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Effect of Distribution in Cross Sectional Area of Corroded Tensile Reinforcing Bars on Load Carrying Behaviour of RC Beam

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ABSTRACT

Reinforcing steel bars embedded in RC structures are often corroded non-uniformly in the practical corrosive environment. The effect of distribution of the cross sectional areas in reinforcements on the load carrying behaviour was investigated in this study. A flexural loading test was performed by using RC beam specimens with corroded tensile reinforcing steel bars provided the distribution in the cross sectional areas in the longitudinal and width directions. Consequently, an estimation method of the load carrying capacity of corroded RC beam was shown, considering the distribution and its scatter in the cross sectional areas of corroded reinforcements. In the method, the flexural loading capacity can be moderately estimated using the reducing diameters of corroded reinforcements, which were directly measured by a slide calliper or judged from the width of cracks due to corrosion at some selected sections in the longitudinal direction of RC beam.

Keywords. Reinforcing steel corrosion, longitudinal distribution in cross sectional area of reinforcement, Flexural loading capacity, Measurement of diameter, Corrosion crack width

INTRODUCTION

A load carrying capacity of the reinforced concrete (RC) member degraded by the corrosion of reinforcing steel bars should be estimated accurately, in order to apply an appropriate strengthening to corroded members. A lot of researches on the effect of corrosion in the longitudinal tensile reinforcing steel bars on the load carrying behaviour have been available up to now. Accurate and quantitative estimation of capacity, however, is often difficult, because of the non-uniformity of corrosion in the member.

Thus, a relationship between the spatial distribution of corrosion in the reinforcement including its scatter and the flexural loading capacity of RC member with such distribution of corrosion should be clarified so that the flexural capacity of corroded RC member can be estimated accurately. For this purpose, in case of the practical member under the corrosive environment, it should be considered that the flexural capacity often have to be derived from not a large number of inspection data on cross sectional areas of corroded reinforcements.

In this study, a flexural loading test was performed by using RC beam specimens with the corroded tensile reinforcements provided the distribution of sectional areas in the longitudinal and width directions. Consequently, an estimation method of the flexural capacity of corroded RC beam was shown, considering the distribution and its scatter in sectional areas of corroded reinforcements.

EXPERIMENTAL PROCEDURE

Test Specimen. Fig. 1 shows the shape and dimensions of test specimen. Test specimen is RC beam having a rectangular shaped cross section of 110 mm in width and 165 (140) mm in height (effective depth), and an overall (span) length of 1800 (1600) mm. Three deformed longitudinal reinforcements of 10 mm (SD345) in diameter were arranged to be tensile reinforcement ratio, p of 0.014 in each cross section. Rectangular shaped stirrups of deformed reinforcement of 6 mm in diameter were distributed as shear reinforcements with the longitudinal spacing of 80 mm in the overall span, so as to fail in flexural tension. Thin timber bars of 6 mm in diameter were used for erection bars, not so as to be corroded. Targeted concrete compressive strength was f'_{cr}=24 MPa.

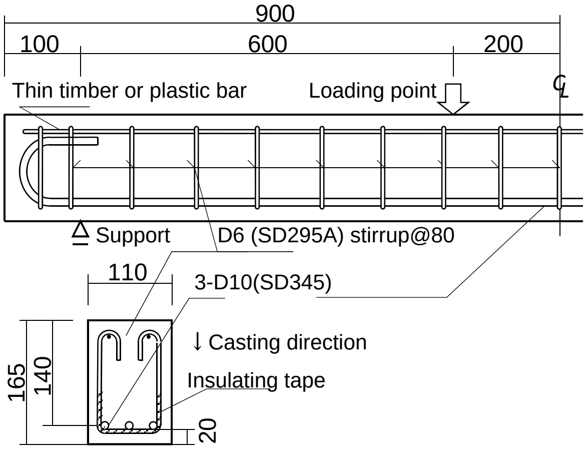


Figure 1. Shape and dimensions of RC beam (unit in mm)

Test Parameters. Overall or a part of length in the tensile reinforcements was corroded by using an accelerated electrolysis corrosion technique. The corroded locations in the reinforcement were the overall span, shear span and constant bending moment (hereinafter “flexural”) span. The flexural span has the largest moment in the span, while the shear span has the moment gradient in the longitudinal direction. By those parameters, the relationship between the location of corrosion and the condition of bending moment was investigated. For the width direction of RC beam, all or one of three reinforcements were corroded.

