Realistic model for corrosion-induced cracking in reinforced concrete structures

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ABSTRACT: The mechanism of pressure and thus stress build-up due to corrosion of a reinforcing bar in a reinforced concrete member is a very complex phenomenon because there is a certain pressure-free corrosion strain which has not been explored in the previous studies. The purpose of the present study is to explore the critical corrosion amount which causes the cracking of concrete cover and also to determine the realistic mechanical properties of corrosion layer including the pressure-free corrosion strain and the stiffness. To this end, a comprehensive experimental and theoretical study has been conducted. Major test variables include concrete strength and cover thickness. The corrosion products which penetrate into the pores and cracks around the steel bar have been considered in the calculation of expansive pressure due to steel corrosion. A concept of pressure-free strain of corrosion product layer was devised and introduced to explain the relation between the expansive pressure and corrosion strain. The proposed theory shows good correlation with corrosion test data of reinforced concrete members.

1 INTRODUCTION

The corrosion products of a reinforcing bar in concrete induce pressure to the surrounding concrete due to the expansion of steel. This expansion causes tensile stresses in concrete around the reinforcing bar and eventually induces cracking through the concrete cover (Bazant 1979, Dagher & Kulendran 1992, Jang 2001, Jang 2003, Liu & Weyers 1998, Lundgren 2001, Martin-Perez 1998, Oh et al. 2002, Oh & Jang 2003a, 2003b, 2004, Ohtsu & Yosimura 1997).

The mechanism of pressure and thus stress build-up due to corrosion is a very complex phenomenon because there is a certain pressure-free corrosion strain which has not been explored in the previous studies. The realistic determination of the stiffness of the corrosion layer is also important because it also directly affects the cracking behavior of concrete.

The purpose of the present study is therefore to explore the critical corrosion amount which causes the surface cracking of concrete cover and also to determine the realistic mechanical properties of corrosion layer including the expansion free (pressure-free) corrosion strain and the stiffness of corrosion layer. To this end, a comprehensive experimental and theoretical study has been conducted. Major test variables include concrete strength and cover thickness. Several series of corrosion tests for a steel bar in concrete have been conducted and the strains at the surface of concrete cover have been measured according to the various amount of steel corrosion. The corrosion products which penetrate into the pores and cracks around the steel bar have been considered in the calculation of expansive pressure due to steel corrosion. The critical amount of corrosion, which causes the initiation of surface cracking, was determined from the present test results.

A concept of free expansion (pressure-free) strain of corrosion product layer was introduced to describe the relation between the expansive pressure and corrosion layer strain. A realistic relation between the expansive pressure and average strain of corrosion product layer in the corrosion region has been derived and the representative stiffness of corrosion layer was also determined.

2 BASIC MECHANISM OF DEFORMATION PROCESS DUE TO STEEL CORROSION

2.1 *Corrosion and Expansion Pressure*

The corrosion of steel bar in concrete causes the increase of volume. The expansive pressure due to volume increase of a steel bar in concrete generally induces the tensile stresses and strains in the surrounding concrete. The tensile strains of surrounding concrete due to steel expansion increase as the corrosion of steel bar progresses. Further increase of tensile strain will cause cracking in the surrounding concrete and the cracking will also happen at the surface of concrete cover during the expansion process.

In order to analyze the cracking of concrete cover due to steel corrosion, it is necessary to know the relation between the amount of corrosion of a steel bar and the internal pressure arising from corrosion. Therefore, a realistic relation between the amount of corrosion and the internal expansion pressure has been derived in this study.

2.2 *Deformation of Corrosion Layer*

The deformation around a steel bar due to corrosion expansion can be described as shown in Figure 1, in which r_b = initial radius of rebar, x_p = loss of radius of rebar due to corrosion, and w_{corr} = the ratio of weight loss due to corrosion to initial weight of rebar, respectively. The loss of rebar area due to corrosion can be expressed as follows.

$$\pi r_b^2 - \pi (r_b - x_p)^2 = \frac{W_{st}}{\rho_{st}} = w_{corr} \pi r_b^2 \tag{1}$$

where W_{st} =mass of rebar consumed by corrosion and ρ_{st} = density of steel bar.

