen RC-0.32-350, the strain values of hoop located in the lower part kept increasing at the peak story shear force. This indicates that the shear crack in pile cap at the peak story shear force expanded.

*3.4.4. Effect of Longitudinal Bars in Pile Cap*

Strain distributions along the upper longitudinal bars in pile cap are shown in Fig.8. The strain at the center was larger than that at the corner in pile cap. As the stress in the column and foundation beam spread gradually throughout the pile cap, all pile cap area was effective. Generally, the effective width

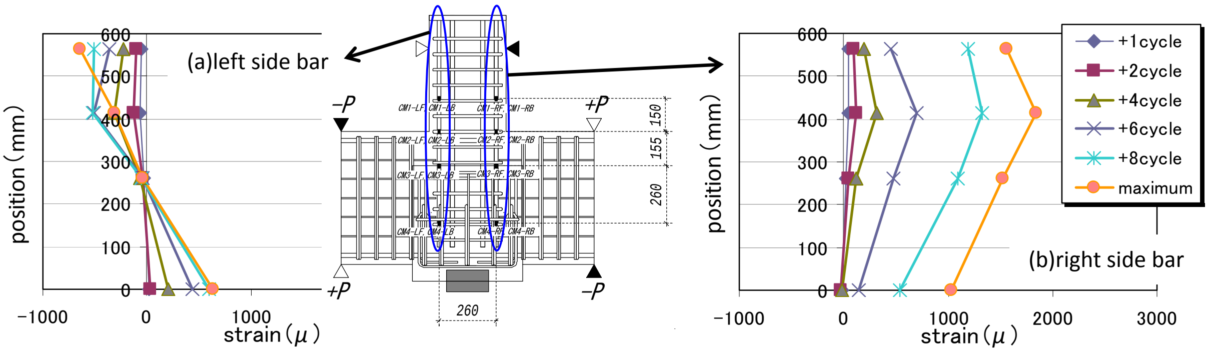



Figure 6. Strain distributions along column longitudinal bars at positive loading(RC-0.32-500)

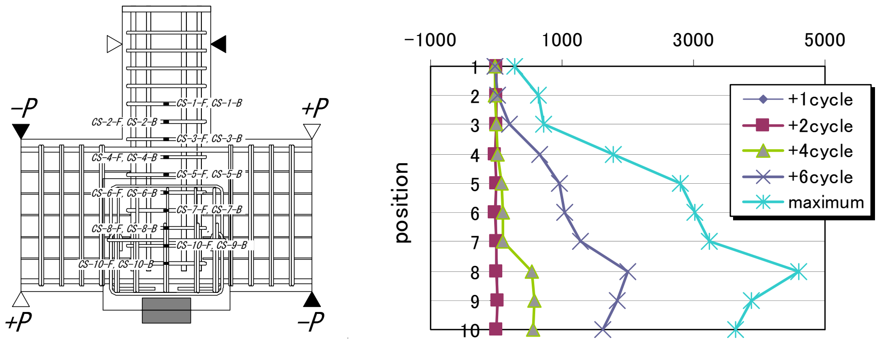



Figure 7. Strain distributions along column hoop at positive loading(RC-0.32-350)

