Numerical Simulation for Corrosion Crack in Concrete Members Considering Penetration of Corrosive Product

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Abstract— **In reality, corrosion products expand and fill not only spaces and pores around steel bar but also micro cracks which are caused by its expansion. This paper attempted to simulate its expansion and penetration into concrete based on elastic expansion model. The apparent strain of corrosion expansion as a function of amount of corroded steel bar was utilized to consider penetration of corrosion product into concrete. Corrosion crack width was calculated based on this function. Experimental work was carried out to validate an apparent expansion model of corrosion expansion. Furthermore, appearance of the first crack and development of crack width on the surface of concrete cover were compared to result of experimental work. The results showed that corrosion crack width calculated using the apparent expansion model had a good correlation with experimental result both in RC and PC members.**

***Keywords** - Corrosion product, micro cracks, elastic expansion, apparent expansion, crack width*

I. INTRODUCTION

Corrosion expansion is one of the main factors which terminate service life of concrete structure. It reduces both capacity of steel bar and concrete. Due to corrosion, diagonal of steel bar is decreased, as a consequence the mechanical properties decline significantly. This tendency also occurs in concrete. Corrosion expansion leads cracks, splitting and delaminating of concrete cover.

Internal pressure is induced to concrete around steel bar due to expansion of corrosive product. Properties of rush have a great influence on corrosion crack in concrete. Normally, it has 2 – 8 times as much volume as virgin steel depending on content of corrosion product in it. Some researchers employed the rust expansion coefficient around 3 by [1]. The latest investigation was conducted by [2]. The coefficient of rust expansion has range from 2.64 to 3.14. The sources data were taken from 8 different locations. The value of 3.14 was produced in concrete member being electro-osmoses treated. Another important property of the rust according [3] is its physical characteristic like a gel .

Reference [4] stated that corrosion product penetrates into space around steel bar and porous zone of concrete in the range between 10 to 20 µm. At this stage, the rust flow is not restrained by concrete. Shortly after the pores around steel tendon are fully-filled, corrosion product will push out the concrete cover. Corrosion crack will be developed when the tensile stress due to pressure of the rust exceeds tensile strength of concrete. Unfortunately, volumes of rust which infiltrate into cracks have not been taken into account.

In numerical modeling, corrosion expansion can be simulated by using internal pressure, displacement and thermal expansion. Reference [5] applied internal pressure to express corrosion expansion. Also nodal displacement was employed by [6] to investigate effect of uniform and non-uniform corrosion expansion in service life of concrete structures. Application of thermal expansion to represent corrosion expansion in concrete was conducted by [7]. In the investigation, corrosion product was modeled such as realities which have 1000 N/mm^2 of Young`s modulus and 0.49 of poison ratio. The results show that appearing of cover cracking on surface by numerical modeling is faster than by experimental. Also development of crack width on cover surface possess similar trend. This is may be due to adoption of elastic expansion in the modeling. Penetration of corrosion product into space around steel bar, pores and cracks which reduce internal pressure have not been accurately considered yet.

Reference [8] simulated penetration of corrosion product in reinforced concrete section. In this study, a two-phase mechanical system composed of corrosion product with non-corroded steel was applied as one integrated phase and concrete as another. Uniform internal pressure was adopted to express corrosion expansion. The penetration of corrosion product into concrete was considered by creating buffer space in the interfacial zone between corroded steel and contacting concrete.

This study attempt to find a method which can represent the penetration of corrosion product into space around steel bar, pores and micro cracks and development of corrosion crack width both in reinforced and pre-stressed concrete members. An elastic expansion which was applied in the previous study [7] is adopted. Based on result of numerical simulation with elastic expansion, numerical simulation with apparent expansion was employed to simulate corrosion expansion considering penetration of corrosive product.

II. EXPERIMENTAL PROCEDURES

A. *Reinforced Concrete (RC) and Pre-stressed concrete (PC) Specimen*

Fig. 1 shows detail of the specimen. There were two specimens beam which consist of reinforced concrete beam and pre-stressed concrete beam. Pre-stress load was transferred through steel bar ∅ 11 mm at center of the beam to concrete. In order to protect the steel bar ∅ 11 mm from corrosion, PC sheath from PVC was utilized. The pre-stress load of 0 N/mm^2 was applied to represent RC specimen and 4.73 N/mm^2 corresponds to PC specimen. Single PC tendon ∅ 6 mm was located at the top and bottom of the beam which had 15 mm concrete cover. Both of them were induced by accelerated corrosion using electric current. Every type of testing is represented by 1 specimen which are RC and PC specimen, where RC is reinforced concrete specimen and PC is pre-stressed concrete specimen. The dimension of the concrete specimen was designed considering the tension of PC steel bar [9].