Equation (1) can be rearranged to obtain the radius loss, x_p as follows.

$$x_p = r_b (1 - \sqrt{1 - w_{corr}}) \tag{2}$$

The volume of corrosion product made by consumed steel is larger than the volume of consumed steel itself. Therefore, the radius of steel bar after corrosion will increase by Δr_b and the following relation holds.

$$\pi (r_b + \Delta r_b)^2 - \pi r_b^2 = \frac{W_{rust}}{\rho_{rust}} - \frac{W_{st}}{\rho_{st}} = \frac{W_{st}}{\rho_{st}} \left(\frac{\rho_{st}}{\alpha \rho_{rust}} - 1 \right) =$$
$$\frac{W_{st}}{\rho_{st}} (v_r - 1) = \pi r_b^2 (v_r - 1) w_{corr} \tag{3}$$

where W_{rust} , ρ_{rust}=mass and density of corrosion products, respectively, and $v_r = \rho_{st} / \alpha \rho_{rust}$ =relative ratio of steel density to corrosion product density. The value of α can be obtained from the fact that the mass of steel component among corrosion products is the same as the mass of steel bar consumed by corrosion, i.e. $W_{st} = \alpha\ W_{rust}$. The value of α is 0.523 for hydrated red rust [$Fe(OH)_3$] and 0.622 for ferrous hydroxides [$Fe(OH)_2$], respectively, because the masses of Fe, O_2, and H_2 per one mol are 55.85g, 32g, and 2g, respectively. The α value ranges from 0.523 to 0.622 depending upon the types of corrosion products. The ratio of steel density to corrosion product density normally ranges from 2 to 4 (Jang 2002). Equation (3) can be rearranged to obtain Δr_b as follows.

$$\Delta r_b = r_b (\sqrt{1 + (v_r - 1) w_{corr}} - 1) \tag{4}$$

Figure 1 shows the volume expansion of corrosion product layer caused by the radius loss of a steel bar.

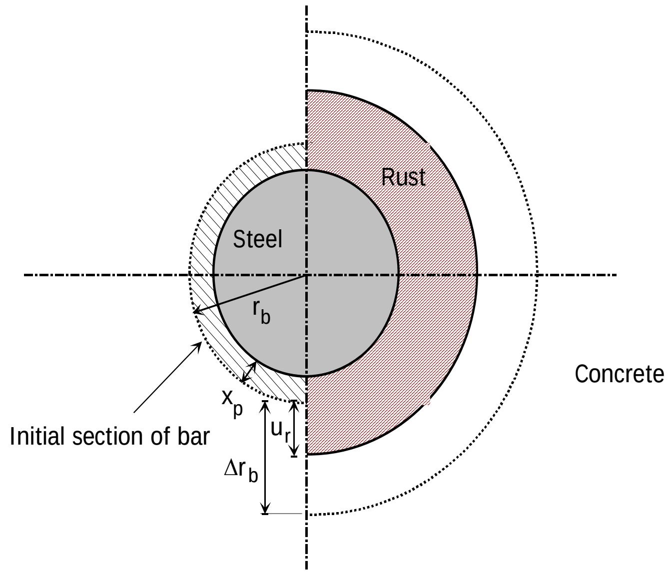

Figure 1. Deformation process due to steel expansion.

Lundgren (2001) considered the compaction effect of corrosion product layer due to surrounding concrete. Therefore, the free-expanded displacement Δr_b is reduced to u_r as shown in Figure 1. The ideal thickness of corrosion product layer, ($x_p + \Delta r_b$) decreases by ($\Delta r_b - u_r$) due to pressure force P caused by the restraint of surrounding concrete (see Figure 1).

