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Effect of Rebar Corrosion on Mechanical Behaviour of RC Structures

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The effects of rebar corrosion on the structural behaviour of reinforced concrete structures were discussed based on recent experimental investigation. The load carrying capacity of the deteriorated beams was quantitatively estimated by evaluating the degree of rebar corrosion in terms of the average cross-sectional loss of longitudinal reinforcing bars and bond deterioration between corroded reinforcing bars and concrete.

Keywords *: rebar corrosion, structural capacity, marine environments, bond deterioration*

1. Introduction

Marine areas are very severe for structures from the viewpoints not only of mechanical actions but also of environmental actions. Materials tend to deteriorate relatively rapidly in marine environments and loss of structural performance/capacity or even structural collapse may be consequences. The most common and costly deterioration mechanism suffered by concrete structures in marine areas is chloride-induced rebar corrosion. In order to predict the long-term behaviour of reinforced concrete (RC) marine structures, it is necessary to 1) model chloride penetration, 2) estimate the amount of chloride necessary for corrosion initiation, 3) estimate the subsequent corrosion rate, and 4) ascertain the effect of corrosion on the limit states and structural behaviour.

This paper focuses on the fourth sequence above: structural behaviour based on the author's recent research. Structural performance, such as load carrying capacity and ductility, of RC beams with corroded reinforcing bars has been investigated experimentally. Embedded reinforcing bars were artificially corroded, and then the beams were subjected to the application of external loads. The test results showed that decrease in load carrying capacity and ductility of the RC beams were derived from the cross-sectional loss of reinforcing bars and the deterioration of the bond between corroded reinforcing bars and concrete. The respective effects of corrosion of main reinforcing bars and stirrups on the load carrying capacity and ductility of the RC beams are discussed. The relationship between the degree of corrosion and the deterioration of bond are also discussed based on experimental results.

2. Behaviour of RC beams with corroded reinforcing bars

2.1 Scope

The influence of rebar corrosion on load carrying capacity of RC beams was experimentally investigated for quantitatively evaluating the remaining load carrying capacity of existing RC structures. Corrosion of reinforcing bars in tested beams was artificially accelerated by three methods. The results of bending tests on the deteriorated beams provided with the relationship between the degree of corrosion and load carrying capacity of the beams. The difference between corrosion produced acceleratedly and that due to exposure to natural marine conditions was examined by comparing the present test results with those of long-term exposure tests under marine environments.

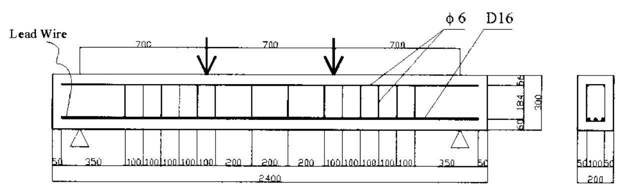

Fig. 1. Tested beam

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2.2 Experimental procedure

RC beams tested are shown in Fig. 1. Three deformed bars of 16 mm nominal diameter were used as longitudinal reinforcing bars, and 12 stirrups were embedded with a spacing of 100 mm. Yield and tensile strengths were 382 and 560 MPa for the longitudinal bar, and 306 and 444 MPa for the stirrup. The concrete cover to longitudinal reinforcing bars was set to 42 mm. The beams used were intended to have the same performance as much as possible, as those for the long-term exposure tests, which were manufactured more than 25 years ago. The details of beam such as materials etc. can be found in the reference.[1)]

For investigating how bending cracks affected the corrosion state of reinforcing bars in concrete, initial cracks were induced in a half of the tested beams, by applying a bending load before the accelerated corrosion procedures. The preliminarily loading was conducted until the maximum width of bending cracks reached the design allowable value of 0.15 mm. The beams with and without initial cracks induced by the preliminary loading are designated as C-series and U-series, respectively.

