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EXPERIMENTAL STUDY ON RC COLUMNS DAMAGED UNDER EXPOSURE TO THE MARINE ENVIRONMENT IN OKINAWA

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ABSTRACT

Real-scaled RC columns have been exposure at a coastal area in the Ryukyu Island, Okinawa, Japan since 2004, to find out the seismic performance of RC columns damaged by chloride attack. In this research, monitored results of the exposure test specimens during three years are discussed. This study concentrates on the early stage of the RC columns damaged by chloride attack. The investigation considers various influences of important factors such as crack on surface of concrete, air born chloride-ions, chloride-ion penetration, and relation of corrosion situation of reinforcing bars with chloride ion and durability. The dimensions of the sections (400 x 400mm) of the columns are near those of a real structure.

The RC columns were tested under reversed cyclic loading and constant axial force, and their seismic performances were verified. As a result, the absorbed energies of the benchmark (non-exposure) specimens and exposure specimens were almost same at drift angle of R = 1.0%. But, the accumulative absorbed energies of the exposure specimens were larger than those of benchmark specimens at drift angle of R = 4.0%.

Introduction

The climate of the Ryukyu Island, Okinawa, Japan is the subtropical environment with the high temperature and high humidity. Therefore, buildings are under a severe corrosion environment. Additionally, it is easy for the RC structures to receive the damage by chloride attack with the coming flying salinity by a typhoon, etc. Moreover, buildings in Okinawa Prefecture constructed before 1977 were used a large amount of sea sand not washed enough. Therefore, the damage by chloride attack in the RC structures due to the reinforcement corrosion is a big problem. T. Yamakawa has been investigated the seismic performance of RC columns with the scale factor of one-third which received damage by chloride attack (Uematsu and Yamakawa 2005). However, the specimens had the cover thickness of one-third of the real thickness, and it might derive a result different from an actual thickness from the viewpoint of the infiltration performance of chloride-ion. On the other hand, cover thickness is important in the research of the damage by chloride attack. Therefore, it is necessary to use the columns with a cover thickness and a section area which is near real-scaled one for the damage by chloride attack. Additionally, to decrease the damage by chloride attack, the behaviors of the RC columns

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in which fly ash with constant cement content has been mixed were investigated. Then, the RC columns have been exposure at the coastal area in Okinawa since 2004, to find out the seismic performance of RC columns damaged by chloride attack.

Test Plan

The reinforcement details of the test specimens are shown in Fig. 1. The investigation was carried out for two groups of RC columns. One group was tested under the cyclic loading test (RC column specimens, see Fig. 1 (a)). Another group (monitored specimens, see Fig. 1 (c)) was tested for chemical and material properties (relations between crack on surface of concrete, corrosion, the chloride-ion penetration, and tensile properties of steel bar). The RC columns have 400 x 400 mm square sections, and their heights are 1600mm (shear span to depth ratio of *M/(VD)* = 2.0). The upper and bottom parts of the columns have the shear reinforcement ratio of p_w = 0.60% (D10-@60mm), and the center part has the ratio of p_w = 0.40% (D10-@90mm). Longitudinal reinforcement ratio is p_g = 1.44% (8-D19). All of RC columns were planed to behave in flexural manner. The cover thickness was 30mm. The monitored specimens had the same sectional area (400 x 400 mm, see Fig. 1 (b)) as the RC column specimens, and their heights are 1000mm. The details of test specimens and the mechanical properties of steel materials are shown in Table 1 and Table 2, respectively. Table 1 shows the nominal concrete strength and the concrete strength passed three years after casting concrete. The experiment variables consist of three different mixed properties including series N, L and F. Concrete strength of series N (with w/c = 61.5%) is often used. Concrete strength of series L (with w/c = 75.0%) is low. Series F is the same as series N with this difference that class 3 fly ash (JIS 1999) of 60kg/m^3 was added partly instead of sand. It revealed that in the concrete mixed with fly ash, the amount of infiltration of the chloride-ion is a little (Sorn and Yamada 2002). Ignition loss of class 3 fly ash is under 8.0%. Therefore, it cannot be used as an appropriate main adhesive material because of its unpredictable behavior. However, it seems that the character like class 3 fly ash is effective in recycling and the corrosion damage.