Four levels of corrosion including non-corroded (sound) condition were arranged as a targeted corrosion mass loss rate (hereinafter “corrosion rate”) of 0, 3, 10 and 20 %, because the higher the scatter of sectional area in the corroded reinforcement would be, the larger the corrosion rate was. When one of three reinforcements was subjected to corrosion, the corrosion rate of 30 % was given in that reinforcement, which corresponded to the mean value of 10 % in three reinforcements including two sound reinforcements.

Simulating Method of Corrosion. An accelerated electrolysis corrosion technique using a DC power supply was employed to simulate corrosion. RC beams were soaked in a bath with electrolytic solution (sodium chloride content of 3 %) up to half depth of them, when the overall length of reinforcements would be subjected to corrosion.

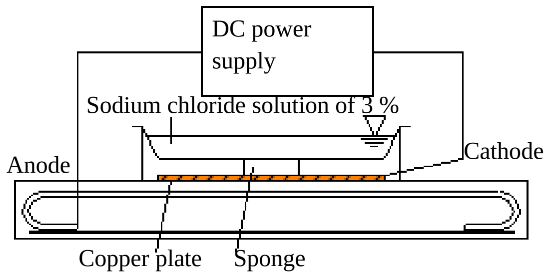


Figure 2. Electrolysis corrosion setup for partial corrosion

On the other hand, an electrolytic solution tank and a copper plate as a cathode were placed on the targeted span of corrosion at the bottom (tensile reinforcement) side of RC beam, as shown in **Fig. 2**, when the reinforcements in the shear or flexural span would be subjected to corrosion. Since the electrolytic solution tank had some small holes on the bottom, which touched the bottom of RC beam, the electrolytic solution to pass the direct current was able to leak and permeate the cover concrete of RC beam. Moreover, a sponge rubber was placed between the solution tank and the copper plate, not so as to leak too much solution.

Measurement of Corrosion Mass Loss and Corrosion Crack Width. The widths of longitudinally oriented corrosion cracks, which were propagated on the bottom or either side of RC beam, were measured at the points with the longitudinal spacing of 50 mm using a crack scale after the accelerated corrosion and before the flexural loading test. The corrosion mass loss was measured by removing the rust of corroded reinforcements in accordance with JCI-SC1, which were taken out of RC beam after the loading test. Diameters of the reinforcement were also measured using a slide caliper at the points with the longitudinal spacing of 50mm, which corresponded to the measuring points of corrosion crack width, and in the direction where its diameter deemed to be the minimum. Measured diameter by the above method may include the drawing reduction of area due to yielding. An extent of the drawing reduction of area was not confirmed. However, since all reinforcements were measured under almost the same condition that those were yielded, the drawing reduction of area was considered to be cancelled.

Loading Test Procedure and Measurement. Unidirectional static loads were applied to two symmetrical points so that the flexural span was 400mm, the overall span being 1260mm, as shown in **Fig. 1**. The loading test was performed up to the point at which the load dropped below 80 % the maximum load in the post-peak region. Measured items in the loading test include the applied load, the deflection at the center span and the deflections at both supports.

