Structural Performance of Corroded RC Column under Seismic Load

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Abstract
It is essential to verify the safety performance of existing reinforced concrete (RC) structures against the seismic load, especially when they are damaged by corrosion. It is considered that the deformation capacity of RC beams or columns decreases due to the corrosion. However, any researchers have not yet proposed adequate evaluation method for the corroded RC members because of a lack of relevant information. This paper describes the study result of the fundamental properties of the deformation capacity of the corroded RC columns.
In this study, eleven cantilever column specimens were subjected to the cyclic loading. To simulate the corrosion of the reinforcing bars, some specimens were provided with the scraped bars or the small-size round bars. The scraped bars were modeled to have the same distribution of a cross sectional area as the real corroded bars under the actual condition. Two column specimens out of remained ones were subjected to electric accelerated corrosion. Each scraped or electric corroded reinforcing bar was modeled to have the same 10% approximative reduction of cross section.
From the test results, it has been confirmed that the corrosion causes the reduction of the deformation capacity of the RC column. The buckling due to the corrosion of main bars causes much reduction of the deformation capacity. Corrosion of hoops also causes reduction of deformation capacity. It has been clarified that the deformation capacity of the corroded RC column can be evaluated by the reduction of cross section of the corroded reinforcing bars.

Keywords: reinforced concrete, column, seismic load, corrosion, ratio of weight reduction

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1.0 Introductions

To maintain reinforced concrete (RC) structures safe against the seismic load, it is important to evaluate the strength and deformation capacity of the structural members. A number of evaluation methods have been proposed so far for calculating structural performance of newly constructed RC members until now. The calculation procedure of the strength of the RC members have well developed and often used in designing structures, and that of the deformation capacity also has been proposed and practically used under some construction projects.

On the other hand, the evaluation method of the safety performance of the existing RC structure is not clarified, particularly when it is damaged by the corrosion. No evaluation method or assessment procedure has been proposed for the corroded RC member because of a lack of experimental data and relevant information. The strength or the deformation capacity of the slender RC beams or columns may well decrease due to the corrosion of main bars and hoops.

In order to present the above-mentioned evaluating method for corroded structural members, this paper describes the study result of the fundamental properties of the deformation capacity of the corroded RC column subjected to the horizontal cyclic loading.

2.0 Test Program

2.1 Details of test specimen

In this study, eleven deteriorated cantilever column specimens were subjected to the cyclic loading. Table 1 gives the relevant properties of the specimens and Fig.1 shows the details of the specimen. All of the specimens are designed in accordance with the previous experiments [1][2], which were intended to research for no corroded RC column. They were 1650 mm long (from the top

Table 1 Relevant properties of specimens

<table>
<tr><th rowspan="3">Specimen No.</th><th colspan="5">Reinforcing bar</th><th rowspan="3">Type of reinforcement (mm)</th><th rowspan="3">Hoop reinforcement ratio (%) ***</th></tr>
<tr><th rowspan="2">Corrosion Position *</th><th colspan="2">Main bar</th><th colspan="2">Hoop bar</th></tr>
<tr><th>Side</th><th>Method</th><th>Side</th><th>Method</th></tr>
<tr><td>No.1</td><td colspan="5">No corrosion (control)</td><td rowspan="5">2-D10@47.5</td><td>0.667</td></tr>
<tr><td>No.2</td><td rowspan="8">225 ±100</td><td>Transverse</td><td rowspan="2">Electric</td><td>Transverse</td><td rowspan="2">Electric</td><td>0.467</td></tr>
<tr><td>No.3</td><td rowspan="3">Loading side</td><td rowspan="2">Loading</td><td rowspan="3">0.667</td></tr>
<tr><td>No.4</td><td rowspan="2">Scraped 30%**</td><td>Scraped 30%**</td></tr>
<tr><td>No.5</td><td colspan="2">No corrosion</td></tr>
<tr><td>No.6</td><td colspan="2" rowspan="4">No corrosion</td><td colspan="2">All sides 30% **</td><td>2-ϕ9@69</td><td>0.410</td></tr>
<tr><td>No.7</td><td>Transverse</td><td rowspan="2">Scraped 30%**</td><td rowspan="2">2-D10@47.5</td><td>0.467</td></tr>
<tr><td>No.8</td><td>Loading</td><td>0.667</td></tr>
<tr><td>No.9</td><td colspan="2">All sides 60% **</td><td>2-ϕ6@47.5</td><td>0.264</td></tr>
<tr><td>No.10</td><td rowspan="2">400 ±100</td><td rowspan="2">Loading side</td><td rowspan="2">Scraped 30%**</td><td colspan="2">No corrosion</td><td>2-D10@47.5</td><td>0.667</td></tr>
<tr><td>No.11</td><td colspan="2">All sides 30% **</td><td>2-ϕ9@69</td><td>0.410</td></tr>
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*Height from the bottom end of the column (mm) **At the maximum scraped cross section