The strain ε_{rust} of corrosion product layer due to compression effect is here defined as follows.

$$\varepsilon_{rust} = \frac{u_r - \Delta r_b}{x_p + \Delta r_b} \tag{5}$$

The corrosion product layer is compressed by the strain ε_{rust} due to expansive pressure P and thus the mechanical characteristic of corrosion layer may be expressed as

$$P = K_{rust} \varepsilon_{rust} \tag{6}$$

in which K_{rust} represents the stiffness of corrosion product layer. This model does not consider the corrosion products that are absorbed into cracks and pores in surrounding concrete. The cracks may happen in the vicinity of reinforcing bar due to circumferential tensile stresses caused by expansion of steel corrosion. Therefore, the corrosion products penetrate into the adjacent cracks in concrete and also into concrete pores. This may be the major drawback of the model previously expressed by Equation (6).

3 TESTS OF CONCRETE CRACKING DUE TO STEEL CORROSION

3.1 *Test Variables*

In the present tests, the surface concrete strains were measured as the corrosion of steel bar in concrete progresses. This will allow the determination of critical corrosion amount which induces the cracking on the surface of concrete cover. To this end, a comprehensive experimental program has been set up to execute the corrosion tests of steel bar in concrete.

The major test variables are the cover thickness and compressive strength of concrete. The concrete cover thicknesses considered were 2, 3, 4, and 5 cm, respectively. In order to consider the effect of compressive strength, the water-cement ratios of concrete were varied from 0.35 to 0.55. The test specimen identification was classified as H, N, and L which represent high strength (H), normal strength (N), and low strength (L) concretes, respectively, depending upon the water-cement (W/C) ratios.

3.2 *Test Materials*

The Type 1 ordinary Portland cement and the river sand with specific gravity of 2.55 were used. The specific gravity of crushed coarse aggregates was 2.6. The slump value of fresh concrete was controlled to be 150 mm and air content was 4.5 percent.

The compressive strengths of concrete for H, N, L series are 45, 40, 28 MPa, respectively. The tensile strengths for H, N, L series are 4.2, 3.9, 3.1 MPa, respectively.

3.3 *Test Specimens*

The size of test specimens was 200×200×200 mm cube and the cover thicknesses were 20, 30, 40, and 50 mm, respectively. The steel bar of 20 mm diameter was put in concrete specimen at the location of designated cover thickness. Therefore, the ratios of cover thickness to rebar diameter (c/d) are 1.0, 1.5, 2.0, and 2.5, respectively.

The region for steel corrosion was limited to the central portion of steel bar as shown in Figure 2. Both ends of steel bar were wrapped with PVC pipes and sealed with epoxy. The cross-hatched region in Figure 2 was exposed to corrosion.

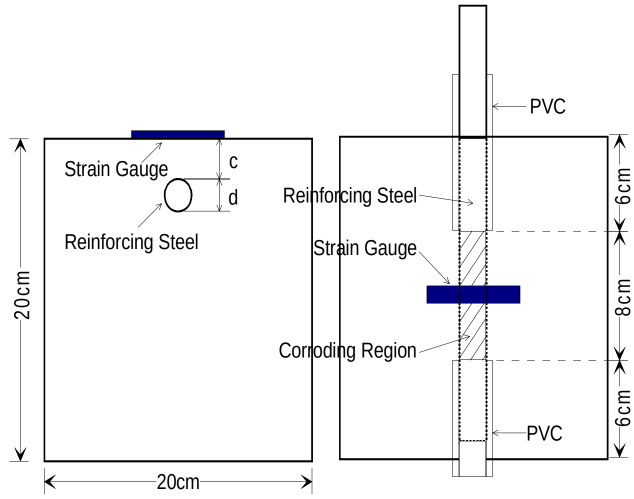

Figure 2. Configuration of test specimen and strain gage attachment.