To rapidly corrode reinforcing bars in concrete, the following three procedures were applied to the beams of both C-series and U-series: 1) electrolytic reaction, 2) wet and dry cycling at high temperature, and 3) seawater splashing. In the electrolytic reaction, direct current is applied to reinforcing bars with the current density of 8.5 A/m^2 with respect to the initial surface area of reinforcing bars. A longitudinal crack due to corrosion started to occur in the beams of U-series after applying the direct current for 32 hours. This duration of 32 hours was determined as a fundamental period of the electrolytic procedure, which was designated by Q. To obtain different corrosion states of reinforcing bars in concrete, the direct current was applied by varying durations. In the procedure of wet and dry cycling, tested beams were placed in a tank, which was filled with seawater at 60 ℃ for 3.5 days, and were subsequently dried in air for 3.5 days at room temperature. This cycle of wetting and drying, a total of 7 days, was defined as 1 cycle, which was continued for 60 cycles. Meanwhile, the beams were picked out for bending tests at the end of 9 and 34 cycles. For the tested beams suffered from seawater splashing, they were located at a seawater splashing site at which seawater was automatically splashed for 3 hours every 12 hours. The exposure durations were 1.5 years and 2.5 years to change the corrosion state of reinforcing bars.

For quantifying the degree of corrosion of reinforcing bars in the tested beams after the accelerated corrosion, cross-sectional loss of longitudinal reinforcing bars was measured by the procedure described in the reference.[2)] Note that the cross-sectional loss defined here cannot evaluate any concentrated corrosion, but provides with an average degree of corrosion.

2.3 Results of corrosion state of reinforcing bars

Table 1 summarizes the measured cross-sectional loss of longitudinal reinforcing bars. There were no obvious influences of existence of initial cracks on the degree of corrosion. In case of slight corrosion, however, the coefficients of variation for C-series were larger than those for U-series. This was because corrosion was concentrated at the locations of initial cracks. As corrosion became severe, the coefficients of variation decreased, indicating that corrosion progressed uniformly over the surface of reinforcing bars. Focusing on the beams with similar degrees of corrosion, the coefficients of variation were almost the same regardless of the methods of corrosion acceleration. Therefore, the degree of corrosion was evaluated by using the average cross-sectional loss of reinforcing bars in the pure bending span of the beams even though there were some cases having large coefficients of variation.

Table 1. Cross-sectional loss of reinforcing bar

Electrolytic reaction (U-series)				
Electrolytic duration	1Q	2Q	4Q	8Q
Cross-sectional loss (%)	1.37	3.41	5.79	8.29
Coefficient of variation (%)	55.0	26.6	32.7	17.5

Electrolytic reaction (C-series)					
Electrolytic duration	0.5Q	1Q	2Q	4Q	8Q
Cross-sectional loss (%)	1.49	1.19	1.60	4.31	9.80
Coefficient of variation (%)	81.4	116.0	71.5	19.0	12.2

Wet and dry cycling / Seawater splashing (U-series)					
Cycles / Exposure duration	9	34	60	1.5 years	2.5 years
Cross-sectional loss (%)	1.63	3.31	5.59	1.01	1.87
Coefficient of variation (%)	69.9	73.9	37.7	119.2	77.9

Wet and dry cycling / Seawater splashing (C-series)					
Cycles / Exposure duration	9	34	60	1.5 years	2.5 years
Cross-sectional loss (%)	1.09	2.21	7.88	1.17	1.49
Coefficient of variation (%)	77.2	80.0	30.4	116.6	102.8

Fig. 2 shows the relationship between cross-sectional loss of reinforcing bars and width of longitudinal cracks caused by corrosion. The cross-sectional loss was measured on test pieces 100 mm long, and the corresponding crack width was the maximum value obtained at the same position of the beams as the measurement of loss. The indicated crack width was obtained by dividing the measured value by the number of longitudinal reinforcing bars, which referred to crack width per bar. It was found that there is a similar tendency in case of wet and dry cycling and seawater splashing, but not in the electrolytic reaction. The difference in crack width was caused by the magnitude of expansion force due to corrosion product around the reinforcing bars. In the electrolytic reaction, the beam was fully immersed in seawater so that corrosion product flowed out into seawater immediately rather than accumulating around the bars. The resultant expansion force was so small that concrete around the bars did not degrade. From this, it was considered that, in case of the electrolytic reaction, deterioration of bond was not so severe, compared with those produced by the wet and dry cycling and the seawater splashing.