***At the transverse side for the scraped bar /Objective ratio of weight reduction for electoric corroded bar

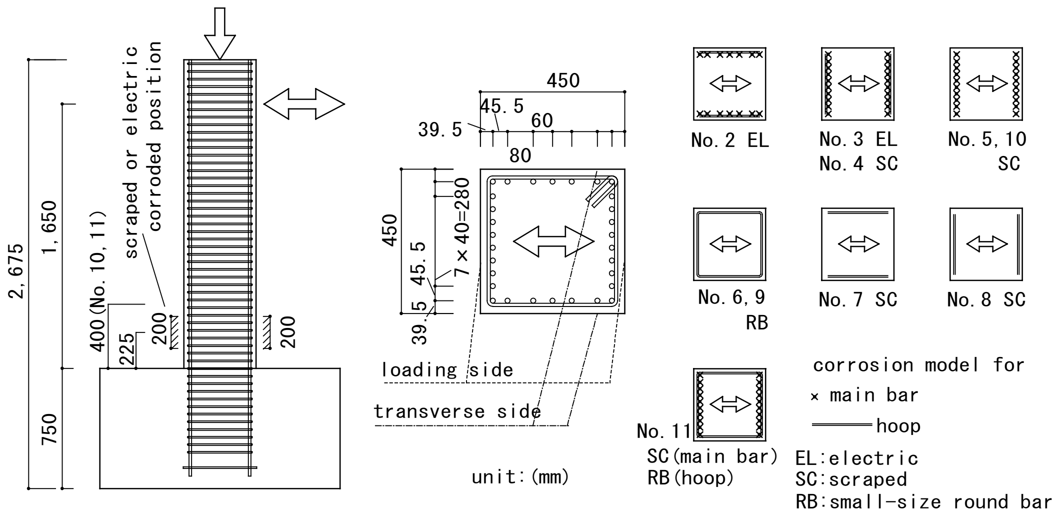


Fig.1 Details of specimen

Table 2 Mechanical properties of concrete

Specimen	Compressive strength (MPa)	Elastic modulus (GPa)	Tensile splitting strength (MPa)
No.1,2,3,4	30.5	25.5	2.64
No.6,7,8,9	29.6	23.6	2.90
No.5,10,11	31.3	25.5	2.70

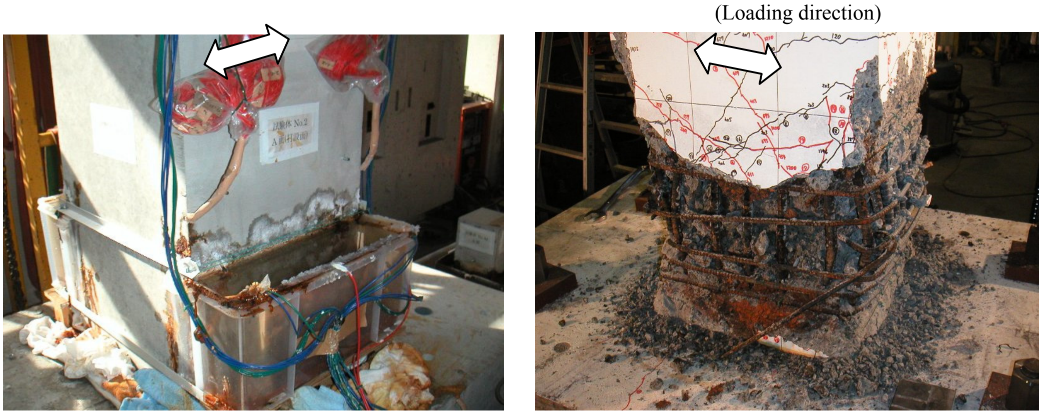
horizontal loading axis to the bottom fixed end) and had the same overall dimensions of a 450x450mm square cross section. The specimens were tested for three relevant properties; corrosion parts, corrosion levels and modeling methods of the corrosion. Table 2 also shows the mechanical properties of the concrete.