3.4 *Test Method*

The test specimen was immersed in NaCl 3% solution and corrosion circuit was connected using direct-current power supply. The rebar in the specimen plays as an anode and the stainless steel plate as a cathode. The electrical potential between anode and cathode accelerates the penetration of chloride ions into concrete and thus accelerates the corrosion of steel bar. The concrete surface strains and electric potentials were measured every 30 minutes and these measurements were continued until the surface strain increases rapidly and reaches sufficient values. The wide-black line in the Figure 2 indicates the strain gages attached in order to measure the strain increase during the expansion process..

3.4.1 *Determination of Corrosion Amount by Faraday's Law*

The amount of corrosion can be calculated by Faraday's law. The amount of substance produced or consumed by the electrical quantity of one Faraday (F) is equal to the extracted substance of one chemical equivalent moved by one mol of electron. Equation (7) represents the amount of mol, X, extracted by electrolysis of substance with n electrons.

$$X = \frac{It}{nF} \qquad (7)$$

in which I=electric current in ampere, A, n = number of mole participating production reaction, and 1F=electric quantity of one mole of electron= 96,500 C. An electric resistance was installed in the corrosion circuit to measure the electric potential. The electric current was then obtained from the resistance value. The total electric change was also obtained by integrating the electric current values with respect to time and then the number of mol of corroded rebar was determined by using Faraday's law.

3.4.2 *Strain Measurement*

The strain values on the surface of concrete specimen were measured according to time. This is to see the increase of tensile strain due to volume expansion of corroded rebar and to find the time at which the crack occurs on the concrete surface. For this purpose, concrete strain gages were attached on the concrete surface near reinforcing bar as shown in Figure 2. The strain gages were installed in the direction perpendicular to the anticipated crack direction. From the measurement of concrete strains, the critical value of corrosion amount which causes the crack occurrence on the concrete surface has been determined.

4 ANALYSES OF TEST RESULTS

4.1 *Surface Strains according to Cover Thickness*

The measured strains on the surface of concrete specimens were plotted. Figure 3 shows the concrete strains according to the amount of corrosion for various specimens with different cover thicknesses. It can be seen from Figure 3 that the development of surface strains is larger and faster as the cover thickness becomes smaller. Namely, much larger strains occur for shallow-thickness specimens at the same corrosion amount. This is because expansive pressure due to same corrosion amount causes much larger surface strains for thinner-covered specimens.

The surface strain increases slowly at lower corrosion amount, but increase rapidly after a certain higher corrosion amount. This may be considered as the start of concrete cracking. The thinner-covered specimens show this rapid increase of strain at relatively lower corrosion amount. The thinner the cover thickness is, the lower the critical corrosion amount is.

4.2 *Surface Strains According to Water-Cement Ratio*

The test results indicate that as the water-cement ratio of concrete decreases the amount of corrosion that induces the same value of surface strain increases. This means that the strength of lower W/C concrete is higher and thus the stiffness is also higher. Higher stiffness of concrete needs higher expansive pressure (and thus higher corrosion amount) in order to develop the same surface strain. However, the water-cement ratio (or strength) of concrete does not affect much the corrosion-induced strains for the specimens with thin cover.

4.3 *Critical Corrosion Amount*

The point of sudden increase of strain in Figure 3 indicates the start of cracking for each specimen. Therefore, the critical corrosion amounts which cause the initiation of surface cracking were determined from the strain vs. corrosion-amount curves as shown in Figure 3. For example, the critical corrosion amount for N4 series with W/C=0.45 and 4 cm cover thickness is found to be about 4.25 %. The test results indicate that the critical corrosion amount increases with an increase of cover thickness and also increases with an increase of concrete strength.

