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Experimental Study on the Seismic Behaviour of Corroded Reinforced Concrete Columns

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Abstract

Reinforced concrete structures are vulnerable to deterioration problems associated with corrosion of steel reinforcement. In particular, strength loss due to corrosion is reported as the most common strength degradation mechanism for reinforced concrete structures. Moreover, there are concerns that corrosion can lead to serious structural damage in a strong earthquake, considering substandard aspects of numerous reinforced concrete structures designed prior to the adoption and enforcement of seismic design codes in South Korea. For this reason, the effect of corrosion combined with various design aspects including lap-splices in the plastic hinge zone are investigated in this study. The seismic responses of reduced-scaled circular column specimens with corroded steel reinforcement were evaluated in a series of cyclic tests. The test results confirm that corrosion has a negative effect on lateral resistance and ductility of reinforced concrete columns, which can cause significant seismic degradation.

Keywords: Experimental Seismic Evaluation; Reinforced Concrete Column; Corrosion.

1 Introduction

Reinforcing bars, so-called rebars, are a key structural component of reinforced concrete (RC) structures. Since they enhance stiffness, strength, and durability of RC structures, the degradation of rebars may decrease the structural performance. It is widely known that corrosion is one of the most critical conditions which are closely related to degradation of rebars and surrounding concrete.

Researchers have examined the effect of rebar corrosion on RC bridges based on field examinations and experimental studies. Kumar et al. (2009) discussed the effect of longitudinal rebar corrosion on the long-term seismic performance of RC bridges. Biondini et al. (2012) also studied the effects of transverse reinforcement corrosion on the softening of cover concrete and reduction of confinement effect. Akiyama et al. (2011) explained the effect of corrosion on the buckling point of longitudinal reinforcement.

Regarding the behaviour of corroded RC members subjected to seismic excitation, the following studies were conducted. In various studies (Akiyama et al., 2011; Biondini et al., 2012; Kato et al., 2006; Kumar et al., 2009; Meda et al., 2014; Vu and Li, 2018), combined structural deterioration due to steel corrosion and seismic damage were discussed. In particular, the deterioration is considered as a critical problem when corrosion appears in the plastic hinge regions of bridge columns, where enough strength and ductility are required. Ou et al. (2012) indicated that corrosion decreased strength of a RC member and also changed the failure mode due to corroded transverse reinforcement.

As discussed above, many studies about corrosion in RC members have been conducted, but relatively few researchers investigated the behaviour of corroded lap splices in RC columns. In particular, Aquino and Hawkins (2007) conducted cyclic tests of 6 circular RC columns with corroded reinforcing bars to study the seismic behaviour of corroded columns retrofitted by carbon composites. The test results showed that load carrying capacity of corroded column decreased by 20%. It was remarkable that the maximum lateral displacement was just 25% of non-corroded column. Bond degradation due to corrosion dictated the losses in ductility and load capacities for the corroded columns.

In South Korea, the seismic design of bridges first appeared in the construction specification for bridges, a part of the design standard for bridges, in 1992 (Ministry of Construction, 1992). After the Great Hanshin Earthquake in 1995, more systematic approach was adopted to the seismic design requirements in various Korean design standards. However, many bridges were designed when the design codes did not have explicit requirements for seismic design, and they are still used. They have problems related the inherent lack of resistance to lateral loads as well as those related to aging. In addition, there were construction practices, which are currently prohibited, such as placing short lap-splices in the plastic hinge region of a RC bridge column. Due to the combination of drawbacks, the seismic performance of aged RC bridge columns in Korea are not expected to satisfy the current code requirements, in general.

A series of cyclic tests was conducted to investigate the effect of corrosion on the seismic responses of substandard circular RC columns in this study. Except for corrosion and short lap-splices in the plastic hinge region, test specimens had the same properties and were tested under the same loading protocol to observe the difference in seismic behaviour.

