Study on Seismic Performance of Reinforced Concrete Cast-in-place Pile

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Abstract

In recent earthquakes, tilting of the building due to the failure of piles was reported. This kind of failure would disturb the continuous using of the building. There was a case that the government building was tilt to the failure of piles and could not use continuously. This kind of failure would disturb the continuous using of the building.

In this study, we focused on cast-in-place pile. The experiment of scaled cast-in-place pile is conducted to clarify seismic performance of the pile. There are 9 specimens. A parameter of the experiment is shear-span ratio, axial force and loading setting. The failure mode of low shear-span ratio specimen is designed as shear failure, and the others are flexural failure. The calculation method of flexural and shear strength of the cast-in-place piles are proposed. The proposed method is assumed the circular cross section of the piles to equivalent rectangular cross section and applied equation for reinforced concrete column. The calculated strength is good agreed with the maximum force of the experiment. Tri-linear skeleton curve of flexural moment – drift angle relationship for flexural failure piles could be evaluated as the column.

To recover quickly after the earthquake, quick repairing and strengthening technique for damaged cast-in-place piles after the earthquake are proposed. One of flexural failure specimen is repaired, and two of flexural failure specimens are retrofitted. Repaired specimen is chipped concrete at crushed area and casted polymer cement mortar for repairing and filled epoxy resin on cracks. The buckled or fractured main reinforcement are remained. The experimental result of repaired specimen shows that stiffness and strength of the repaired specimen is about 80% of that of previous specimen.

Retrofitted specimens are chipped concrete at the crash area, cut main reinforcement, placed post-installed adhesive anchors for moment resistance, set steel box separated from bottom-stub and casted non-shrinkage mortar. Deference between two retrofitted specimens are implantation length of post-installed anchors. The experimental results show that stiffness and strength of damaged specimen are improved due to the proposed strengthening method using post-installed anchors.

Keywords: reinforced concrete, cast-in-place pile, flexural strength, shear strength

1. Introduction

In recent earthquakes, tilting of the building due to the failure of piles was reported [1]. There was a case that the government building was tilt to the failure of piles and could not use continuously. This kind of failure would disturb the continuous using of the building.

In this study, we focused on cast-in-place pile. There were some studies about seismic performance of the cast-in-place pile. Kobayashi et al. [2] conducted static test for base-pile joint. They reported that a flexural failure was caused on the top of piles, and maximum force is 1.1 to 1.3 times larger than the calculated strength due to the fiber dimension analysis. Hibino et al. [3] conducted static test for cast-in-place pile using high strength reinforcement. They reported that the maximum force is 0.9 to 1.2 times larger than that calculated value. To clarify seismic capacity of cast-in-place pile, unified experiment is needed.

On the other hand, quick repairing and strengthening for damaged cast-in-place pile after the earthquake is required. Hirade et al. [4] conducted static test for repaired cast-in-place pile. A flexural failure pile was infilled epoxy resin on cracks, cast polymer cement mortar on the concrete spawned part, and confined using steel tube. The maximum strength was improved as 1.2 times for previous strength.

In this study, the experiment for cast-in-place piles to clarify seismic capacity is conducted. And also, the experiment for repairing and strengthening techniques for damaged cast-in-place pile is conducted.

2. Experiment of Cast-in-place Piles

2.1 Outline of Specimens

The experiment of scaled cast-in-place pile is conducted to clarify seismic performance of the pile. The target is cast-in-place piles used on 8-story reinforced concrete building. There are 9 specimens, 1/3 scaled cast-in-place piles. The piles are upside down, pile head are set at bottom of specimen due to the loading condition.

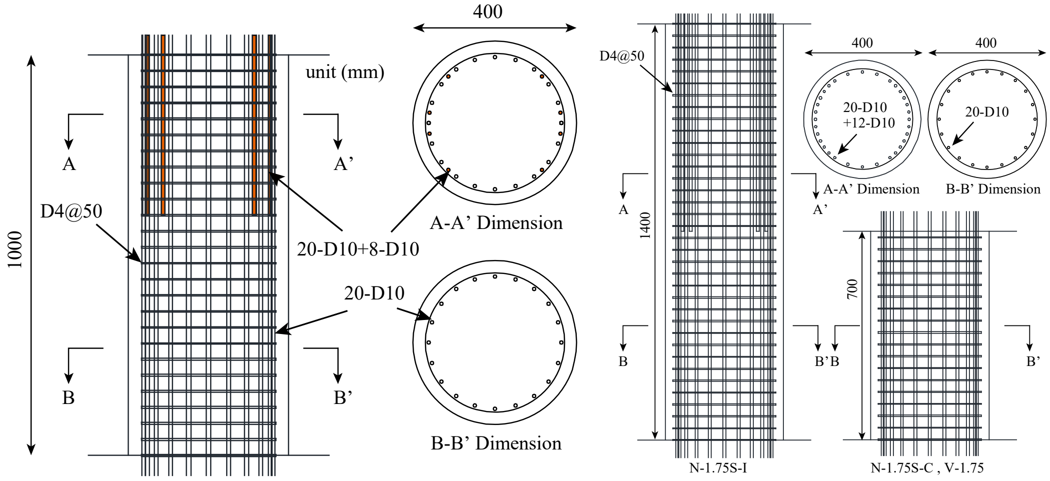
Bar arrangement of specimen are shown in Fig.1. The list of specimens is shown in Tab.1.The parameter of the experiment is shear-span ratio, axial force ration and loading setting. Diameter of piles are 400mm, and main reinforcement at the pile head is 20-D10, shear reinforcement is D4@40. The high strength steel rebar is only used for main reinforcement of specimen N-1.4S-H. Axial force ratio, axial force divided by compressive strength of concrete, is 0.15 or 0.40 (specimen N-*), that is almost equal to the long-term and short-term axial force of the piles. Specimen V-* is applied variable axial force. Shear span ratio of specimens is 3.0, 2.0 and 1.4. Shear span ratio of specimen N-3L is 3.0 and axial force ratio of that is 0.15 until the loading cycles, maximum rotation angle is 2.0%, and switched to 3.0 of share span ratio and 0.40 of axial force ratio.

