STRENGTHENING WITH CFRP SHEET FOR RC FLEXURAL MEMBER DETERIORATED BY REINFORCING STEEL CORROSION

T Yamamoto, Kyoto University, Japan
A Hattori, Kyoto University, Japan
T Miyagawa, Kyoto University, Japan

Abstract

In this study, in order to establish an application scheme of a carbon fiber reinforced plastic sheet (hereafter, CFRP sheet) for strengthening an RC flexural member deteriorated by corrosion of reinforcing steel bar (rebar), RC flexural members strengthened using CFRP sheet with corroded rebar are subjected to a flexural loading test. In the experiment, corrosion mass loss rate and volumetric confinement ratio achieved by CFRP sheet were varied. Corrosion of rebar was simulated by the accelerated corrosion method using a DC power supply. The results show that RC flexural members strengthened by confinement using CFRP sheet may fail to attain significant improvement in flexural ductility, since the rupture of longitudinal rebar, whose elongation is decreased by corrosion, occurred before compression failure at the flexural compression zone. The results also show that cracking due to corrosion of rebar reduced the flexural loading capacity and ductility of RC flexural members confined using the CFRP sheet, since the corrosion cracks reduced the compressive strength and ultimate strain of confined concrete in the flexural compression zone. Based on the results, a calculation method for ductility strengthening design, which takes into consideration the degradation of elongation in corroded rebars and longitudinal distribution of curvature, is presented.

Keywords: corrosion of reinforcing steel bars, flexural behavior, confinement strengthening, flexural strengthening, carbon fiber sheet

1. Introduction

One of the strengthening methods applied to RC flexural members is to confine the members with CFRP sheet. The strengthening by confinement in the flexural compression zone with CFRP sheet increases the ultimate strain of that zone, leading to improvement of the plastic deformation capacity of RC flexural members. In order to obtain sufficient improvement, reinforcing steel bar (rebar) in the tension zone of RC flexural members must exhibit sufficient elongation. However, when RC flexural members strengthened by confinement are suffered from corrosion of rebars, rupture of the rebar in the tension zone may occur before compression failure at the flexural compression zone, because the corrosion reduces the elongation of rebars [1]. As a result, the ductility intended by confined strengthening is not obtained.

The objective of this study is to establish an application scheme of strengthening by confinement using CFRP sheet for RC flexural members whose rebar has already corroded. In order to examine this point, the reversed cyclic loading test was carried out on RC beams with corroded longitudinal rebars, which had been strengthened by confinement using CFRP sheet. The following test parame-

Table 1. Test parameters

Strengthening type(s)	*Volumetric confinement ratio* ρ_{CF} *(%)*	*Corrosion mass loss (%)*
None	0.00	0.0, 3.7, 5.7
Confinement strengthening	0.66	0.0, 3.7 (3.3*), 5.7 (7.1*)
Confinement + Flexural strengthening	0.66 + *Flexural (1 layer)*	3.7, 5.7

*: Values in parentheses denote the corrosion mass loss rates of RC beams, which were cast from rebars that had been corroded by spraying salt solution.

ters were mainly considered in this study: corrosion rate of longitudinal rebar, and confinement ratio of CFRP sheet. Another objective of this study is to derive a method for estimating ultimate failure mode of RC flexural members strengthened by confinement, which takes into consideration the degradation of elongation in corroded rebar and longitudinal distribution of curvature.

2. Experimental procedures

2.1 Test parameters

Test parameters are shown in **Table 1**.

(1) Corrosion mass loss rates

Corrosion of rebar in RC flexural beams was simulated by an accelerated corrosion method using a DC power supply. Corrosion mass loss rates, which represent the degree of rebar corrosion, were measured according to the JCI-SC1 method (in 60°C/10% di-ammonium hydrogen citrate solution for 24 hours).

Corrosion mass loss rates were 0.0% (sound rebar), 3.7%, and 5.7%. The corrosion mass loss rate of 3.7% was achieved by 77.8 mA hour/cm^2, which is total current density per surface area of rebar in RC beams, and resulted in an average cracking width due to corrosion of 0.43 mm along the longitudinal surface of an RC beam. The corrosion mass loss rate of 5.7% was achieved by 200 mA hour/cm^2 and resulted in an average cracking width of 0.87 mm. The corrosion rates of 3.7% and 5.7% correspond to the latter acceleration phase and the early deterioration phase in degradation of RC flexural members suffering from chloride corrosion, respectively.