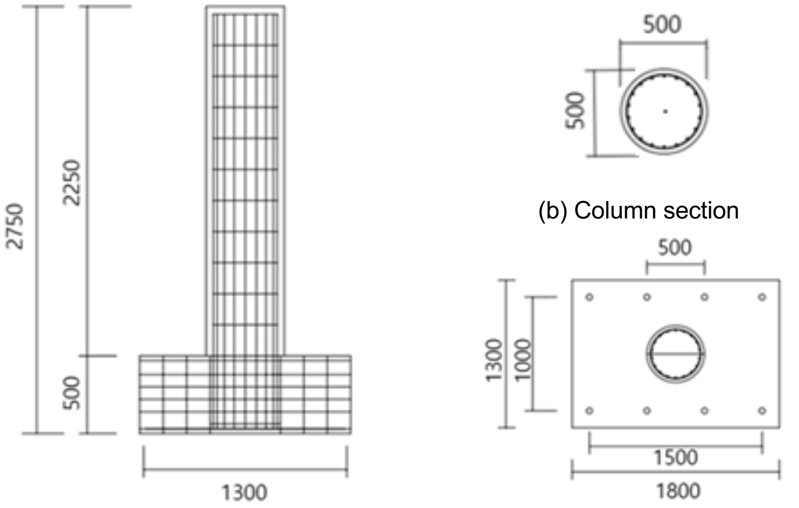
2 Experimental Program

2.1 Specimen Design

A total of 7 reduced-scaled substandard circular RC column specimens were constructed. They have the same dimensions as shown in Figure 1. The diameter of the section is 500 mm, and the height of each column is 2,250 mm. Since there is gap between the centre of lateral load and the top of the column, the vertical distance from the base to the centre of lateral load corresponds to 2,000 mm, and the aspect ratio is 4.0. The ratio is in the range of those of common bridge columns. Besides diameter and height, all specimens had the same compressive strength of concrete, yield strength of rebars, and the reinforcement ratio. The transverse reinforcement ratio, spacing and details were not satisfactory according to the current seismic design code requirements.

Among them, rebars near the base of 5 specimens were corroded by inducing accelerated corrosion. The detailed process is described in Section 2.2. Comparing the responses of the specimens with and without corrosion, the effect of rebar corrosion can be observed.

Another variable is the existence of short lap-splices in the plastic hinge region. It was applied to 3 specimens with and without corrosion. Even though less than 50% of rebars should be spliced at any section in the case of short lap-splices, it is assumed that 100% of rebars were spliced at a section in plastic hinge region of some bridge columns. It is considered as a common construction practice in South Korea before the enforcement of seismic design code. Considering the extreme case, the percentage of spliced rebars is 0% or 100% in this study.



(a) Arrangement of rebars of the column and the footing

(b) Column section

(c) Plan of the column on the footing

Figure 1. Specimen configuration (all dimensions are in mm)

Table 1. Characteristics and properties of test specimens

Specimens		Corrosion	Lap-splices	Properties for all specimens	
NL series (No lap-splices)	NC-NL	No	No	D [mm]	500
	C1-NL	Yes		H [mm]	2,000
	C2-NL	Yes		Aspect ratio	4.0
	C3-NL	Yes		fc' [MPa]	24
LS series (Lap-splices)	NC-LS	No	Yes	fy, fyh [MPa]	300
	C1-LS	Yes		Longitudinal reinforcement ratio	1.16
	C2-LS	Yes		Transverse reinforcement ratio	0.13

2.2 Accelerated Corrosion

Depending on surroundings, the variance of duration to reach significant corrosion on rebars in RC members is considerable. Even if the RC member is near the ocean, where corrosion is easily developed, it may take more than several years to observe severe rust on the buried rebars. To shorten the duration, specimens were aged by accelerated corrosion. Figure 2 shows the schematic diagram and photos of the accelerated corrosion setup. The specimens were placed in PVC containers after metal mesh anodes had been fixed on their surface to provide the electrical contacts. The rebars of the specimen and the mesh were connected to electrical resistance and allowable voltage of the circuit. Continuously providing NaCl solution and oxygen for several months, the corrosion progress of rebars in the plastic region was observed.

(a) Schematic diagram of the setup

(b) Electric wires attached to the rebars

(c) Placing mesh anodes

Figure 2. Schematic diagram and photos of accelerated corrosion setup

2.3 Test Setup and Instrumentation

To conduct cyclic tests of RC column specimens, the test setup was utilized as shown in Figure 3. One horizontal actuator was attached to the side of an upper part of the column, and applied horizontal displacement, which is assumed to be a result of seismic input. The height from the base to the centre of the lateral force is 2,000 mm. On the top, compression was applied to the column in the vertical direction using a steel beam and two hydraulic cylinders.