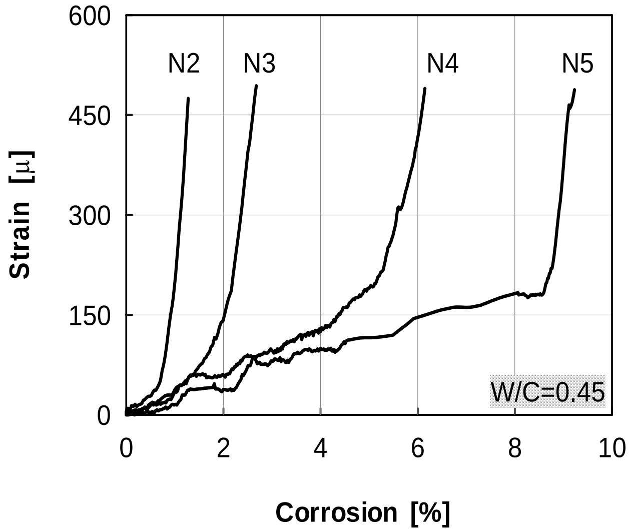

Figure 3. Measured surface strains according to corrosion amount for various cover thicknesses (W/C=0.45).

5 NONLINEAR ANALYSIS FOR CORROSION EXPANSION

5.1 *Analysis Outline*

Finite element analysis has been executed to explore the stress and strain distributions of concrete around the reinforcing bar due to corrosion expansion. The strains on the surface of concrete cover induced from internal pressure due to corrosion expansion have been calculated.

The eight-node plane strain element has been employed to model the test specimens. The material properties obtained from the tests have been used in the analysis. The bilinear stress-deformation relation after tensile strength was employed. The Newton-Raphson method was used for iterative nonlinear analysis.

In order to overcome the difficulties in convergence near peak load, the arc-length method was introduced. The arc-length method follows smoothly the load-displacement curve and enables to predict the behavior after peak load. Finer mesh pattern was used near the reinforcing bar.

The internal pressure due to corrosion expansion was applied to the radial direction at the outer line of reinforcing bar.

5.2 *Surface Strains*

The concrete strains on the surface of cover were obtained from the analysis. Figure 4 shows the relations between the surface strains and internal pressures for normal strength concrete specimens with different cover thicknesses. The surface strains increase almost linearly at low internal pressures and then increase rapidly after certain critical pressure. The overall trend of strain-pressure relation in Figure 4 is very much similar to the relation of experimentally-observed strain-corrosion amount in Figure 3.

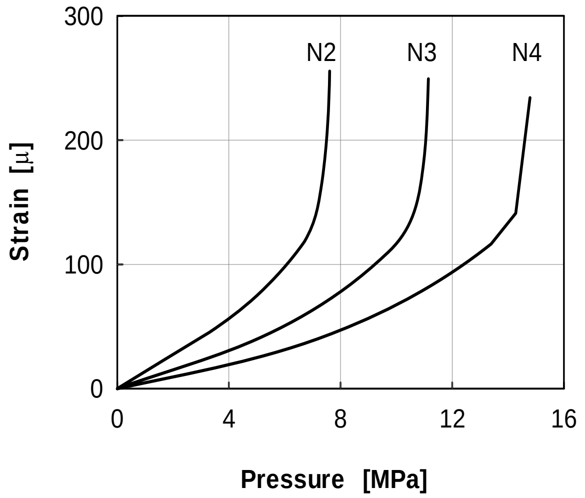

Figure 4. Analysis results for concrete surface strains due to internal pressure increase

6 EXPANSION PRESSURE ACCORDING TO CORROSION AMOUNT

6.1 *Cracks and Pores in Concrete*

The strains on the surface of concrete cover and the radial displacements at the outer line of rebar due to expansive pressure P were determined from the finite element analysis. The surface strains according to corrosion amounts were also obtained from the present tests. From the values of surface strains, radial displacements u_r, and corrosion amount w_{corr}, the strain ε_{rust} of Equation (5) can be determined with the use of Eqs. (2) ~ (4). Therefore, the relation between the internal pressure P and the strain of corrosion layer ε_{rust} was obtained..

A major drawback of Lundgren's model is that it does not consider the effects of penetration of corrosion products into the pores and cracks adjacent to the rebar. The cracks occur in concrete around the rebar due to corrosion expansion. These cracks may play a role to absorb the corrosion products and thus reduce the expansive pressure. In the present study, therefore, the effects of cracks and pores of surrounding concrete have been considered in the modeling of expansive pressure and corrosion layer strain.