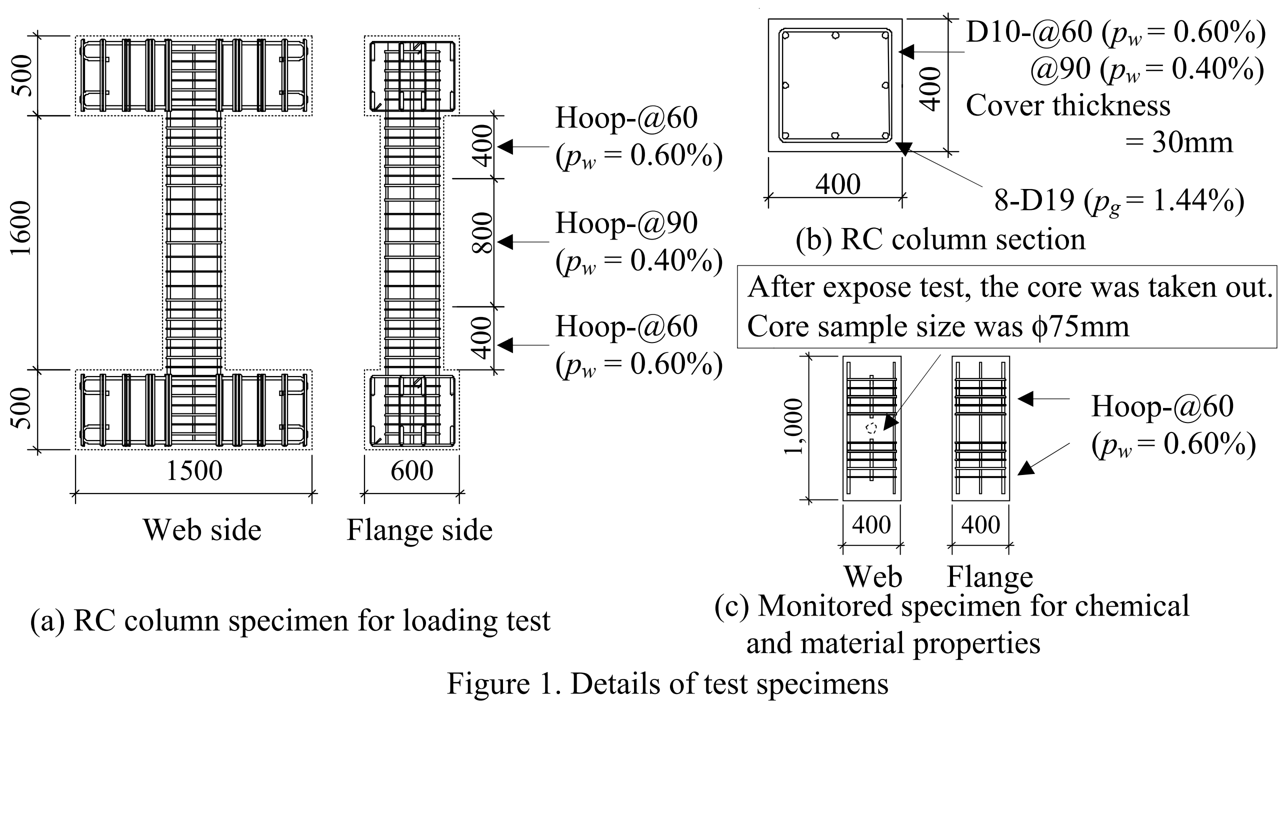


Figure 1. Details of test specimens

Each RC column specimen and its corresponding monitored specimen are assumed as a couple. Three series of test specimens (series N, L and F) are considered that each series includes four couples (one benchmark and three exposure test specimens).

The RC columns, the monitored specimens and concrete cylinders have been exposure at the coastal area in Okinawa since July 2004. The appearance of the exposure test place is shown in Fig. 2. It is the place where seawater splashes, when it is windy. Moreover, the benchmark specimens (one couple of RC columns and monitored specimens) were kept on the University of the Ryukyus to be influenced less by chloride attack.

In the July 2007, one pair of each series (RC column specimens and the monitored specimens of C07C-N3, C07C-L3, and C07C-F3) carried to the University of the Ryukyus. The benchmark and the exposure test specimens have passed three years since they were setting on the exposure place.