Material properties of concrete is shown in Tab. 2 and material properties of steel is shown in Tab.3. The design strength of concrete is 33N/mm^2.

Table 1 –List of specimen

Specimen	Shear Span Ratio	Axial Force Ratio η	Remarks
N-3L	3.0	0.15	R<2.0%
	2.0	0.40	R>2.0%
N-2S	2.0	0.40	
N-2L		0.15	
V-2		0 to 0.40	varying axial forces
N-1.75S-I	1.8	0.40	
N-1.75S-C			Cantilever Loading
V-1.75		-0.20 to 0.40	varying axial forces
N-1.4S-H	1.4	0.40	Longitudinal reinforcement: USD785
N-1.4S			Longitudinal reinforcement: SD390

Name of Specimen: (Axial loading condition)- (Sher span ratio) (Axial force ratio) – (Remarks)
(Axial Loading Condition); N: Constant axial force, V: Various axial force
(Axial force Ratio); L: 0.4 as short-term axial force, S: 0.15 as long-term axial force
(Remarks); I: Inverse loading, C: Cantilever loading, H: Using high-strength steel rebar for main reinforcement



a) Specimen N-3L, N-2S, N-2L, V-2, N-1.4S, -H b) Specimen N-1.75S-I, -C, V-1.75

Figure 1 –Bar arrangement of specimen

Table 2 –Material properties of concrete

Specimen	Location	Young's Module [N/mm^2]	Compressive Strength [N/mm^2]
N-1.4S-H N-1.4S	Upper Stub, Pile	2.51×10^4	35.1
	Bottom Stub	2.72×10^4	38.7
N-1.75S-I, N-1.75S-C, V-1.75	Upper Stub, Pile	2.47×10^4	37.0
	Bottom Stub	2.37×10^4	36.1

Table 3 –Material properties of steel

	Material	Young's Module [N/mm^2]	Yield Strength [N/mm^2]	Yield Strain [μ]	Maximum Strength [N/mm^2]
D4	SD295A	1.78×10^5	374	2068	527
D10	SD390	1.91×10^5	425	2459	625
D10	USD785	1.91×10^5	963	4980	1090

2.2 Loading

Loading setup is shown in Fig. 2. Axial force is applied by pin-connected vertical jack. Horizontal force is applied by two horizontal jacks connected to loading beam. Load of horizontal jacks are controlled as same. The specimen is tested under reversed cyclic loading with incremental horizontal drift angle, relative horizontal displacement of upper stub from bottom stub divided by inner height of pile. Drift angle (= R) amplitude is set to 0.125, 0.25, 0.5, 1.0, 2.0, 3.0, 4.0, 5.0 %rad..

