INFLUENCE OF REINFORCING STEEL CORROSION ON FLEXURAL BEHAVIOR OF RC MEMBER CONFINED WITH CFRP SHEET

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1 INTRODUCTION

One of the strengthening methods for reinforced concrete member is to confine the member using carbon fiber sheet (thereinafter, CFRP sheet). Strengthening by the confinement at the compression zone of the flexural member using CFRP sheet increases the ultimate strain of that zone. This leads to improvement of the plastic deformation capacity of the member. On the other hand, in order to obtain enough improvement, it is necessary for reinforcing steel at the tension zone of the flexural member to have an enough ultimate strain. However, when the reinforcing steel corrosion is occurred in the confined flexural member, rupture of reinforcing steel at the tension zone may occurs ahead of compression failure at the compression zone, because mechanical properties of reinforcing steel decrease due to corrosion. The result may be that the ductility desired by strengthening with confinement is insufficient.

The objectives of this study are to establish the application scheme of strengthening by confinement using CFRP sheet for a member in which reinforcing steel corrosion has already occurred and to clarify the performance change in ductility due to reinforcing steel corrosion after strengthening by confinement using CFRP sheet has been applied for a flexural member. In order to examine these points, reversed cyclic loading test was carried out for RC beams, with corroded longitudinal reinforcing steel, strengthened by confinement using CFRP sheet. The following test parameters were considered in this study: corrosion loss of longitudinal reinforcing steel, confinement ratio of CFRP sheet and number of loading cycles.

2 EXPERIMENTAL PROCEDURES

2.1 Specimens

Dimension of RC beams with corroded reinforcing steel is shown in Fig.1. The RC beams have 100^B x 200^Hmm cross-section and 1400mm span length. The corroded 2-D10 (SD295A) were arranged as longitudinal reinforcement in both upper and lower sections symmetrically (p=0.81%). In the shear spans, stirrups were arranged with a spacing of 45mm (p_w=1.41%) to prevent shear failure under reversed cyclic loading.

These RC beams were cast using the reinforcing steel (D10), which were beforehand corroded only in central 700mm length by spraying salt water ($NaCl$: 3%) in the room temperature around 10°C. Corrosion mass loss rate is described afterwards in 2.2.1.

The details of RC beams strengthened by confinement using CFRP sheet of 50mm in width, 3500N/mm^2 in strength and 2.3 x 10^{5}N/mm^2 in Young's modulus are shown in Fig.2. The CFRP sheet was wrapped spirally only within 700mm of flexural zone. The confinement ratio is described in the next paragraph in 2.2.2.

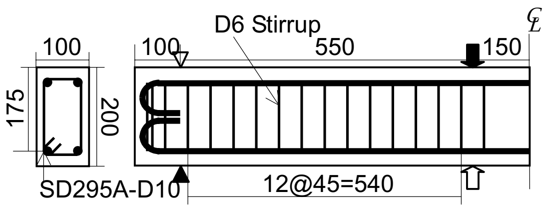
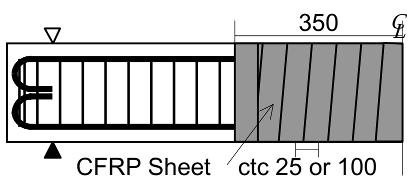


Fig.1 Dimension of RC beams (unit: mm)



(unit: mm)

Fig.2 RC beams confined with CFRP sheet

Table 1 Test specimens and parameters

Specimens	Corrosion mass loss rate (%)	Volumetric confinement ratio ρ_{CF} (%)	Number of loading cycles N
N0	0.0	0.00	1
L0		0.17	
H0		0.66	
N1	3.3	0.00	
L1		0.17	
H1		0.66	
N2	23.0	0.00	
L2		0.17	
H2		0.66	
N1(3)	3.3	0.00	3
L1(3)		0.17	
H1(3)		0.66	

2.2 Test parameters

Test specimens and parameters are shown in Table 1.

2.2.1 Corrosion mass loss rate

The corrosion mass loss rates were 0.0% (sound reinforcing steel), 3.3% and 23.0% in the central 700mm length of longitudinal reinforcing steel. Corrosion of 3.3% and 23.0% correspond to acceleration phase and deterioration phase in degradation of RC member, respectively.

