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THE MECHANICAL BEHAVIOUR OF RC BEAMS DAMAGED BY CORROSION OF REINFORCEMENT

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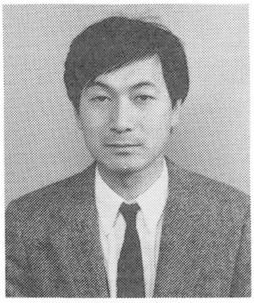

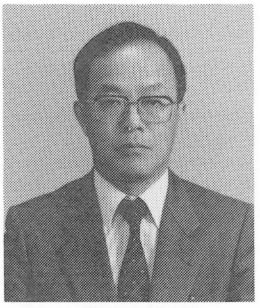

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SYNOPSIS

The mechanical behaviour and the failure mechanism of RC beams damaged by corrosion of reinforcement are not only experimentally but also theoretically studied. In the experiments, loading and bond tests are conducted for RC specimens damaged with an accelerated galvanostatic corrosion method. Theoretical studies are made to investigate the mechanical behaviour of these damaged beams using elasto-plastic finite element analysis. From these experimental and theoretical studies, it is discussed how deteriorating condition affect the action of these damaged beams.

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1. INTRODUCTION

Recently, damages of RC structure by corrosion of reinforcement have been reported from many countries[1]. Typical examples of damages are weight loss in certain part of reinforcement, generation of cracks and peeling off along axial direction of reinforcements. The main causes of these corrosion in structure have been explained that they are attributable to progress of neutrized zone, penetration of salts which came flying, or mixing of chlorine by the uses of beach sand or admixture[2].

As an evaluation method of safety of these damaged RC beams, the load carrying capacity for the RC beam must be investigated. It will be normally calculated by weight loss of reinforcement. This estimation may be a useful method, if damaged RC beams fail in flexure. However, these damaged beams do not always fail in flexure, and the action of these damaged beams are not clear in relation to other conditions, such as the reduction of bond strength, the generation of cracks due to swelling of corrosion products, etc., when the weight loss is so small as not to affect the yield strength[3]~[7]. It is necessary to clarify how such conditions affect the action of these damaged beams.

From these point of view, in this study, the mechanical behaviour and the failure mechanism of the damaged RC beam is not only experimentally but also theoretically studied. In the experiments, loading and bond tests were conducted for RC specimens damaged with an accelerated galvanostatic corrosion method. It was confirmed that the deterioration and the changes of properties occurred in damaged RC specimens, i.e., the reduction in stiffness and load carrying capacity, the reduction in bond strength, generation of internal stress caused by swelling pressure of corrosion products or longitudinal cracks, and inadequate transmission of stresses by this cracks. However, only from experiment, it is not easy to judge how the conditions affect the deterioration of the damaged beams. So, in addition to the experimental study, a theoretical study was conducted in order to investigate the relationship between the mechanical behaviour of damaged beams and the deterioration using elasto-plastic finite element analysis.

2. EXPERIMENTS FOR DAMAGED RC BEAMS

The loading and bond tests were conducted for RC specimens damaged with an accelerated galvanostatic corrosion method, along with numerical analysis which will be discussed later.

2.1 Specimens

The RC beams for loading tests were shown in Fig.1, which had single reinforcement without stirrups. The ratio of reinforcement was 1.3%, and the ratio of shear span(a/d) was 4.2. The specimens for pull-out test were shown in Fig.2.

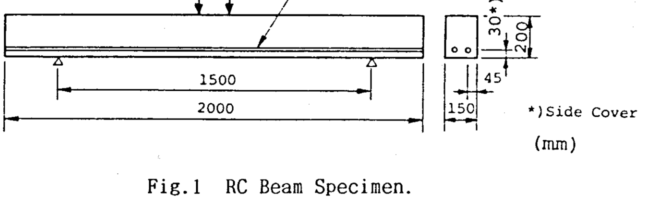

Fig.1 RC Beam Specimen.

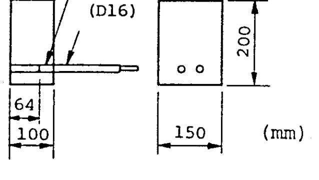

Fig.2 Pull-Out Test Specimen.

They had the same sections with the RC beams in order to give the same condition to the galvanostatic corrosion, and were made with the same materials, i.e., the strength of concrete was 35.6MPa, the tensile strength was 3.2MPa, the modulus of elasticity of concrete was 2.65×10^4MPa, and the yield strength of reinforcement was 353MPa, the modulus of elasticity was 2.06×10^5MPa. Table 1 showed mix proportion of the concrete.