Furthermore, in order to investigate the influence of cracking due to corrosion on load-carrying behavior, RC beams, which did not have any cracking due to corrosion but were produced with corroded rebars, were also prepared. Those RC beams were cast with rebars that had been corroded only in the center 700 mm of its length by spraying salt solution (3% NaCl solution) at room temperature (around 10°C). Corrosion mass loss rates were 3.3% and 7.1%.

(2) Volumetric confinement ratios with CFRP sheet

Confinement ratios with the CFRP sheet were expressed in volumetric confinement ratios. The values of confinement ratio were 0.00% (without strengthening) and 0.66%. The plastic deformation capacity of RC flexural member strengthened by 0.66% confinement may be significantly improved. The CFRP sheet has a width of 50 mm, a thickness of 0.111 mm, a tensile strength of 3500 N/mm^2, and Young's modulus of 2.3 x 10^5 N/mm^2.

Additionally, in order to clarify the effect of combined use of confined and flexural strengthening on load-carrying behavior of strengthened RC beams with corroded rebar, the flexural loading test was also carried out for RC beams which had been strengthened by a single layer of longitudinal CFRP sheet externally bonded at the upper and bottom ends of the section.

2.2 RC beams

Figure 1 shows the dimension of RC beams with corroded rebar. RC beams have a cross section of 100^B x 200^H mm and a span length of 1400 mm. Two D10 (SD295A) were symmetrically arranged as longitudinal reinforcements, in the upper and lower portions (p=0.81%). The average compressive strength of concrete is 30.2 N/mm^2. In shear spans, stirrups were arranged with a spacing of 45 mm (p_w=1.41%: shear reinforcement ratio) in order to prevent a shear failure under reversed cyclic loading. An anti-corrosion coating with epoxy resin was applied to stirrups in order to protect them from corrosion by the accelerated corrosion of longitudinal rebars.

After casting and curing, each RC beam, except for sound (control) specimens, was subjected to an accelerated galvanic corrosion process using a DC power supply. In the accelerated galvanic corrosion setup, RC beams were placed in a tank, where 3% NaCl solution was used as an electrolyte, and total current density per surface area of rebar in the RC beam shown in **2.1(1)** was applied so that the longitudinal rebar serve as anodes and copper plates as cathodes.

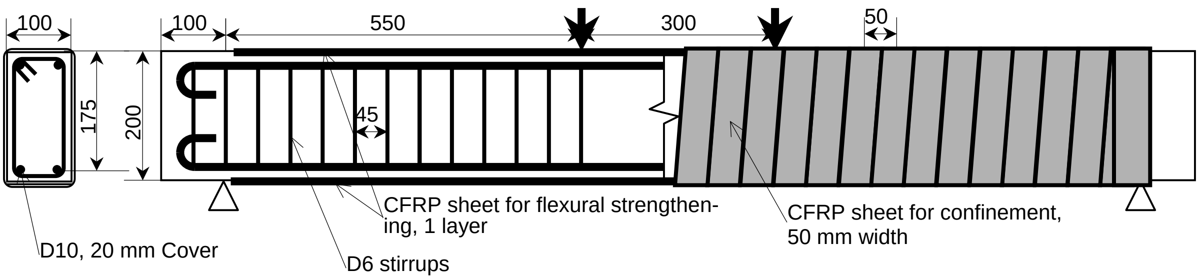

Fig. 1. Dimensions of RC beams (unit: mm)

Details of RC beams strengthened by confinement with CFRP sheet are shown in **Figure 1**. The CFRP sheet was wrapped spirally over the entire span such that the centerline spacing of sheet width was 50 mm. Confinement ratios are described in the previous paragraph in **2.1(2)**. In RC beams shown in **2.1(2)**, in which confined and flexural strengthening were combined, one layer of CFRP sheet was externally and longitudinally bonded at the upper and bottom ends of the section over the entire span for flexural strengthening, and then the CFRP sheet was wrapped spirally for confined strengthening.