Table 1. Details of test specimens for cyclic loading tests

	Series-N		Series - L		Series - F	
	Specimen		Specimen		Specimen	
	B.M.	Exposure	B.M.	Exposure	B.M.	Exposure
	C07C-N0	C07C-N3	C07C-L0	C07C-L3	C07C-F0	C07C-F3
Water cement ratio (w/c)	61.5%		75.0%		61.5%	
σ_B (nominal strength)	21.0 MPa		13.5 MPa		21.0 MPa	
σ_B (4 weeks)	32.2 MPa		24.3 MPa		35.5 MPa	
σ_B(3 years)	36.9 MPa	37.6 MPa	29.7 MPa	25.5 MPa	43.9 MPa	43.1 MPa
Casting date	2004.5.21		2004.5.28		2004.6.4	
Exposure period	2004/7/31～2007/7/30 (3 years)					
Loading test date	2007.10.2	2007.9.21	2007.9.27	2007.9.25	2007.10.1	2007.9.26
Age (day)	3.4 years (1229 days)	3.4 years (1218 days)	3.3 years (1217 days)	3.3 years (1215 days)	3.3 years (1214 days)	3.3 years (1209 days)
Mineral admixture	-		-		Class 3 fly ash 60kg/m^3	
Common details	Rebar = 8-D19 (p_g = 1.44%); Hoop = D10-@60 (p_w = 0.60%), D10-@90 (p_w = 0.40%); Shear span to depth ratio:$M/(VD)$ = 2.0; Axial force ratio:$N/(bD\sigma_B)$ = 0.2; Cover thickness = 30mm.					

Notes: σ_B (nominal strength) = nominal strength of concrete; σ_B (4 weeks) = cylinder strength of concrete; B.M. = benchmark specimen; σ_B (3 years) = cylinder strength of concrete after 3 years; p_g = ratio of total longitudinal reinforcement; p_w = shear reinforcement ratio.

Table 2. Properties of reinforcements

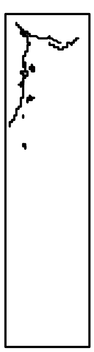
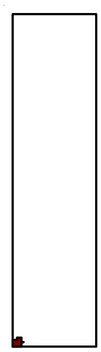
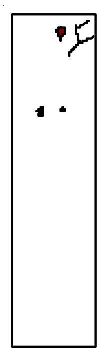
		a (mm^2)	σ_y (MPa)	σ_u (MPa)	ε_y (%)
Rebar	D19	287	384	575	25.5
Hoop	D10	71	401	569	22.8

Note; a = cross section area, σ_y = tensile yield strength of steel,
σ_u = tensile fracture strength of steel, ε_y = tensile fracture strain of steel.

Figure 2. Exposure of RC column specimens in Okinawa seashore

The Exposure Test to the Marine Environment in Okinawa

The exposure test had been conducted in the west coast in Okinawa since July 2004, after the construction about two months had passed. The exposure test investigation has been done by visual observation every about six months. The items of the investigation are widths of the cracks on the cover concrete, and the places where cracks happen, and rest of surface damage. Cracks on concrete surface of the sea-side after exposure test for three years, and the situation of the corrosion of steel bars when the cover concrete is removed after cyclic loading test, are shown in Fig. 3. It is understood from Fig. 3 that the damage of C07C-N3 and C07C-F3 were severe. They are thought that this is because water and oxygen were supplied from the crack on the concrete upper surface.

C07C-N3		C07C-L3		C07C-F3	
Cracks*	Steel bars**	Cracks*	Steel bars**	Cracks*	Steel bars**
					

Cracks* : cracks of cover concrete before loading test
Steel bars**: corrosion of steel bars after exposure and loading tests

Figure 3. Cracks of cover concrete and corrosion of steel bars in column specimens

In the RC column specimen C07C-L3, the crack was not found on the surface of concrete. However, the steel bars have corroded severely. The reason is that the water cement ratio is large (w/c=75.0%), therefore the expansion pressure with the corrosion production did not grow because the concrete was not dense, and the crack did not happen (Nakahodo and Yamakawa 2004). Reinforcing bars of the benchmark column specimens did not receive damage.

To verify the seismic performance of the RC column specimens with chloride-ion due to the reinforcement corrosion, the core was taken out from the sea-side and the land-side, at the center parts of the prepared monitored specimens (see Fig. 1 (c)).