On the basis of the results of tensile tests on corroded reinforcing bars, the relationship between the degree of corrosion and the yield point of reinforcing bar was obtained as shown in Fig. 3. The actual cross-sectional area in consideration with loss in cross-section due to corrosion was used in the calculations, not nominal cross-sectional area. It was found that the influence of corrosion on mechanical properties of reinforcing bars was negligible if loss in cross-section was properly taken into account. This fact was observed regardless of the methods of corrosion acceleration.

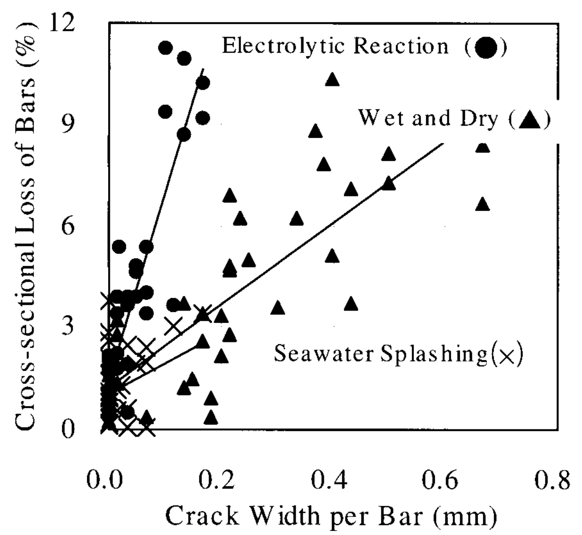


Fig. 2. Cross sectional loss vs crack width

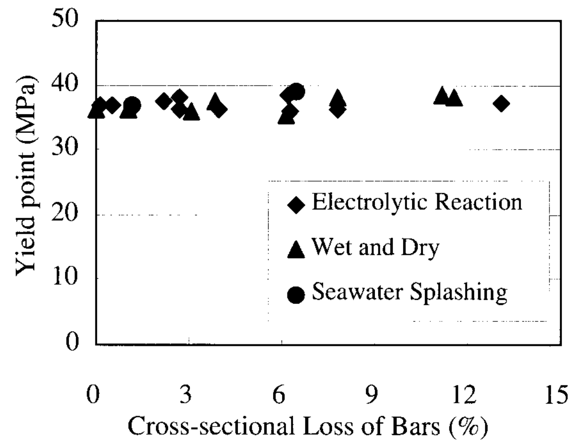


Fig. 3. Yield point of corroded bars

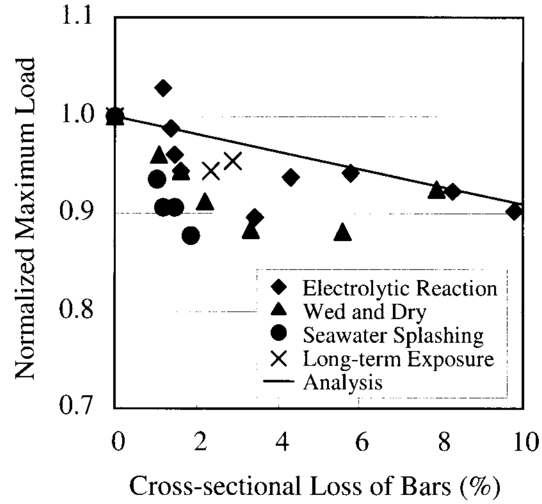


Fig. 4. Load-carrying capacity of the beam

2.4 Load carrying capacity of deteriorated beams and discussion

All the beams failed in bending regardless of the methods of corrosion acceleration and the degree of corrosion. Existence of initial cracks hardly affected the test results as well as the cross-sectional loss of reinforcing bars mentioned before. Therefore, influence of failure mode and existence of initial cracks were not considered in the following discussion. Fig. 4 shows the relationship between cross-sectional loss of reinforcing bars due to corrosion and load carrying capacity of the tested beams. The maximum loads of the beams were normalized by those of the undamaged reference beam. As shown in the Fig., decrease in load carrying capacity due to corrosion was well understood by focusing on the average cross-sectional loss of longitudinal reinforcing bars.