2.2.2 Confinement ratio with CFRP sheet

The confinement ratios with the CFRP sheet at the flexural zone were expressed as volumetric confinement ratio. The values were 0.00% (without strengthening), 0.17% and 0.66%. Confinement of 0.17% corresponds to the value applied in practical strengthening. More effective confinement may be expected by the value of 0.66%.

2.2.3 Number of loading cycles at each step

In order to investigate the influence of number of loading cycles on flexural behavior, one and three loading cycles at (2n-1) times the yield displacement were adopted.

2.3 Measurement of corrosion mass loss and tension test of corroded reinforcing steel

Corrosion mass loss rate, which represented degree of reinforcing steel corrosion, was measured using reinforcing steel of 700mm corroded under the same environment as reinforcing steel for the RC beams. After measuring corrosion mass loss rate according to JCI-SC1 method (in 60°C/10% di-ammonium hydrogen citrate solution for 24 hours), tension test was carried out for these corroded reinforcing steel.

2.4 Loading test procedures

Reversed cyclic load was applied to two symmetrical points so that the flexural and shear spans were 300 mm and 550 mm, respectively, with the overall span being 1400 mm. One or Three loading cycles at (2n-1) times the yield displacement were applied. The yield displacement, δ_y, was determined from the bent of load-displacement curve in sound specimen without strengthening (N0 specimen). The ultimate state was defined as the point at which the load dropped below 80% of the maximum load in the post peak region. The applied load and the displacement at the mid-span and supports were measured.

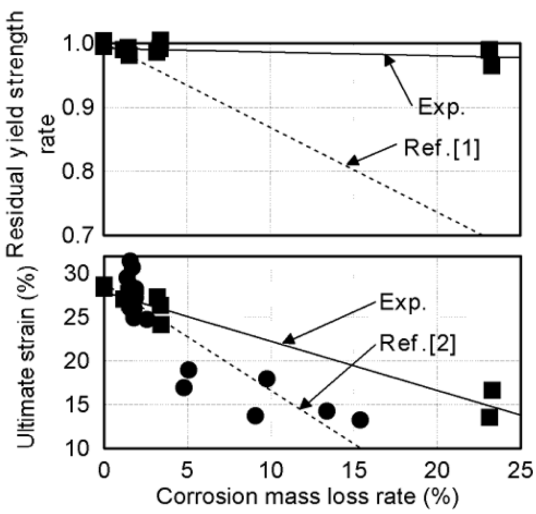


Fig.3 Yield strength and ultimate strain of corroded reinforcing steel

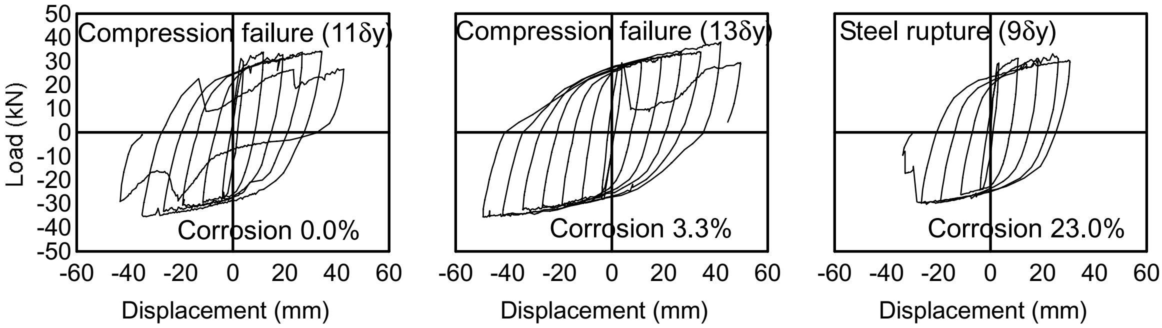


Fig.4 Load-displacement curves (Volumetric confinement ratio ρ_{CF}=0.00%)