The result of the amount of the chloride-ion infiltration is shown in Fig. 4. The hatch in Fig. 4 shows the range of the amount of the limit chloride-ion ($Cl^- = 1.2 kg/m^3$) (JSCE 2007) where corrosion is generated. Chloride-ion infiltration tests were ended, when the amount of chloride-ion of the benchmark monitored specimen was ignorable ($Cl^- \leqq 0.30 kg/m^3$).

In the monitored specimen C07C-L3, the amount of chloride-ion penetration was large compared with other series. The specimen C07C-L3 exceeded the range of the amount of the limit chloride-ion from the surface of concrete in about 7.0cm depth during the exposure period of only three years. All of its rebars and hoops were in the environment that could easily corrode.

In the monitored specimen C07C-N3, there were a lot of chloride-ion penetrations, but they were less than those in the specimen C07C-L3. The penetration was up to the depth of 6cm. This value of penetration provides the possibility of corrosion of rebars and hoops.

In the monitored specimen C07C-F3, the infiltration of chloride-ion of one series was the least. It was at position of 4.0cm depth. There was a possibility that a part of hoops are corroded. The amount of infiltration of chloride-ion increased in the specimens CO7C-L3, CO7C-N3, and CO7C-F3, respectively.

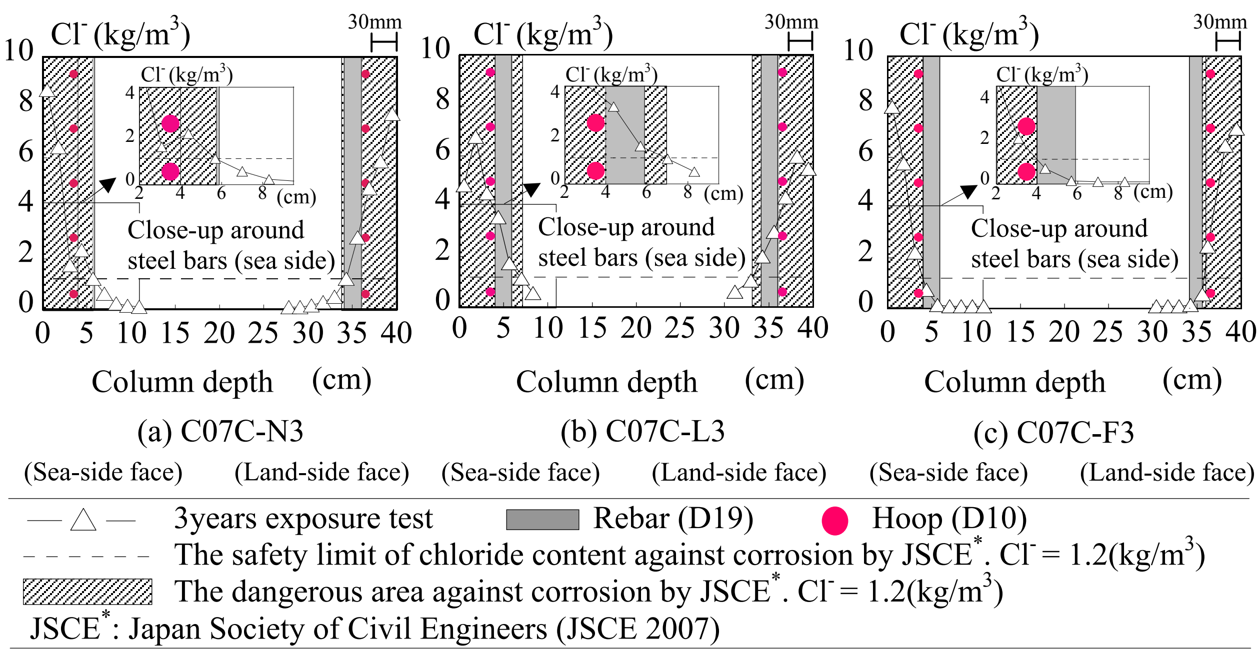
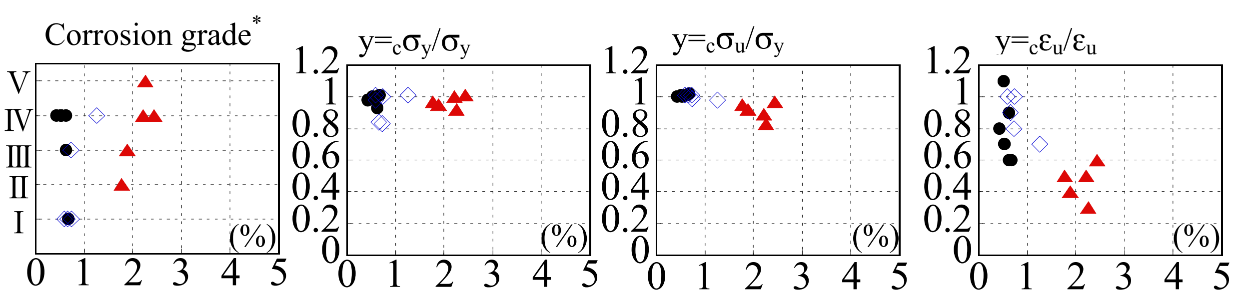


