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An experimental study on the retrofitting effects of reinforced concrete columns damaged by rebar corrosion strengthened with carbon fiber sheets

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Abstract

This paper presents the results of an experiment study on the structural behavior of reinforced concrete (RC) columns damaged by rebar corrosion and the retrofitting effects of damaged RC columns strengthened with carbon fiber sheets (CFS). In the experiment, a cyclic horizontal loading test was carried out using RC columns damaged by different degrees of rebar corrosion and strengthened with CFS. As a result, it was revealed that the deterioration of their structural behavior was mainly caused by the decline in the confining effect due to the falling off of concrete cover and the reduction of mechanical properties of corrosion rebar. In addition, the test proved that shear strengthening using CFS is an very effective retrofit technique that prevents bond splitting cracks and shear cracks from growing and improves the ductility of RC columns with corroded rebars due to the confining effect of CFS.

Keywords: Corrosion; Reinforcement; Degradation; Mechanical properties; Durability

1. Introduction

In order to ensure safety of reinforced concrete (RC) structures whose reinforcing steel has been severely corroded, it is necessary not only to repair the damage appropriately, but also to evaluate the strength of RC members according to the degree of rebar corrosion [1,2]. The losses in the structural performance of RC members with corroded rebars are caused by the losses in the effective cross-sectional area of concrete due to cracking in the cover concrete, losses in the mechanical performance of rebars due to the losses in their cross-sectional area, and losses in the bond performance of concrete with rebars [3,4]. RC columns, the main structural members of RC structures, usually sustain axial forces of dead loads and live loads. When hit by an earthquake, however, they are repeatedly subjected to bending moment and shearing forces caused by horizontal forces and may go into brittle failure such as shear failure or bond failure [5]. On the other hand, an RC column containing extremely corroded rebars is prone to brittle shear failure under seismic loads [6]. Therefore, it is essential to clarify the influence of rebar corrosion on the strength of an RC column in order to ensure its seismic performance. As far as studies on seismic performance of RC members with corroded rebars are concerned, there are currently some reports on beams subjected to bending, but only a few attempts have so far been made at columns, in which axial force is predominant [7,8].

Aiming at understanding the influence of rebar corrosion on the strength of RC columns, a cyclic horizontal loading test was carried out in this study, using specimens with three levels of corrosion in the hoops. In so doing, the mode of failure and changes in the strength of RC columns were

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Table 1
Configuration of specimens

No.	Specimen symbol	Integrated electric current (A h)	Volumetric ratio of hoops, P_w (%)	Axial force ratio η	Notes
1	RC-SOUND	0			sound specimen
2	RC-COR-1	1344			un-retrofitted (Level 1)
3	RICF-COR-1	1344	D10 at 80	0.2	injection + CFS (Level 1)
4	RC-COR-2	2688	0.6 (%)		un-retrofitted (Level 2)
5	RMCF-COR-2	2688			back-filled + CFS (Level 2)
6	RC-COR-3	5376			un-retrofitted (Level 3)

In the specimen symbol RC-COR-1, the first part, RC, stands for un-retrofitted (other symbols are RICF = injection + CFS and RMCF = backfilled + CFS); the second part stands for the presence of corrosion (where SOUND = no corrosion and COR = corroded); and the third part, 1, stands for the level of corrosion (1 = Level 1, 2 = Level 2, and 3 = Level 3).

examined. Furthermore, the authors carried out shear strengthening on RC columns with corroded rebars using carbon fiber sheet (CFS) and examined its retrofitting effect.

2. Experimental procedure

2.1. Configuration of specimens

Six specimens were designed, whose types were determined by the level of corrosion and the presence of CFS as a retrofitting material. Table 1 gives the configurations of the specimens.

2.2. Configuration of specimens

Mix proportions and mechanical properties of the concrete are given in Tables 2 and 3, respectively. The rebars were SD 295A, and their mechanical properties are given in Table 4. The CFS consisted of fibers arranged in a uniform direction. Table 5 gives the material properties of the CFS.

2.3. Preparation of the specimens

Fig. 1 shows the shape of the specimens and the way in which CFS was applied. As shown in Fig. 2, corrosion of hoops was accelerated by the electrochemical corrosion method. The hoops in the test region were used as the anode and copper plates installed around the test region were used as the cathode, through which a constant current of 4 A was applied. The level of corrosion was controlled by the volume of integrated electric current; a current was sent for 2 weeks for Level 1 corrosion (RC-COR-1 and RICF-COR-1), for 4 weeks for Level 2 corrosion (RC-COR-2 and RMCF-COR-2), and for 8 weeks for Level 3 corrosion (RC-COR-3). Then, development of corrosion cracks at each corrosion level was observed. After cracks of RICF-COR-1 were repaired with epoxy resin, shear strengthening was carried out by wrapping the whole test region with CFS in the peripheral direction. The same shear strengthening was also carried out on RMCF-COR-2 after its concrete cover was chipped way and back-filled with lightweight epoxy resin mortar.