The net amount of corrosion product, V_{net} may be summarized as follows.

$$V_{net} = V_{rust} - V_{crack} - V_{pore} \tag{8}$$

in which V_{net} = net amount of corrosion product, V_{rust} = total corrosion product, V_{crack} and V_{pore} = the amounts of corrosion product which penetrates into the surrounding cracks and pores, respectively. The total corrosion product V_{rust} may be derived as

$$V_{rust} = w_{corr} W_0 \left(\frac{1}{\alpha\rho_{rust}} - \frac{1}{\rho_{st}}\right)$$

$$= \pi r_b^2 (v_r - 1) \; w_{corr} \tag{9}$$

The volume of cracks, V_{crack} can be calculated by multiplying the total width of cracks by the depth of cracks.

$$V_{crack} = \frac{1}{2} h\,(\Sigma w_c) \tag{10}$$

in which h = the crack propagation depth which is obtained from the nonlinear finite element analysis at a specified internal pressure, and Σw_c = sum of the crack widths at the outer face of the rebar.

The total crack width Σw_c can be obtained from the circumferential tensile strain ε_θ at the outer line of rebar which arises from expansion pressure. Therefore, Equation (10) can be rewritten as follows.

$$V_{crack} = \frac{1}{2} h\,(\Sigma w_c) = \frac{1}{2} h(2\pi r_b)(\varepsilon_\theta - \varepsilon_0)$$

$$= \pi r_b h(u_r / r_b - \varepsilon_\theta) \tag{11}$$

in which $\varepsilon_\theta = u_r / r_b$; and ε_0= the strain at tensile strength = cracking strain of concrete = 0.002. The volume of pore, V_{pore} may be written as

$$V_{pore} = V_{net}\,\phi_r \tag{12}$$

In which ϕ_r = the porosity of concrete at the surface location of displaced (expanded) rebar = the porosity at the location $(r_b + u_r)$ from the rebar centroid.

The modified increase of rebar radius Δr_b^* may now be newly derived from Equation (4) and Eqs. (8)~(9).

$$\Delta r_b^* = r_b\left(\sqrt{1 + (v_r - 1)w_{corr} - (V_{crack} + V_{pore}) / \pi r_b^2} - 1\right) \tag{13}$$

The strain ε_{rust} is now rewritten as

$$\varepsilon_{rust} = \frac{u_r - \Delta r_b*}{x_p + \Delta r_b*} \quad (14)$$

The effects of cracks and pores have been considered in the present study as derived in Eqs. (8)~(14). It is generally anticipated that the consideration of cracks and pores around the rebar gives smaller values in radial displacement u_r, the strain ε_{rust} and the stiffness K_{rust} of corrosion layer.

6.2 *Variation of Porosities from Steel Interface to Distant Concrete*

The present study indicates that increase of porosity reduces the strain ε_{rust} for same expansive pressure. The porosity here represents that porosity at the displaced location u_r, not the porosity in pure distant concrete. Therefore, it is necessary to derive a porosity relation between the porosity ϕ_i at original steel-concrete interface and the porosity ϕ_0 at far-field distant concrete.

$$\phi_d = \phi_0 + (\phi_i - \phi_0) \exp(-kd) \quad (15)$$

in which ϕ_d = the porosity at the distance d from the original steel bar. The porosity of normal concrete ϕ_0 may be obtained from the literature and the Powers-Brownyard model which is a function of aggregate content, cement content, water content, and the densities of those ingredients has been used in this study.

The porosity ϕ_i at the initial interface is assumed to be 0.90 and the k value of 200 gives approximately the interface thickness of 20μm (Bourdette et al. 1995, Jang 2003). It is generally known that the interface thickness between steel bar and concrete is about 10~30μm (Jang 2003).