2.3 Loading test procedures

Reversed cyclic loading was applied to two symmetrical points so that flexural and shear spans were 300 mm and 550 mm, respectively, the overall span being 1400 mm. One loading scheme at (2n-1) times the yield displacement was adopted. The yield displacement, δ_y=3.80mm, was determined from the bend of the load-displacement curve in the sound RC beam without strengthening. The ultimate state of RC beams was defined as the point at which the load dropped below 80% the maximum load in the post-peak region. Applied load and displacement were measured at the mid-span and the supports.

3. Test results and discussion

3.1 Maximum load

Figure 2 shows the influence of corrosion mass loss rate on maximum load of each RC beam. When longitudinal rebars were deteriorated by accelerated corrosion, maximum load decreased with increasing mass loss rate, regardless of strengthening by confinement. The ratio of reduction of maximum load in this study is smaller than that of a previous study [2], where similar RC beams were subjected to the corrosive condition by spraying NaCl solution for 36 months rather than accelerated corrosion. In RC beams that had been deteriorated by the accelerated corrosion, maximum load was reached with damage at the flexural compression zone and, after a time, the rupture of longitudinal rebar occurred in the post-peak region. On the other hand, in RC beams that had been deteriorated by spraying NaCl solution, maximum load was determined by the rupture of longitudinal rebar, the ultimate state, in the early phase of load-displacement relationship. Corrosive condition caused by spraying NaCl solution is considered to have resulted in the severe and localized corrosion of longitudinal rebar.

Figure 3 shows the influence of corrosion cracks on maximum load. The reduction in maximum load of RC beams deteriorated by accelerated corrosion is more severe than that of RC beams cast from rebars that had been corroded beforehand by spraying NaCl solution. The maximum load decreased because of the longitudinal cracks due to corrosion lowering the nominal compressive

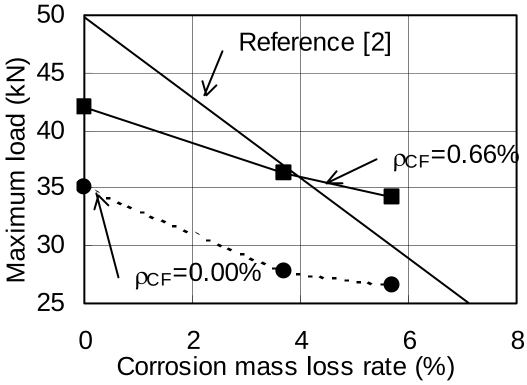

Fig. 2. Influence of corrosion mass loss rate on maximum load

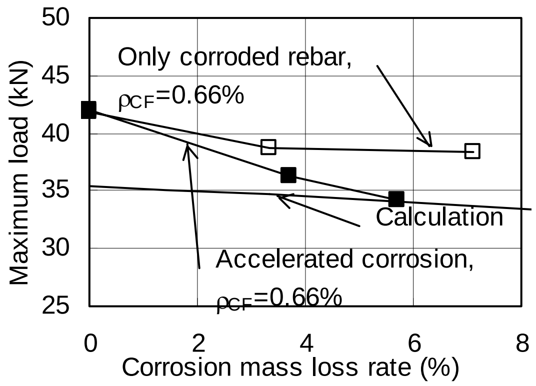

Fig. 3. Influence of cracking due to corrosion on maximum load

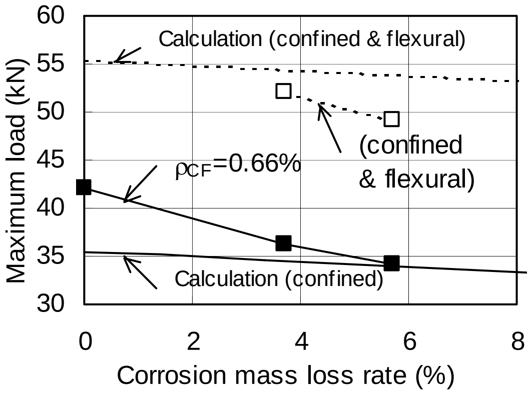

Fig. 4. Influence of combined use of confinement and flexural strengthening on maximum load