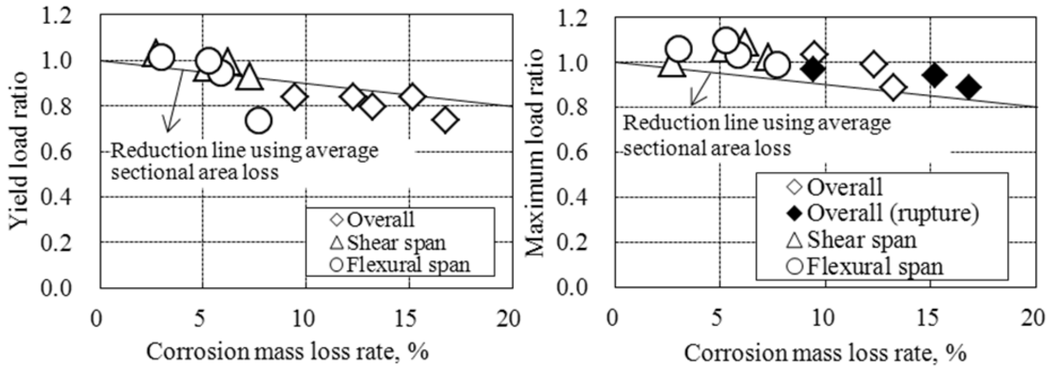
RESULTS AND DISCUSSION

Condition of Corrosion. **Table 1** shows the corrosion rate, and the mean value and the standard deviation of a residual sectional area in the corroded reinforcements, including the results of loading test. Measured corrosion rates in most of RC beams were below the tar-

Table 1. Results of corrosion measurements and flexural loading test

Longi. distribution	Width distribution	Targeted corr. rate (%)	Measured corr. rate (%)			Ave.	Ave. residual sectional area (mm^2)			Standard dev. of residual sectional area			P_y [*1] (kN)	P_m [*2] (kN)	Failure mode
			L	M	R		L	M	R	L	M	R			
Sound		0											42.3	48.2	FT [*3]
Overall	One of three	30	13.1	12.2	11.6	12.3	50.4	49.0	53.3	5.1	5.2	3.3	35.5	47.6	FT
			11.3	15.9	12.5	13.2	52.6	46.7	50.8	2.9	5.0	4.4	33.7	42.7	FT
	All	10	8.2	*12.0*	8.2	9.5	56.5	52.6	55.2	5.1	6.9	3.1	-	46.6	R [*4]
			8.2	10.3	9.9	9.5	54.0	51.5	53.4	1.8	4.0	3.2	35.5	49.8	FT
		20	14.8	*19.9*	10.7	15.2	50.7	44.4	53.2	7.2	9.1	2.9	35.5	45.4	R
			12.4	*25.0*	13.1	16.8	52.0	39.4	51.9	2.8	9.4	4.0	31.2	42.8	R
Shear span	One of three	30	7.6	9.6	4.7	7.3	54.1	51.8	54.4	1.0	3.7	1.1	39.4	49.3	FT
	All	3	2.8	2.9	2.5	2.8	56.1	55.3	56.3	0.5	0.7	0.6	43.6	47.9	FT
		10	4.2	6.8	4.6	5.2	58.6	55.9	57.5	2.3	2.2	1.3	41.0	51.0	FT
		20	5.6	7.7	5.3	6.2	56.4	55.5	55.4	0.4	1.0	0.8	42.0	52.4	FT
Flexural span	One of three	30	10.0	7.7	5.3	7.7	54.1	53.1	55.6	1.7	1.7	0.7	31.2	47.6	FT
	All	3	2.9	2.9	3.2	3.0	56.1	56.1	55.7	0.4	0.8	0.6	43.0	51.2	FT
		10	5.0	6.7	5.9	5.8	55.5	53.4	54.7	0.5	1.9	0.8	40.1	49.8	FT
		20	4.3	5.2	6.4	5.3	54.9	54.8	55.3	0.3	1.0	1.1	42.2	52.8	FT

*1: Yield load, *2: Maximum load, *3: Flexural tension, *4: Rupture of reinforcement, Italic figure: Ruptured reinforcement in loading



(a) yield load (b) maximum load

Figure 4. relationship between the yield/maximum load ratio and the corrosion rate

geted one. In case of RC beam where either end of three reinforcements would be subjected to corrosion, the reinforcements not to be corroded were also corroded. Consequently, the intended distribution of sectional area in the width direction was not able to be obtained. That was attributed to the corrosion of not-intended reinforcements caused by the permeation of the electrolysis solution into the concrete located between reinforcements.

Flexural Loading Test Results and discussion. Some RC beams with the corrosion rate of around 20% resulted in the rapture of reinforcement. Even in case of RC beam with the corroded reinforcement in shear span, the shear failure prior to the flexural failure was not confirmed.