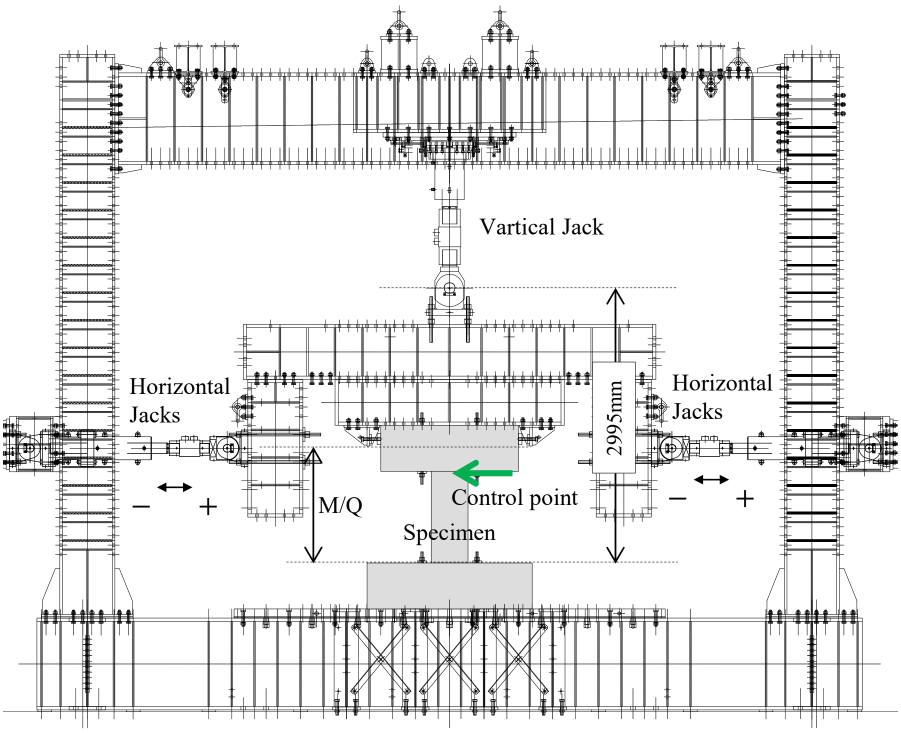


Figure 2 –Loading setup

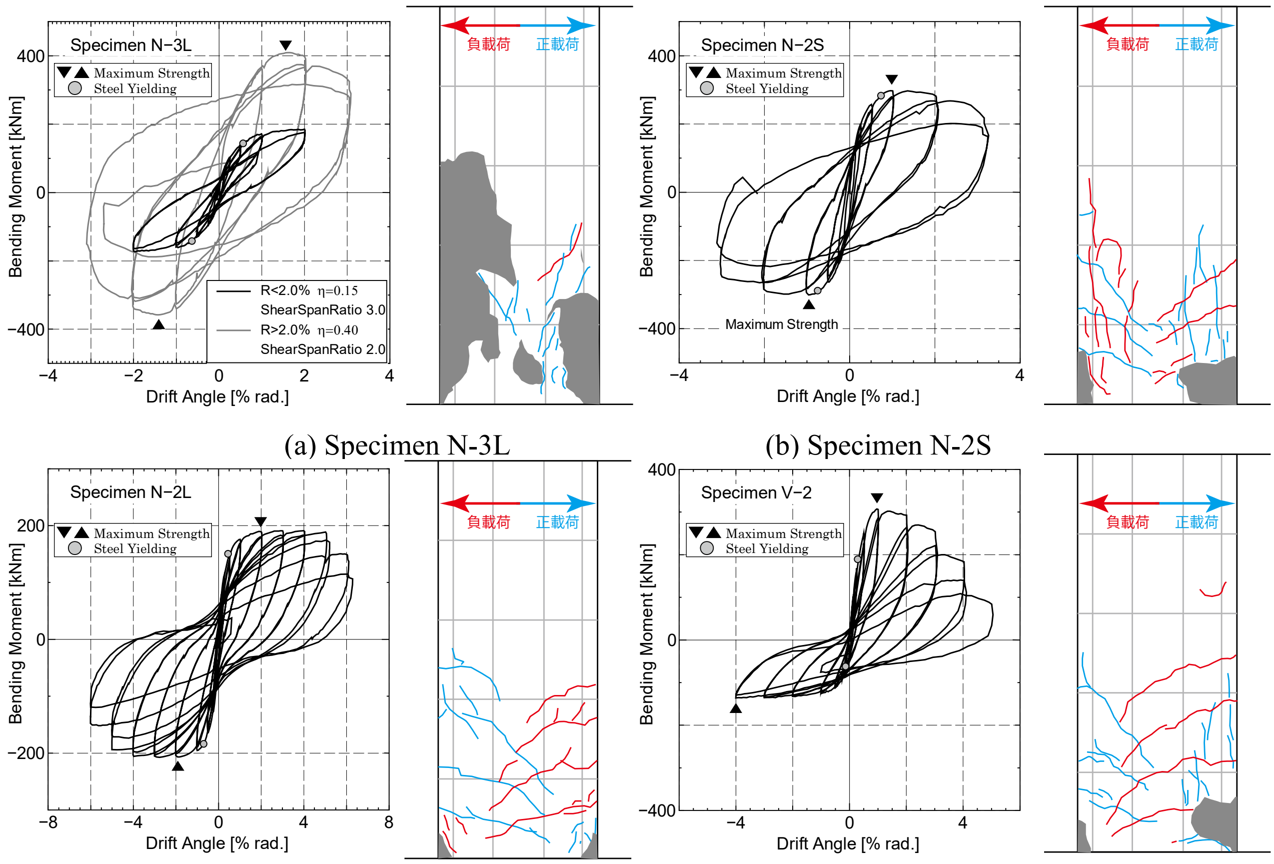
2.3 Experimental Results

Relationship between flexural moment at pile head and drift angle of specimen N-3L, N-2S, N-2L, V-2 is shown in Fig.3. Crack pattern after the loading is also shown in Fig.3. The flexural moment at pile head is calculated considering P-Δ effect as following equation.

$$M = Q \cdot h_0 + N \cdot \delta_N \tag{1}$$

Where, M is flexural moment at the pile head, Q is shear force, h_0 is inner height, N is axial force, δ_N is horizontal displacement at pin-joint of vertical jacks.

In specimen N-3L, shear span ratio is set to 3.0 and axial force ratio is 0.15, the most outside main reinforcement was yielded at the pile head on R=0.6%, concrete spawn was occurred on R=2.0%. After that, shear span ratio is switched to 2.0 and axial force ratio is 0.40. The maximum flexural moment was recorded on R=1.5%. In specimen N-2S, the most outside main reinforcement was yielded at the pile head on R=0.7%, concrete spawn was occurred on R=1.0%. After that, concrete spawn area was improved, and compressive failure of concrete due to the flexural moment was occurred on R=-3.0% of 2nd cycle. In specimen N-2L, the most outside main reinforcement was yielded at the pile head on R=0.5%, concrete spawn was occurred on R=2.0%. The maximum flexural moment was recorded on R=2.0%. In the positive direction of specimen V-2, axial force ratio increased to 0.4, the most outside main reinforcement was yielded at the pile head on R=0.7%, concrete spawn was occurred on R=1.0%, maximum flexural moment was recorded on R=1.0%. In the negative direction of specimen V-2, axial force ratio decreased to -0.15, the most outside main reinforcement was yielded at the pile head on R=-0.4%.