Table 1 Mix Proportion of Concrete.

Nominal Strength (MPa)	Slump (cm)	Maximum Size of Coares Aggregate (mm)	Air Content (%)	Water Cement Ratio (%)	Sand Percentage (%)
20.6	8.0	25	4.0	59.0	42.4

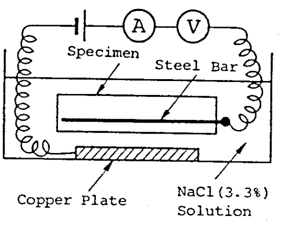

Fig.3 Galvanostatic Corrosion System.

2.2 Galvanostatic Corrosion of Reinforcement

The accelerated galvanostatic method was shown in Fig.3, and the reinforcement was corroded by the application of external electric current. This method causes uniform corrosion of whole body of reinforcement, and it is possible to control the degree of corrosion by integration of electric current. In this study, specimens which were corroded under the condition of electric current density 0.5mA/cm^2 for 0-day(non-corroded), 3-days, 6-days, 10-days, and 15-days were used. Fig.4 ~ 6 show the state of galvanostatic corroded beam specimen after 15-days. It was obvious that the generation of internal stresses due to swelling of corrosion products and the cracks developed up to the bottom surface as well as up to the side surface. The maximum crack width was 0.75mm, and the percentage of weight loss of reinforcement was about 5%.

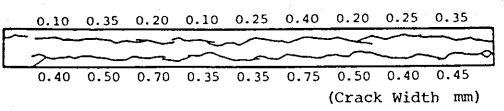

Fig.4 Growth of Cracks after 15-days Current Period.

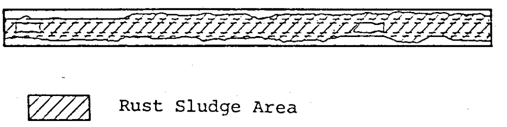

Fig.5 Rust Sludge Area after 15-days Current Period.

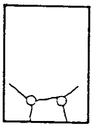

Fig.6 Growth of Cracks after 15-days Current Period.

2.3 Loading Tests

The loading tests shown in Fig.7 were conducted for non-corroded and damaged beam specimens. The load distribution beam shown in Fig.7 was adopted in order to obtain the relation between load and deflection over the piont of load carrying capacity[8]. Fig.8,9, and Table 1 showed the results of loading tests. From these results, non-corroded and galvanostatic corroded specimens for the current period of 3-days showed normal behaviour, and failed in flexure with steel bars yielded. On the other hand, the specimens for the current period of 10-days and 15-days showed deteriorated behaviour, and failed in bond shear in the brittle manner, and the reduction in stiffness and the load carrying capacity occurred. It is impossible to explain these behaviours by weight loss of reinforcement because of difference in failure type. And specimens for the current period of 6-days showed intermediate behaviour.

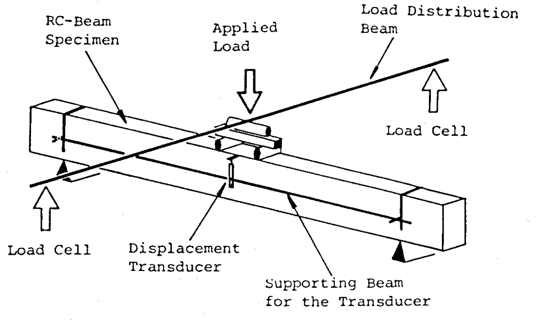

Fig.7 Loading Test.

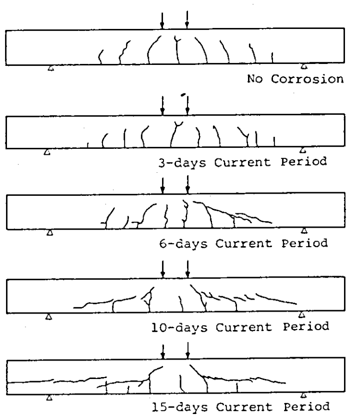

Fig.8 Crack Pattern at Failure.

Table 2 Summary of Results for Loading Test.