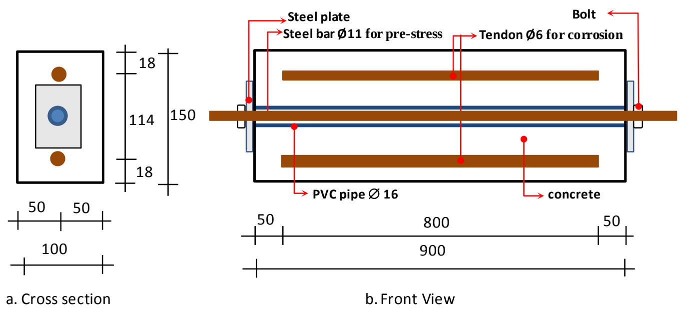


Figure 1. Specimen of RC and PC beam

Specifications of the materials are shown in Table 1. PC tendon and PC steel bar was tested based on [9]. The proportion of the concrete mixture is shown in Table 2 [10]. Prior to cast fresh concrete into the form, the tendon ∅ 6 mm of each beam was weighed to obtain the initial weight. Specimens were cured being covered with wet mattress for 10 days. Compressive strength of concrete was tested by the cylindrical specimen whose dimension is ∅ 100 mm and 200 mm height.

Table 1. Specifications of the materials

Mechanical properties	Type of Material		
	Concrete	PC tendon ∅6	PC steel bar ∅11
YoungModulus, E (MPa)	34070	201000	201000
Poisson (v)	0.2	0.3	0.3
Tensile Strength (MPa)	3.01	2018	1080
Compressive Strength (MPa)	32	-	-
Yield Strength (MPa)	-	1922	930

Table 2. Proportion of concrete mixture

Material	Unit (kg/m^3)
Water	154
Cement, High early strength type	390
Sand	622
Gravel	1189
Additive, water reducing agent (ltr/m^3)	3.9
Gmax, maximum size of gravel (mm)	25
w/c, water/cement weight ratio (%)	39.5
s/a, sand/total aggregate volume ratio (%)	35.5

B. *Artificial Corrosion Test*

Fig. 2 shows a schematic of the electric corrosion test. Direct electric current is applied to promote corrosion process. Electrolytic corrosion test was conducted to produce rust in short time. Specimens were immersed in the water which contained 3% sodium chloride as an electrolyte. Only the tendon ∅ 6 mm was corroded.

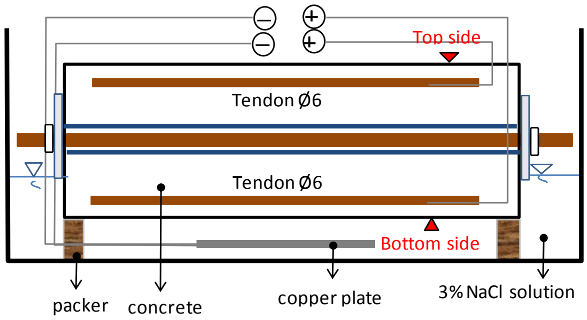


Figure 2. Schematic of corrosion test

C. *Crack width and mass loss*

Electric current which induced in corrosion test was recorded in the data logger every 30 minute. Accumulative current (∑I.T) was calculated at the end of corrosion test. Amount of corroded tendon can be predicted using equation below.

$$W = \alpha.\sum I.T \tag{1}$$

where is :
W = amount of corroded tendon (gr)
α = coefficient of electrolytic corrosion (g/A.hr)
I = current (A)
T = time (hr)

Coefficient of electrolytic corrosion is 1.0744 gr/A.hr. It calculates according to α = M / (z.F), where M is the atomic mass of the metal (Fe = 56 gr), z is the ionic valence of the metal (Fe = 2) and F is Faradays constant (96,485 A.s). Thereafter, mass loss of the tendon can be calculated by subtracting the initial weight from the weight after being corroded. Reduction of the tendon mass before ending of corrosion was calculated using interpolation based on accumulative current at the time.

Crack occurred on the bottom side (see Fig. 2) is only considered. Occurrence of cracks was checked every day.

When the first crack appears on the surface, the time of occurrence of the crack was recorded. Occurrence of the first crack was judged when crack width reached 0.01 mm. Thereafter crack width was measured using manual scale on 3 point which was in the middle of the beam, 100 mm to left side and right side from mid point. Average of those 3 crack widths was employed in the discussion.

Fig. 2 shows a schematic of the electric corrosion test. Direct electric current is applied to promote corrosion process. Electrolytic corrosion test was conducted to produce rust in short time. Specimens were immersed in the water which contained 3% sodium chloride as an electrolyte. Only the tendon ∅ 6 mm was corroded.

During the test, accumulative electric current and crack width are recorded at the certain time. After the corrosion test was completed the corroded tendons were taken out. Rust was then removed from the tendon using a wire brush and after that immersed in the 10% ammonium citrate solution in one day. Finally, weight of corroded tendon was obtained.