Table 2
Mixing properties of concrete

W/C (%)	S/A (%)	Slump (cm)	Unit weight (kg/m^3)			
			W	C	S	G
65	45	18	185	285	776	1007

Table 3
Mechanical properties of concrete

Compressive strength (MPa)	Elastic modulus (MPa)	Poisson's ratio
39.2	29,400	0.19

2.4. Loading method and measurement items

Fig. 3 shows the system of loading. Using the loading device developed by the Building Research Institute (BRI) in Japan, with displacement being controlled, cyclic positive–negative loading of constant axial forces was implemented according to the hysteresis curve of loading shown in Fig. 4. The measured items were horizontal force, axial force, horizontal displacement, vertical displacement, rotation angle of the specimen ends, and strain rebars and CFS. The extent of rebar corrosion was studied after the test.

3. Tests results and discussion

3.1. Cracking of concrete cover and the extent of rebar corrosion

Fig. 5 gives overall views of cracking in the specimens observed after carrying out electrolytic corrosion. The axial

Table 4
Mechanical properties of rebars

Type	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elastic modulus (N/mm^2)
D16	362.8	537.4	191,000
D10	347.2	540.3	174,000

Table 5
Material properties of CFS

Weight (g/mm^2)	Sectional area (cm^2/m)	Tensile strength (N/mm^2)	Elastic modulus (N/mm^2)
175	0.97	3500	290,000

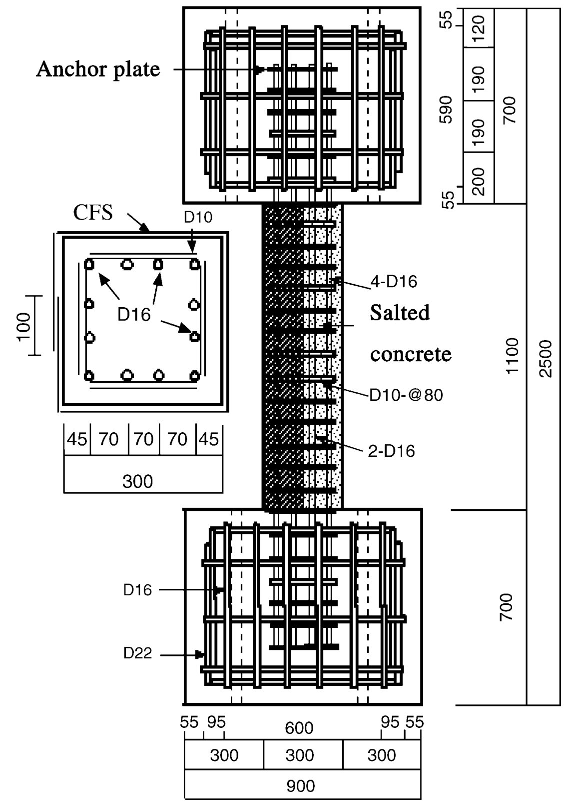

Fig. 1. Shape of the specimen (unit: mm).

cracks alongside the longitudinal reinforcement and the corner cracks were more serious in the hoop direction. According to the visual observations carried out on both longitudinal reinforcement and hoops after the cyclic loading test, the rebars had black rust caused by the electrolytic corrosion all over (Fig. 6), and their surfaces had flake rust and partial losses of the sectional area. Particularly notable was RC-COR-3, a specimen with Level 3 corrosion, where some of the rebars lost more than half of their sectional area. The characteristic of the corrosion observed was that the rust concentrated on or near corrosion cracks and on the corners of hoops. The reason for this seems to be that cracks are prone to water infiltration and that the corners of the hoops are under high stresses induced when being bent in the preparation of rebars.

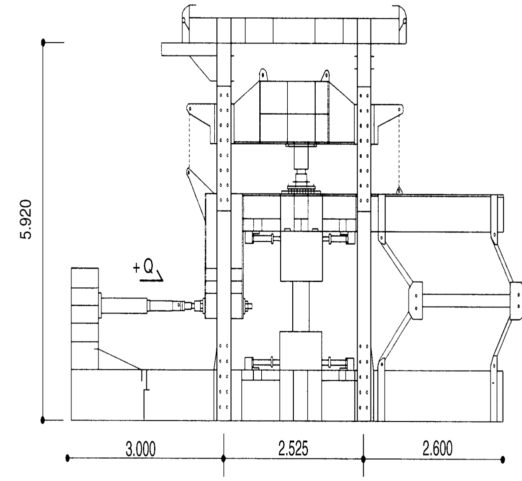

Fig. 3. Loading device.