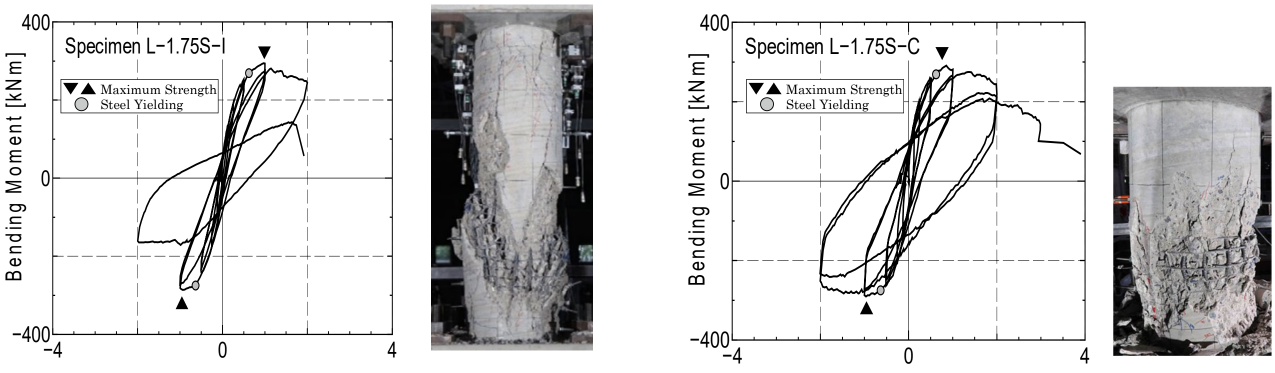
(a) Specimen N-3L (b) Specimen N-2S

(c) Specimen N-2L (d) Specimen V-2

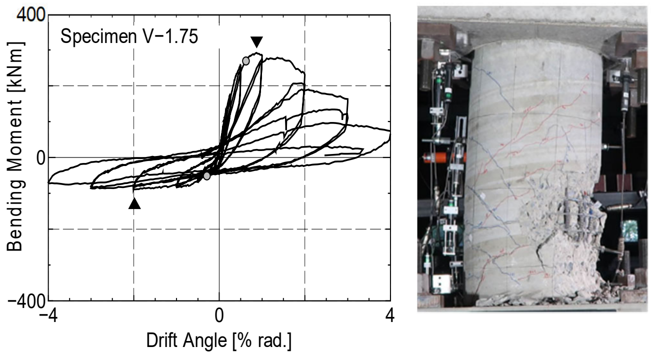
Figure 3 –Relationship between bending moment at pile head and drift angle and Crack pattern after the loading

Relationship between flexural moment at pile head and drift angle of specimen N-1.75S-I, N-1.75S-C, V-1.75 is shown in Fig.4. Crack pattern after the loading is also shown in Fig.4.

In specimen N-1.75S-I, the most outside main reinforcement was yielded at the pile head on R=0.66%, and at the pile bottom on R=0.80%, shear cracks at the pile head concrete was occurred on R=1.1%, shear failure was occurred on R=1.75% and axial loading capacity was lost. The maximum flexural moment was recorded on R=1.0%. In specimen N-1.75S-C, the failure pattern was almost same with specimen N-1.75S-C. The maximum flexural moment was recorded on R=0.86%, and axial loading capacity was lost after R=3.0%. In positive direction of specimen V-1.75, axial force ratio increased up to 0.36, the most outside main reinforcement was yielded at the pile head on R=0.6%, main reinforcement buckling was observed on R=2.0%, and axial loading capacity was lost on R=4.0% of 2nd cycle. In negative direction of specimen V-1.75, axial force ratio decreased up to -0.21, the most outside main reinforcement was yielded at the pile head on R=-0.33%.



(a) Specimen N-2L (b) Specimen V-2

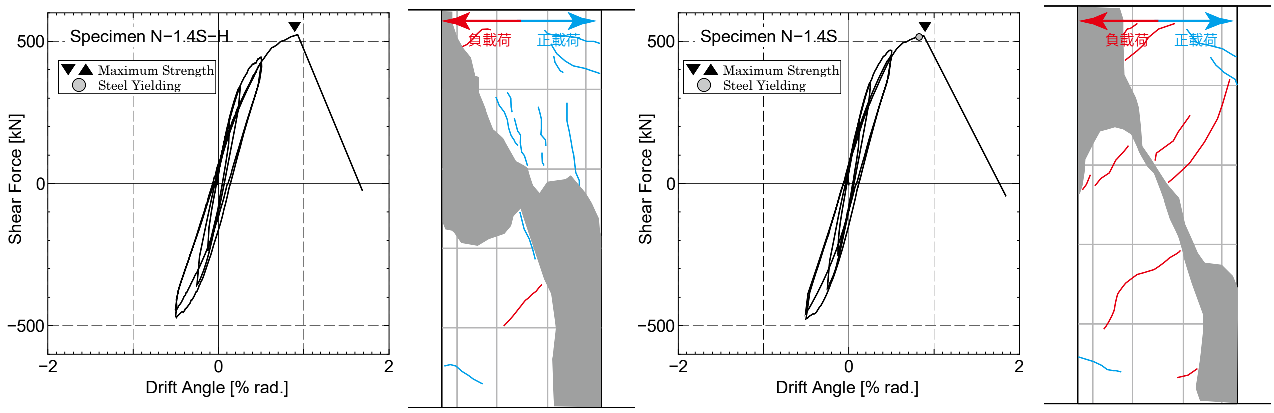


(c) Specimen N-2L

Figure 4 –Relationship between bending moment at pile head and drift angle and crack pattern

Relationship between shear force and drift angle of specimen N-1.4S-H, N-1.4S is shown in Fig.6. Crack pattern after the loading is also shown in Fig.6.