The results of bending tests on the beams exposed to actual marine environments for 23 years[1] are also indicated in Fig. 4. They were consistent with the trend of experimental results of the test damaged by corrosion acceleration. Therefore, the deterioration state of the beams, which was artificially produced by the accelerated corrosion procedures, was not greatly different from that observed in natural marine environments.

Calculated maximum loads of the beams are also illustrated as a solid line in Fig. 4. The loss in cross-section of reinforcing bars due to corrosion was considered in this calculation. Almost all measured maximum loads of the beams were smaller than the calculated ones. The cause of this isolation was deterioration of bond properties between reinforcing bars and concrete due to corrosion. The bond properties became worse due to corrosion so that bond stress distribution around the longitudinal reinforcing bars approached a uniform shape. Then, tensile stress in the bars did not transmit into concrete efficiently, resulting in loss of the tension-stiffening effect of concrete. Consequently, localized deformation of the beams occurred, and strain in the compression fiber became large compared with the reference beam. Therefore, to evaluate the maximum load of reinforced concrete beams damaged by corrosion of reinforcing bars, deterioration of bond properties between reinforcing bars and concrete should be considered as well as loss in cross-section of reinforcing bars.

Focusing on the difference in load carrying capacity due to the methods of corrosion acceleration, the decrease in maximum load in case of the wet and dry cycling and the seawater splashing was larger than that of the electrolytic reaction. In the relationship between the degree of corrosion and crack width, it was considered that deterioration of bond properties was severer in case of the wet and dry cycling and the seawater splashing than for the electrolytic reaction. The worse the bond deterioration, the smaller the maximum load of the beams. Therefore, the deterioration state of bond properties between reinforcing bars and concrete should be appropriately evaluated, which will be described later.

3. Behaviour of RC beam with corrosion of stirrups

3.1 Scope

Since the concrete cover to stirrups is generally smaller than that to main reinforcing bars, stirrups may be exposed to severer corrosion environment. Taking this condition into consideration, the effects of corrosion of not only main reinforcing bars but also stirrups were discussed on the structural performance of RC beams.

3.2 Experimental procedure

The tested beam was 250 mm wide, 250 mm high, and 3300 mm. The cover depths were 60 mm for the upper main reinforcing bars and 44 mm for the lower main reinforcing bars; both are 19 mm in diameter. The stirrups of 16 mm in diameter were embedded with a spacing of 150 mm. The compressive strength of the concrete was 37.6 MPa at the time of loading. The yield stresses were 366 MPa for the main reinforcing bars and 401 MPa for the stirrups.

A total of five RC beams were load tested. In three of them, N-0, N-1, and N-2, general steel reinforcing bars and stirrups were used. Epoxy-coated reinforcing bars were used either as main reinforcing bars, EP-M, or as stirrups, EP-S for investigating the respective effect of corrosion on structural performance of the RC beams. The procedure for corroding reinforcing bars applied was the electrolytic reaction; the same way as that for bending beams described before.

The RC beam was supported with a loading span of 2000 mm and a load was applied symmetrically at the two points 500 mm apart. A reversed cyclic load was applied of which details were described in the already published paper.[3] After the loading test, corrosion of reinforcing bars was investigated as that mentioned before.

3.3 Results and discussion

Table 2 lists the cross-sectional loss of main reinforcing bars and stirrups. By comparing the average cross-sectional loss of reinforcement, the state of corrosion in the RC beam was not uniform. It is, therefore, important to carefully consider the scattering of corrosion, but the average cross-sectional loss is discussed in this paper with the same reason mentioned before.

The formation of cracks of N-2, EP-S, and EP-M at $3\delta_y$ (δ_y is the midspan deflection of the beam at the first yield of main reinforcing bar) is shown in Fig. 5. After the electrolytic reaction, cracks were formed on the side surfaces of the RC beams along the main reinforcing bars. Cracks along the stirrups were observed in EP-M. Due to the reversed cyclic load, flexural cracks occurred at first. When shear cracks appeared in the shear span of the RC beam, the load suddenly decreased. In N-2, the greatest cross-sectional loss of reinforcing bars, the cover concrete fell down after $+1\delta_y$. In the RC beams except N-0, cracks due to loading oriented to existing cracks due to corrosion.