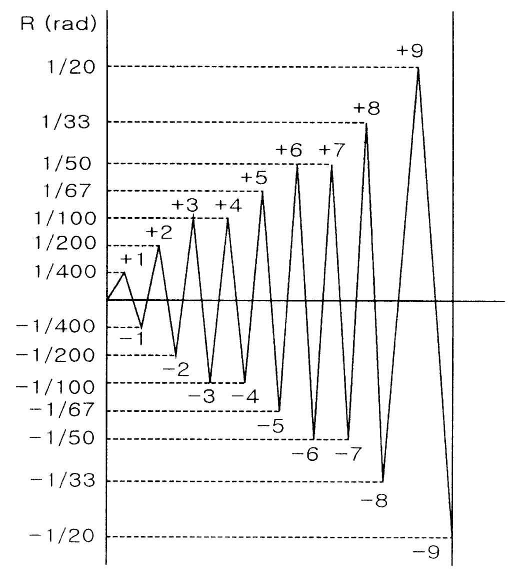

Fig. 4. Hysteresis curve of loading.

3.2. Failure mode of specimens and list of test results

Table 6 is a list of the test results, and Fig. 7 shows the state of failure of the specimens. For RC-SOUND specimens, it was observed that concrete was crushed at a rotation angle of 1/100 when the longitudinal reinforcement

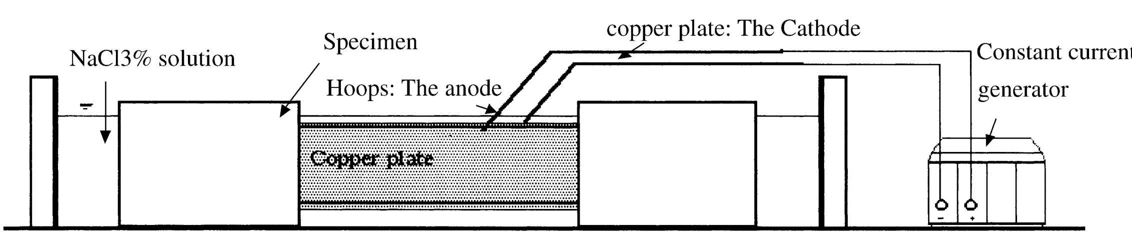

Fig. 2. Acceleration of corrosion of hoops in an RC column by the electrochemical corrosion method.

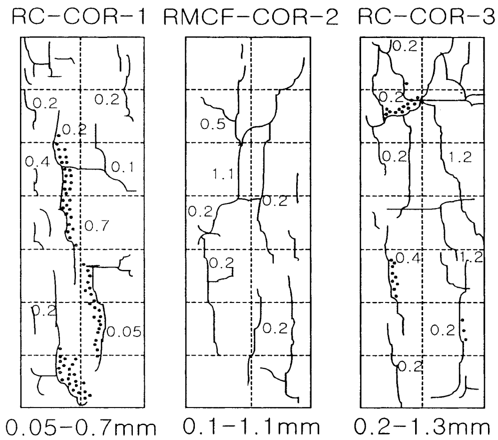

Fig. 5. Cracks in cover concrete.

had yielded. Afterwards, numerous X-shaped bond cracks occurred at a rotation angle of 1/67, which eventually led to bond splitting failure. On the other hand, the specimens with corrosion, RC-COR-1 and RC-COR-2, showed the same behavior; their corrosion cracks continued to grow as loading was being implemented. Bond cracks, which were notable in the sound specimen, were small in number even at a rotation angle of 1/67. The reason for this was that the rebar corrosion reduced the bond strength between concrete and rebars, and therefore, stresses on the longitudinal reinforcement were not transmitted to the concrete. At a rotation angle of 1/20, their concrete cover fell off completely. From this observation on the specimens after failure, it was concluded that the falling off of concrete cover was caused by the corrosion cracks, which occurred all over the concrete cover including the boundary region between the concrete cover and the core (i.e., where rebars were installed) and then further developed by connecting with each other. Shearing failure was observed in RC-COR-3, where the failure of the hoops was immediately followed by the buckling of the longitudinal reinforcement. In RICF-COR-1, a retrofitted specimen, flexural cracks occurred along the direction of CFS at a rotation angle of 1/50. Then, at 1/20, the specimen went into shearing failure with the CFS at the corners in the upper part of the test region fracturing. In RMCF-COR-2, flexural cracks occurred in the direction of CFS at a rotation angle of 1/100. As the specimen did not lose its strength at 1/20, more loading was applied. It eventually went into shearing failure at 1/15 with the CFS at the corners in the upper part of the test region fracturing.