In specimen N-1.4S-H, shear crack was occurred on R=0.93% and shear failure was occurred. Failure pattern of specimen N-1.4S was almost same with specimen N-1.4S-H.



(a) Specimen N-1.4S-H (b) Specimen N-1.4S

Figure 6 –Relationship between shear force and drift angle and Crack pattern after the loading

2.4 Evaluation for Seismic Capacity

The calculation method of flexural and shear strength of the cast-in-place piles are proposed. The proposed method is assumed the circular cross section of the piles to equivalent rectangular cross section and applied equation for reinforced concrete column. To calculate the flexural and shear strength, circular cross section of pile is replaced to equivalent rectangular cross section, shown in Fig. 7 and Fig. 8.

To calculate the flexural strength, equivalent square cross section that has same area of circular section of pile is assumed. Valid reinforcement area is put into two places. Calculation method of flexural strength for reinforced concrete column [5] is applied to equivalent square cross section, as following equation.

$$M_u = 0.5 g_1 a_g \sigma_y d_e + 0.5 N d_e (1 - \eta) \tag{2}$$

Where, g_1 is couple stress distance ratio (=0.8), a_g is total area of main reinforcement, σ_y is yield strength of main reinforcement, d_e is length of equivalent square cross section.

To calculate the shear strength, equivalent rectangular cross section that has same depth as a diameter of pile is assumed. Valid reinforcement area is put into two places. Calculation method of shear strength for reinforced concrete column [5] is applied to equivalent rectangular cross section, as following equation.

$$Q_{su} = \left\{ \frac{0.068 p_{te}^{0.23} (F_c + 18)}{M/Qd_e + 0.12} + 0.85\sqrt{p_{we}\sigma_{wye}} + 0.1\sigma_0 \right\} b_e j_e \tag{3}$$

Where, p_{te} is tensile reinforcement ratio for equivalent rectangular cross section, d_e is valid depth, b_e is equivalent length of rectangular cross section, p_{we} is shear reinforcement ratio for equivalent rectangular cross section, σ_y is yield strength of shear reinforcement, σ_0 is axial stress, j_e is valid depth (=7/8 de).

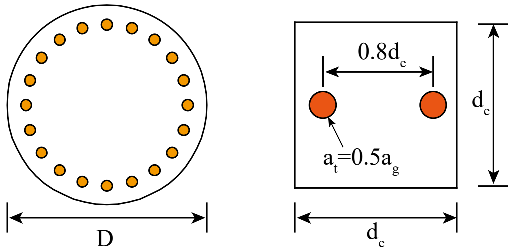


Figure 7 –Equivalent square cross section for flexural strength evaluation

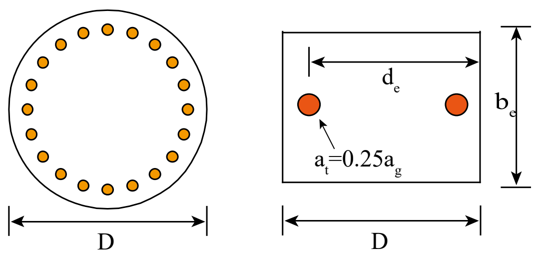


Figure 8 – Equivalent rectangular cross section for shear strength evaluation

Calculation results and experimental results are shown in Tab.4. At flexural failure specimen, failure type is FF, FY and FS, ratio of maximum flexural moment to calculated flexural strength is 1.05 to 1.52, the proposed method could evaluate flexural strength of the pile to a safety side. At shear failure specimen, ratio of maximum shear force to shear strength is 1.33 to 1.34, the proposed method could evaluate shear strength of the pile to a safety side.

Table 4 – Calculation and experimental results

Specimen	$Q_{e,max}(+)$ [kN]	$Q_{e,max}(-)$ [kN]	$M_{e,max}(+)$ [kNm]	$M_{e,max}(-)$ [kNm]	Failure Mode	M_u [kNm]	Q_{mu} [kN]	Q_{su} [kN]	Q_{su} / Q_{mu} [-]	$M_{e,max}$ / M_u [-]	$Q_{e,max}/Q_{su}$ [-]
N-3L	154.1	-118.6	184.9	-142.3	FY	176.0	146.7	209.3	1.43	**1.05**	0.74
	512.0	-447.5	409.6	-358.0	FF	268.6	335.8	322.5	0.96	**1.52**	1.59
N-2S	371.8	-375.5	297.4	-300.4	FS	268.6	335.8	322.5	0.96	**1.11**	1.15
N-2L	238.5	-259.3	190.8	-207.4	FF	176.0	220.0	243.8	1.11	**1.08**	0.98
V-2(+)	382.8	-	306.2	-	FF	268.6	335.8	322.5	0.96	**1.14**	1.19
V-2(-)	-	-170.0	-	-136.0	FF	108.8	135.9	208.3	1.53	**1.25**	0.82
N-1.75S-I	388.8	-377.9	294.7	290.7	FS	262.6	375.2	315.0	0.84	**1.12**	1.23
N-1.75S-C	349.9	-354.4	291.0	287.7	FS	262.6	375.2	315.0	0.84	**1.11**	1.11
V-1.75(+)	355.4		290.1		FF	261.7	373.9	312.3	0.84	**1.11**	1.14
V-1.75(-)		-136.1		-89.2	-	63.4	90.6	174.1	1.92	1.41	0.78
N-1.4S-H	523.9	-	304.8	-	S	278.8	507.2	390.7	0.77	1.09	**1.34**
N-1.4S	520.4	-	302.1	-	S	386.4	702.5	390.7	0.56	0.78	**1.33**

