Fracture Mechanics of Concrete Structures
Proceedings FRAMCOS-3
AEDIFICATIO Publishers, D-79104 Freiburg, Germany

CRACK PROPAGATION ANALYSIS OF CONCRETE DUE TO EXPANSION OF REINFORCEMENT CORROSION

T. Matsuo and T. Kanazu
Central Research Institute of Electric Power Industry, Japan

Abstract

In this report, cracking of cover concrete due to the expansion stress induced by reinforcement corrosion was analyzed. This analysis can estimate the limit value of reinforcement corrosion which is defined as a rust volume when a crack due to expansion stress penetrate the entire cover concrete. The analyzed examples were in close agreement with the experimental results.
Key words: Reinforcement corrosion, crack propagation, fracture energy, tension softening

1 Introduction

Recently, crack propagation analysis of concrete based on fracture mechanics has been studied extensively to develop a rational strength estimation of concrete structures, in which fracture energy, tension softening behavior and other factors are considered.

In this study, we showed the results of crack propagation analyses of concrete due to expansion of reinforcement corrosion comparing with the experimental results.

It has been generally considered that mechanical performance of reinforced concrete deteriorated by salt injury degrades when a crack due to expansion stress penetrates the entire cover concrete. This is based on the fads that a rust volume is still marginal when a crack penetrates the entire cover concrete, but reinforcement corrosion progresses quickly after the crack has penetrated the entire cover concrete, and the relationship between reinforcement corrosion and mechanical performance has not been made clear.

Many simulations about cracking of concrete due to expansion of reinforcement corrosion have been executed, but it has not been found how much expansion stress is induced by reinforcement corrosion, and few numerical analyses have been conducted to compare with test results

2 Experiment

In this study, electrochemical corrosion tests, which could reproduce the deteriorated conditions of reinforced concrete by salt injury, were performed. We investigate influence of factors on concrete cracking due to expansion of reinforcement corrosion, such as water-cement ratio (45%, 55%, 65%) and cover concrete thickness (20mm, 40mm, 65mm) of specimens.

Mix proportion of concrete is shown in Table 1, and material properties of concrete are shown in Table 2. The dimensions of specimens are 6x6x10(cm), 10x10x10(cm), and 15x15x10(cm)(see Fig.1). The experimental equipment is shown in Fig. 2.

Table 1 Mix proportion of concrete

W/C (%)	s/a (%)	Slump (cm)	Air (%)	Unit weight (kg/m^3)				
				W (kg)	C (kg)	S (kg)	A (kg)	SP(%)
45	44	10±2.5	3±1	165	367	800	1038	0.92
55	46	10±2.5	3±1	165	300	862	1031	0.75
65	48	10±2.5	3±1	165	254	919	1014	0.64

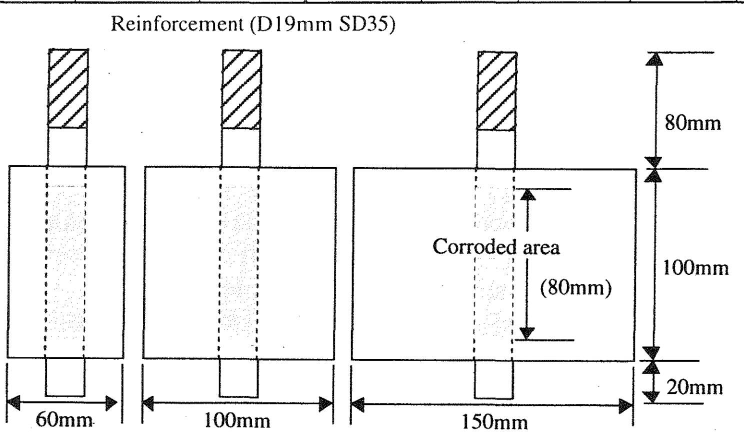


Fig.1 RC specimens in electrochemical corrosion test

Table 2 Material properties of concrete

W/C	Compressive Strength f'c (MPa)	Modulus of elasticity Ec (GPa)	Tensile strength ft (MPa)
45%	54.4	37.2	3.91
55%	42.8	33.7	3.12
65%	40.3	33.9	3.10

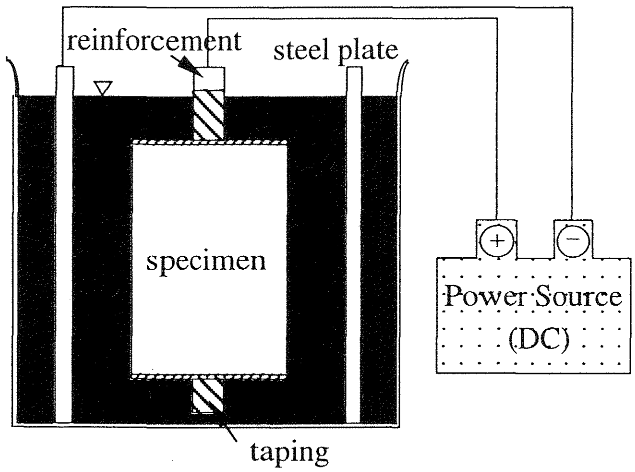


Fig.2 Experimental equipment

Cracking of cover concrete due to the expansion stress induced by reinforcement corrosion is influenced by cover concrete thickness of the specimens. The relationship between cover concrete thickness and the limit value of reinforcement corrosion per unit reinforcement surface area is shown in Fig.3.