For accurate observation, instrumentation was planned to measure the lateral displacement of the column and strain of longitudinal and transverse rebars. A displacement transducer measured the lateral displacement at the height of the centre of lateral force. To observe local behaviours, strain gauges were attached to the rebars and additional displacement transducers were placed outside of the column.

(a) Test setup

(b) Instrumentation to observe local behaviours

(c) Controller and displacement transducers

Figure 3. Test setup and instrumentation

2.4 Loading

In the lateral direction, cyclic loading was applied by a horizontal actuator, under the displacement-control scheme as shown in Figure 4. The displacement history was planned to reach the target drift ratios of ±0.3%, ±0.5%, ±1.0%, ±2.0%, ±3.0%, ±4.0%, ±6.0%, ±8.0%, and the corresponding target displacements were ±6 mm, ±10 mm, ±20 mm, ±40 mm, ±60 mm, ±80 mm, ±120 mm, ±160 mm. They were less than the displacement limit of the horizontal actuator. Two cycles were repeated for each drift ratio level. The velocity was 12 mm/sec for the cycles up to the target drift ratio level of 1.0%, 18 mm/sec between ±2.0%~±3.0, 24 mm/sec between ±4.0%~±6.0%, and 32 mm/sec from ±8.0%.

In the vertical direction, static loading was applied. Since the assumed axial load ratio was 10%, the compressive load around 470 kN was applied by hydraulic cylinders.

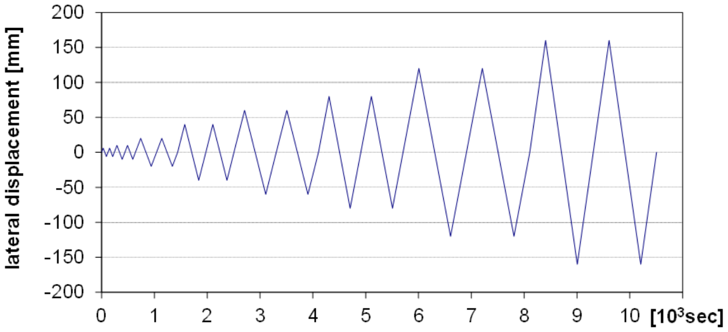


Figure 4. Lateral displacement protocol

3 Experimental Results

Based on the experimental program specified in Section 2, a series of cyclic tests was conducted, and the responses of 7 test specimens were investigated. In this chapter, general observations and global responses of the test specimens are discussed.

3.1 General Observations

Each specimen group shared similar behaviours during the tests, and had a similar failure mode. NL specimens, the columns without lap-splices, were governed by flexure failure. Since the columns were not designed to satisfy seismic design requirements, the displacement ductility was not significantly large. In NL specimens, corrosion decreased the displacement ductility, but it was not a major factor that changes the failure mode. In addition, corrosion affects the maximum lateral load in positive and negative sides, but the change is limited. LS specimens, the columns with short lap-splices in the plastic hinge region, mainly had bond failures. The failure mode was shown as the mixture of flexural and bond failure in the case of NC-LS without corrosion, but those of C1-LS and C2-LS were clearly bond failures. The difference shows that corrosion affected the failure mode of LS specimens. The maximum lateral loads of C1-LS and C2-LS were less than that of NC-LS, and the difference is in the range between 7.8% and 20.5%. It implies that the effect of corrosion on the maximum lateral load of LS specimens is less limited than that of NL specimens.