$Q_{e,max}$(+)(-): Maximum Shear Force, $M_{e,max}$(+)(-) : Maximum Bending Moment at Pile Head
Failure Mode: FY/Flexural Yield, FF/Flexural Failure, FS/Shear Failure after Flexural Yielding, S/Shear Failure
M_u: Bending Strength, Q_{mu}: Shear force on Bending Failure, Q_{su}: Shear Strength

Evaluation method of tri-linear skeleton curve of flexural moment – drift angle relationship for flexural failure piles is discussed. The target specimen is specimen N-3L, N-2S and N-2L.

Initial stiffness of piles is calculated to couple with flexural stiffness and shear stiffness for circular cross section, considering stiffness of concrete and main reinforcement. First break point means flexural crack point. Second break point means flexural yielding. Main reinforcements of the piles are arranged on peripheral at even intervals. Flexural yielding strength is assumed as flexural moment when half of main reinforcement are yield. Drift angle at flexural yield are evaluated with yield stiffness, stiffness lowering rate α_y multiplied to initial stiffness. Stiffness lowering rate is calculated as following equation.

$$\alpha_y = (0.043 + 1.64np_t + 0.043a/D + 0.33\eta_0)(d/D)^2 \qquad (4)$$

Where, n is modulus ratio of steel and concrete (=15), p_t is tensilire reinforcement ratio, a is shear span, D is depth, η_0 is axial force ratio, d is varying depth.

Comparison results of evaluated moment – angle relationship with experimental results are shown in Fig.9. Evaluated tri-linear skeleton curve is good agreed with experimental results. At the point that drift angle equals the calculated drift at flexural yield, strain distribution of main reinforcement of specimen N-2S is shown in Fig. 10. This result shows that almost half of main reinforcement are yield on calculated flexural yield point. That means the assumption to calculate flexural yield strength that half of main reinforcement are reached to yield, is good agreed with experimental results.

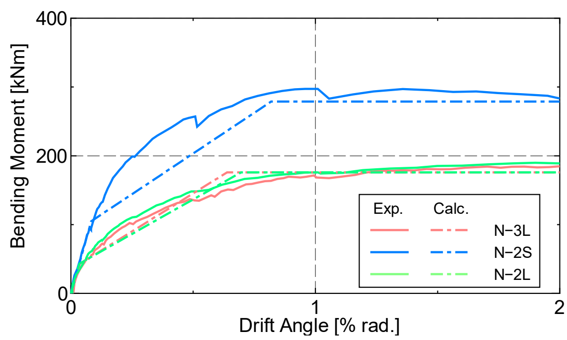


Figure 9 – Equivalent rectangular cross section for shear strength evaluation

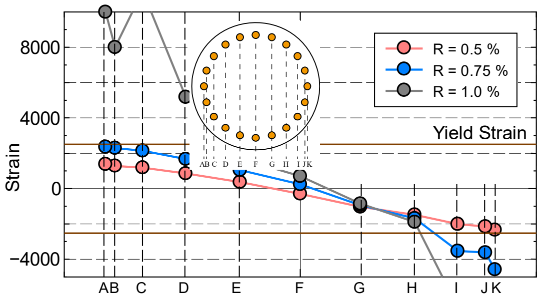


Figure 10 – Equivalent rectangular cross section for shear strength evaluation

3. Experiment of Repairing and Strengthening for Damaged Cast-in-place Piles

2.1 Outline of Repairing and Strengthening

If the cast-in-place pile under the building was heavily damaged by the earthquake, the building would be tilling and it can't use continuously. For that case, quick repairing and strengthening technique for damaged piles after the earthquake are required. In this study, the quick repairing and strengthening technique using post-installed adhesive anchors and steel boxes are proposed, and the experiment that simulated the quick repairing and strengthening for damaged specimen were conducted.

Specimen N-3L, bending failure was occurred at the pile head on the pre-experiment, was repaired (called specimen N-3L-R). The procedure of repairing technique as follows; chipped concrete at the crushed area, casted polymer cement mortar for repairing and filled epoxy resin on cracks. The buckled or fractured main reinforcement are remained.

Photo 1- Repaired specimen of damaged pile

Specimen N-2S and N-2L, bending failure was occurred at the pile head on the pre-experiment, are retrofitted using post-installed adhesive anchors as tensile reinforcement (called N-2S-R and N-2L-R). The outline of the strengthening techniques for the damaged piles is shown in Fig.11.The procedure of strengthening technique is as follows; chipped concrete at the crash area, cut main reinforcement, placed post-installed adhesive anchors (epoxy resign, injection type, core boring) , set steel box (separated from bottom-stub) , cast non-shrinkage mortar. The parameter of specimen is implantation length of anchors. For specimen N-2L-R, implantation length of anchors is 12da, where d_a is diameter of anchor, that failure mode is designed to steel yielding due to the Japanese design code [6]. To calculate the bond strength of anchors, the pre-test results, bond strength test for anchors, are used. For specimen N-2S-R, the implantation length are determined as a general fixation length of reinforced concrete structure, equals to $30d_a$.