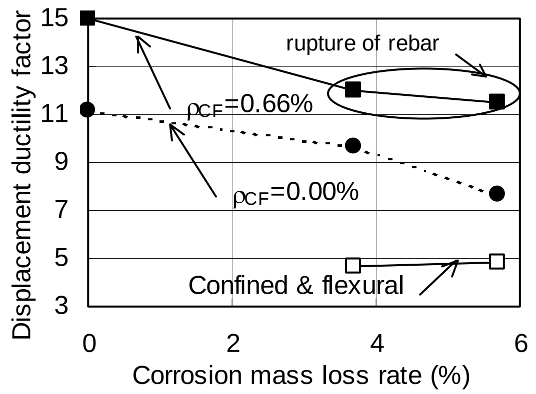

Fig. 5. Influence of corrosion mass loss rate on displacement ductility factor

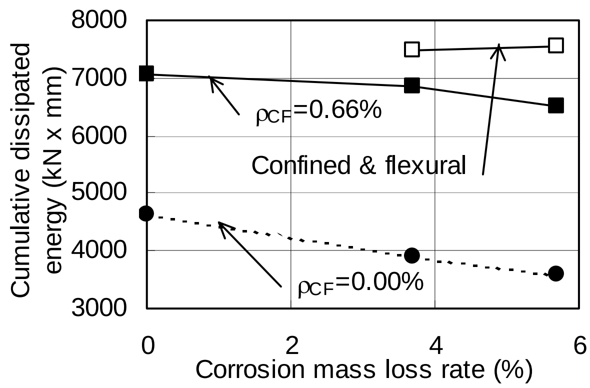

Fig. 6. Influence of corrosion mass loss rate on cumulative dissipated energy up to $9\delta_y$

strength of confined concrete at the flexural compression zone [3], in addition to the influence of the localized corrosion and degradation of bond strength between rebar and concrete.

Figure 3 also shows the calculated results of RC beams strengthened by confinement. These results were obtained by sectional moment-curvature analysis, under the plane-sections hypothesis. This calculation used the stress-strain model for the concrete confined by CFRP sheet [4]. The bilinear model was used for longitudinal rebar. The sectional area of corroded rebar was calculated under the assumption that the sectional area loss rate corresponded to longitudinally uniform corrosion mass loss rate. Comparison of calculated values obtained under the assumption of uniform sectional area loss of corroded rebars with the result of RC beams cast with rebars that had been corroded indicates very close agreement on the ratio of reduction; that is, the slope of the linear regression line. However, when the cracking occurred because of the accelerated corrosion of rebar in RC beams, the ratio of reduction of the maximum load was greater than the calculated values, because the cracking and degradation of bond strength between concrete and rebar due to corrosion affected the flexural loading capacity.

Figure 4 shows the influence of combined use of confined and flexural strengthening on maximum load. The maximum load of each RC beam decreased with increasing corrosion mass loss rate. However, for any given corrosion mass loss rate, the maximum load of RC beams with combined use of confined and flexural strengthening is greater than that with only confined strengthening. Therefore, the combined use of confined and flexural strengthening is effective for improving flexural loading capacity in RC beams deteriorated by the corrosion of longitudinal rebar. However, the reduction rate of maximum load is greater than the calculated value. Accordingly, the calculation should consider the cracking and degradation of bond strength between concrete and rebar due to corrosion.

3.2 Ductility

Figure 5 shows the influence of corrosion mass loss rate on displacement ductility factor. Displacement ductility factor is defined as the ratio of ultimate displacement, δ_u, to yield displacement, δ_y. Displacement ductility factor of RC beams with or without confined strengthening, where longitudinal rebars were degraded by the accelerated corrosion, decreased with increasing corrosion mass loss rate. Spalling of concrete at the flexural compression zone due to the buckling of longitudinal rebar easily occurred by corrosion cracks. The spalling of concrete occurred rapidly and the buckling length was long, because (inner) existing lateral confinements were not distributed over the flexural span. Meanwhile, the displacement ductility factor of an RC beam at a corrosion mass loss rate of 5.7% is almost the same as that of a sound RC beam without confined strengthening, because the RC beam strengthened by confinement reached its ultimate state by rupture of longitudinal rebar, whose elongation was degraded by corrosion [1]. Therefore, the strengthening by confinement using CFRP sheet could not significantly improve the ductility over that of sound RC flexural members.