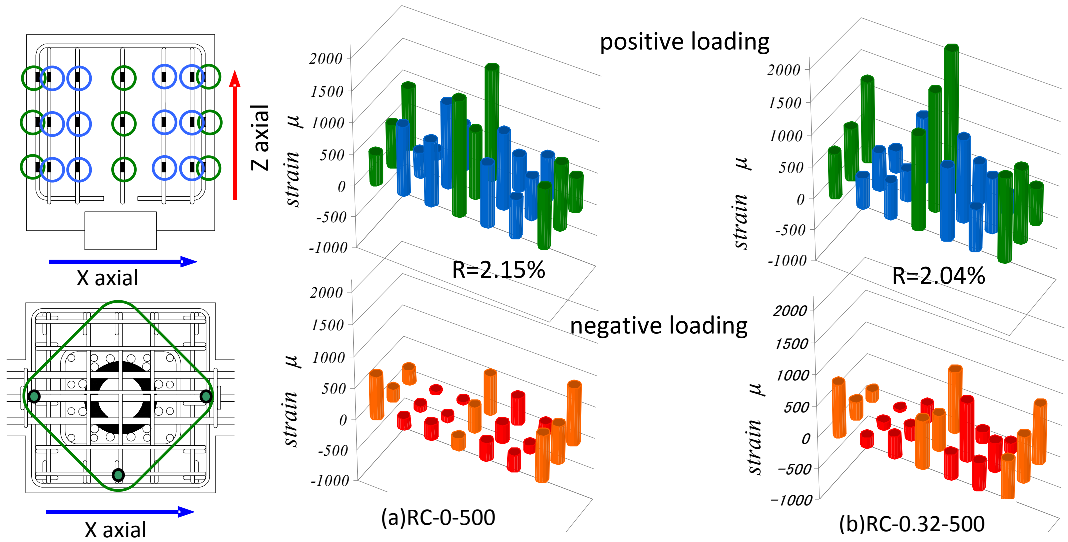



Figure 8. Strain distributions along longitudinal bars in pile cap(vertical direction)

in beam-column joint for superstructure was calculated the average column width and beam width, and the effective depth was column depth.

Strain distributions along the bottom longitudinal bars in pile cap are shown in Fig.9. The strain value was hardly changing until the 4 cycle. After that, the strain value increased gradually, and for the strain of bottom longitudinal bars, the portion which strain increased, and the changeless portion were divided clearly. On the other hand, the strain increased to the whole region, therefore the upper longitudinal bar (horizontal) shared the stress. The role of upper longitudinal bar was not only reinforcement but also the prevention of crack.

### 3.5. Pile Cap Shear Strength and Shear Distortion

For the pile cap, the critical section of foundation beam differed depending on the loading directions,