3.3. Load–deformation curves

Figs. 8 and 9 show the influence of rebar corrosion. The rigidity of RC-SOUND decreased at a rotation angle of 1/100 due to the yielding of rebars and concrete. In both RC-COR-1 and RC-COR-2, corrosion cracks progressed at a rotation angle of 1/100, and then the specimens reached the maximum strength while their rigidity was deteriorating due to the loss of bond between rebars and concrete. Their strength then declined because of the repeated loading. The strength of RC-COR-3 started to decrease at a rotation angle of 1/100 owing to the loss of bond. Then, when its hoops had fractured, the longitudinal reinforcement became unable to sustain the axial force and buckled. The strength thus deteriorated rapidly, and the specimen eventually went into brittle shearing failure. In some parts, the extent of corrosion after the test was such that rebars were reduced to half in volume locally, and fracture occurred at these points. It was thus revealed that the decline in the strength and the deformability of an RC column with rebar corrosion is caused by the following: deterioration of the mechanical property of the rebars due to corrosion, fracture of the rebars due to local corrosion, and loss of the confining effect of concrete due to the falling off of concrete cover after repeated loads.

Figs. 10 and 11 show the load–deformation curves of the corroded specimens to which CFS was applied for

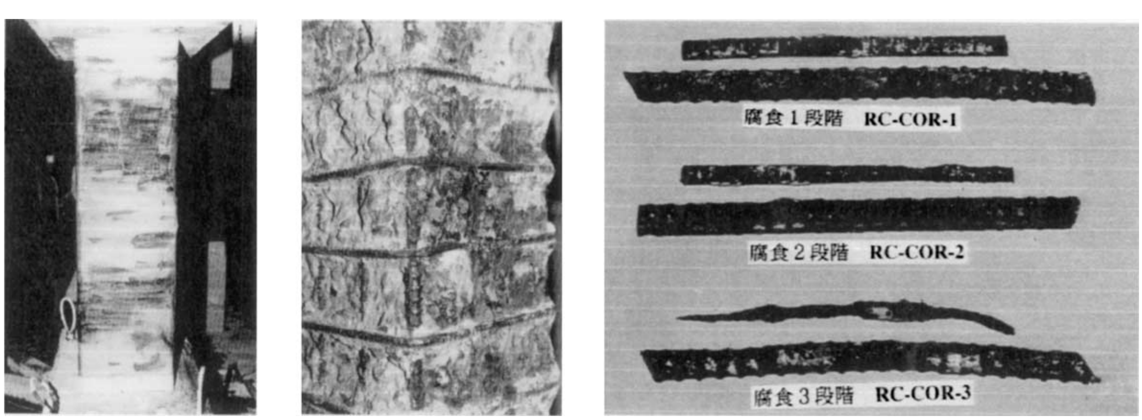

Fig. 6. State of crack and rebar corrosion.

Table 6
List of the test results

Specimen symbol	Initial rigidity (kN/cm)	Yield strength, Q_y		Maximum strength, Q_{max}		Maximum deformation, φ_{max}	Ductility factor, μ_Δ	Model of failure
		kN	rad	kN	rad	rad		
RC-SOUND	561.9	282.4	1/110	288.3	1/100	1/52	2.10	MC → BO
RC-COR-1	616.8	255.6	1/129	258.3	1/104	1/68	1.62	BO
RICF-COR-1	635.5	283.8	1/118	292.2	1/101	1/23	4.72	MC → SC
RC-COR-2	600.2	232.4	1/157	234.8	1/115	1/67	1.64	BO
RMCF-COR-2	490.3	247.1	1/129	259.8	1/100	1/22	5.01	MC → SC
RC-COR-3	628.6	246.6	1/159	251.6	1/146	1/100	1.10	BO → SC

Initial rigidity: up to a rotation angle of 1/400; *maximum deformation rotation angle:* the rotation angle at which the strength is reduced to 80% after reaching the maximum strength; *ductility factor:* maximum deformation rotation angle/yield rotation angle of the sound specimen; *mode of failure:* SC = shearing failure, MC = flexural failure, BO = bond splitting failure.

shear strengthening after repair. Flexural cracking occurred in the direction of fibers at a rotation angle of 1/100 to 1/50, and the strength decreased because of the repeated loads. However, the decrease was small, and much improvement was observed in the ductility, both owing to the fact that repair materials and CFS prevented shear