Figure 4. Chloride–ion in monitored specimens for exposure test period 3 years

The reinforcing bars were taken out from the monitored specimens. It was classified into five categories for visual observation by state of corrosion grades of Table 3 (AIJ 1997), and tensile tests were done for them. In this paper, the results of experimental tests on longitudinal rebars are discussed only, because, firstly, all of RC columns were planed to behave in flexural manner. Secondly, in the *V-R* response of the specimens, there are not significant strength degradations. Thirdly, the hoops of RC columns did not break during loading tests. The relations among amount of the rebar weight reduction ratio, corrosion grade, tensile yield strength, tensile fracture strength, and tensile fracture strain are shown in Fig. 5, respectively. The yield point does not clearly appear when reinforcing bars corrode. Therefore, in the reinforcing bars with a severe corrosion, the offset yield point is used. Especially, their tensile fracture strains decreased compared with the sound one. From Fig. 5 (a), it was understood that the corrosion grade increases as the weight reduction ratio increases. Especially, C07C-L3 with a lot of chloride-ion, the corrosion grade was considerable. A change is not observed at remaining tensile yield strength ($y = {}_c\sigma_y/\sigma_y$) in Fig 5 (b). Tensile fracture strength decreased slightly, as the weight reduction ratio increases (Fig. 5 (c)). Moreover, the tensile fracture strain decreased greatly to about 30% of the sound one. It is necessary to observe the value of tensile fracture strain carefully, because it affects flexural failure (Fig. 5(d)).

Table 3. State of corrosion grades by AIJ (AIJ 1997)

Grade	State of rebar corrosion
Ⅰ	Initial stage on starting to rust
Ⅱ	Partially corroded
Ⅲ	Completely corroded but non-pitting corrosion
Ⅳ	Completely corroded and under 20% loss in section
Ⅴ	Completely corroded and over 20% loss in section



X=Weight reduction ratio (%)
(a) Corrosion grade

X=Weight reduction ratio (%)
(b) Tensile yield strength (After corrosion)

X=Weight reduction ratio (%)
(c) Tensile fracture strength (After corrosion)

X=Weight reduction ratio (%)
(d) Tensile fracture strain (After corrosion)

●C07C-N3 ▲C07C-L3 ◇C07C-F3

Corrosion grade*: rebars classified into five categories for the visual observation by AIJ (AIJ 1997).

σ_y= tensile yield strength of steel (sound) ${}_c\sigma_y$= tensile yield strength of steel (corrosion)

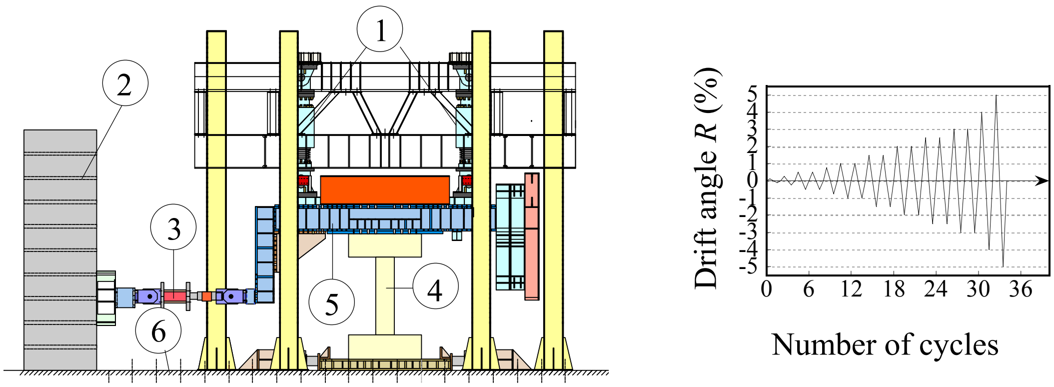
σ_u= tensile fracture strength of steel (sound) ${}_c\sigma_u$= tensile fracture strength of steel (corrosion)