Figure 5 also shows the influence of the combined use of confined and flexural strengthening on the displacement ductility factor. The displacement ductility factor of RC beams with the combined use of confined and flexural strengthening is smaller than that without strengthening, because for any given corrosion mass loss rate, flexural strengthened RC beams reached their ultimate state by the rupture of longitudinal CFRP sheet bonded externally at the upper and bottom ends of the section.

Figure 6 shows the influence of corrosion mass loss rate on the cumulative dissipated energy up to displacement of $9\delta_y$. The area enclosed by a hysteresis loop represents dissipated energy. When ductility is expressed by the dissipated energy, an increasing in ductility can be shown, because the combined use of confined and flexural strengthening increases the flexural loading capacity, and consequently the energy dissipation increases.

4. Estimating Method for ultimate failure mode

Ultimate failure mode was estimated so that RC flexural members strengthened by confinement resulted not in rupture of longitudinal rebar, but in compression failure in the flexural compression zone, because the latter could have sufficient ductility. Especially, when RC flexural members strengthened by confinement are suffered from corrosion of rebars, rupture of the rebar shown in above discussion is apt to occur by the degradation of elongation in corroded rebar. Therefore, estimation of ultimate failure mode is important for strengthening design of RC flexural members with corroded rebar. The procedure of the estimation method is as follows:

I. Obtain the relationship between the corrosion mass loss rate and strain of longitudinal rebar in the lower section when the concrete strain in the upper extreme fiber is ultimate strain in each volumetric confinement ratio.
II. Obtain the relationship between the corrosion mass loss rate and elongation of corroded rebar by linear regression on the results of previous studies [5].
III. Compare relation I with relation II. When the elongation of corroded rebar is greater than the strain of longitudinal rebar in the lower section at the ultimate state, RC flexural members strengthened by confinement will result not in rupture of longitudinal rebar, but in compression failure in the flexural compression zone.

The strain of longitudinal rebars in the lower section at the ultimate state is obtained by use of average curvature section under the assumption that flexural cracking is distributed homogeneously over the flexural span, as shown in **Figure 7**. However, in fact, the magnitude of curvature around flexural cracking sections is larger than that in non-cracking sections, as shown in **Figure. 7**. Hereafter, large curvature zones around flexural cracking sections are expressed as concentrated curvature zones. In these zones, longitudinal rebars require greater elongation than in non-cracking sections, in order to prevent RC flexural members strengthened by confinement causing the rupture of longitudinal rebar.