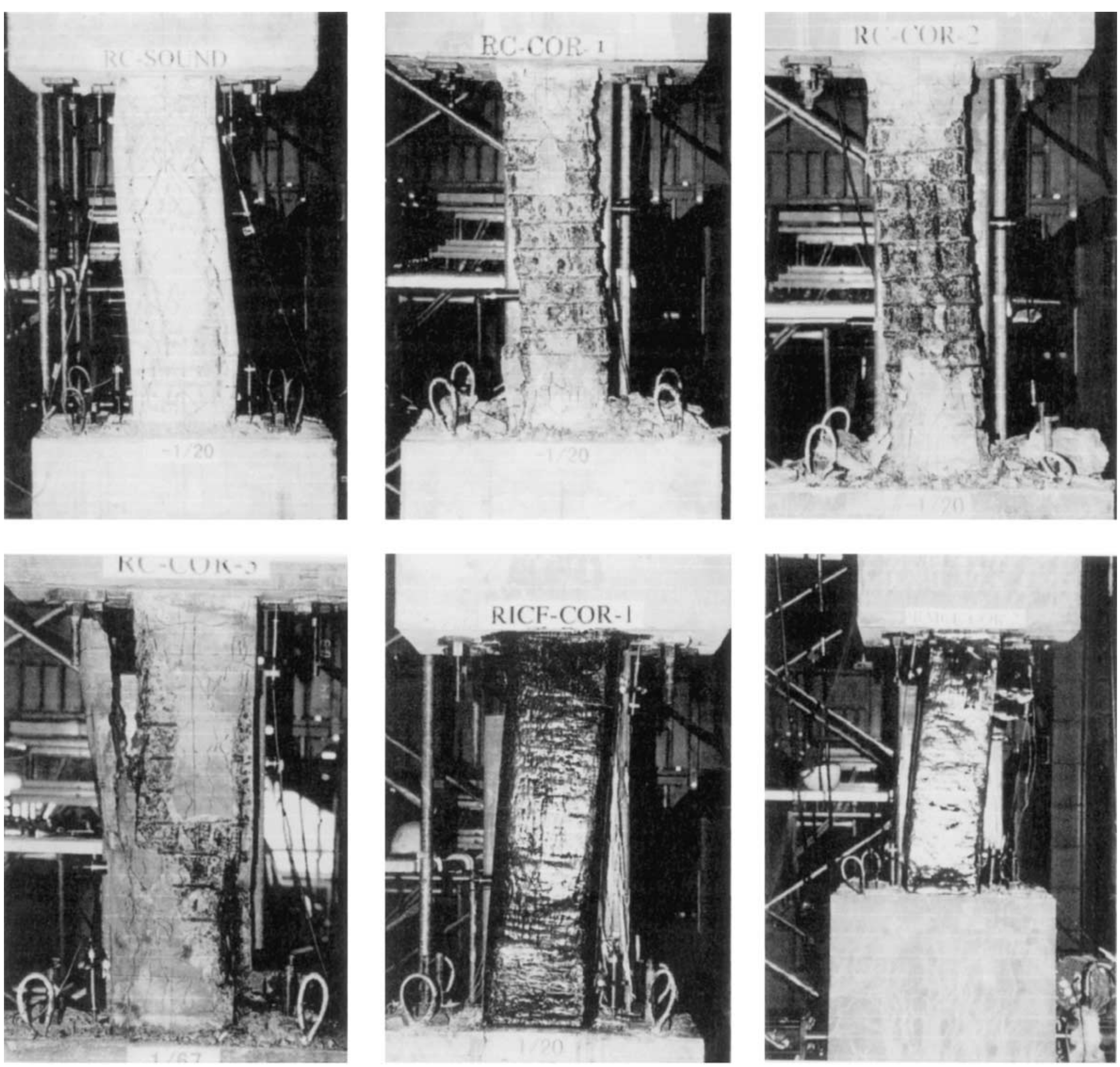

Fig. 7. Views of failure of the specimens.

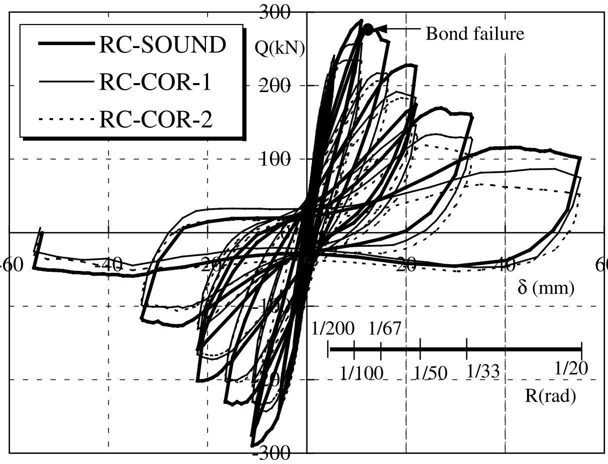

Fig. 8. Load–deformation curves (influence of rebar corrosion).