The envelope curves of the relationship between applied load and midspan deflection are shown in Fig. 6 (a). The load carrying capacity and ultimate deflection became small as the cross-sectional loss of main reinforcing bars and of stirrups was large. The decrease in load carrying

Table 2. Cross-sectional loss of reinforcing bars

(Unit: %)

Beam No.		N-0		N-1		N-2		EP-M		EP-S	
	Position	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower	Upper
Main bar	Min.	0.0		13.0	8.8	16.7	19.2	0.0		9.1	10.0
	Max.			24.4	15.7	23.1	25.6			13.7	19.2
	Average			16.1	12.9	20.8	20.0			10.9	13.7
Stirrup	Min.	0.0		30.0		21.3		6.7		0.0	
	Max.			100.0*		100.0*		14.0			
	Average			38.0		69.2		10.7			

*) breakage of bar

capacity and ultimate deflection was caused by prevention of smooth stress transmission between corroded reinforcing bars and concrete due to the deterioration of bond. The ultimate deflection, δ_u, is defined as that at which the applied load decreased to the first yield load after the maximum load. In addition, the core concrete was not well confined by stirrups because of their corrosion. Therefore, the ultimate deflection of corroded beams was more decreased than that of N-0.

It is impossible to identify the respective effects of corrosion of main reinforcing bars and stirrups on the ductility of N beam, because the cross-sectional loss of stirrups was large when the cross-sectional loss of main reinforcing bars was large. In Fig. 6 (b), the relationships between applied load and midspan deflection of EP-S and EP-M are shown. That of N-0 is also drawn in the Fig. for comparison. In EP-S, where corrosion occurred only in main reinforcing bars during downward loads, load carrying capacity was smaller than that of N-0.

In the case of upward loads, however, the load carrying capacity was almost the same as that of N-0 despite that the cross-sectional loss of upper main reinforcing bars was greater than that of lower reinforcing bars. EP-M, where corrosion occurred only in stirrups, had almost the same load carrying capacity as N-0. However, the ultimate deflection was smaller in both downward and upward

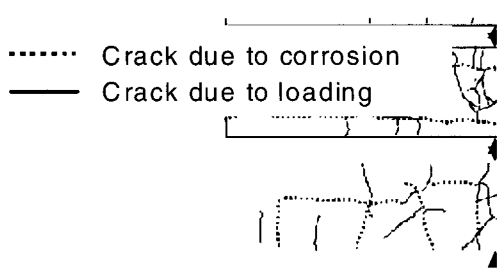
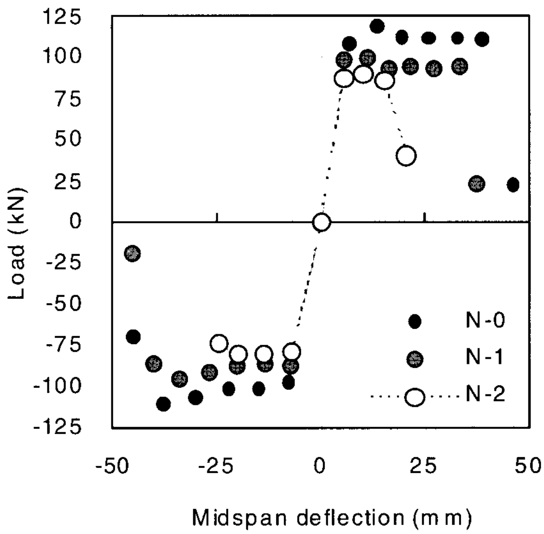
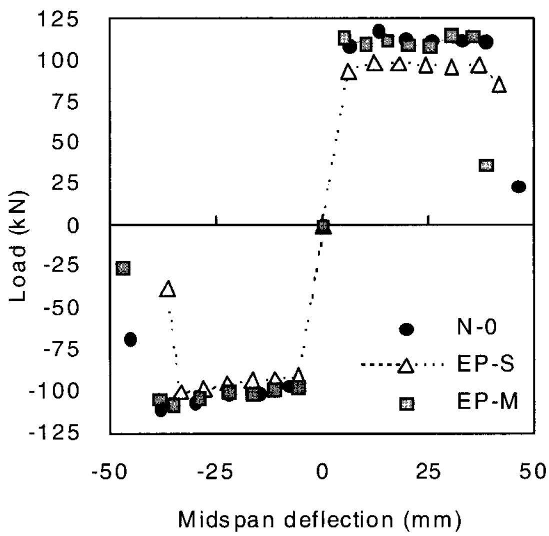