2.2 Materials

To simulate the corrosion of the reinforcing bars, two column specimens No.2 and No.3 were subjected to the electric accelerated corrosion process. After a minimum period of 28 days after casting, an external water tank was attached to two sides of the specimens. Electrical direct current from the electric (galvanostatic) power supply was adopted between the reinforcing bars and the cupper electrode plates in the external water tank. The accumulated corrosion current density with time was planned for the ratio of weight reduction (to its original weight) of the reinforcing bar as to have the same designed 15 percent referring to the previous experimental results in [3]. Fig.2 shows the experimental condition for electric accelerated corrosion and situation of the corrosion.

The electric corrosion process is a method frequently used to simulate substantial corrosion phenomena; however, it may cause so much corrosion variance and unexpected uncertainness. Therefore six column specimens No.4,5,7,8,10 and 11 were provided with the scraped and whittled deformed-bars and two column specimens No.6 and No.9 were provided with the small size round-bars so that those reinforcing bars could simulate mechanical properties of the corroded reinforcing bars. The scraped bars were modeled to have the same distribution of cross sectional area as the substantially corroded referential bars obtained from the beam specimen exposed to the open air or subjected to the electric accelerated corrosion [4]. The distribution of cross sectional area of the referential corroded bars were investigated in short 1mm interval by the three dimensional shape scanner [4] equipped with laser beam device, which can measure the shape of objective articles without contact. Table 3 shows the representative investigation result of the cross sectional area of the referential corroded bars. The ratio of averaged cross sectional reduction is approximately 15%, and that of maximum reduction is 30%.

According to this investigation result, the scraped bars were modeled as shown in Fig.3, so they were plainly scraped to the same 15% reduction for the designed 100mm length, and roundly scraped to the 30% maximum reduction at the partial 15mm portion. Fig.4 also shows the mechanical properties, relationship between the stress (ratio of tensile load divided by the nominal cross sectional area) and the strain (ratio of displacement divided by the original gauge length) of the scraped model bar. Yielding of the model bar firstly appeared at the roundly scraped portion, and secondly followed at the plainly scraped long region. Reduction of the strength at elastic limit, the ultimate strength and the ultimate elongation was observed to be simulation of the mechanical property of substantially corroded bar.



(a) Experimental condition (b) Situation of corrosion

Fig.2 Electric accelerated corrosion (test specimen No.2)

Table 3 Representative investigation result of cross sectional area of referential corroded bar

Corrosion method	A_{ave}(mm^2)	A_{min}(mm^2)	R_{ave}	R_{max}
Exposed to open air	100	86.5	0.173	0.285
Electric accelerated	99.3	84.6	0.179	0.301

A_{ave} : Averaged cross section (mm^2) A_{min} : Minimum cross section (mm^2)

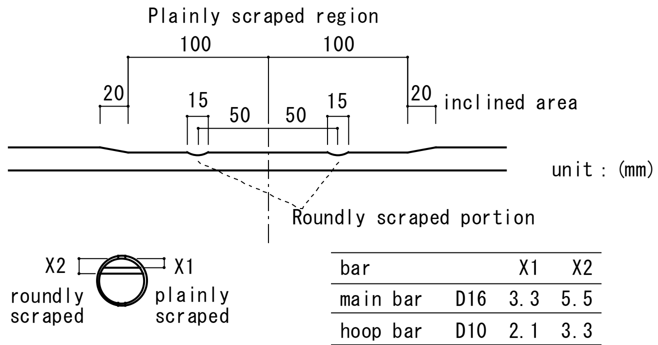
$A_{ave,n}$: Averaged cross section $A_{ave,n}$=121(mm^2)

R_{ave} : Ratio of averaged cross sectional reduction $R_{ave} = (A_{ave,n} - A_{ave}) / A_{ave,n}$