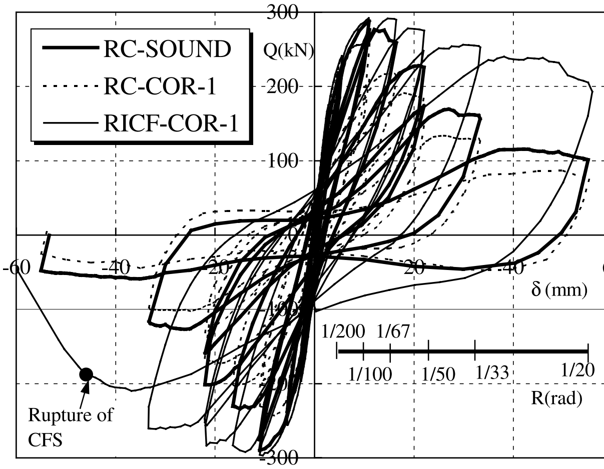

Fig. 10. Load–deformation curves (injection + CFS.)

cracking and corrosion cracks from growing and that the CFS had a confining effect. RICF-COR-1 rapidly lost its strength at a rotation angle of 1/20 due to the fracture of the sheets; however, because the strength of RMCF-COR-2 did not deteriorate even at 1/20, further loading was applied to it. The specimen rapidly lost its strength at 1/15 due to the fracture of the sheets at corners and the specimen went into shearing failure.

3.4. Initial rigidity and rotation angle at maximum deformation

Fig. 12 shows the initial rigidity. The initial rigidity of the corroded specimens was larger than that of the sound specimen. This seems to be due to the key effect of rust and the confining effect on the core concrete induced by the expansion pressure of rebar corrosion. While the rigidity of RICF-COR-1 was not so different from that of RC-COR-1 with Level 1 corrosion, the rigidity of RMCF-COR-2 was smaller than that of RC-COR-2 because the elastic modulus of lightweight epoxy resin mortar is smaller than that of concrete. Fig. 13 shows the rotation angle at maximum deformation (φ_{max}). Where the extent of rebar corrosion was larger, φ_{max} was smaller due to the loss of bond between the rebars and concrete. On the other hand, the maximum deformations of RICF-COR-1 and RMCF-COR-2, the specimens with CFS, were much larger than other corroded specimens, because bond splitting was prevented by repair and the sheets had a confining effect.

3.5. Cumulative energy absorption

Figs. 14 and 15 show the cumulative energy absorption derived from the product of horizontal load and horizontal deformation. Where the extent of corrosion was larger, the energy absorption was smaller when the extent of deformation was the same; this difference became prominent when the rotation angle was larger. However, retrofitting with CFS increased cumulative strain energy absorption greatly.

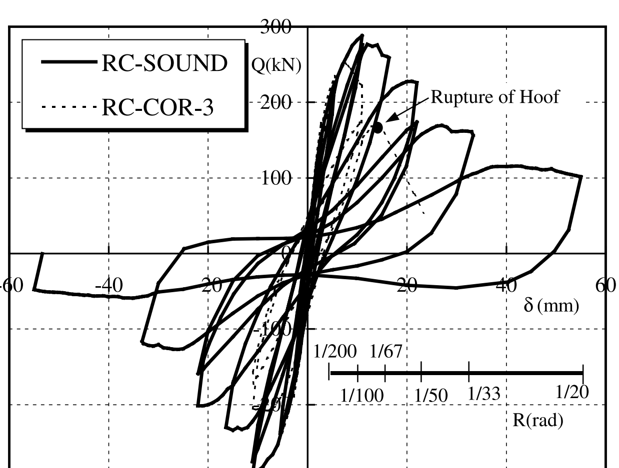

Fig. 9. Load–deformation curves (influence of rebar corrosion).

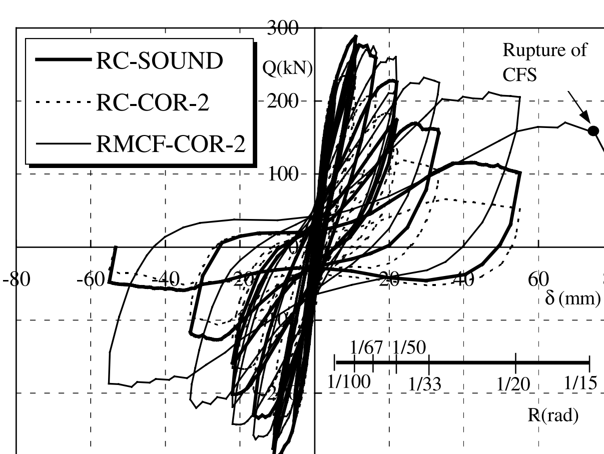

Fig. 11. Load–deformation curves (back-filled + CFS).