Fig. 5. Crack formation at $3\delta_y$



(a) Un-coated bars



(b) Epoxy-coated bars

Fig. 6. Load vs midspan deflection

loads. Therefore, it can be concluded that corrosion of main reinforcing bars has an influence on load carrying capacity and ductility, while corrosion of stirrups has a great influence on ductility.

In order to clarify the effects of rebar corrosion on ductility, the relationship between cross-sectional loss of main reinforcing bars and the normalized ductility is shown in Fig. 7. The relationship between cross-sectional loss of stirrups and the normalized ductility is shown in Fig. 8. The ductility was the ratio of the ultimate and yield deflection δ_u / δ_y, which was normalized by the ductility of the RC beams without rebar corrosion. There was a drop in normalized ductility when cross-sectional loss reached 15% for main reinforcing bars and 40% for stirrups. Therefore, since corrosion occurred both in the main reinforcing bars and stirrups in N beams, the respective effect of main reinforcing bars and stirrups

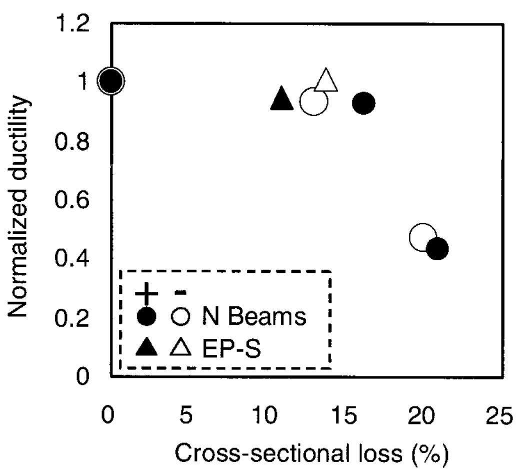


Fig. 7. Ductility by corrosion of main bars

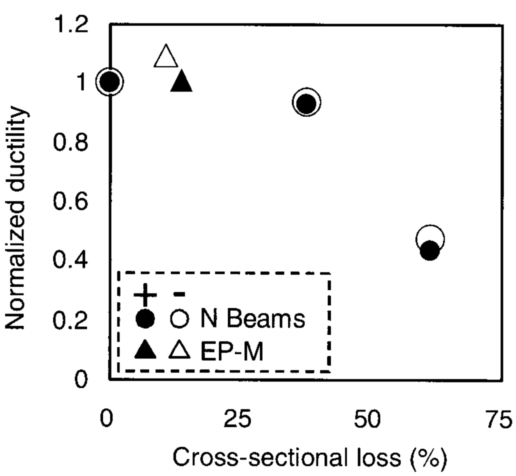


Fig. 8. Ductility by corrosion of stirrups

corrosion on the ductility is discussed by focusing on EP-M and EP-S. Corrosion of main reinforcing bars caused reduction in ductility because of the cross-sectional loss of reinforcing bars and deterioration of bond between reinforcing bar and concrete. From the results of EP-S, it can be predicted that if the cross-sectional loss of main reinforcing bars becomes larger than 10 to 15% it would have a strong effect on the ductility. On the other hand, corrosion of stirrups caused reduction in ductility because of the reduction in the confined effect of stirrups on the core concrete in addition to loss in cross section and deterioration of the bond.

4. Deterioration of bond due to rebar corrosion

4.1 Scope

As described before, in evaluating the effects of rebar corrosion on the structural behaviour of RC members, it is necessary to take into account the deterioration of bond between corroded reinforcing bar and concrete. Here, deterioration of bond due to rebar corrosion was experimentally investigated by the axial-tension test.[4] Then, the effect of rebar corrosion and the deterioration of bond were discussed on tension stiffening and the crack distribution performance of concrete.