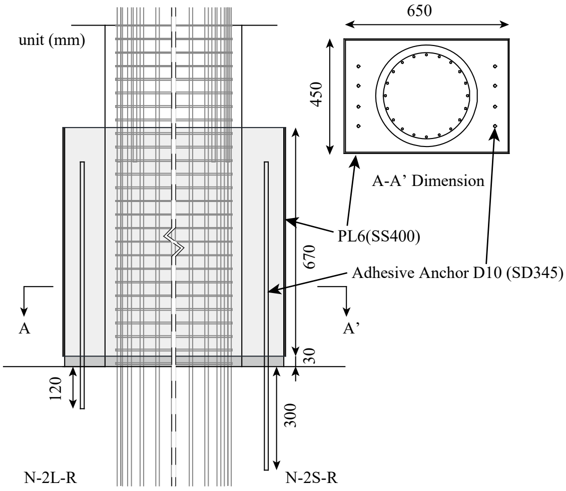


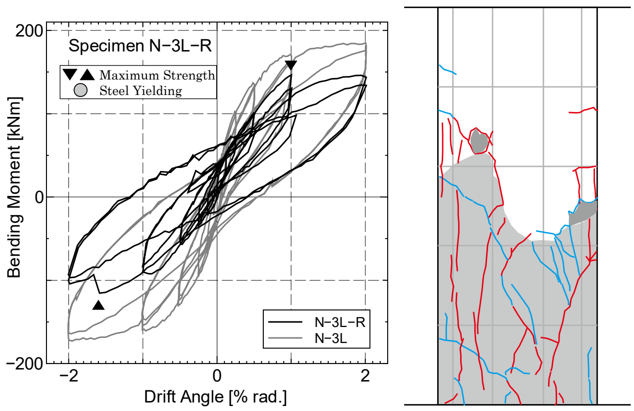
Figure 11- Outline of strengthening specimen

Photo 2- Strengthening specimen for damaged cast-in-place pile

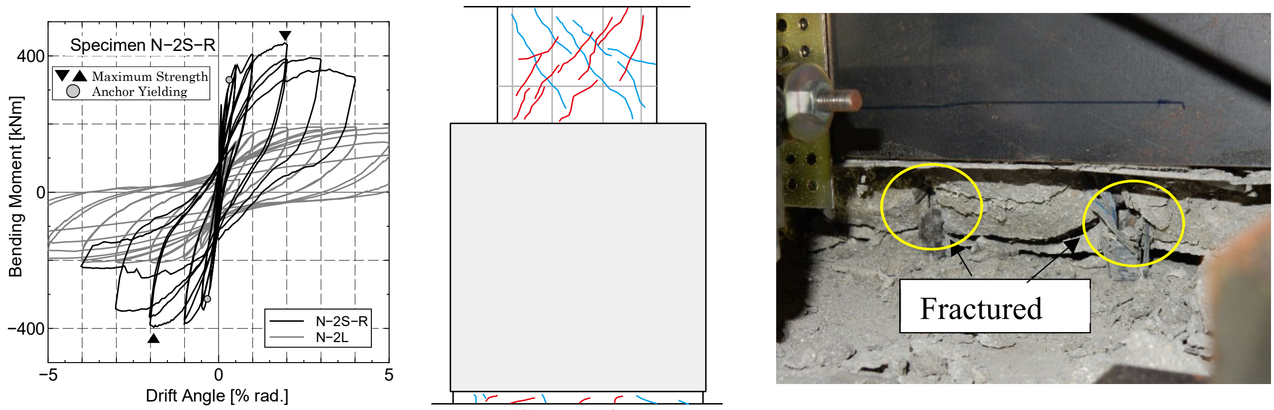
2.2 Experimental Results

Relationship between flexural moment at pile head and drift angle of specimen N-3L-R, N-2S-R, N-2L-R is shown in Fig.12. Crack pattern after the loading is also shown in Fig.12.

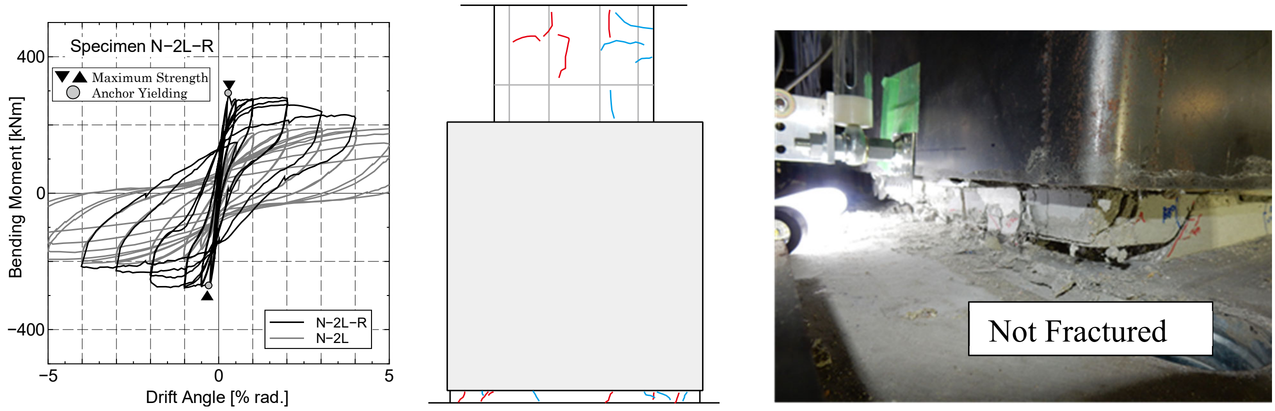
For repaired specimen N-3L-R, mortar at the edge of repaired area is spawned on R=1.0% cycles, and reached maximum strength. For strengthening specimen N-2S-R, post-installed anchor is yield on R=0.3%, mortar crashed at the pile head on R=2.0%, and post-installed anchors are fractured on R=4.0% cycles. For specimen N-2L-R, post-installed anchor is yield on R=0.3%, mortar crashed at the pile head on R=3.0%, post-installed anchors are not fractured.