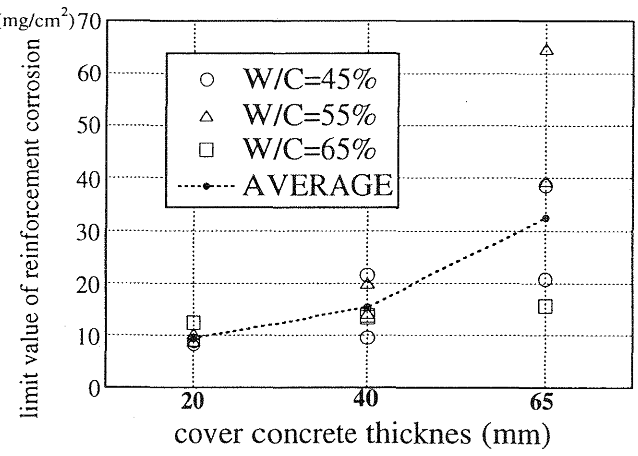


Fig.3 Limit value of reinforcement corrosion

3 Analysis

3.1 Modeling of Crack propagation Mechanism

Generally speaking, cracking appears crosswise at the early stage of reinforcement corrosion, and then only a crack propagates further(Fig. 4.).Crack propagation phenomena of concrete due to expansion of reinforcement corrosion was analyzed by 2D-FEM based on fracture mechanics.

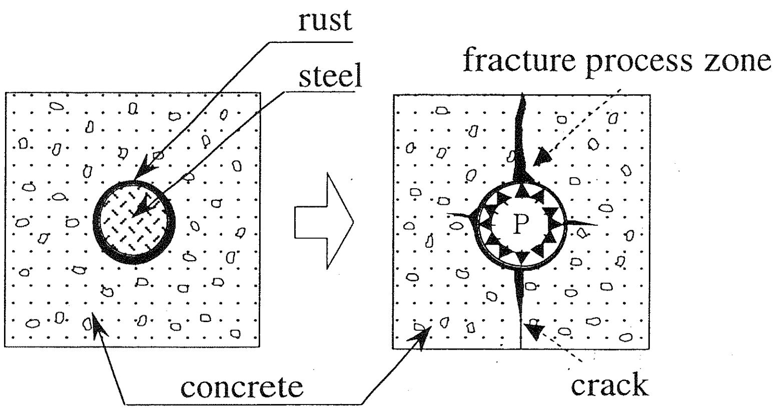
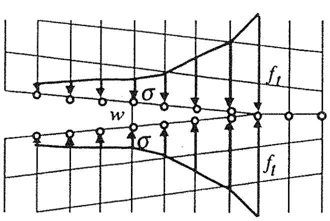


Fig.4 Conceptual Behavior of Crack Propagation

3.2 Analytical Method

2D-FEM analytical program using 'fictitious crack model was applied.
The s-w relation of crack element shown in Fig.5.is given at the crack opening, and the shear stiffness is assumed zero in the direction perpendicular to crack opening.



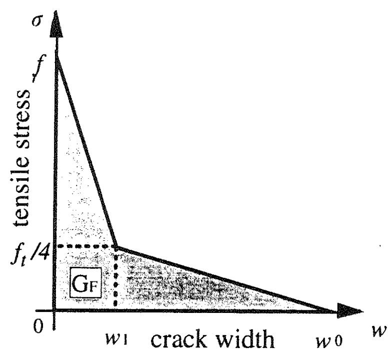


Fig.5 Fictitious crack model Fig.6 Bi-linear softening diagrams

Material properties in Table 2 were applied in the analysis, and fracture energy of concrete was calculated from by the CEB-FIP MC90 equation(1) ,which is given as a function of compressive strength.

$$G_F=0.03\times\left(\frac{f_c'}{10}\right)^{0.7} \quad (Nm/m^2) \qquad (1)$$

Fig. 7. shows FEM-Mesh employed in the analysis. Only a quarter section of the specimen was modeled in consideration of symmetry. Expansion of reinforcement corrosion was modeled by the uniform forced displacement normal to the circumference of the reinforcement.

Generally a volume expansion ratio of rust to steel depends on its components, stress condition ,etc. According to the results so far obtained, the volume expansion ratio of rust with respect to original volume prior to corrosion was found to be around 2.5 ,which was used in the analysis.