ε_u= tensile fracture strain of steel (sound) ${}_c\varepsilon_u$= tensile fracture strain of steel (corrosion)

Figure 5. Mechanical property versus weight reduction ratio of corroded longitudinal rebars

Cyclic Loading Test Plan

The loading tests were carried out under a constant axial compression force ratio *(N/bDσ_B)* of 0.2 per square columns, corresponding to the axial force in the long term, and cyclic horizontal loading. The test setup and loading program are illustrated in Fig. 6. During cyclic loading, the loading beam (in Fig. 6) always remains parallel to the strong floor. Lateral loading cycles include one cycle at drift angles of R = 0.125, 0.25% and two successive cycles at R = 0.5, 1.0, 1.5, 2.0, 2.5, 3.0%. To investigate the elasto-plastic behavior under large deformation, the loading test was continued up to drift angles of R = 4.0% and 5.0% for one cycle.



1. Servohydraulic actuator 2. Horizontal loading reaction wall 3. Horizontal oil jack
4. Specimen 5. Loading beam 6. Strong floor

Figure 6. Test setup and loading program

Test Results

The exposure RC column specimens C07C-N3, C07C-L3, C70C-F3 and the benchmark RC column specimens C07C-N0, C07C-L0, C07C-F0 were tested after three years of their constructions. The exposure RC column specimens were kept at a coastal area, but benchmark RC column specimens were kept at the University of Ryukyus to be influenced less by chloride attack. The observed cracking patterns (web of sea-side face) after loading tests are presented in Fig. 7. The experimental results of the relationships between the lateral force strength V and the story drift angle R are presented in Fig. 8. The calculated flexural and shear strengths shown in Fig. 8 used the cylinder concrete strengths which had passed three years after they had constructed (see Table 1). The strength of sound steel bars are used in calculation the flexural and shear strengths (see Table 2).

The RC column specimen C07C-F0 was the benchmark specimen that did not expose and its lateral force was largest (see Fig. 8). The specimens C07C-N0 and C07C-L0 are benchmark specimens. The difference of cylinder concrete strength of each series is considered in verification. The cylinder concrete strength of C07C- L0 is small, because the water cement ratio is large (w/c = 75.0%). C07C-F0 and C07C-N0 series have the same water cement ratios (w/c = 61.5%).

In exposure RC column specimen C07C-L3, the failure mode was flexural type. The test result agreed well with the calculated flexural strength by AIJ simplified equation (AIJ 1999).

In all the specimens except the RC column specimen C07C-L3, the failure mode was flexural type. Afterwards, the lateral force strength had decreased that coincided with the calculated shear strength by AIJ simplified equation (AIJ 1999). In exposure RC column specimen C07C-N3, it was considered that the shear failure happened at drift angle of $R = 5.0\%$.

The measured skeleton curves in which benchmark RC column specimens and exposure specimens compared are shown in Fig. 9. As shown in Fig. 9, there is no big difference between the skeleton curves of the exposure specimens and the benchmark one for series L and F. In series N, there was a difference. However, the difference from the lateral force strength V and the drift angle R relation is not clear. Then, they are compared by the amount of the accumulated absorbed energies. The accumulated absorbed energies W versus drift angle R are presented in Fig. 10. In each series, the difference begins from drift angle $R = 1.0$ %