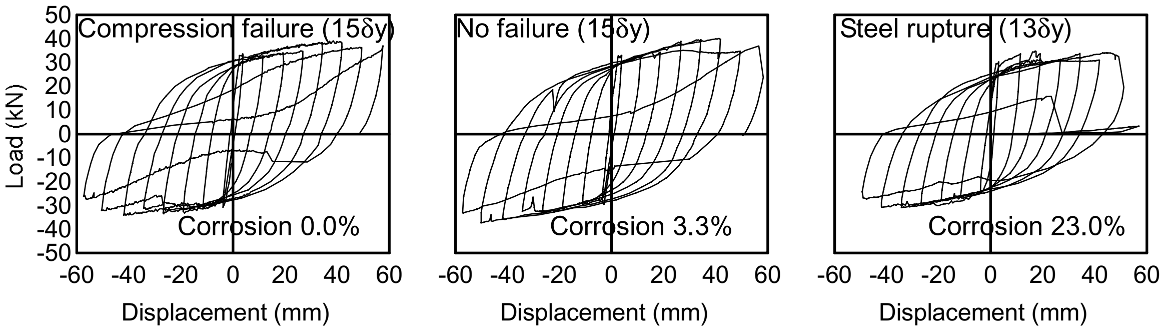


Fig.5 Load-displacement curves (Volumetric confinement ratio ρ_{CF}=0.17%)

3 TEST RESULTS AND DISCUSSIONS

3.1 Tension test of corroded reinforcing steel

Influences of corrosion mass loss rate on yield strength and ultimate strain of reinforcing steel are shown in Fig.3. The dotted lines were obtained by linear regression on the results of previous studies [1], [2]. In those studies, tension tests were conducted by reinforcing steels, which were corroded in concrete specimens. The yield strength was determined using sectional area of corroded reinforcing steel calculated assuming that sectional area loss rate was corresponding to longitudinally uniform corrosion mass loss rate.

Although the yield strength decreased as corrosion mass loss rate increased in the result of previous study [1], the yield strength did not decrease remarkably. On the other hand, the ultimate strain decreased as corrosion mass loss rate increased. Corrosion pitting affected the ultimate strain, that is ductility, more significantly than strength of reinforcing steel. However, the degree of reduction in the result of this study was smaller than in that of previous one [2]. Reinforcing steel corroded in concrete with chloride ion had significant corrosion pitting due to un-uniform density or quantity of water, oxygen and chloride ion along the reinforcing steel. On the other hand, spraying salt water in this experiment made reinforcing steels corroded uniformly. Accordingly, the mechanical property of those did not decrease so much.

3.2 Flexural loading test

3.2.1 Load-displacement behavior and ultimate failure mode

Load-displacement curves of all specimens with their ultimate failure modes are shown in Fig.4-7. In one loading cycle at each reversed cyclic step, although compression failure occurred with corrosion mass loss rate of 0.0% to 3.3%, rupture of longitudinal reinforcing steel occurred at corrosion mass loss rate of 23.0%. When three loading cycles of each step and corrosion mass loss rate of 3.3% were adopted, compression failure occurred with volumetric confinement ratio of 0.00% and 0.17%. On the other hand, rupture of longitudinal reinforcing steel occurred with volumetric confinement ratio of 0.66%. In addition to effect of the number of applied cyclic loading, the increase of ultimate strain at compression zone due to confinement by CFRP sheet led to difference of failure mode.

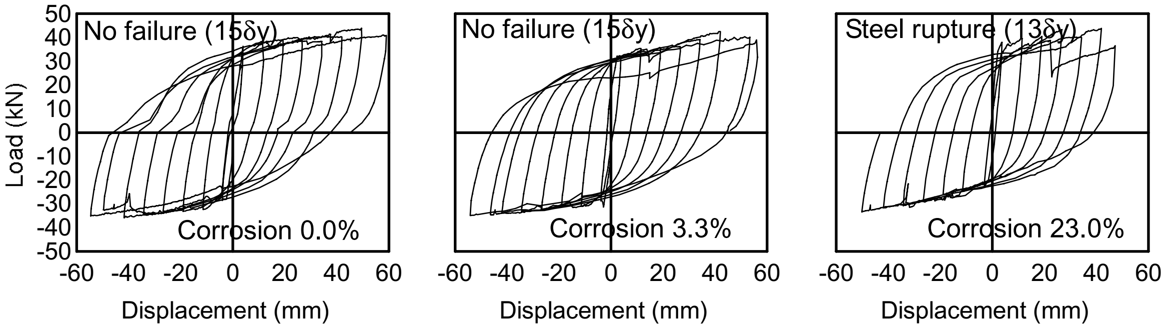


Fig.6 Load-displacement curves (Volumetric confinement ratio ρ_{CF}=0.66%)