R_{max} : Ratio of maximum cross sectional reduction $R_{max} = (A_{ave,n} - A_{min,n}) / A_{ave,n}$

2.3 Loading test

Fig.5 shows the test setup of the loading test. Each RC column specimen was subjected to the horizontal cyclic loading statically with the vertical constant axial loading. The column specimen was loaded under the loading program as shown in Fig.6. In this figure, δ_y indicates the displacement at the yielding time of the no corroded control specimen No.1.



bar		X1	X2
main bar	D16	3.3	5.5
hoop bar	D10	2.1	3.3

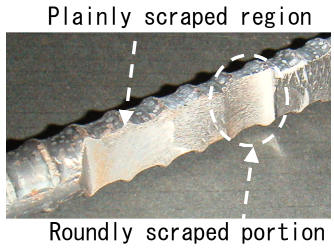
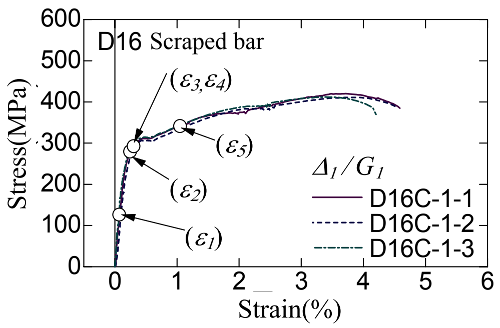


Fig.3 Details of scraped bars



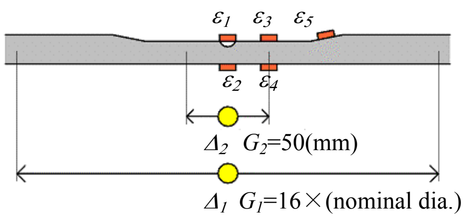


Fig.4 Mechanical properties of scraped bar.

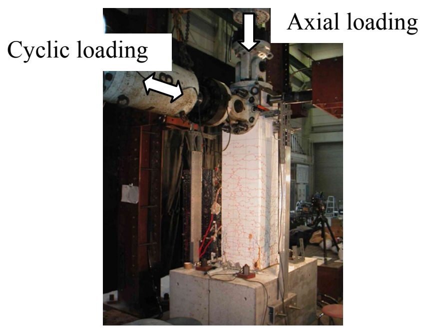
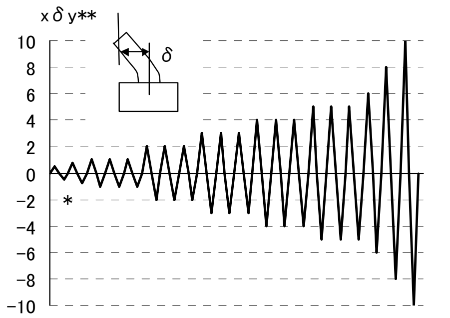


Fig.5 Test setup of loading test



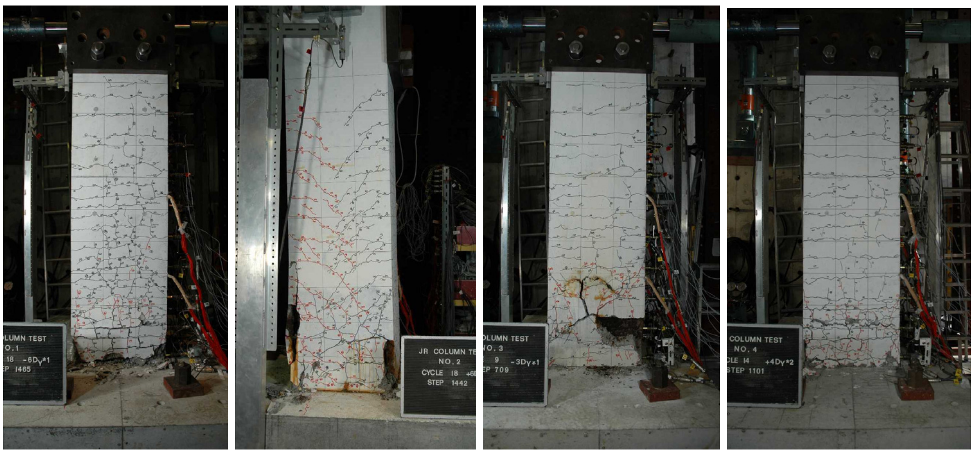
* loaded only 1cycle for Py/2 and 3Py/4
where, Py is the calculated yield strength of the no corroded control specimen No.1