Specimen	Current Period ($0.5mA/cm^2$)	Crack Width (mm)	Steel Yield Load (ton)	Load Carrying Capacity (ton)		Failure Type
					Average ( )-Rate	
0-A 0-B 0-C	No Corrosion	-- -- --	5.04 5.38 5.19	6.00 6.52 6.33	6.29 (1.00)	Flexure
3-A 3-B 3-C	3-days	-- -- --	5.36 5.24 5.92	6.18 6.16 6.45	6.26 (1.00)	Flexure
6-A 6-B 6-C	6-days	0.10 0.10 0.10	5.09 5.40 5.32	5.65 5.53 5.73	5.64 (0.90)	Shear - Compression
10-A 10-B 10-C	10-days	0.45 0.65 0.45	5.16 -- --	5.71 5.37 4.96	5.35 (0.85)	Bond - Shear
15-A 15-B	15-days	0.75 0.50	-- --	5.60 5.45	5.55 (0.88)	Bond - Shear

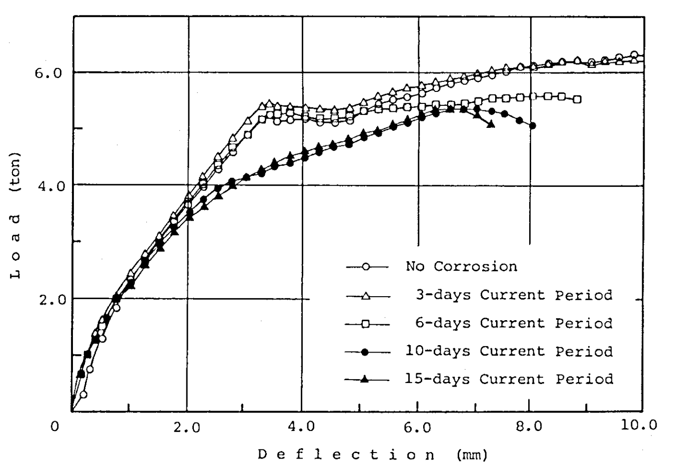

Fig.9 Load - Deflection Relation.

Reports of former experiment[3],[4],[6] described that the reduction in load carrying capacity was observed in RC beams which had single reinforcement without stirrups by galvanostatic corrosion. These experimental results would coincide with the results of this study. However these reports described that the reduction in load carrying capacity was not observed in RC beams with stirrup even when damaged with galvanostatic corrosion. These behaviour must be investigated with the experimental results of this study.

2.4 Bond Tests

Pull-out tests shown in Fig.10 were conducted. This test is not entirely realistic as a measure of bond strength in a beam, because it carries no shear on the section[9]. But this is an useful test to estimate the changes of properties of the friction, cohesion and mechanical engagement between concrete and reinforcement. In this test, 5 specimens in each stage of corrosion degree were used. The results are shown in Fig.11. Reports of former experiment[10] described that the reduction in maximum bond strength did not occure at the degree of corrosion by using push-out tests. In this pull-out test, the reduction in maximum bond strength occurred at the degree of corrosion which was attained after 3-days current period. The increase of stiffness also occurred at the degree of corrosion in all cases.

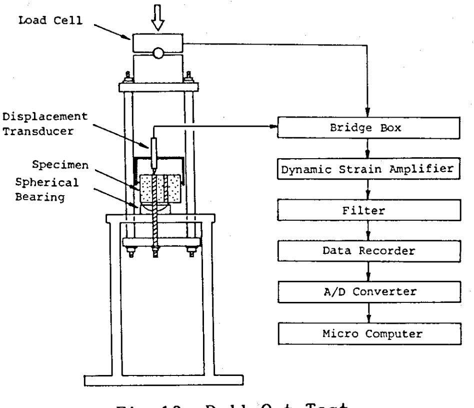

Fig.10 Pull Out Test.

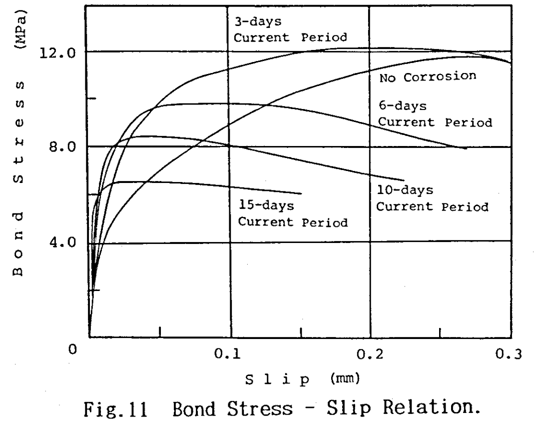

Fig.11 Bond Stress - Slip Relation.

In addition to the pull-out test, punching-shear tests shown in Fig.12,13 were conducted, because the cracks developed up to the side and the bottom surfaces by galvanostatic corrosion and the inadequate stresses transmission between concrete and reinforcement by these cracks had to be investigated. In this test, 3 specimens shown in Fig.12 which had cracks generated by using galvanostatic corrosion, were used. The maximum shear stress transmission at the cracked face was 0.58MPa in the experiment, which is much less than the shear strength of concrete (generally 1/4~1/7 of the compression strength). So, the inadequate transmission of stresses by these cracks was confirmed.