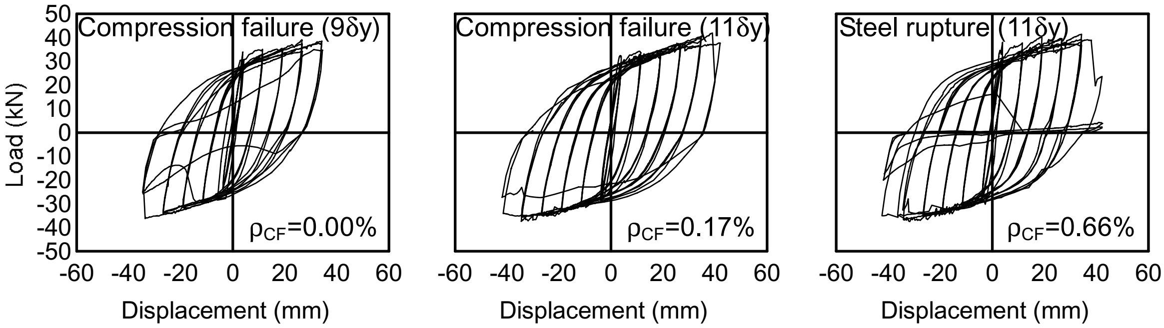


Fig.7 Load-displacement curves (3 loading cycles (corrosion mass loss rate 3.3%))

3.2.2 Maximum load

Influence of corrosion mass loss rate on maximum load of each specimen is shown in Fig.8 with the derived curves obtained by sectional moment-curvature analysis, assuming the plane-sections hypothesis. In this analysis, along with the strength and Young's modulus that were obtained by tension test, the stress-strain model of JSCE [3] for plane concrete in specimen without strengthening and that for concrete confined using CFRP sheet [4] were used. The model of JSCE [5] was used for longitudinal reinforcing steel. The sectional area of corroded reinforcing steel was calculated assuming that sectional area loss rate was corresponding to longitudinally uniform corrosion mass loss rate.

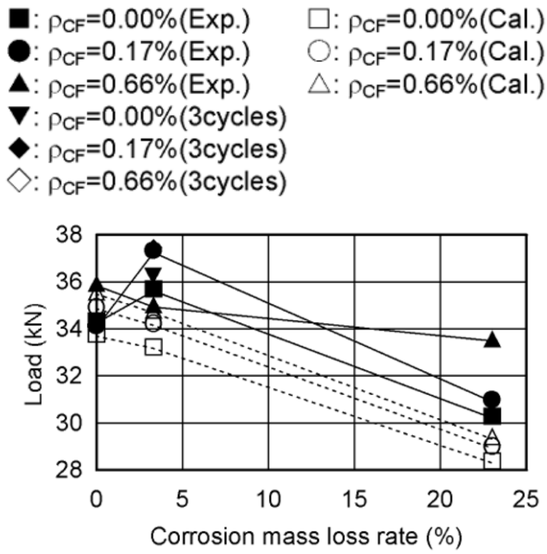


Fig.8 Maximum Load

From the experimental result, at corrosion mass loss rate of 3.3% maximum load did not decrease in any confinement volumetric ratio and number of loading cycles. On the other hand, maximum load at corrosion mass loss rate of 23.0% was reduced approximately by 10% from that of sound specimen.

Comparison of calculated values obtained assuming uniform sectional area loss of corroded reinforcing steel with the experimental data indicated very good agreement on the ratio of reduction. However, when reinforcing steel is corroded in concrete, the reduction of maximum load is larger than that of this experiment, because cover cracks and degradation of bond strength between concrete and reinforcing steel due to corrosion are significant.

3.2.3 Ductility

Influences of corrosion mass loss rate on displacement ductility factor and cumulative dissipated energy up to ultimate state are shown in Fig.9 and Fig.10, respectively. Displacement ductility factor was defined as ratio of the ultimate displacement, δ_u, to the yield displacement, δ_y. The area encircled by hysteresis loop represented dissipated energy. Displacement ductility factor and cumulative dissipated energy of specimen in which ultimate failure did not occur was presented by displacement ductility factor of 15 and cumulative value up to 15 times the yield displacement, respectively.