Fig. 4 show the relationship between the yield/maximum load ratio and the corrosion rate in the targeted span of corrosion. The yield/maximum load ratio indicates the ratio of the yield/maximum load in corroded RC beam to that in sound one. Those figures include the reduction lines in the calculated yield and maximum loads, which were derived from RC sectional analysis, assuming that the corrosion rate corresponded to the sectional area loss of corroded reinforcements. The yield loads of corroded RC beams were defined with the point in load-deflection curve, where the stiffness of corroded RC beam began to decrease, because the clear yield point was difficult to be found.

The reduction rate in the experimental yield load shows an agreement with that in calculated one up to the corrosion rate of 7%, while the reduction rate in the experiment increased beyond 7%. The larger the corrosion rate was, the smaller the minimum sectional area of corroded reinforcement became, because the scatter of sectional area in the longitudinal direction would be high. The yielding of RC beam depends on the minimum cross section. Thus, the large reduction in the experimental yield load was shown. Even in RC beam with the corroded reinforcement of the shear span, the yield load slightly decreased as the corrosion rate increased. It is estimated that the yield load decreased, because the reinforcement in the shear span close to the flexural span yielded prior to that in the flexural span.

The maximum load of RC beams with the corroded reinforcement in overall and flexural span decreased as the corrosion rate increased, while the reduction rate in the experimental maximum load showed an agreement with that of the calculated one including RC beam resulted in the rupture of reinforcement. No drastic reduction in the maximum load could be shown, because the reinforcement kept its elongation up to the ultimate curvature in the upper extreme fiber. This may be attributed that the effect of strain hardening of reinforcement can compensate the reduction of tensile force according to the cross sectional loss of corroded reinforcement, while the yield load is determined by the first yielding in the minimum sectional area of corroded reinforcement.

CALCULATION METHOD OF FLEXURAL CAPACITY CONSIDERING DISTRIBUTION OF CORROSION

Calculation Outline. A simultaneous measurement of the diameter in corroded reinforcement with the inspection on chloride ion content or carbonation depth at the same sections is available to the estimation of flexural capacity, determining a characteristic value of the diameter in the longitudinal direction based on some measured values and then applying it to RC sectional analysis. The above idea was applied to experimental results, using the longitudinal profile derived from the detail measurement of diameter with the spacing of 50 mm.

First of all, three sections, which corresponded to inspection locations in the practical member, were chosen at random from experimentally measured sections with the spacing of 50 mm. The large number of inspection section will bring an accurate frequency distribution in the corroded reinforcement area. However, too many inspections must cost a lot of money and time. Therefore, the minimum required three sections were determined to perform the appropriate statistical processing in this study, whereas the relationship between the number of chosen section and the accuracy of frequency distribution should be discussed. Three diameters are to be chosen from the longitudinal profile in diameter with the spacing of 50 mm in experiment instead of the practical measurement of diameters in chosen three sections, though that procedure is unique to this study. Five times in trial choice of three sections are performed per one RC beam. A representative value of diameters in each section is determined by a mean value of three reinforcements.

Next, the mean value, d_m and standard deviation, σ of diameter in the longitudinal direction of RC beam are derived from the above three representative values in each section. **Fig. 5** shows a typical frequency distribution of diameters. Based on that distribution, a normal distribution is assumed as a model of distribution in corroded reinforcement diameter. Thus, a characteristic value of diameter, d_k can be indicated by the following equation.

$$d_k = d_m - k \times \sigma \tag{1}$$

The characteristic value is shown by using the coefficient, k of 1.64, which corresponds to