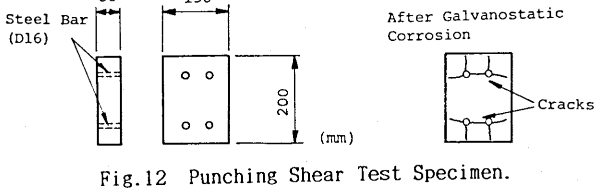

Fig.12 Punching Shear Test Specimen.

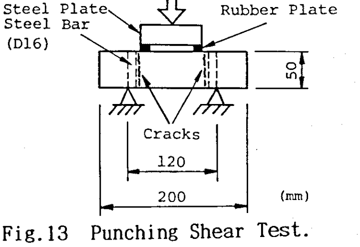

Fig.13 Punching Shear Test.

2.5 Deterioration in Damaged Beams

It was confirmed that the reduction in stiffness and the load carrying capacity occurred in the damaged beam, and the changes of properties by galvanostatic corrosion were shown in the experiment. These changes of properties were derived from the deterioration of bond strength which was confirmed by the pull out tests, the inadequate transmission of stresses by cracking of axial direction shown in punching shear test, and the generation of internal stresses caused by the swelling of corrosion products. However, only from the results of this experiments, it is not easy to judge how the conditions affect the action of these damaged beams directly, or secondarily. Then, as an analytical method, the elasto-plastic finite element analysis was used for the examination of respective conditions.

3. ELASTO-PLASTIC FINITE ELEMENT METHOD

3.1 Modelization of Concrete and Steel Bar

The constitutive equation for concrete and steel bar were based on plastic flow theory, these materials were assumed homogeneous. The model by Chen et al.[11] and the model by von Mieses[12] were used. The failure criteria for concrete followed the Chen's model. With respect to the crack, The Smeared Cracking Model which considered a continuous crack within a finite element was used. The finite elements were shown in Fig.14, constant strain triangular elements was adopted. As to the properties of concrete and steel bar used in analysis, material constants obtained from the experiments shown in former were used.

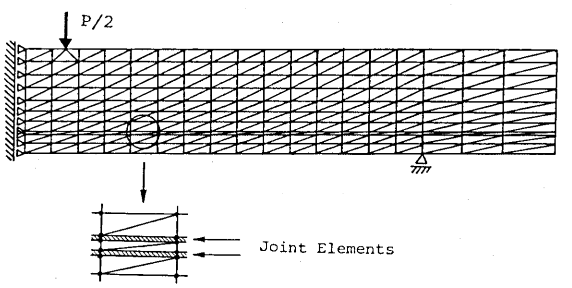

Fig.14 Finite Elements for the RC Beam Specimen.

3.2 Modelization of Interface

For the interface between concrete and steel bar, joint elements by Goodman et al.[13] shown in Fig.15(t=0.2cm) were used. By using this element, it is possible to express the deterioration obtained from the pull-out test or the punching shear tests in the numerical analysis[14]. This joint element is compatible with a constant strain triangular element. In the model of Goodman et al., the normal stress, the shear stress and the moment were treated as stress components. However, the moment was not taken into consideration in this study. The stiffness matrix is shown in next equation.

$$\begin{bmatrix} \tau \\ \sigma \end{bmatrix} = \begin{bmatrix} Ks & 0 \\ 0 & Kn \end{bmatrix} \begin{bmatrix} \gamma \\ \varepsilon \end{bmatrix} \tag{1}$$

In this matrix, Ks and Kn are stiffness moduli.

3.3 Numerical Procedure

The load increment analysis on plain stress condition was employed in the finite element method. In each step, conditions of each finite element were checked; if some elements had failure, the stresses were released, and then the procedure was repeated until the released force due to failures of other elements disappeared. For solving the linear systems of equation, the conjugate gradient method was employed.

4. ESTIMATION OF DETERIORATION FACTORS BY ANALYSIS

Using finite element analysis, the influence of the changes of properties by corrosion of reinforcement on the behaviour of damaged RC beam were discussed. In this study, non-corroded beams and galvanostatic corroded beams for the current period of 15-days were concerned.

4.1 Treatment of Deteriorated Properties

In analysis, deteriorations of friction, cohesion and mechanical engagement between reinforcement and concrete which can be evaluated by pull-out test, are found possible to express by changing the properties of joint elements. Further, internal stress which was caused by swelling pressure of rust can be expressed by initial stress, and the inadequate transmission of stresses caused by axial cracking could be expressed similarly by changing the properties of joint elements. Here, the treating method of above mentioned deterioration will be explained.