In little corrosion mass loss rate, displacement ductility factor and dissipated energy of specimen confined using CFRP sheet was larger than that of specimen without strengthening. On the other hand, at corrosion mass loss rate of 23.0%, that is significant corrosion, displacement ductility factor and dissipated energy decreased remarkably from that of sound specimen, because rupture of longitudinal reinforcing steel occurred ahead of compression failure at the compression zone in those specimens. Furthermore, in three loading cycles displacement ductility factor of specimen with volumetric confinement ratio of 0.66% in which rupture of longitudinal reinforcement steel occurred was about the same as that of specimen with 0.17% in which compression failure occurred.

From the above discussion,

- strengthening by confinement using CFRP sheet for the flexural member, in which reinforcing little steel corrosion occurred, can restore or improve the ductility.
- However, at the significant corrosion such as corrosion mass loss of 20% something, it is difficult to determine that strengthening by confinement using CFRP sheet can improve ductility dramatically over the sound member.
- On the other hand, even if corrosion mass loss is slight such as 3.3%, excessive confinement using CFRP sheet should be avoided and the combined use of confinement and flexural strengthening is required in the case that reversed cyclic load works in the post-peak region.
- Moreover, if more reinforcing steel corrosion is estimated after strengthening by confinement using CFRP sheet, reinforcing steel should need some protection against corrosion.

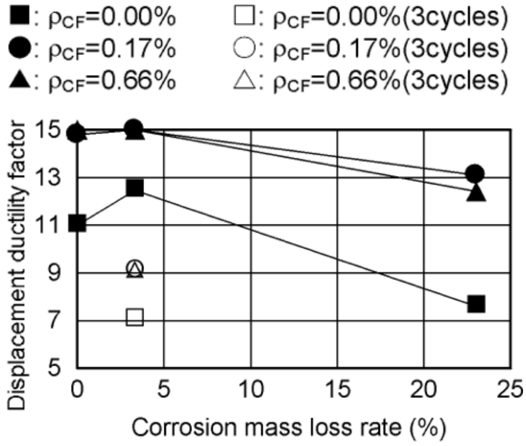


Fig.9 Displacement ductility factor

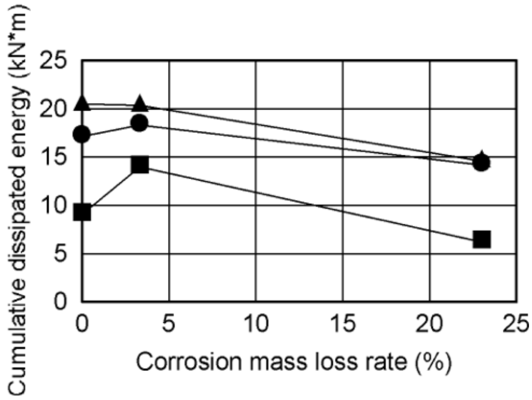


Fig.10 Dissipated energy

3.2.4 Estimation of ultimate failure mode

Estimation of ultimate failure mode was conducted according the following procedure.

1. Obtain the relation between corrosion mass loss rate and strain of longitudinal reinforcing steel in lower section when concrete strain in upper extreme fiber is ultimate in each volumetric confinement ratio.
2. Obtain the relation between corrosion mass loss rate and ultimate strain of corroded reinforcing steel by linear regression on the results of previous studies [2]. Severe condition was applied to this estimation by omitting the data in this study, where the degree of reduction was smaller than in that of [2].
3. Compare relation 1. with relation 2.