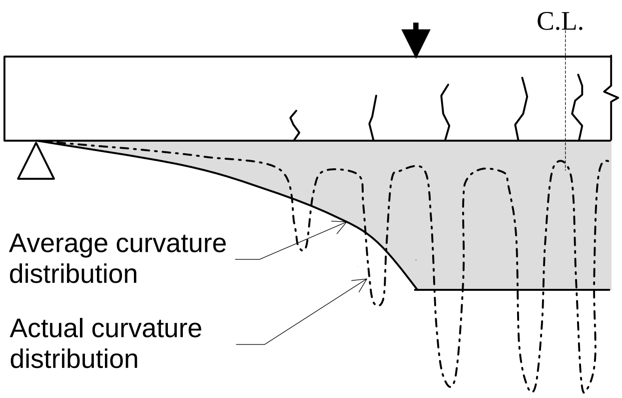

Fig. 7. Outline of longitudinal curvature distribution

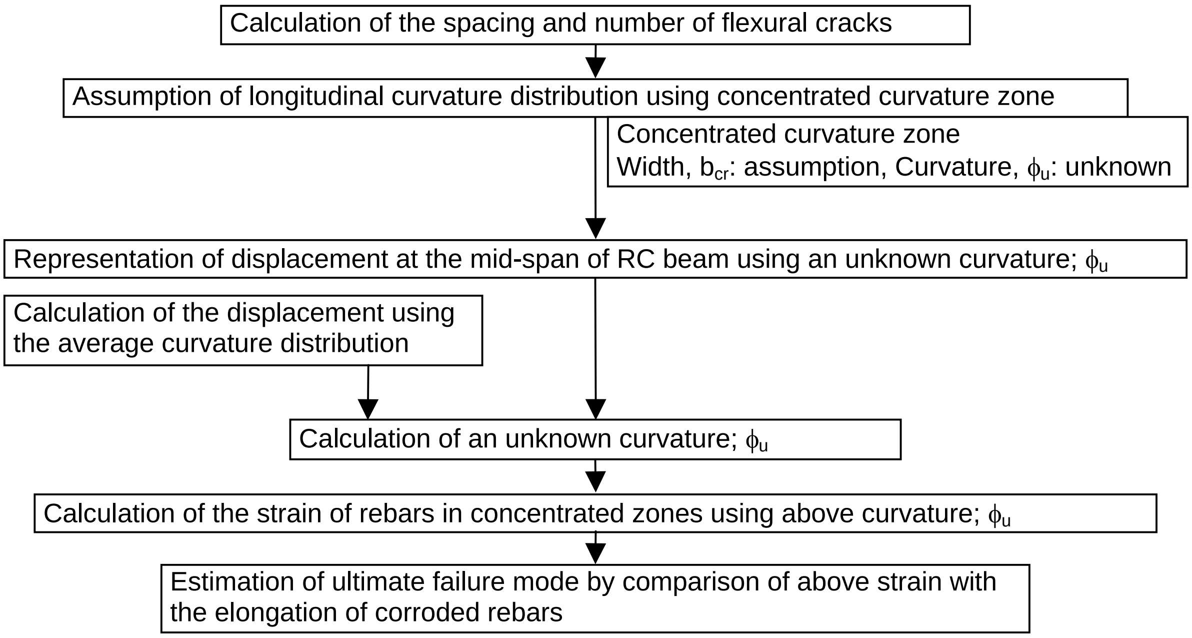

Fig. 8. Flow chart of calculation

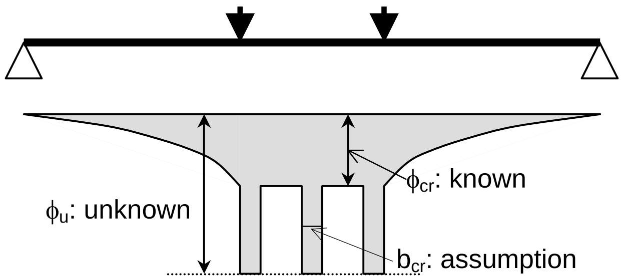

Fig. 9. Longitudinal curvature distribution using concentrated curvature zone

The strain of longitudinal rebars in the lower section at the ultimate state was calculated according to the flow chart shown in **Figure 8** and the following procedure.

i) The spacing and number of flexural cracks are calculated from the following equation [6].

$$\ell = 1.1\, k_1\, k_2\, k_3 \{4C + 0.7(C_s - \phi)\} \qquad (1)$$

where k_1 is a coefficient for bond conditions of the surface of rebar deformed various manners, k_2 is a coefficient for the quality of concrete, k_3 is a coefficient for rebar arranged with different effective depths, ℓ is the spacing of flexural cracks (mm), C is the thickness of cover concrete (mm), C_s is the spacing of longitudinal rebars in the width direction, and ϕ is the diameter of rebar.

The influences of the degradation of bond strength and cracking due to corrosion seem to be considered in coefficient k_1 or k_2. However, in this calculation, k_1=1.0 was used for sound deformed rebar and k_2=1.0 was used for the case where concrete compressive strength is 30.2 N/mm^2. The results of calculation indicate that the spacing of flexural cracks is about 120 mm. Therefore, three flexural cracks occurred within the flexural span of 300 mm, assuming that one flexural crack occurred at mid-span.

ii) The longitudinal curvature distribution is drawn in **Figure 9** from the concentrated curvature zones obtained from i).

iii) The displacement at the mid-span of RC beam is represented by use of an unknown curvature; ϕ_u assuming that the longitudinal curvature distribution in shear spans is the same as that obtained by general moment-curvature analysis and the curvature at the occurrence of flexural cracking is used for the section except in concentrated curvature zones in the flexural span. Furthermore, a

Table 2. Results of calculation

Confinement ratio, ρ_{CF} (%)	*Corrosion mass loss rates at rupture of rebar (%)*		
	Assumed average	*Assumed concentrated curvature*	
		b_{cr}=25 mm	*b_{cr}=30 mm*
0.00	21.6	8.65	11.0
0.66	13.3	0.920	4.93

few values are assumed as the longitudinal width; b_{cr} of concentrated curvature zone, such as 25 mm and 30 mm.