(1) Correspondence with Properties of Joint Elements
Deterioration based on pull-out test, is possible to express by regarding the relation τ-γ in equation(1) as the relation between bond stress of reinforcement and strain. In this case, the thickness of joint element in depth-wise direction is determined by the value corresponding to the circumferential length of reinforcement. Concerning the evaluation of stiffness Ks of joint elements, inverse analyses for results of the pull-out test shown in Fig.10 were carried out by dividing elements which was illustrated in Fig.16.

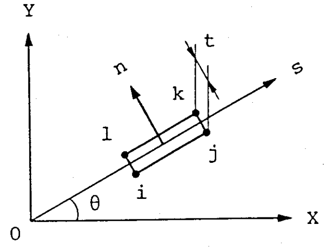

Fig.15 Joint Element[13].

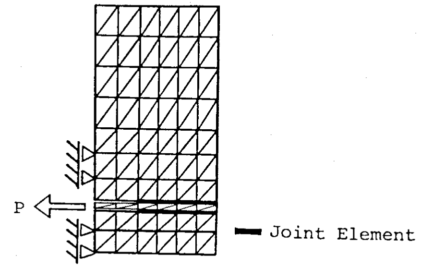

Fig.16 Finite Elements for the Pull-Out Test Specimen.

The relation τ-γ was assumed to be the next exponential curve in this study (ref. Fig.17).

$$\tau = \tau max \left(1 - \exp\left(- \frac{G}{\tau max} \gamma\right)\right) \tag{2}$$

τmax is maximum bond strength shown in Fig.11, and G is a constant which could be determined by the inverse analysis. Accordingly, stiffness Ks in equation(1) is determined by the slope of this curve. The constants which were determined in this way were G=490MPa and τmax=11.8MPa for non-corrosion, G=980MPa and τmax=6.4MPa for galvanostatic corrosion after 15-days current period. The results of inverse analysis were shown in Fig.18. In σ-ε relation, 4900MPa was used as value of stiffness Kn which corresponded to complete bond. Thus, the properties of joint elements determined, and could reflect in the analysis of deterioration which were shown by pull out test.

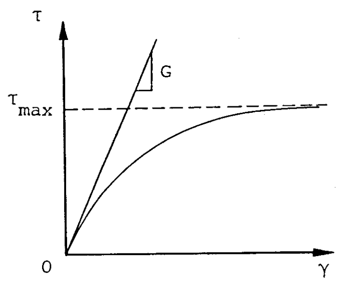

Fig.17 Proposed Relation Between τ and γ.

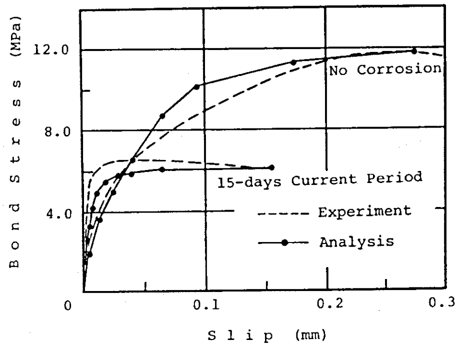

Fig.18 Comparison Between Experiment and Analysis for the Pull-Out Test.

Beside, inadequate transmission of stresses caused by cracks of axial direction is possible to express by regarding the relation τ-γ as the relation between shear stress which is transmitted by cracked surface and strain. In this case, thickness of joint elements in depth direction is considered to be the thickness of RC beam. Here, it is desirable to determine the properties of joint elements which correspond to the deterioration caused by cracks of axial direction, by similar method showed above, but the determination is difficult only from the results of punching shear test which was shown in Fig.13. Consequently, the relation τ-γ was assumed to conform with equation(2), and τmax is shear strength at cracked surface. Accordingly, τmax=0.58MPa which was obtained by the punching shear tests was used in analysis. Further, constant G is supposed to be lowered in cracked surface compared to that of concrete, then G=78.4MPa was determined to use in analysis. Thus the inadequate transmission of stresses which was shown by the experiment, is possible to express by the use of joint element.