(a) Specimen N-3L-R



(b) Specimen N-2S-R



(c) Specimen N-2L-R

Figure 12-Relationship between shear force and drift angle and Crack pattern after the loading

2.3 Effect of Repairing

Comparison result of relationship between bending moment and drift angle of specimen N-3L and N-3L-R is shown in Fig. 12(a). Initial stiffness and maximum strength of repaired specimen N-3L-R are about 0.8 times as the pre-repaired specimen N-3L. It means that repairing effect is limited. The maximum bending moment of repaired specimen N-3L-R is less than calculated bending strength.

2.4 effect of strengthening

Comparison result of relationship between bending moment and drift angle of specimen N-2L, N-2S-R, N-2L-R is shown in Fig.13. Stiffness and strength is quite improved by strengthening. For specimen N-2L-R, implantation length of anchors is 12da, bending moment at the pile head is continuously decreased after anchor yielding occurred. It means that the post-installed anchors are slip out due to the cyclic loading. On the other hand, for specimen N-2S-R, implantation length of anchors is 30da, bending moment is continuously increased after anchor yielding occurred, and these anchors are fractured. Specimen N-2S-R describes large hysteresis loop after anchor yielding than that of specimen N-2L-R.

To evaluate flexural strength of retrofitted specimen N-2S-R and N-2L-R, Eq. (2) is applied on the assumption that total area of main reinforcement a_g is replaced to total area of anchors. Shear strength of retrofitted specimen N-2S-R and N-2L-R is evaluated at the non-retrofitted zone, that because the shear strength of retrofitted area is quite larger than that of non-retrofitted zone. Calculated results shows that failure mode is flexural failure, and maximum bending moment is 1.2 to 1.7 times larger than the calculated value.

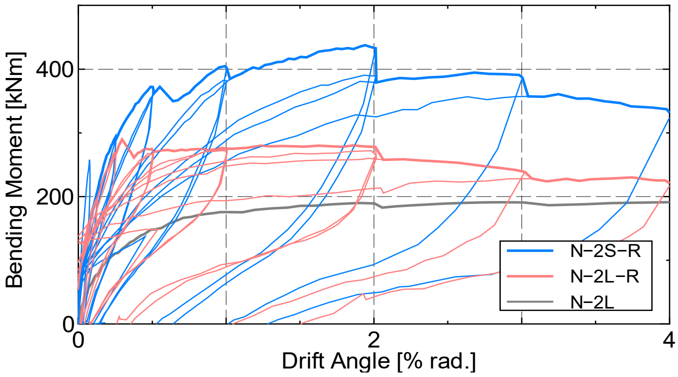


Figure 13-Comaprison of relationship between bending moment and drift angle

4. Conclusions

In this study, the experiment for cast-in-place piles to clarify seismic capacity is conducted. And also, the experiment for repairing and strengthening techniques for damaged cast-in-place pile is conducted.

- Maximum bending moment and shear force of cast-in-place specimens could be evaluated to applying calculation method of reinforced concrete columns on the assumption of the equivalent rectangle cross section.
- Tri-linear skeleton curve of flexural moment – drift angle relationship for flexural failure piles could be evaluated as the column.
- To repair the flexural failure specimen using polymer cement mortar, about 80% of stiffness and strength are recovered.
- A stiffness and strength of retrofitted specimen using post-installed adhesive anchors and steel box is improved than previous one. To fully exert the retrofitted effect, the implantation length of anchors should be designed as enough. The maximum strength could be evaluated as the column.

5. References

[1] Kaneko O, Nakai S, Abe A, Iiba M, Kuze N, Hirade T (2014): Situations and Analysis of Damage to Pile Foundations of Buildings in 2011 Great East Japan Earthquake (in Japanese). *Geotechnical Engineering Magazine*, **62(1)**, 16-19.

[2] Kobayashi K et Al. (1998): Study on Structural Behavior of Cast-in-place Pile and Ground Beam under Lateral Loading (in Japanese). *Journal of structural and Construction Engineering*, Architectural Institute of Japan, **509**, 83-90

[3] Hibino Y et Al. (2010): Flexural Behavior of Belled Piles with High-Strength Longitudinal Reinforcement (in Japanese), *summaries of technical paper of annual meeting*, Architectural Institute of Japan, **4**, 585-588

[4] Hirade T et Al. (2016): Static Loading Test for Foundation Beam-Pile-Column Exterior Joint subassemblies Part 3: Repaired Experimental Test (in Japanese). *Summaries of technical paper of annual meeting*, Architectural Institute of Japan, **4**, 387-388

[5] National Institute for Land and Infrastructure Management et al. (2015): *Commentary on Structural Regulations of the Building Standard Law of Japan (in Japanese)*

[6] Architectural Institute of Japan (2010): *Design Recommendation for Composite Constructions (in Japanese)*