The displacement u_r at the first cracking on the surface of concrete cover was obtained from the analysis for each test specimen. The average porosity ϕ_{ave} between ϕ_i at the steel interface and ϕ_r at u_r was obtained from the average area under the porosity distribution curve. These average porosities have been used to derive the relation between P and ε_{rust}.

6.3 *Pressure-free Strain* ε_{fe}

Figure 5 shows the relation between P and ε_{rust} for various values of v_r where v_r represents the relative ratio of steel density to corrosion product density (see Equation (3)). It can be seen that an increase of v_r causes the increase of ε_{rust} which is required to induce the same expansion pressure. This means that larger value of v_r represents the corrosion product of low density and thus the compressed strain ε_{rust} of corrosion product layer must be larger to induce the same amount of expansion pressure. The detail examination of Figure 5 enables to determine the so-called free expansion (or pressure-free) strain ε_{fe} which induces no expansion pressure. This was not considered in Lundgren's model in Eqs. (5) ~ (6).

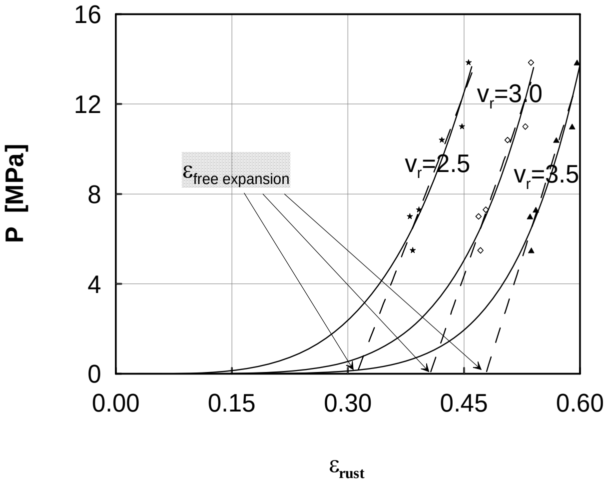

Figure 5. Variation of P according to ε_{rust} for various v_r values.

Therefore, new definition of the strain $\varepsilon_{rust}*$ has been established in this study as follows.

$$\varepsilon_{rust}* = \varepsilon_{rust} - \varepsilon_{fe} = \frac{u_r - \Delta r_b*}{x_p + \Delta r_b*} - \varepsilon_{fe} \quad (16)$$

It is seen from Figure 5 that linear relations are obtained between P and $\varepsilon_{rust}*$ as follows.

$$P = K_{rust}* \varepsilon_{rust}* \quad (17)$$

7 COMPARISON OF PROPOSED MODEL WITH TEST DATA

Figure 6 exhibits the comparison of the proposed model with test data on the surface strains and corrosion amounts for cover thicknesses of 4 cm. It can be again seen that the effect of concrete strength is rather small for small cover thickness, but it becomes larger for normally adopted large cover thicknesses. This is important in practice because the concrete structures exposed to sea environments normally have medium or large cover thicknesses to enhance the durability.

The comparisons of proposed analysis with test data were also made on the surface strains and corrosion amounts for various cases. Generally, good correlation between the analysis and test data has been observed. Those comparisons are not included here due to the length limitation of the paper.

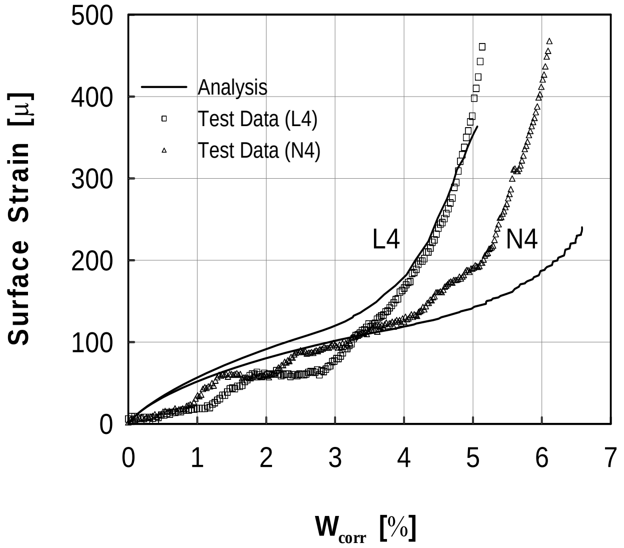

Figure 6. Comparisons of the effects of concrete strength on the surface strains according to corrosion amount w_{corr} for normal cover thickness of 4 cm.