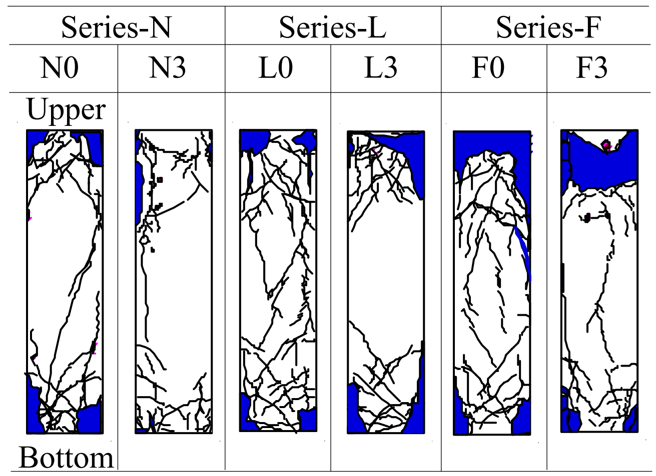


Figure 7. Observed final cracking patterns of seaside face after loading tests

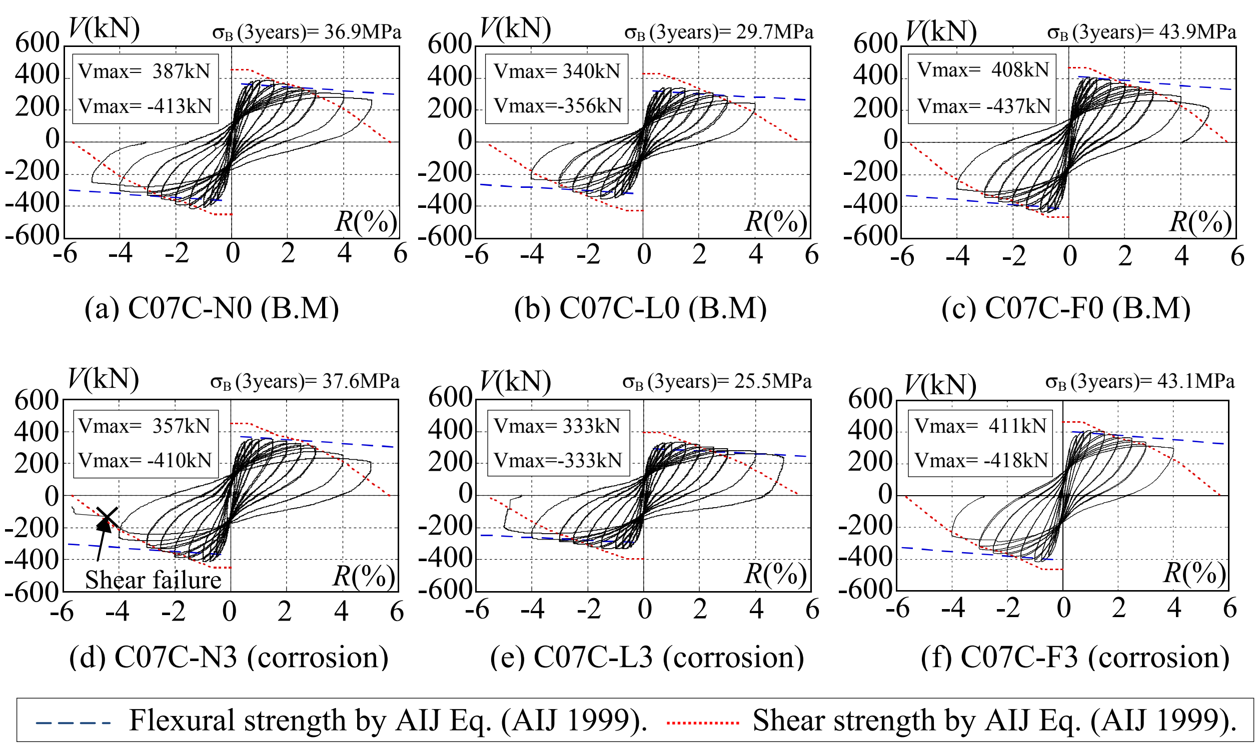


Figure 8. *V-R* relationships

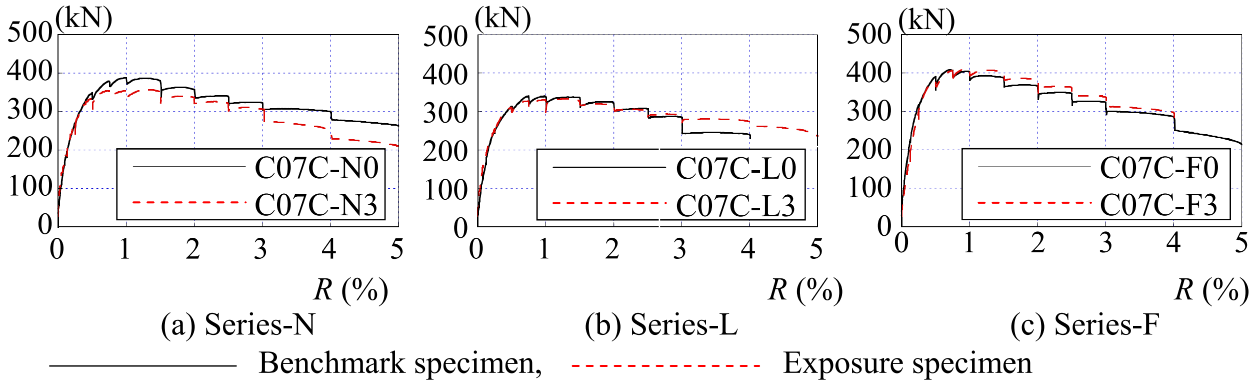


Figure 9. Comparison of measured skeleton curves

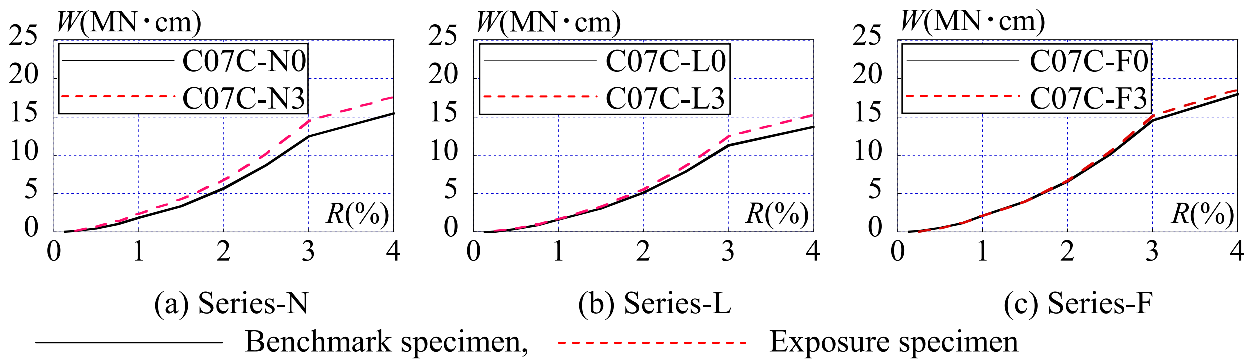


Figure 10. Comparison of accumulated absorbed energies

to R = 2.0 %, and the amount of the accumulated absorbed energy of the exposure specimen exceeded the benchmark one slightly in R = 4.0%. Especially, in series N and L, in which corrosion was severe, differences in absorbed energies are clearly understood. According to the past study (Yamada 1992), it is interpreted that this phenomenon happens because the area of rebar expands, and the bond strength of the rebar improved in the effect of adhesiveness of corrosion.

Conclusions

(1) In the RC columns specimen C07C-L3, the crack was not found on the surface of concrete. However, the reinforcing bars have corroded severely. The reason is that the water cement ratio is large, and therefore the expansion pressure with the corrosion product did not grow because concrete was not dense, and consequently the crack did not happen.

(2) In the monitored specimens C07C-F3 with the concrete mixed class 3 fly-ash in outer placement, the amount of chloride-ion of infiltration was less than those of other series.

(3) On early stage of the RC column specimen damaged by chloride attack, cracks occurred to the cover concrete surface of a part of specimens as for the one that the exposure period passes three years and the corrosion grade of longitudinal rebars became Ⅲ or Ⅳ(AIJ 1997). But the

absorbed energies of the benchmark specimens and exposure specimens were almost same at drift angle range of R = 1.0%. The accumulative absorbed energy of the exposure specimens were larger than those of benchmark specimens at drift angle of R = 4.0%

(4) The moderate degree of corrosion in the longitudinal reinforcements has not significant influence on the flexural seismic performance of RC columns, especially for drift angles of $R \leqq 2.0\%$.

Acknowledgments

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