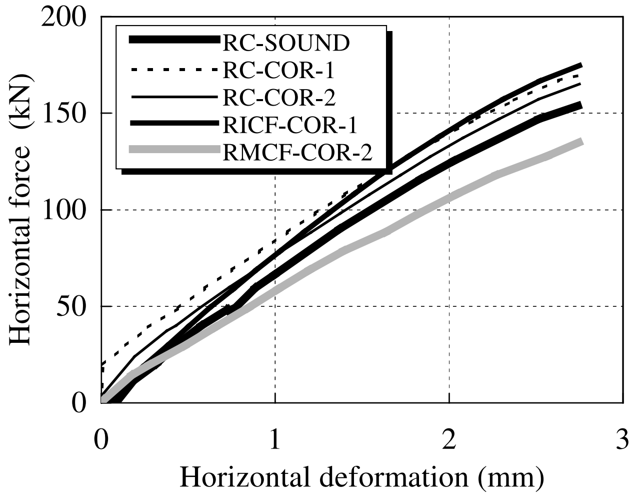

Fig. 12. Initial rigidity.

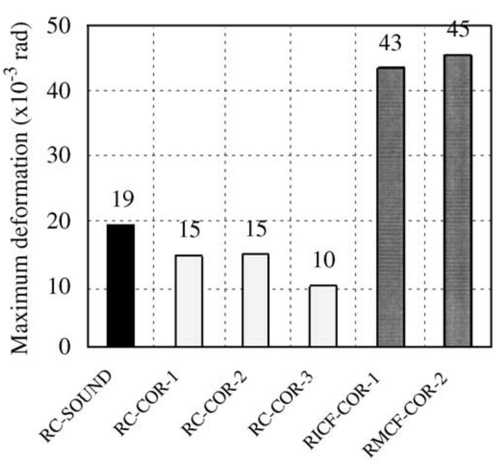

Fig. 13. Rotation angle at maximum deformation.

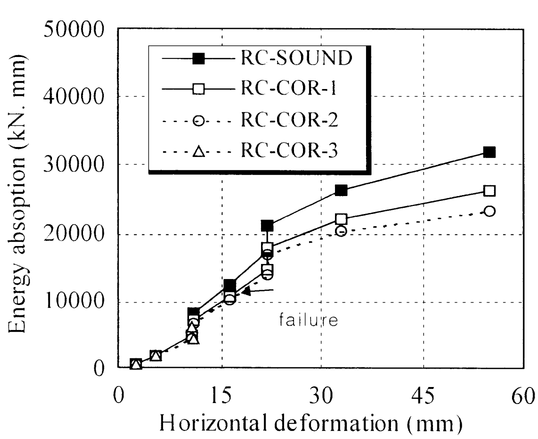

Fig. 14. Cumulative energy absorption.

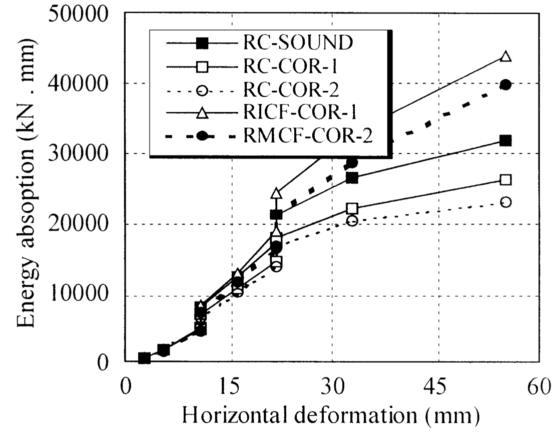

Fig. 15. Cumulative energy absorption.

Fig. 16 shows ductility factors of each specimen, which were derived from the proportion of the maximum deformation rotation angle of each specimen to the rotation angle of RC-SOUND, the sound specimen, at yield point. Though a ductility factor was smaller where the extent of rebar corrosion was larger, the ductility factors of specimens with CFS were almost twice as large as those of unretrofitted specimens. It was thus confirmed that the application of CFS sheets for shear strengthening is an effective retrofit technique for RC columns whose ductility has deteriorated owing to rebar corrosion.