Fig.6 Loading program

3.0 Test result and consideration

3.1 Failure condition

Fig.7 shows the condition at the beginning of the spalling of the column side surface of the representative specimen No.1 to No.4. Early spalling before the loading step at the displacement $4\delta_y$ was visible in the test specimen No.3 and No.4, in which scraped or electric corroded bar was arranged at the loading side. Cover concrete at the corrosion area was fallen all in one together in the test specimen No.3 and No.4, whereas cover concrete near the fixed end was fallen portion by portion gradually in the no corroded control specimen No.1. The load-displacement curve of the column specimen provided with the scraped bars is similar to that of the specimen subjected to the electric accelerated corrosion. After the maximum loading step, reduction of the horizontal load earlier than the no corroded control specimen No.1 was visible at the test specimen No.2, in which electric corroded bar was designed at the transverse side. It has been confirmed that the corrosion causes the reduction of the deformation capacity of the RC column.
Fig.8 indicates the envelope curve of the load-displacement relationship.
According to Fig.8(a) concerning the difference due to corrosion methods, the envelope curves of the two corrosion-modeled specimens also bear some parallels. Considering the above-mentioned condition at the beginning of the side spalling, it is apparent that the reduction of the load of these two column specimens was also caused by the same failure mechanism. Therefore, the difference caused by the corrosion method is merely less; consequently, it is obvious that the specimens with electric corroded bars were well modeled by that with the scraped bars. Although the load of the test specimen No.3 with the electric corroded hoops shows a little earlier reduction than that of the test specimen No.4 with the scraped hoops, it was obviously caused by the difference of the corrosion level.
According to Fig.8(b) concerning the influence of the corrosion (or scraped) sides, the envelope

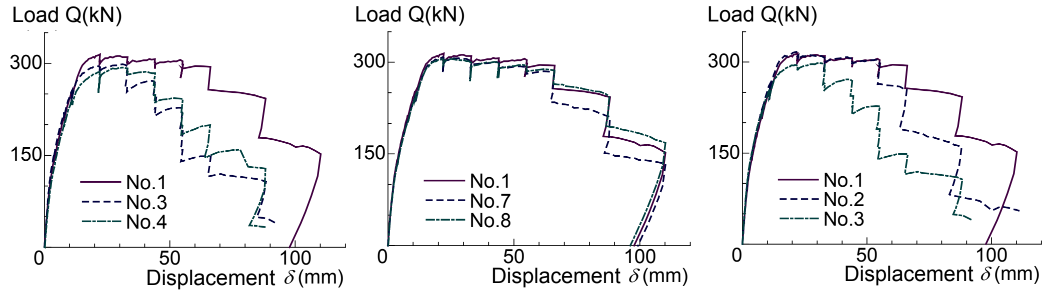


(a)No.1 ($-6\delta_y$*1) (b)No.2 ($+6\delta_y$*1) (c)No.3 ($-3\delta_y$*1) (d)No.4 ($+4\delta_y$*2)

Fig.7 Condition at beginning of spalling

(Note: (b) shows transverse side, others show loading sides) curve of the test specimen No.8 with the scraped hoop bar provided at the loading side is almost equivalent to that of the no corroded control specimen No.1. On the other hand, the envelope load of the test specimen No.7 with the scraped hoop bar provided at the transverse side is smaller than the control specimen No.1. It is confirmed that the reduction of the deformation capacity is also caused by the corrosion of hoop bar. It is also clarified that the damage of the hoop bar at the loading side have no adverse effect to the load-displacement relationship of the member, but that of at the transverse side reduces its deformation capacity.

According to Fig.8(c) concerning the effect of the electric corroded position, the envelope curve of the test specimen No.2 with the transverse side corrosion shows latter reduction than that of the test specimen No.3 with the loading side corrosion. According to Fig.8(b), the damage of the hoop bar at the loading side exerts no effect on the deformation capacity. Therefore it is evident that the reduction of the deformation capacity of the test specimen No.3 with the loading side corrosion has caused due to corrosion of the main bar. It is apparent that the buckling due to loading side corrosion of main bars caused much reduction of the deformation capacity.