4.2 Experimental procedure

The outline of tested specimens and test setup are shown in Fig. 9. The specimen had a rectangular cross section of 200 mm wide and 150 mm high. The total length of the concrete was 2000 mm. One steel bar with screw threads of 19 mm in diameter was embedded at the centreline of the tested specimen. The compressive strength of the concrete was 40 MPa at the time of test and the yield stress of steel bars was 366 MPa. An axial-tension load was applied at the both ends of the embedded steel bar using a center-hole hydraulic jack. During the test, applied load was measured by a load cell. Average strain was calculated from measured displacements at the both ends of specimen.

4.3 Results and discussion

Table 3 lists the cross-sectional loss of steel bar. The states of corrosion were not uniform. The coefficient of variation of cross-sectional loss became large as the cross-sectional loss increased. Therefore, it is important to carefully consider the scattering of corrosion, but the average value of measured data is discussed here.

Examples of crack formation are shown in Fig. 10. Cracks, forming vertical to steel bar, occurred and distri-

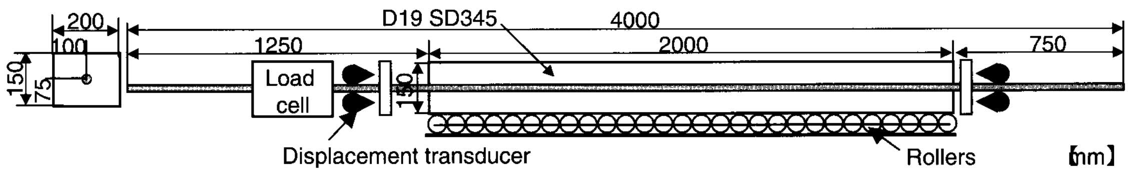


Fig. 9. Test setup

buted in the no-corroded specimen. In the corroded specimens, initial cracks were formed along the steel bar by the electrolytic procedure. However, after the loading test, there were fewer cracks formed than those of no-corroded specimen. Fig. 11 shows the relationship between cross-sectional loss of steel bar and crack distribution index. The crack distribution index is defined as the ratio of number of cracks due to loading to that of in the no-corroded specimen. The crack distribution index decreased with increase in cross-sectional loss of steel bar. Tensile stress in steel bar was not transmitted to concrete efficiently due to deterioration of bond. Therefore, loss in tension stiffening effect of concrete caused localized deformation of specimens.

The relationships between average strain of specimen and applied load are shown in Fig. 12. Load carrying capacity of corroded specimens was smaller than that of no-corroded specimen in the same strain. Moreover, the relationship between average strain and applied load of the heavily corroded specimen (the average cross-sectional loss of steel bar was 10.2 %) was approaching the line of a simple steel bar (not embedded in concrete). It is considered to be caused by loss in tension stiffening effect due to deterioration of bond.

In order to evaluate the effect of rebar corrosion on bond quantitatively, the bond fracture energy was obtained from the load vs average strain curve. The relationship between cross-sectional loss of steel bar and the bond fracture energy is shown in Fig. 13. The bond fracture energy was decreased with increase in the average cross-sectional loss of steel bar and became almost constant when the cross-sectional loss was larger than 5.8%. The results by Matsuo et al.[5] are also plotted in the same Fig.. The effect of cross-sectional loss of steel bar on bond

Table 3. Cross-sectional loss of steel bars

Average (%)	0.0	0.8	2.5	2.7	5.3	10.2
Min. (%)	-	0.04	1.67	1.54	2.54	7.45
Max. (%)	-	1.71	3.98	3.83	6.88	15.04
Coefficient of variation	-	0.44	0.60	0.53	0.98	1.88