8 CONCLUSION

The purpose of the present study is to explore the-critical corrosion amount which causes the surface cracking of concrete cover and also to determine the realistic mechanical properties of corrosion layer around a rebar which affect the expansion and cracking behavior of concrete structures under sea environments.

It is found that the critical corrosion amount increases greatly with an increase of cover thickness. The concrete strength also affects the critical corrosion amount. The effects of pores and cracks around a rebar have been considered in the modeling of expansion pressure and the strain of corrosion layer. A new concept of free expansion (pressure-free) strain was devised and introduced to derive the modified strain of corrosion product layer. The stiffness of corrosion product layer has been also determined and used to establish a new relation between expansion pressure and the strain of corrosion product layer. The analysis results have been compared with test data and they show generally good agreement.

Future studies may be necessary to develop a realistic method to directly measure the internal expansion pressure due to steel corrosion, which is not an easy task at present.

REFERENCES

Bazant, Z. P. 1979. Physical model for steel corrosion in concrete sea structures-Application. *J. Struct. Div., ASCE*, 105(6): 1155-1166.

Bourdette, B. et al. 1995. Modeling of the transition zone porosity. *Cem Concr Res* 25(4): 741-751.

Dagher, H. J. & Kulendran , S. 1992. Finite element modeling of corrosion damage in concrete structures. *ACI Structural Journal*, 89(6)..

Jang, B. S. 2001. Life time estimation method of reinforced concrete structures considering the effects of reinforcements on the chloride diffusion and the non-uniform corrosion distribution. PhD dissertation, Dept. of Civil Engineering., Seoul National University, Seoul. KOREA

Jang, S. Y. 2003. Modeling of chloride transport and carbonation in concrete and pre-diction of service life of concrete structures considering corrosion of steel reinforcements. PhD dissertation, Dept. of Civil Engineering., Seoul National University, Seoul. KOREA.

Liu, Y. & Weyers, R. E. 1998. Modeling the time to corrosion cracking in chloride contaminated reinforced concrete structures. *ACI Mat. J.*, 95(6): 675-681.

Lundgren , K. 2001. Modeling bond between corroded reinforcement and concrete. *Proceeding of the fourth international conference on fracture mechanics of concrete and concrete structures, Cachan, France, May 28 ~ June 1*, Fracture Mechanics of Concrete Structures, 1: 247-254.

Martin-Perez, B. 1998. Service life modeling of RC highway structures exposed to chlorides. PhD dissertation, Dept. of Civil Engineering, University of Toronto, Toronto, Canada.

Oh, B. H. & Jang, B. S. 2003. Chloride diffusion analysis of concrete structures considering the effects of reinforcements, *ACI Material Journal*, 100(2): 143-149.

Oh, B. H. et al. 2002. Development of high performance concrete having high resistance to chloride penetration. *Nuclear Engineering and Design*, 212(1-3): 221-231.

Oh, B. H. & Jang, S. Y. 2003. Experimental investigation of the threshold chloride concentration for corrosion initiation in reinforced concrete structures. *Magazine of Concrete Research*, 55(2):117-124.

Oh, B. H. & Jang, S. Y. 2004. Prediction of diffusivity of concrete based on simple analytic equations. *Cement and Concrete Research,* 34(3): 463-480.

Ohtsu, M. & Yosimura, S. 1997. Analysis of crack propagation and crack initiation due to corrosion of reinforcement. *Construction and Building Materials*, 11(7-8): 437-442.