(a) comparison of corrosion method

(b) comparison of corrosion sides (scraped hoop)

(c) comparison of corrosion sides (electric)

Fig.8 Envelope curve of load-displacement relationship

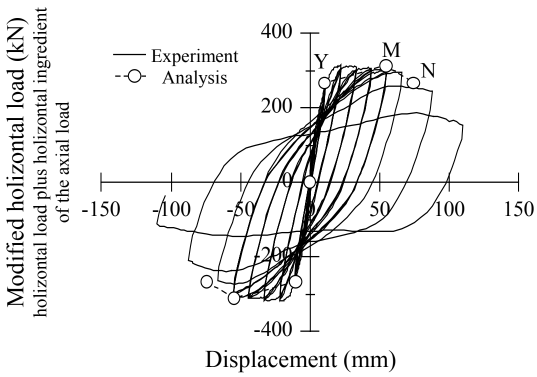


Fig.9 Load-displacement relationship of control test specimen No.1 compared with the estimated value of skeleton point

3.2 Evaluation of skeleton point

Fig.9 shows the relationship between the load and the displacement compared with the estimated value of the skeleton point [1] [2], where the skeleton point Y shows the yield point, point M shows the maximum displacement in which the maximum loading was approximately maintained, and point N shows the maximum displacement in which the yielding load was approximately maintained. The load-displacement curve of the no corroded control specimen No.1 is estimated in sufficient accuracy by the estimated skeleton point Y, M and N.

Table 4 shows the ratio of weight reduction and the experimental result of the skeleton points M and N. Where, the skeleton points M and N are defined as shown in Fig.9 referring to the yielding load of the control test specimen No.1.

In this consideration, the ratio of weight reduction of the main (*L*ongitudinal) reinforcing bar C_L was assumed to have influence on the skeleton point M. To evaluate the skeleton point M by C_L, only the specimens with the hoop of C_{HT}=0 (specimen No.1,3,4,5 and 8) were taken into account. Fig.10(a) shows the relationship between C_L and $\delta_{m,corr}/\delta_m$ including its regression line. The effect of the corrosion on the skeleton point M can be expressed as shown in Eq.(1), considering that the left side of the regression line in Fig.10(a) can be substituted for $\theta_{m,corr}/\theta_m$.

$$\theta_{m,corr}/\theta_m=1-2.32C_L \tag{1}$$

Where, θ_m :joint translation angle of the skeleton point M, $\theta_{m,corr}$: θ_m of the corroded member

Consequently, the ratio of weight reduction of the hoop at the transverse side C_{HT} was assumed to have influence on the skeleton point N. To evaluate the skeleton point N by C_{HT}, only the specimens with the main bar of C_L=0 (specimen No.1,2,6,7,8 and 9) were taken into account. Fig.10(b) shows the relationship between C_{HT} and $\delta_{n,corr}/\delta_n$ including its regression line. The effect

Table 4 Ratio of weight reduction and skeleton points

Specimen No.	Ratio of weight reduction		Skeleton Point				Compared with No.1	
			M		N			
	C_L	C_{HT}	P_m(kN)	δ_m(mm)	P_y(kN)	δ_n(mm)	$\delta_{m,corr}/\delta_m$	$\delta_{n,corr}/\delta_n$
1 control	0	0	294	66.2	253	84.0	1.00	1.00
2 EL	0	0.193	302	55.1		66.6	0.83	0.79
3 EL	0.107	0	295	33.1		48.4	0.50	0.58
4 SC	0.177	0	284	44.1		52.4	0.67	0.62
5 SC	0.177	0	284	44.1		52.6	0.67	0.63
6 RB	0	0.385	283	55.1		68.8	0.83	0.82
7 SC	0	0.145	284	66.1		75.4	1.00	0.90
8 SC	0	0	286	66.1		83.4	1.00	0.99
9 RB	0	0.604	287	55.1		57.8	0.83	0.69
10 SC	0.177	0	284	55.2		60.1	0.83	0.72
11 SC&RB	0.177	0.385	286	44.2		51.3	0.67	0.61