iv) An unknown curvature; ϕ_u is calculated under the assumption that the displacement at the mid-span obtained using an unknown; ϕ_u from iii) is equal to the displacement obtained by the general moment-curvature analysis using average curvature sections.

v) The strain of longitudinal rebar in concentrated curvature zones is calculated from the curvature; ϕ_u obtained from iv). This calculation uses the same stress-strain models of concrete and longitudinal rebar as mentioned in **3.1**.

vi) The ultimate failure mode is estimated by comparison of the strain from v) with relation II.

Table 2 shows the results of calculation along with the results obtained by the general moment-curvature analysis [1]. When the concentrated curvature zone was considered and 25 mm was used as the longitudinal width of concentrated curvature zones, the rupture of longitudinal rebar occurred before compression failure in small corrosion mass loss rate. Therefore, consideration of ultimate failure mode is important, even when the corrosion mass loss rate is small, since larger elongation is needed for longitudinal rebar at concentrated curvature zones of RC flexural members strengthened by confinement. Furthermore, comparison of estimated corrosion mass loss rate at the rupture of rebar using the width of 30 mm with the experimental value indicates better agreement than that obtained using a width of 25 mm. However, the longitudinal width; b_{cr} of concentrated curvature zones could not be examined, because RC beams were wrapped by CFRP sheet and were significantly damaged by the loading test.

The estimation method of ultimate failure mode for RC flexural members strengthened by confinement, which considers the degradation of elongation in corroded rebar and the longitudinal distribution of curvature is shown. However, the following problems may be found: flexural cracking is localized by the degradation of bond strength between concrete and rebar due to corrosion, and consequently the flexural cracks are fewer than those found by calculation in i). The rebar is pulled out slightly from the flexural cracking section. Longitudinal cracking due to corrosion reduces the compressive strength and the ultimate strain of concrete confined with CFRP sheet at the flexural compression zone.

5. Conclusions

The following conclusions were obtained in this study:

1. The maximum load of RC beams, where longitudinal rebars have been deteriorated by accelerated corrosion, decreases with increasing corrosion mass loss rate. However, the ratio of reduction of maximum load in this study is smaller than that found in a previous study, where specimens similar to those used in this study were subjected to corrosion by spraying with NaCl solution for 36 months rather then accelerated corrosion.
2. Comparison of calculated maximum load obtained under the assumption of uniform sectional area loss of corroded rebar with experimental values, obtained from beams that were cast from rebars that had been corroded beforehand, indicate very close agreement on the ratio of reduction. However, when cracking occurred because of accelerated corrosion of rebar in RC beams, the ratio of reduction of maximum load was larger than that of calculated values, because the longitudinal cracking due to corrosion reduced the compressive strength of confined concrete at the flexural compression zone, and because of the influence of localized corrosion and degradation of bond strength between rebar and concrete.
3. For any given corrosion mass loss rate, the maximum load of RC beams with combined use of confined and flexural strengthening is greater than that with only confined strengthening. Therefore, the combined use of confined and flexural strengthening is effective for improving flexural loading capacity in RC beams deteriorated by longitudinal rebar corrosion. When ductility is expressed by the dissipated energy, an increase in ductility can be shown, because the combined use of confined and flexural strengthening increases the flexural loading capacity, which in turn increases energy dissipation.

4. The displacement ductility factor of RC beams, whose longitudinal rebars were deteriorated by accelerated corrosion, decreased with increasing corrosion mass loss rate. Strengthening by confinement using a CFRP sheet could not improve the ductility significantly over that of sound RC flexural members, because the RC beam strengthened by confinement reached its ultimate state by the rupture of longitudinal rebar whose elongation had been degraded by corrosion.
5. The estimation method of ultimate failure mode for RC flexural members strengthened by confinement, which considers the degradation of elongation in corroded rebar and the longitudinal distribution of curvature, was shown. Consideration of ultimate failure mode is important, even when corrosion mass loss rate is small, since longitudinal rebar at concentrated curvature zones of RC flexural members strengthened by confinement require greater elongation.

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