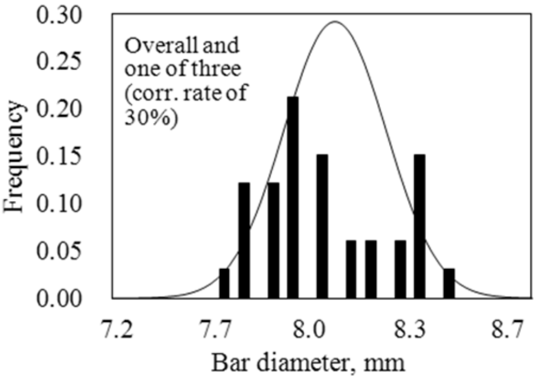


Figure 5. Typical frequency distribution of diameters

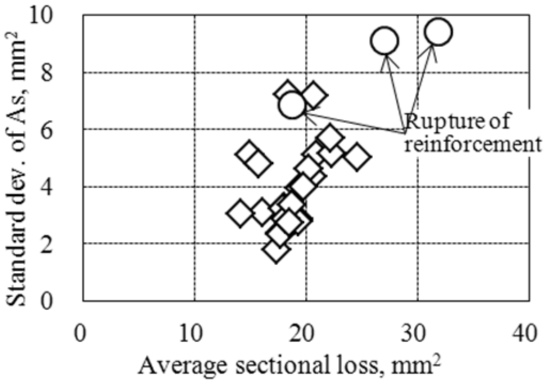


Figure 6. Relationship between ave. sectional loss and standard dev. of A_s

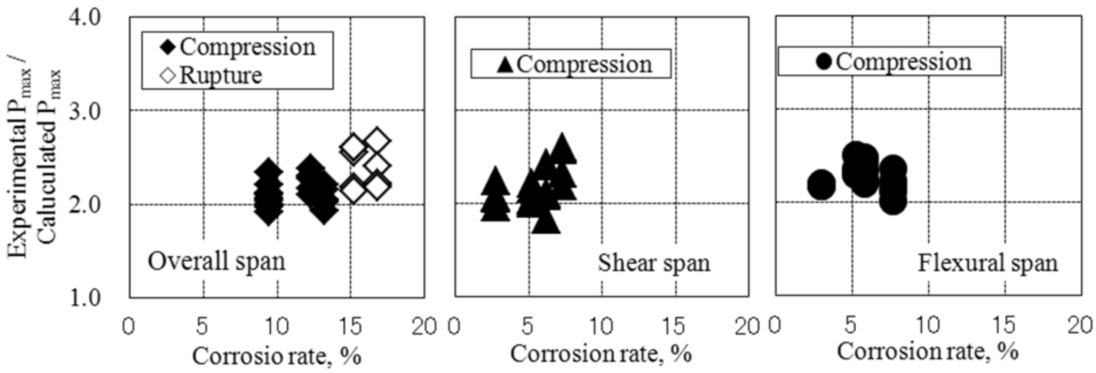


Figure 7. Relationship between experimental P_{max} / calculated P_{max} ratio and the corrosion rate (population: overall span)

the probability of 0.95 not to be below the characteristic value in diameters of corroded RC beam.

The flexural capacity was calculated by RC sectional analysis using an equivalent stress brock, assuming the liner distribution of strain in depth and the complete bond of reinforcement in concrete. Since the degradation in bond due to corrosion mainly seemed to affect the deformation capacity such as stiffness or ductility, only the reduction in sectional area of corroded reinforcements was considered.

However, the localization of deformation, that is the localized increasing of sectional curvature, will bring the ultimate failure by the rupture of reinforcement and, consequently, larger reduction in the maximum load due to the rupture than the compressive failure in concrete. For that case, the calculated flexural capacity derived from the assumption of the compressive failure in the upper extreme fiber may not be moderate for the experimental one resulted in the rupture. For that reason, the failure mode was identified using the standard deviation of diameter in corroded reinforcement. **Fig. 6** shows the relationship between the average reduction in sectional area and the standard deviation of the residual area of corroded reinforcement. The failure mode of rupture in the reinforcement was shown in the average reduction more than 20 mm^2 and the standard deviation more than 7 mm^2. Thus, the failure mode of rupture in the reinforcement should be screened using the longitudinal scatter of corroded reinforcement area and then, this method can be applied to RC beam, which is judged to fail in compression of concrete. On the other hand, the flexural capacity has to be obtained using another method considering the rupture failure of the reinforcement.