EL: electric corrosion SC: with scraped bar RB: with small-size round bar of the corrosion on the skeleton point N can be expressed as shown in Eq.(2), considering that the left side of the regression line in Fig.10(b) can be substituted for $\theta_{n,corr}/\theta_n$.

$$\theta_{n,corr}/\theta_n=1-0.547C_{HT} \tag{2}$$

Where, θ_n :joint translation angle of the skeleton point N, $\theta_{n,corr}$: θ_n of the corroded member
Considering the coefficient of the Eq.(1) and Eq.(2) multiplied on the ratio of weight reduction, coefficient on the C_L is 2.32; that is obviously larger than the coefficient on the C_{HT} (0.547). According to this result, it is apparent that the effect of the main bar corrosion is very large on the comparison of the hoop corrosion. It is obvious that the deformation capacity of the corroded RC column can be evaluated in accordance with the reduction of cross section of the corroded reinforcing bars. However, the influence of the corrosion of the main bar will be lessen if the ratio of the main bar amount is small. In other words, there is a possibility that the influence of the corrosion on the deformation capacity will certainly depends on the ratio of the reinforcement amount. To solve this question, further investigation is necessary.

4.0 Conclusion

In order to propose the assessment procedure for the deformation capacity of the corroded RC member, eleven cantilever column specimens are subjected to the cyclic loading. From the test results, it is obvious that the corrosion causes the reduction of the deformation capacity of the RC columns. The buckling due to the corrosion of main bars caused much reduction of the deformation capacity. Likewise, corrosion of hoops caused reduction of deformation capacity. It is apparent that it is possible to evaluate the deformation capacity of the corroded RC column by the reduction of cross section of the corroded reinforcing bars.

5.0 Acknowledgment

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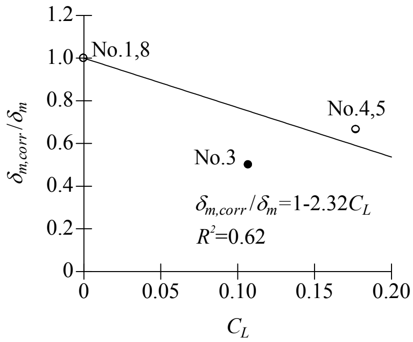
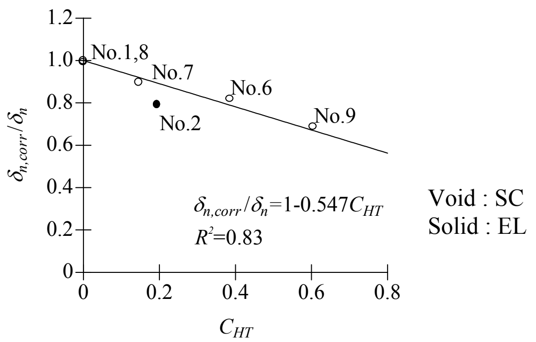


(a) Relationship between C_L and $\delta_{m,corr}/\delta_m$



(b) Relationship between C_{HT} and $\delta_{n,corr}/\delta_n$

Fig.10 Evaluation of skeleton point M and N

6.0 References

1. Watanabe, T., Tanimura, Y., Takiguchi, M. and Sato, T., “Evaluation Method of Deformation Capacity Related to Damage Conditions for Reinforced Concrete Members,” *Journal of Materials, Concrete Structures and Pavements*, JSCE, No.683/V-52, 2001, pp.31-45. (in Japanese)
2. Takiguchi, M., Watanabe, T., Sato, T. and Tanaka, H., “Evaluation of Ductility for Reinforced Concrete Members,” *Quarterly Report of RTRI*, Vol.40, No.3, 1999, pp.165-170.
3. Oyado, M., Hasegawa, M. and Sato, T., "Characteristics of Fatigue and Evaluation of RC Beam Damaged by Accelerated Corrosion," *Quarterly Report of RTRI*, Vol.44, No.2, 2003, pp.72-77.
4. Oyado, M., Kanakubo, T., Yamamoto, Y. and Sato, T., “Influence of Corrosion of Reinforcing Bars on Bending Performance of Reinforced Concrete Members,” *Journal of Materials, Concrete Structures and Pavements*, JSCE, Vol.62 (2006), No.3, 2006, pp.542-554. (in Japanese)