(2) Introduction of Initial Stress

Fig.19 is diagrammatic illustration of the condition of cracking which was caused by the swelling of corrosion products[15]~[17], and distribution of tensile stress on X axis. From this figure, as the degree of swelling increases, longitudinal cracks in the bottom and side surfaces are found to connect with each other (Fig.19(c)), but internal stresses are introduced into concrete in intermediate stage, and stress near tensile stress is found to be introduced at the end point of cracks (Fig.19(a)(b)). It is easy to estimate that this area of high tensile stress forms weak point zone. Such internal stresses can be expressed by the initial stress. However, 2 dimensional analysis was applied in this study, thus the internal stress was treated as an initial stress under uniform condition in depth-wise direction, as tensile stress which was introduced vertically to axis of reinforcement. When the state in Fig.19(b), according to references [16],[17], initial stress σi is about 0.59MPa, if the distribution in section is equalized in depth-wise direction of RC beam. However, such evaluation method could not express the existence of the area of high stress which is supposed to form weak point. Then, as introducing

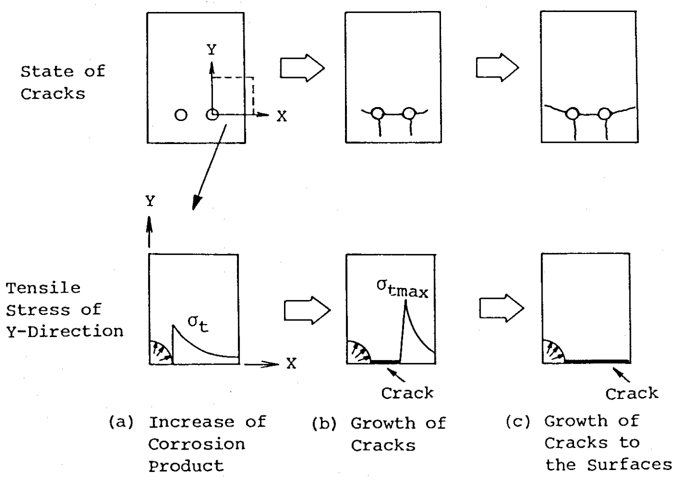

Fig.19 The State of Tensile Stress and Cracks.

amount of initial stress σi in analysis, σi=0.59MPa, and σi=1.18MPa were determined to consider. The element introduced initial stress was fixed to the shaded portion in Fig.20, because swelling cracks was confirmed to develop on the upper side of reinforcement(ref. Fig.6), and for the properties of joint elements, G=490MPa and τmax=11.8MPa for non-corrosion were used. Thus, initial stress which was generated by swelling pressure of rust is possible to express in analysis.

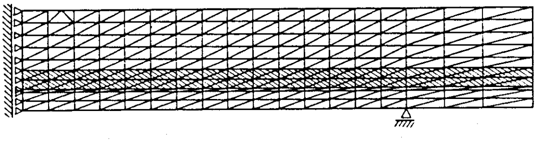

Fig.20 Elements Introduced Initial Stress.

4.2 Results of Analysis

As described above, bond deterioration of reinforcement based on pull-out test, internal stress caused by the swelling pressure of corrosion products, and the inadequate transmission of stresses to reinforcement caused by longitudinal cracks were expressed. Investigations on their influences on the behaviour of damaged RC beams were carried out.

(1) Bond Deterioration (Case-1)
Bond deterioration based on pull-out test is possible to express as shown in 4.1 (1). Fig.21 shows the results of analysis, i.e. the relation between load and displacement at span center along with the results of loading test. The results of analysis with properties of non-corroded specimen show some higher stiffness compared to that of experimental result, but both may be considered to show agreement. However, in analysis using bond properties of galvanostatic corrosion after 15-days current period, it was impossible to express the change of behaviour of damaged RC specimens which was observed in experiment. Consequently, the direct influence of deterioration of friction, cohasion and mechanical engagement between reinforcement and concrete were supposed small.

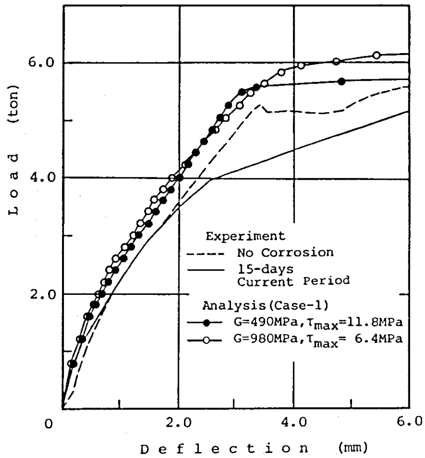

Fig.21 Comparison Between Experiment and Analysis(Case-1).