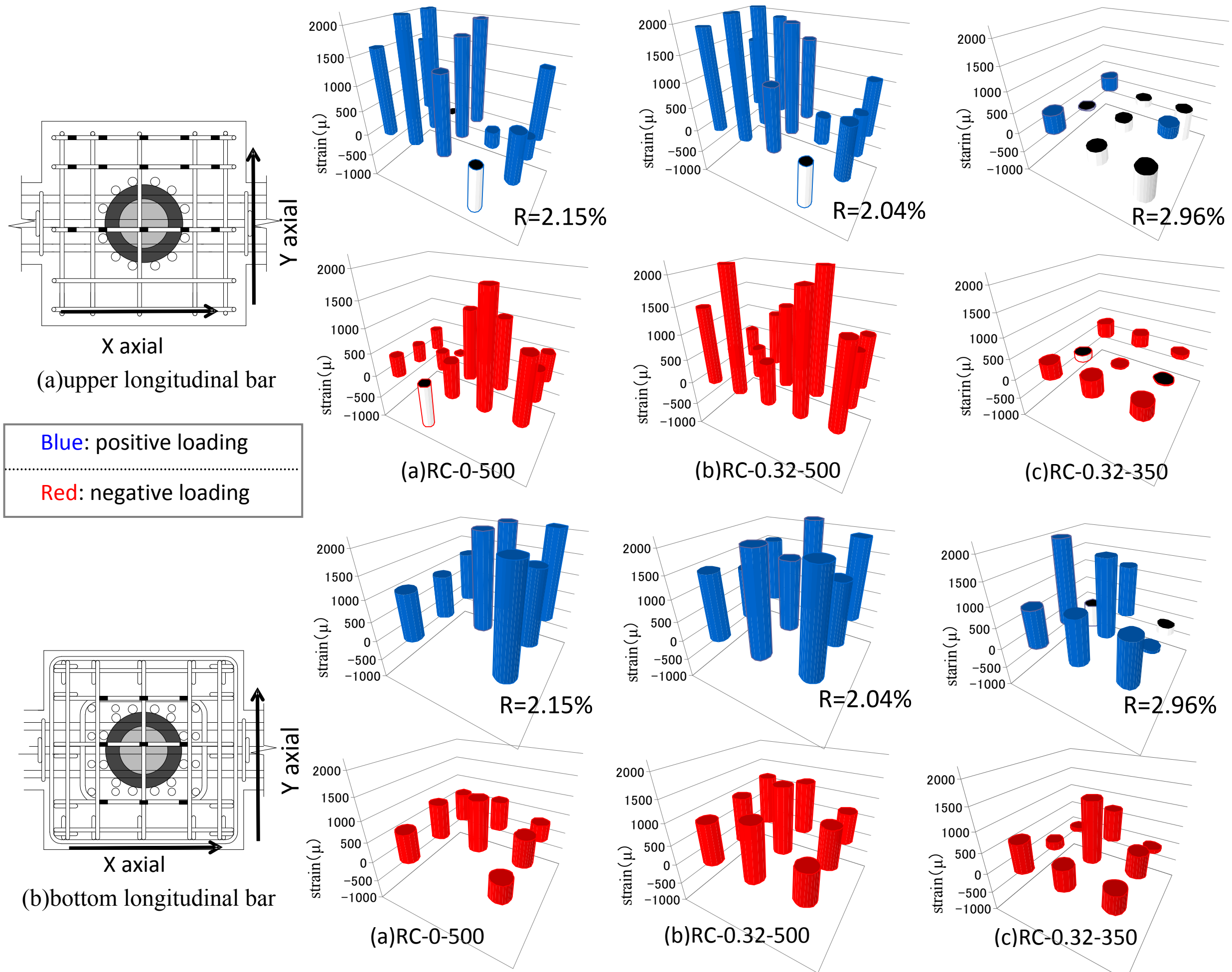


Figure 9. Strain distributions along longitudinal bars in pile cap (horizontal direction)

in other words, the column face became the beam critical section at the negative loading, and the pile cap boundary became the beam critical section at the positive loading. Naturally the foundation beam shear force was different, too. But in this paper, the both shear forces were averaged, the column, pile cap and pile were simplified to one vertical element. But, their width and depth were different. Then the four virtual vertical member sections were assumed as shown Table.3.2. and the pile cap shear stress was calculated. The measured value is compared with the computed beam-column joint shear strength by AIJ provisions[Architectural Institute of Japan (1999)]. The pile cap shear stress ($\tau_{exp}$: MPa) was obtained by Eqn. (3.1) based on interior beam-column joint taking account of the virtual vertical section as shown Table.3.2.

$$\tau_{\exp} = \frac{V_{\exp}}{b_j \cdot D_j} \quad (3.1)$$

$$V_{\exp} = \frac{M_1 + M_2}{j} - V_c \quad (3.2)$$

where $M_1$ and $M_2$ are a foundation beam flexural moments at virtual vertical member critical section, j is a lever arm length between tensile resultant force and concrete compressive force on foundation beam section (7/8d), $V_c$ is a column shear, bj is an average between a virtual vertical member width and foundation beam width, Dj is a virtual vertical member depth.

Diagonal shear crack strength was obtained by Eqn. (3.3) based on the principal stress field. Ultimate shear strength was obtained by Eqn. (3.5) based on AIJ provisions[Architectural Institute of Japan (1999)].

$$\tau_{cr} = \sqrt{\sigma_t^{\,2} + \sigma_t \cdot \sigma_0} \tag{3.3}$$

$$\sigma_t = 0.33 \times \sqrt{\sigma_B} \tag{3.4}$$

$$\tau_{\max} = 0.8 \cdot \phi \cdot \sigma_B^{\ 0.7} \tag{3.5}$$

Where $\sigma_B$ is a concrete compressive strength, $\sigma_0$ is the axial compressive stress to a virtual vertical member, φ is coefficient of transverse beam (=0.85). The comparisons between diagonal shear crack

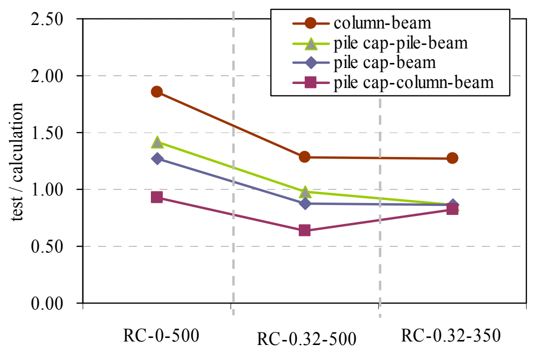



Figure 10. Comparison between shear crack strength in test and calculation

Table 3.2. Virtual vertical member sections

| Case | Virtual vertical member section | Type A width | Type A depth | Type B width | Type B depth |
|---|---|---|---|---|---|
| C-1 | Column | 250mm | 350mm | 250mm | 250mm |
| C-2 | Average between column and pile cap | 300mm | 425mm | 263mm | 350mm |
| C-3 | Pile cap | 350mm | 500mm | 275mm | 350mm |
| C-4 | Average between column, pile cap and pile | 290mm | 396mm | 265mm | 346mm |