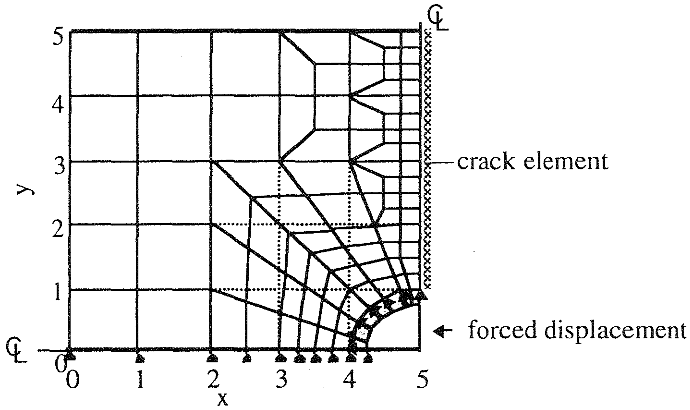


Fig.7 FEM Mesh

The rust thickness of reinforcement r_0 is given by

$$r_0=\frac{W_r}{\rho_s} \tag{2}$$

If a forced displacement U is equal to the expansion volume of rust, then

$$(dV-1)\times r_0=U \tag{3}$$

Therefore, the value of reinforcement corrosion is given by

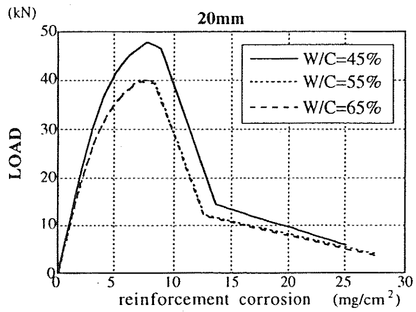
$$W_r=\frac{\rho_s \cdot U}{(dV-1)} \tag{4}$$

where

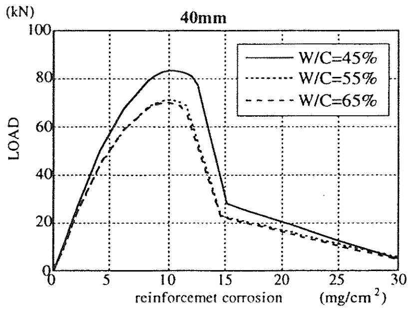
Wr ; unit area mass of reinforcement corrosion (g/cm^2)
rs ; density of steel (g/cm^3) (=7.85)
U ; forced displacement (cm)
dV ; expansion volume of rust (=2.5)

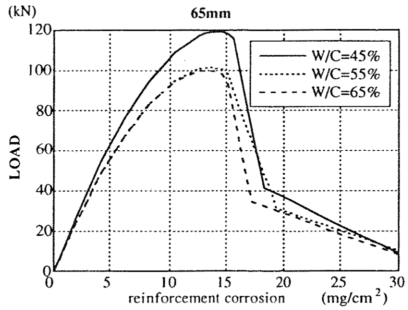
3.4 Analytical results

Fig. 8 shows P-Wr curve(analyzed results) in the case that the cover concrete thickness are 20(mm), 40(mm), and 65(mm) respectively. Load stands for total forces in the x-direction induced by expansion due to reinforcement corrosion.



(a) Cover concrete thickness(20mm)





(b) Cover concrete thickness(40mm) (c) Cover concrete thickness(65mm)

Fig.8 P-Wr curve(analytical results)

3.5 Comparison with test results

From test results, the limit values of reinforcement corrosion were 9.4, 15.4 and 32.5(mg/cm^2) for cover concrete thickness of 20, 40 and 65(mm), respectively. On the other hand, corresponding values at the maximum loads obtained by in the analyses were 7.5, 10.0 and 13.8(mg/cm^2) for cover concrete thickness of 20(mm), 40(mm), 65(mm), respectively.

The analyzed results were smaller than the test results. It is because the limit value of reinforcement corrosion in the test is defined as a rust weight per unit surface area of reinforcement when cracking in the surface of concrete is observed, corresponds to the situation in which cracking has fully developed to the concrete surface.

Fig.9. shows calculated stress distribution in cover concrete from the surface of reinforcement. According to Fig.9, the maximum load is attained at the (3)level, and also the area under the curve is maximum. The applied load drops steeply just after the level(4) point.The stress on the surface of cover concrete reaches tensile strength f_t between the level(4) and the level(5).