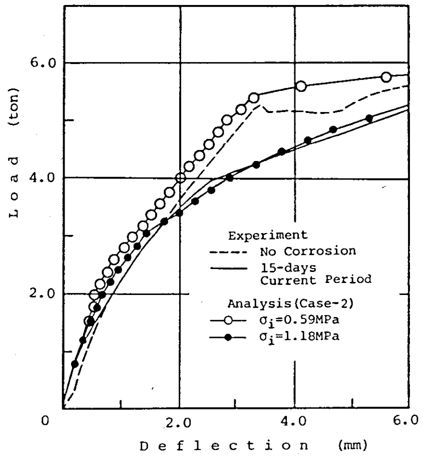

Fig.22 Comparison Between Experiment and Analysis(Case-2).

(2) Internal stress (Case-2)

Internal stress is introduced to concrete by swelling of corrosion products, and is expressed by initial stress σi as shown in 4.1 (2). Fig.22 shows the results of analysis. From Fig.22 influence is hardly recognizable when σi=0.59MPa is taken, but when σi=1.18MPa is taken, the reduction in stiffness of damaged RC beams which was observed in experiment, was possible to express. The reason that the expression of deteriorating behaviour was possible, can be explained as follows. Smeared analytical cracks along the axis of reinforcement as showed in Fig.23(b) were generated in part of element to which initial stress was introduced in load incremental analysis, and transmission of shearing stress between concrete and reinforcement was obstructed. The state in which the face of poor shearing transmission is similar to the state which was shown in Fig.19 (c), and the explanation for damaged RC beams is possible by the inadequate transmission of stresses by longitudinal cracks shown as follow Case-3.

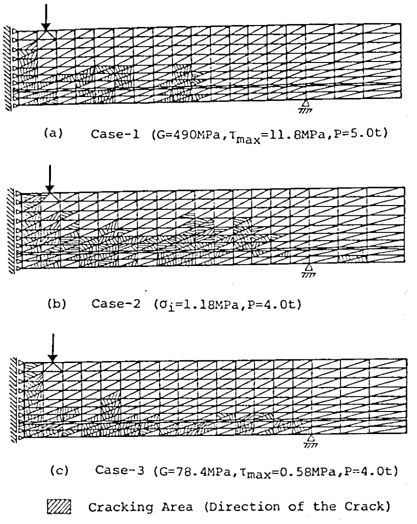

Fig.23 Failure Pattern.

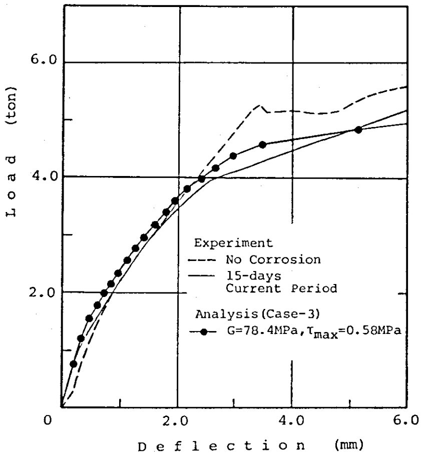

Fig.24 Comparison Between Experiment and Analysis(Case-3).

(3) Longitudinal Crack (Case-3)
As the degree of swelling of corrosion products increases, longitudinal cracks are developed to the surfaces of RC beam, and this condition is possible to express by the properties of joint element as shown in 4.1 (1). Fig.24 shows the results of analysis. These results showed the reduction in stiffness of damaged RC beams, and it was possible to express the behaviour of damaged RC beam which was observed in experiment.

4.3 Estimation of Deterioration Factors

Concerning factors which affect deteriorating behaviour of damaged RC beams, analytical examinations were carried out as described above. As the explanation for results of deterioration behaviour of damaged RC beam was impossible by deterioration of friction, cohesion and mechanical engagement of reinforcement which were evaluated by the pull-out test, but the deficit of the transmission of shearing stress between concrete and reinforcement caused by the internal stress, longitudinal cracks by swelling of corrosion products, affected the behaviour.

5. SUMMARY

Loading tests were conducted for RC beam specimens damaged with accelerated galvanostatic corrosion method, and reduction of load carrying capacity and stiffness were observed in damaged RC beam compared to non-corroded RC beam. Estimation of cause of deteriorating behaviour was carried out by elasto-plastic finite element analysis. As the result of analysis, behaviour of damaged RC beam was possible to explain by using the model which express inadequate transmission of stresses between reinforcement and concrete, and this inadequate transmission of stresses was estimated to be one of factors which has influence upon deteriorating behaviour.