4. Conclusions

To study the structural behavior of RC columns damaged by rebar corrosion and the retrofitting effects of damaged RC columns strengthened with CFS, a cyclic horizontal loading test was carried out using RC columns damaged by different degrees of rebar corrosion and

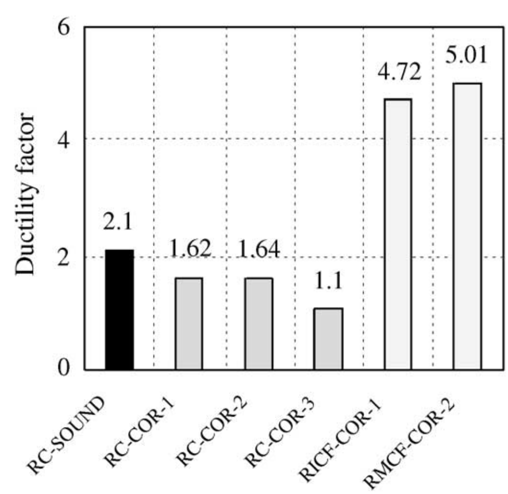

Fig. 16. Ductility factor.

strengthened with CFS. The results obtained from these experiments are summarized as follows:

1. The corrosion of rebars by the electrochemical corrosion method concentrated on near corrosion cracks and the corners of the hoops. The reason for this seems to be that cracks are prone to water infiltration and that the corners of the hoops are under high stresses induced when being bent in the preparation of rebars.
2. The local corrosion of hoops of an RC column, where axial force is dominant, causes fracture of the hoops and brittle shear failure due to the buckling of the longitudinal reinforcement when subjected to cyclic positive–negative shear forces as in earthquake.
3. The causes for the decline in the strength and deformability of an RC column with corroded rebars are the following: decline in the mechanical property of rebars due to corrosion, fracture of rebars caused by local corrosion of the rebars, loss of bond between rebars and concrete owing to repeat loads, and decline in the confining effect of concrete due to the falling off of concrete cover.
4. Shear strengthening using CFS is an extremely effective retrofitting method which prevents bond splitting cracks and shear cracks from growing and improves the ductility of RC columns with corroded bars because of the confining effects of CFS.
5. The subjects to be investigated in the future include the quantitative and analytical investigation of not only the relationship between the degree of rebar corrosion and the structure performance of RC column but also the retrofitting effect strengthened with CFS.

Nomenclature

P_W volumetric ratio of hoops (%)
η axial force ratio
Q horizontal force of RC columns (kN)
δ horizontal deformation of RC columns (mm)
Q_y yield load of RC columns (kN)
Q_{max} maximum load of RC columns (kN)
φ rotation angle of RC columns (rad)
φ_{max} rotation angle at maximum deformation (rad)
ε_{cfs} strain of CFS (μm)
Γ cumulative strain energy absorption (kN mm)
μ_Δ displacement ductility factor

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References

[1] Y. Matsuzaki, An experimental study on mechanical property of reinforced concrete columns with shear strengthening with continuous fiber sheets, Proc. Jpn. Concr. Inst. Annu. Conf. 18-2 (1996) 1463-1468.
[2] S. Masuo, A study on retrofit performance tests on reinforced concrete columns and steel framed reinforced concrete columns and design formula, Proc. Jpn. Concr. Inst. Annu. Conf. 18-1 (1996) 21-30.
[3] H.S. Lee, F. Tomosawa, T. Noguchi, Effects of rebar corrosion on the structural performance of singly reinforced beams, Durab. Build. Mater. Compon. 7 (1) (1996) 571–580.
[4] J. Rodriguez, Corrosion of reinforcement and service life of concrete structure, Durab. Build. Mater. Compon. 7 (1) (1996) 117–126.
[5] Architectural Institute of Japan, Data on Ultimate Strength Design of Reinforced Concrete Structures (No. 17, Strength and Ductility of Reinforced Concrete Columns), Tokyo, 1987, pp. 62–85.
[6] K. Nakayama, T. Yamakawa, S. Iraha, A. Biwada, An experimental study on plastic behaviour of reinforced concrete columns corroded in electrolytic corrosion test, Proc. Jpn. Concr. Inst. Annu. Conf. 17 (1) (1995) 883-888.
[7] Y. Tachibana, Y. Kajikawa, M. Kawamura, The behaviour of RC beams damaged by corrosion of reinforcement, Proc. Jpn. Soc. Civ. Eng. 402 (V-10) (1989) 105–114.
[8] G.J. Al-Sulaimani, Influence of corrosion and cracking on bond behaviour and strength of reinforced concrete members, ACI Struct. J. 87 (2) (1990) 220–231.