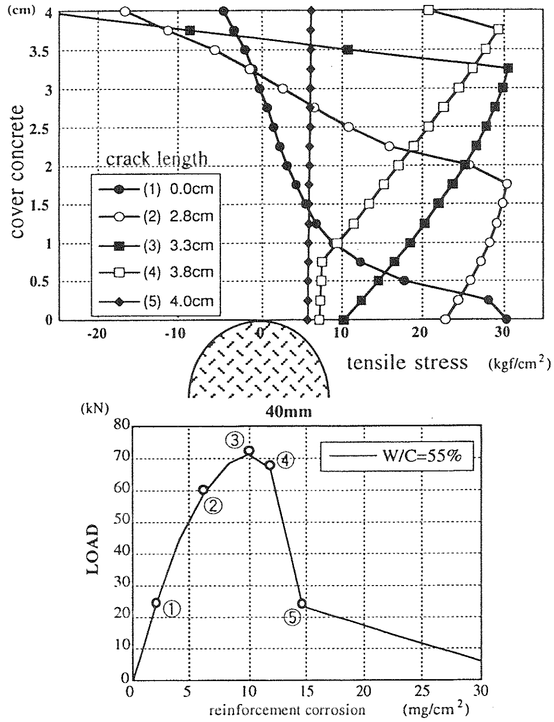


Fig.9 Stress distribution diagram of cover concrete

Fig.10 shows comparisons of the limit value of reinforcement corrosion obtained experimentally and analytically. Two cases of analysis were performed. Analysis-1 is the value of reinforcement corrosion at the maximum load, and analysis-2 is the value of reinforcement corrosion when the stress on the surface of cover concrete reached the tensile strengthf_t. Since the data point corresponding to W/C=65(%) and cover thickness of 65(mm) was abnormally high in Fig.3, it was deleted in the comparison.

In the analysis-1, the limit values of reinforcement corrosion are 8.5, 12.0 and 15.7(mg/cm^2) for cover concrete thickness of 20, 40 and 65(mm), respectively.

Analytical values of reinforcement corrosion in the case of cover of cover thickness of 65(mm) were considerably larger that those obtained in the tests. Other test results were comparatively in good agreement with analytical ones.

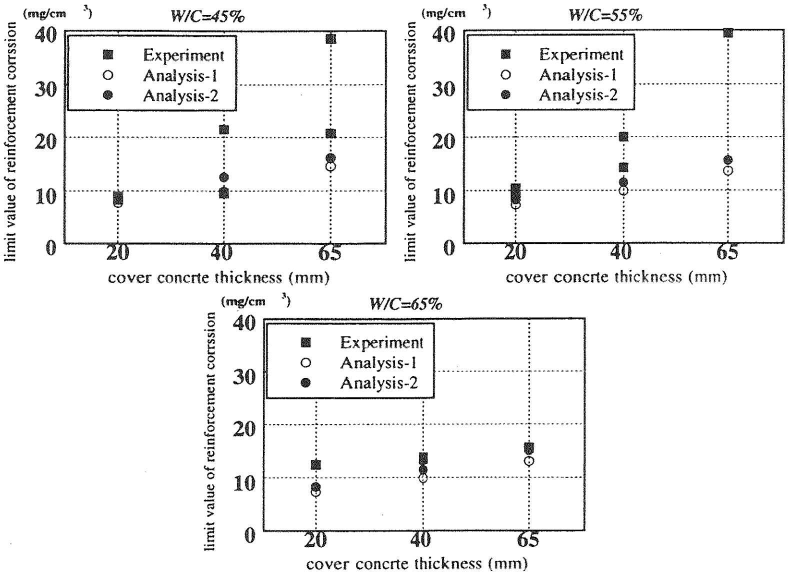


Fig.10 Comparison between test results and analytical results

4 Conclusions

Cracking behavior of cover concrete due to the expansion stress induced by reinforcement corrosion was analyzed. This analysis can estimate the limit value of reinforcement corrosion which is defined as a rust volume when a crack due to expansion stress penetrates the entire cover concrete. The analyzed results in general agreed well with the experimental ones.

This analysis can simulate crack propagation process and estimate the limit value of reinforcement corrosion if reinforcement corrosion can be estimated by means of theoretical and experimental investigations.

This method will be applicable to the prediction mechanical performance of reinforced concrete structure deteriorated by salt injury in the future.

5. References

CEB (1993) CEB-FIP model code, **Bulletin d'Information**, 213/214.

JCI (1993) **Applications of Fracture Mechanics to Concrete Structures,** 580p.

Morikawa, M., Seki, H. and Okumura, Y. (1987) Basic study on cracking of concrete due to expansion by rebar corrosion, **J. Struct. Mech. Earthq. Engrg.**, JSCE, 378/V-6, 97-105.

Niwa, J. (1993) Size effect analysis on the flexural strength of concrete beams with the nonlinear rod element, **Proc. of JCI**, 15(2), 75-80.

Suda, K., Misra, S., and Motohashi, K. (1992) Analytical studies on critical amount of corrosion for longitudinal cracking, **Prof. of JCI**, 14(1), 751-756.