It was shown by experiment that the inadequate transmission of stresses was caused by longitudinal cracks which was developed along the side of RC beam by swelling of corrosion products. Thus, this generation of cracked face was shown to be a turning point for discussing the mechanical behaviour of RC beams damaged by corrosion of reinforcement. Moreover, even in the state that longitudinal cracks did not reach to the side surface of RC beam, it was found that there was possibility of causing inadequate transmission of stresses because of the existence of weak zone which was introduced internal tensile stress by swelling pressure in the end of cracks.

In the case of discussing the load carrying capacity, these consideration is applicable to RC beams without stirrup for providing strength against shearing. With respect to RC beams with stirrup, reports of former experiment[3]~[6], described that remarkable reduction in load carrying capacity was not observed in RC beams even when damaged with galvanostatic corrosion. This result could be explained with above mentioned consideration, the transmission of shearing stress between concrete and reinforcement is secured through stirrups even when bond property of reinforcement is deteriorated. Consequently, in actual structure, in addition to the weight loss of reinforcement, the effect of stirrups for these transmission of stresses must be discussed about the behaviour of damaged beams.

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References

[1] Japan Concrete Institute, Deterioration of Reinforced Concrete Structure by Chlorides. Concrete J., Vol.25, 1987. (in Japanese)
[2] Kobayashi,K., Mechanism of Deterioration of Concrete Structures by Corrosion of Reinforcement. The Civil Engineering J., Vol.25 No.10, pp.89-94, 1984. (in Japanese)
[3] Uomoto,T., Tsuji,K. and Kakizawa,T., Mechanism of Deterioration of Concrete Structures Caused by Corrosion of Reinforcing Bars. Proc. of JCI, Vol.6, pp.173-6, 1984. (in Japanese)
[4] Takewaka,K. and Matsumoto,S., Behaviour of Reinforced Concrete Members Deteriorated by Corrosion of Reinforcement. Proc. of JCI, Vol.6, pp.177-80, 1984. (in Japanese)
[5] Okada,K., Kobayashi,K., Miyagawa,T. and Kutomi,O., Influence of Longitudinal Crack due to Reinforcement Corrosion on Characteristics of Reinforced Concrete Member. Proc. of JCI, Vol.7, pp.113-6, 1985. (in Japanese)
[6] Misra,S. and Uomoto,T., Effect of Corrosion of Reinforcement on the Load Carrying Capacity of RC Beams. Proc. of JCI, Vol.6 No.2, pp.675-80, 1987.
[7] Misra,S. and Uomoto,T., A Study on Structural Implications of Reinforcement Corrosion. Proc. of the 42th annual conference of JSCE V, pp.408-9, 1987.
[8] Koyanagi,W., Rokugo,K. and Uchida,Y., Stability and Measurement of Concrete Failure. Concrete J. Vol.20 No.6, pp.83-9, 1982. (in Japanese)
[9] Ferguson,P.M., Turpin,R.D. and Timpson,J.N., Minimum Bar Spacing of Bond and Shear Strength, J. of ACI, pp.869-97, 1954.
[10] Morinaga,S., Chlorides and Cracks, Cement & Concrete, No.451, pp.110-17, 1984. (in Japanese)
[11] Chen,A.C.T. and Chen,W.F., Constitutive Relation for Concrete. Proc. of ASCE, Vol.101 No.EM4. pp.465-81, 1975.
[12] von Mieses,R., Mechanik der Plastishen Form anderung von Kristallen, Zeitschrift fur Angewandte Mathematik und Mechanik(ZAMM), Vol.18, pp.161-85, 1928.
[13] Goodman,R.E., Taylor,R.L. and Brekke,T.L., A Model for the Mechanics of Jointed Rock. Proc. of ASCE, Vol.94 No.SM3. pp.637-59, 1968.
[14] Kajikawa,Y., Tachibana,Y. and Yoshida,H., Mechanical and Failure Behaviour of Plane Models composed of aggregates and Mortar, Proc. of JSCE, No.356/I-3, pp.369-77, 1985. (in Japanese)
[15] Morikawa,M., Seki,H. and Okumura,T., Basic Study on Cracking of Concrete due to Expansion by Rebar Corrosion, Proc. of JSCE, No.378/V-6, pp.97-106, 1987. (in Japanese)
[16] Tsunomoto,M., Kajikawa,Y. and Tachibana,Y., Elasto-Plastic Analysis of Expansive Behaviour due to Corrosion of Reinforcement, Proc. of the 42th annual conference of JSCE V, pp.404-5, 1987. (in Japanese)
[17] Konishi,Y., Seki,H., Matsui,K. and Matsushima,M., FEM Analysis of Cracking due to Corrosion of Reinforcement, Proc. of the 42th annual conference of JSCE V, pp.406-7, 1987. (in Japanese)