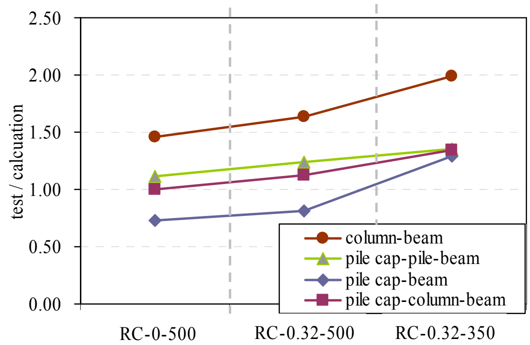
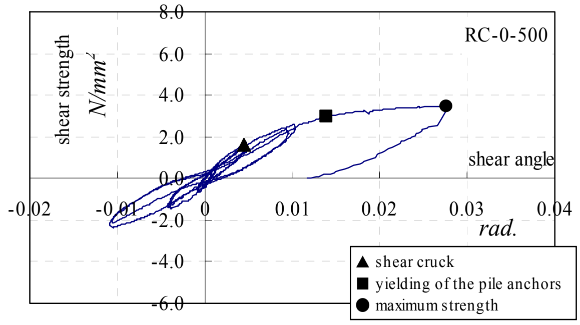
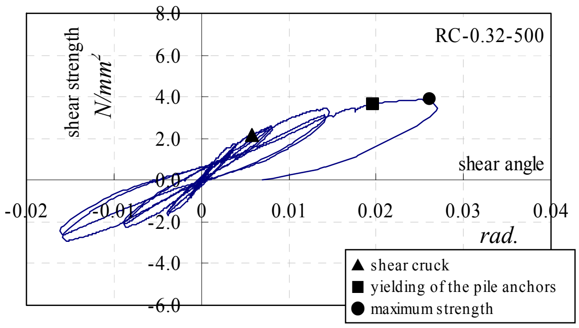



Figure 11. Comparison between ultimate strength in test and calculation



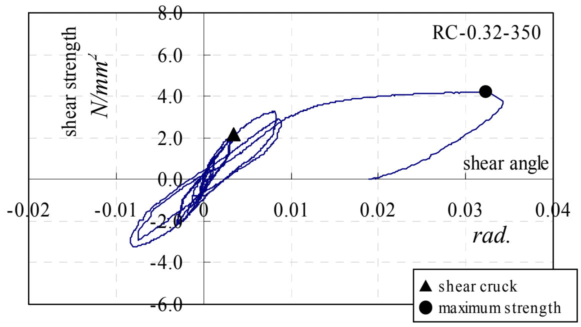




Figure 12. Relationship between pile cap shear strength and shear distortion

strength in test ($_{cr}\tau_{exp}$)and calculations ($\tau_{cr}$) are shown in Fig.10. The virtual vertical member section agreed well with the average between the column and the pile cap section (case C-2) or the average between the pile, the column and the pile cap section (case C-4). The comparisons between the ultimate shear strength in test ($_{max}\tau_{exp}$)and calculations ($\tau_{max}$) are shown in Fig.11. The virtual vertical member section agreed well with the column section (case C-1). It was concluded that type A specimens failed by yielding of the pile, then the pile cap did not fail in shear. As it turned out, in case of calculating ultimate shear strength, the virtual vertical member section agreed well with the average between the column and the pile cap section (case C-2) or the average between the pile, the column and the pile cap section (case C-4), too. The relationship between pile cap shear stress and shear distortion in case of the average between the pile, the column and the pile cap section (case C-4) for the virtual vertical member section are shown in Fig.12. For specimen RC-0-500 which was not applied the axial force, the restoring force characteristics shaped the reverse-S-shape which was little slipped. The diagonal shear crack strength for specimen RC-0.32-500 was almost as same as that for specimen RC-0.32-350, but that for specimen RC-0-500 which was not applied the axial force was little smaller than that for other specimens. For specimen RC-0.32-350 which failed pile cap shear and was smaller pile cap, the ultimate shear strength and the stiff were bigger than other specimens, but the ultimate shear strength at the shear distortion of 0.01rad.subjected to the second loading was less than that at same shear distortion subjected to the virgin loading.

## 4. CONCLUSIONS

We performed lateral load reversal tested of subassemblages with one pile, column, foundation beam and pile-cap, and considered the earthquake resistant performance of 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.

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