(a) NC-NL (DR*=4.0%) (b) NC-LS (DR=4.0%) (c) C1-LS (DR=3.0%)

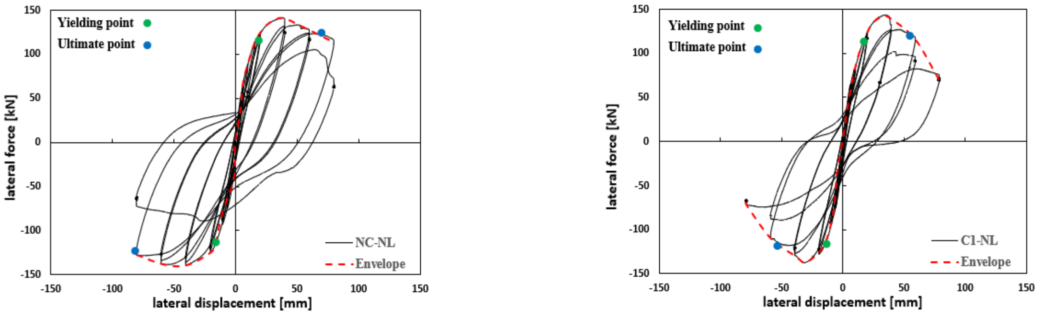
*DR stands for “drift ratio”.

Figure 5. Damage near the base of NC-NL, NC-LS, C1-LS at the final cycle

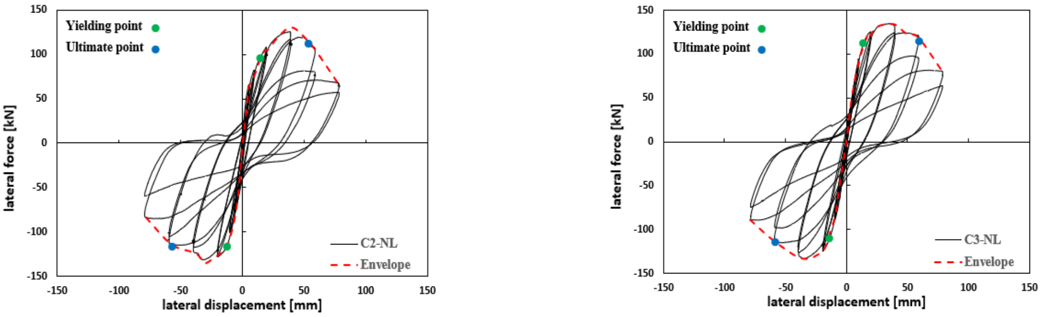
The corrosion rate was obtained by comparing the weight of rebars with and without rust. The specific length of corroded rebars were collected from the plastic hinge region of columns after cyclic tests. The length of each rebar specimen was measured accurately, and its weight was also measured after rust removal. Based on the weight of unused rebars with the same type and length, the weight loss by corrosion could be calculated. As a result, the average corrosion rates were appeared as follows: 7.6% for corroded column specimens in NL series, and 8.8% for those in LS series.

3.2 Force–Displacement Relationships

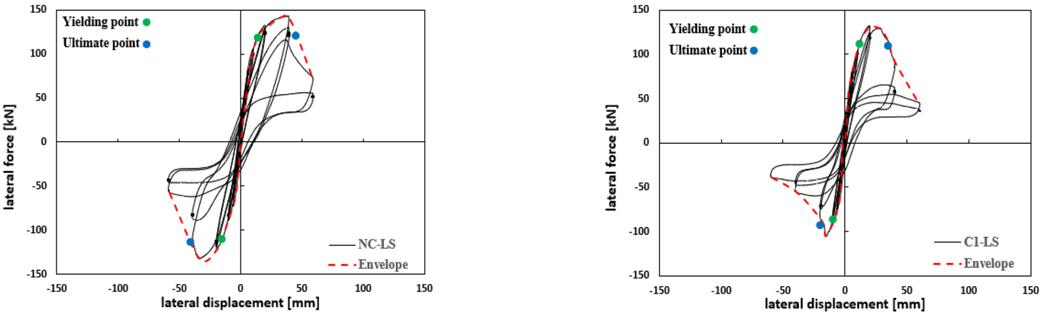
Figure 6 shows the lateral force-displacement relationship and major points in the corresponding curve of each column. A part of observations mentioned in Section 3.1 can be drawn from the curves. It is noteworthy that there are significant differences on the positive and negative sides of the curves of C1-LS and C2-LS. In addition, the respective enclosed area of C1-LS and C2-LS curves is significantly smaller than that of NC-LS curve.