In this analysis, the same stress-strain models of concrete and longitudinal reinforcing steel as 3.2.2 were used. Therefore, strain hardening of reinforcing steel was not considered. Analysis on reduced yield strength due to corrosion pitting, in addition to a constant yield strength of 350N/mm^2, was conducted. The yield strength of corroded reinforcing steel was calculated using the relation of reference [1] by the following equation:

$$f_{sy(corrosion)}/f_{sy(sound)}=1.00-1.32 \text{ x (corrosion mass loss rate)} \qquad (1)$$

Results of analysis are shown in Table 2. Rupture of longitudinal reinforcing steel occurred ahead of compression failure in small corrosion mass loss rate, as volumetric confinement ratio increased. In the case of reduced yield strength due to corrosion pitting, corrosion mass loss rate when rupture of longitudinal reinforcing steel occurred was smaller than that assuming constant yield strength, because neutral axis was closer to sectional upper end due to reduction of yield strength. Rupture of longitudinal reinforcing steel occurred in all volumetric confinement ratios at corrosion mass loss rate of 23.0% corresponded to experimental one. However, when three loading cycles and corrosion mass loss rate of 3.3% were adopted in experiment, rupture of longitudinal reinforcing steel occurred at corrosion mass loss rate of 0.66%. Therefore, it is important to clarify the relation between corrosion mass loss rate and ultimate strain of corroded reinforcing steel under reversed cyclic loading, with consideration of influences of corrosion pitting on ultimate strain.

Table 2 Estimation of corrosion mass loss rate that rupture of reinforcing steel

Volumetric confinement ratio ρ_{CF} (%)	Constant yield strength	Reduced yield strength
	Corrosion mass loss rate (%)	
0.00	21.6	20.6
0.17	19.1	17.6
0.66	13.3	11.3

4 CONCLUSIONS

The conclusions obtained in this study are as follows:

(1) From the result of tension test of reinforcing steel corroded by spraying salt water, although the yield strength did not decrease remarkably, the ultimate strain decreased as corrosion mass loss rate increased. Corrosion pitting affected the ultimate strain, that is ductility, more significantly than strength of reinforcing steel.

(2) From the result of loading test for specimens which had corroded reinforcing steel and strengthened by confinement using CFRP sheet, at corrosion mass loss rate of 3.3% maximum load did not decrease. However, maximum load at corrosion mass loss rate of 23.0% was reduced approximately by 10% from that of sound specimen. Comparison of calculated maximum loads obtained by sectional moment-curvature analysis assuming uniform sectional area loss of corroded reinforcing steel with the experimental ones indicated very good agreement on the ratio of reduction as corrosion mass loss rate increased.

(3) Ductility of specimen confined using CFRP sheet was larger than that of specimen without strengthening in little corrosion mass loss rate. However, at corrosion mass loss rate of 23.0%, that is significant corrosion, ductility decreased remarkably from that of sound specimen, because rupture of longitudinal reinforcing steel occurred in those specimens. Furthermore, in three loading cycles, the specimen with corrosion mass loss rate of 3.3% and volumetric confinement ratio of 0.66% resulted in rupture of longitudinal reinforcement steel. Therefore, excessive confinement using CFRP sheet should be avoided and the combined use of confinement and flexural strengthening is required in the case that reversed cyclic load works in the post-peak region. Moreover, if more reinforcing steel corrosion is estimated after strengthening by confinement using CFRP sheet, reinforcing steel should need some protection against corrosion.

(4) Estimation of ultimate failure mode was conducted by comparing the relation between corrosion mass loss rate and strain of longitudinal reinforcing steel in lower section at the ultimate state with the relation between corrosion mass loss rate and ultimate strain of corroded reinforcing steel. The result is that rupture of longitudinal reinforcing steel occurs ahead of compression failure in small corrosion mass loss rate, as volumetric confinement ratio increased.

REFERENCES

[1] JCI: Technical Committee Report on Rehabilitation for Concrete Structure. pp.43-45, Aug., 1998 (in Japanese)
[2] Ooi, T.: Evaluation of Reinforcing Steel Corrosion in Concrete Cylinder., Proc. of the 25th JUCC Congress on Cement and Concrete, JUCC, pp.111-116, Oct., 1998 (in Japanese)
[3] JSCE: Standard Specification for Design of Concrete Structures. pp.23-25, Mar., 1996 (in Japanese)
[4] Hosotani, M., Kawashima, K. and Hoshikuma, J.: A Stress-Strain Model for Concrete Cylinders Confined by Carbon Fiber Sheets. Journal of Materials, Concrete Structures and Pavements, JSCE, No.592/V-39, pp.37-52, May, 1998 (in Japanese)
[5] JSCE: Standard Specification for Design of Concrete Structures. pp.36-37, Mar., 1996 (in Japanese)