In Case of Overall Span as Population. **Fig. 7** shows the relationship between the ratio of experimental value to calculated one in the maximum load and the corrosion rate, when a population for the choice of three sections is overall span of RC beam. The value over 1 in the vertical axis means the appropriate estimation in safety. In case of overall span corrosion, the calculated maximum loads indicated the safe results in all RC beams. However, the ratio often showed more than 2 and the characteristic values of diameter were too moderately estimated, while the ratio of 1.2-1.3 seemed to be reasonable in consideration of safety factor for the sectional analysis results. Thus, too safe results can be found for experimental results derived from the electrolysis corrosion, because it produces relatively uniform corrosion. However, in the practical corrosion such as a chloride ion induced one, further investigation should be needed to determine the coefficient, *k*. Furthermore, the ratio of experimental value to calculated one in the maximum load could be reduced by introducing the stress-strain model for concrete with a confinement effect or for reinforcing steel with a strain hardening effect into the sectional analysis.

Even in case of shear or flexural span corrosion, too safe results also can be found. Overall span population could include a lot of sections below the characteristic values in the sectional area, if the sections with sound (less corroded) reinforcement were chosen and consequently, unsafe results could be shown. However, since the corrosion loss was too small to scatter the sectional areas and the span to be corroded was extended into the not-intended span in the partial corrosion of this experiment, too safe results were obtained.

In Case of Corrosion Crack Portion as Population. Choosing three sections at random in the inspection is not practical for partially corroded RC member. The portion to inspect in corroded RC member should be intended. In the following section, the population to get the characteristic value was determined by classifying the portion with or without the corrosion cracks. **Fig. 8** shows the relationship between the ratio of the experiment to the calculation and the corrosion rate, when the population for the choice of three sections is the overall length or the cracked portions of RC beam. The population as the cracked portion can decrease the deviation from the median and the scattering of calculated results. As mentioned above, since the corrosion loss was small in this experiment, the significantly high scatter cannot be found even in case of overall length as population. However, it is possible to decrease the scatter of the calculation in larger corrosion rate.

In Case of Estimation of Diameter using Corrosion Crack Width. Corrosion cracks can be more conveniently available for information to determine the diameter of corroded reinforcement than the direct inspection using core sampling. Based on the relationship between the corrosion crack width and the residual sectional area of corroded reinforcement, the flexural capacity was calculated using the characteristic value derived from the three diameters estimated by corrosion crack widths. **Fig. 9** shows the relationship between the corrosion crack width and the sectional loss of reinforcement in this and previous (Handa, 2010) study. The relationship between the corrosion crack width, w_{cr} and the sectional loss, ΔA_{cr} can be shown by the linear regression as the following equation.

$$\Delta A_{cr}\ (\mathrm{mm}^2) = 25.6 \times w_{cr}\ (\mathrm{mm}) \qquad (2)$$

Judging from the scatter condition in **Fig. 9**, the linear regression is not always appropriate.

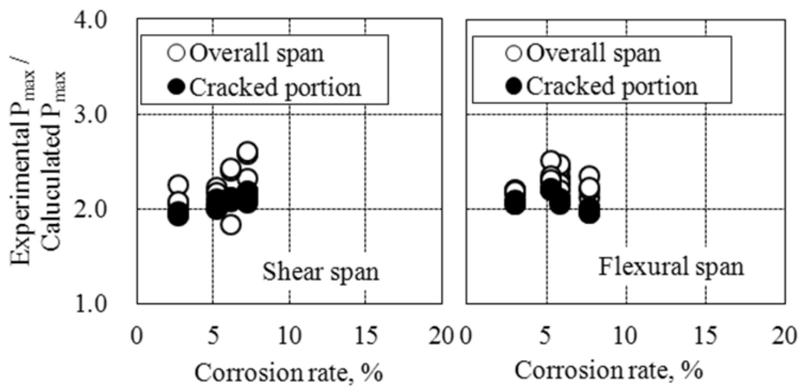


Figure 8. Relationship between exp./cal. ratio and corrosion rate (population: overall span vs. cracked portion)