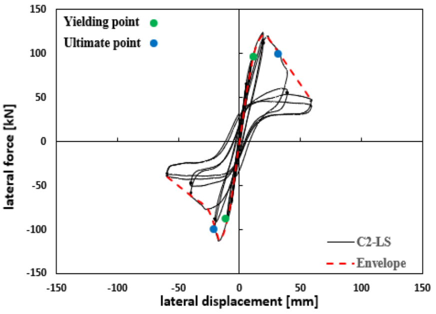
(a) NC-NL (b) C1-NL



(c) C2-NL (d) C3-NL



(g) NC-LS (h) C1-LS



(i) C2-LS

Figure 6. Lateral force-displacement relationships

3.3 Displacement Ductility and Energy Dissipation

Table 2 summarizes the displacement ductility and energy dissipation of each specimen. The positive and negative signs indicate that the corresponding values are calculated from the loads and displacements in quadrant I and quadrant III of Figure 6, respectively. Energy dissipation was obtained from the cumulative enclosed area of each curve. In corroded NL specimens, the displacement ductility was decreased by 28% in average, compared to NC-NL. In some case, a decrease by 40% was observed. In corroded LS specimens, it was decreased by 44% in average, compared to NC-LS, and a decrease by up to 68% was observed on the negative side of the curve. A similar trend is shown in energy dissipation. In NL specimens, the decrease by 11% in average was caused by corrosion. In LS specimens, the decrease by 32% was observed. It is clearly shown that corrosion negatively affects the ductile behaviour and energy dissipation of the RC columns, and the effect is more significant, when the flexure-dominant RC columns have short lap-splices in the plastic hinge region where damage concentration is expected.

Table 2. Displacement ductility and energy dissipation

Test specimens		**Displacement ductility**	**Energy dissipation [10^3 kN-mm]**
NL group (without lap-splices)	NC-NL	(+) 5.57, (-) 5.93, (Avg.) 5.75	39.4
	C1-NL	(+) 3.37, (-) 4.67, (Avg.) 4.02	34.7
	C2-NL	(+) 4.38, (-) 6.79, (Avg.) 4.09	34.4
	C3-NL	(+) 4.88, (-) 3.75 (Avg.) 4.32	36.1
LS group (with lap-splices)	NC-LS	(+) 3.61, (-) 3.39, (Avg.) 3.50	17.9
	C1-LS	(+) 2.82, (-) 1.09, (Avg.) 1.96	12.3
	C2-LS	(+) 2.30, (-) 1.63, (Avg.) 1.97	12.2

4 Summary and Conclusions

In a series of cyclic tests, the global responses of substandard RC columns were studied. The effects of corrosion and short lap-splices in the plastic hinge region on the seismic behaviour of RC columns were investigated considering lateral force-displacement relationship, displacement ductility and energy dissipation of each RC column specimen. The major findings are as follows:

a. Even at the average corrosion ratio of 7.4%~8.8%, corrosion affects the seismic behaviour of substandard RC columns. The displacement ductility and energy dissipation decreased. The maximum lateral load, i.e., lateral load bearing capacity was affected as well, but the change was insignificant. It is noteworthy that the amount of change depends on the type of response. In other words, the response related to lateral displacement is more affected by corrosion than that directly related to lateral resistance.

b. The effect of corrosion is more significant when short lap-splices exist in the plastic hinge region. LS specimens had more considerable decrease in the lateral resistance, displacement ductility and energy dissipation, compared to NL specimens. It is noteworthy that the decrease in lateral resistance is more noticeable when both of corrosion and lap-splices exist, and it is considered as a result of bond failure of the lap-splices. It implies that the failure mode can be changed by corrosion, and that it depends on the original design of columns as well as corrosion.

As shown in the test results, the substandard RC columns subjected to medium-to-high level of corrosion generally undergo the decrease in seismic performance. It may be insignificant in the load-related responses, but it can be more significant in the displacement-related responses. In other words, the long-term seismic performance of a RC structure can be seriously threatened by rebar corrosion, which causes various types of degradation of RC columns. In particular, the seismic performance of RC columns with inherent deficiencies can be worsened seriously by rebar corrosion. In this regard, the seismic retrofit of existing substandard RC columns is necessary to achieve the safety of essential RC structures.

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