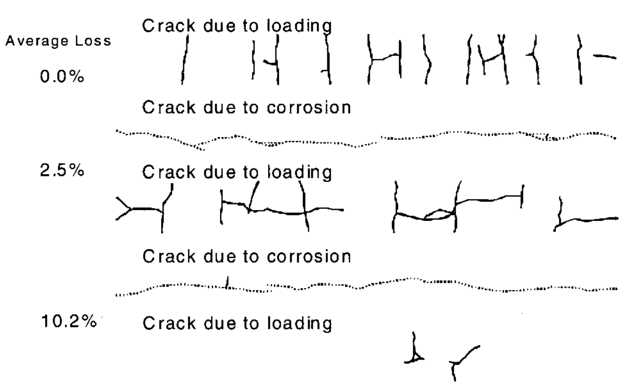


Fig. 10. Cracks formation

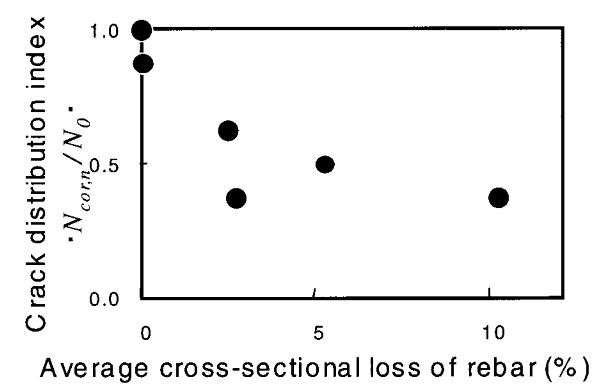


Fig. 11. Crack distribution index

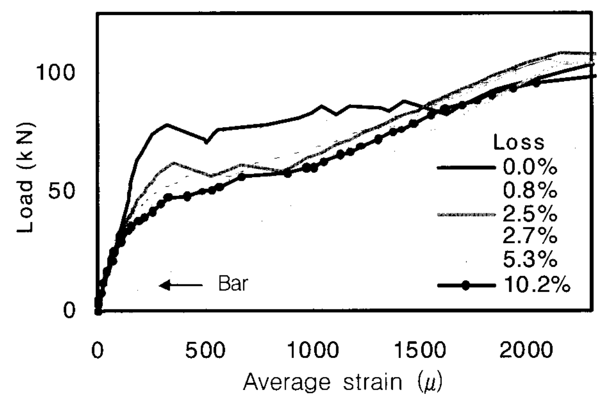


Fig. 12. Load vs. average strain

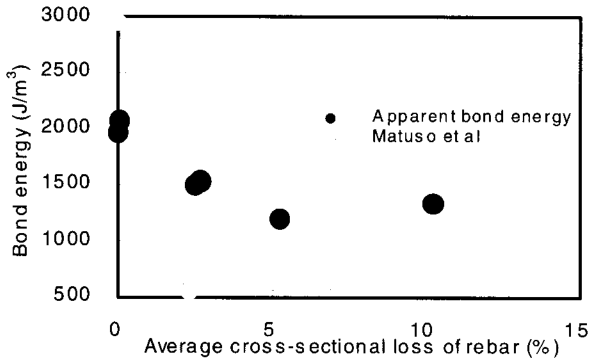


Fig. 13. Bond fracture energy

fracture energy in the previous research was more remarkable than that of the present test. This was probably caused by dimensions of specimen and diameter and surface geometry of bar. It was, therefore, concluded that bond between corroded reinforcing bar and concrete can be quantitatively evaluated by bond fracture energy with considering dimensions of specimen and shape and diameter of bar.

5. Concluding remarks

The load carrying capacity of deteriorated beams can be quantitatively estimated by evaluating the degree of corrosion in terms of the average cross-sectional loss of longitudinal reinforcing bars. It was made clear that corrosion of main reinforcing bars had an influence on the load carrying capacity and ductility of the RC beams, while corrosion of stirrups had a great influence on ductility. The loss in ductility was caused by reduction of the confined effect on the core concrete as well as cross sectional loss of reinforcement and deterioration of the bond. For analysis and design, bond between corroded reinforcing bar and concrete could be quantitatively evaluated by bond fracture energy.

Using the experimental results and discussions described in this paper, the author has been implementing a comprehensive lifecycle management system for coastal RC structures.[6] This paper was prepared based on the results of several studies in Structural Mechanics Division of Port and Airport Research Institute. The author would like to extend his appreciation to all co-researchers there, particularly Dr. Mitsuyasu Iwanami and Dr. Ema Kato.

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