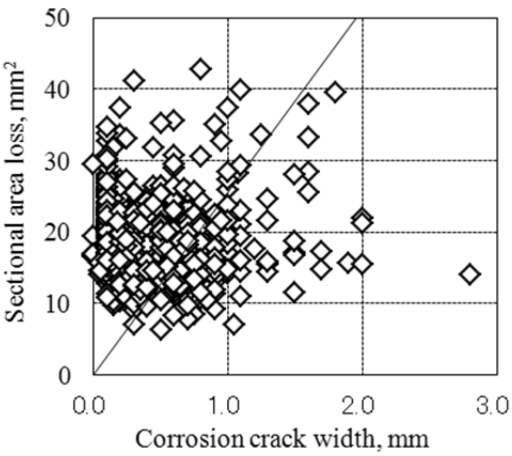


Figure 9. Relationship between sectional loss and crack width

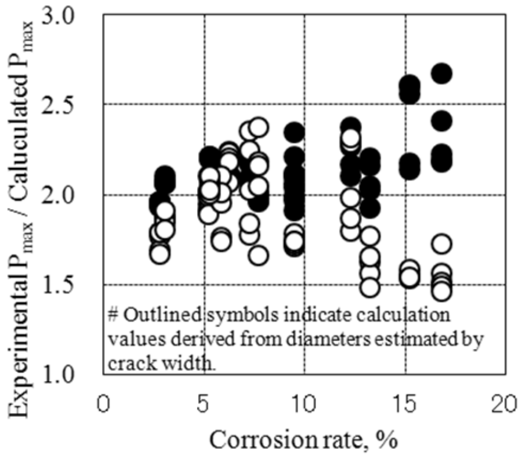


Figure 10. Relationship between exp./cal. ratio and corrosion rate (measured diameter vs. estimated diameter using crack width)

Therefore, it is noted that the diameters estimated by the corrosion crack widths are often separated from the actual diameter.

The diameter of three sections can be obtained by equation (2) using the corrosion crack widths of three sections chosen from overall span as population. The calculation procedure to get the flexural capacity is the same as the above. **Fig. 10** shows the relationship between the ratio of the experiment to the calculation and the corrosion rate, when the three diameters were determined by actually measured diameters or the estimation from the corrosion crack widths. In case of partial corrosion in shear and flexural span, the cracked portion was used for the population.

In case of estimation of diameter using corrosion crack width, the safe results also can be found. However, the ratio decreased as the corrosion loss increased and then, further corrosion loss can lead unsafe results. Quite a few diameters were above the linear regression line as shown in **Fig. 9**, because the electrolysis corrosion was difficult to increase the crack width due to the leakage of corrosion products through the crack and increased only the corrosion loss. Thus, it is estimated that more largely estimated sectional area of reinforcement using the corrosion crack width than actually measured diameters led smaller ratio of calculation to experiment as shown in **Fig. 10**. This indicates that the calculation results depend on the relationship between the corrosion crack width and the sectional area loss.

The above calculation in this study was performed by using the distribution of corrosion in RC beams simulated by the accelerated electrolysis corrosion. However, it should be considered that the reinforcement will be corroded more uniformly in the electrolysis corrosion than the practical or sodium chloride spraying corrosion. Therefore, there is the possibility that the estimation of the flexural capacity in case of corrosion frequency distribution with higher scatter is not always safe according to the determination of the characteristic value of the sectional area of corroded reinforcement. Further investigation on method to determine the characteristic value should be needed to lead the appropriately moderate evaluation.

CONCLUSIONS

The main results obtained in the present study are summarized as follows:

The flexural capacity of corroded RC beam was estimated by directly measuring the diameters of corroded reinforcement in some sections along with another inspection regarding corrosion and then, determining the longitudinal characteristic value of the cross sectional area of corroded reinforcement. This calculation method could lead the safe evaluation with less scatter in the results, when the characteristic value of the diameter measured in only the cracked portion due to corrosion was used.

The flexural capacity of corroded RC beam also can be safely calculated by using the characteristic value of diameters estimated by the corrosion crack width. There is, however, the possibility that the estimation of the flexural capacity in case of corrosion frequency distribution with higher scatter is not always safe according to the determination of the characteristic value of the sectional area of corroded reinforcement.

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