III. NUMERICAL SIMULATION

A. Modeling of corrosive expansion of tendon

It is assumed that tendon expands as Fig. 3 and based on equation 2 from [9].

$$\frac{(r_0+dr)^2 - \ .r_0^2}{\ -1} = \ .r_0^2 - \ (r_0+\Delta r)^2 \qquad (2)$$

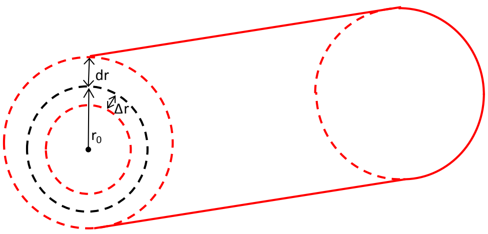


Figure 3. Corrosive expansion in cross section of steel bar

Where, dr is radius increment of steel due to corrosive expansion under unrestraint condition (mm), Δr is radius loss of steel (mm), r_0 is original steel radius (mm) and γ is expansion coefficient of rust. Ratio between volumes of corrosion product to the volume of steel consumed in the corrosion process ( ) was determined based on the experiment of [2] which was equal to 3.14. Pre-stressing steel tendon was modeled as an elastic expansive material. Corroded steel was converted into mass loss by equation 3.

$$W_{loss} = \frac{[.r_0^2 - (r_0 - \Delta r)^2].\ _s}{2\ .r_0} = \frac{[2r_0.\Delta r - \Delta r^2].\ _s}{2r_0} \qquad (3)$$

where W_{loss} is mass loss in gr/mm^2 and $_s$ is mass density of steel (7850.10^{-6} gr/mm^3).

It has been known that concrete is a porous material which has millions pores in it. Correspond to corrosion of steel bar in concrete structures, corrosion product will easily penetrate in the pores due to the type of corrosion product is a gel which has mechanical and physical properties like water [12]. At this moment, corrosion product will expand freely and without induce stresses on the concrete cover. Fig. 3 shows the process of corrosion expansion. Amount of corrosion will reduce volume of original steel bar. Due to the volume of corrosion product is larger than the original steel bar, thickness of corrosion expansion is calculated as,

$$d_r = r_0 \left(\sqrt{1 + W_{loss}\frac{(\ -1)}{\pi r_0^2 \rho_s}} - 1\right) \qquad (4)$$

where is coefficient of rust expansion. Furthermore, if this expansion runs freely without restrain from concrete cover, then strain of corrosion expansion is such as,

$$\varepsilon_{exp} = \sqrt{1 + W_{loss}\frac{(\gamma-1)}{\pi r_0^2 \rho_s}} - 1 \qquad (5)$$

B. Finite element modeling of concrete specimen

Uniaxial tensile strength (f_t), modulus of elasticity (E) and fracture energy (G_f) were estimated from compressive strength and maximum aggregate size as stated in CEB model code [13]. The material properties applied are presented in Table 3. The specimen was modeled using eight-node isoparametric solid brick element and the meshing is shown in Fig. 5. External compressive loads are applied on concrete surfaces to simulate the pre-stress action by steel tendon as shown in Fig. 6. Two different external pressure loads P which are 0 N/mm^2 and 4.73 N/mm^2.

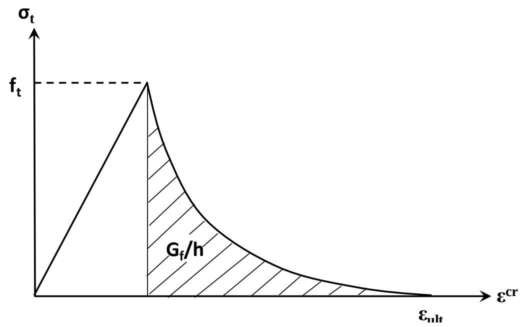


Figure 4. Constitutive model of concrete in tension

The numerical analysis was executed by the finite element code Diana-version 9.4.4 [14]. The softening model according Fig. 4 is used between stresses and strains [15]. The constant value c_1 is equal 0.31. The softening branch is defined in the following equation.

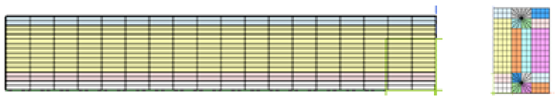
$$f_t = \frac{E^{cr}}{1 - x^{c_1}} \quad \text{where } x = \frac{\ ^{cr}}{\ _{ult}} \qquad (6)$$

Table 3. Properties of concrete and expansive material

Properties	Material	
	Concrete	Expansive material
-Type	Isotropic	Orthotropic
-E (MPa)	34070	1000 (x,y,z axes)
- ν	0.2	0.49 (x,y axes) 10^{-12}(z axes)
-f_t (MPa)	3.01	-
-Gf (N/mm)	0.1417	
-α	-	0.0012 (x,y axes) 10^{-12}(z axes)

Where ν is Poisson`s ratio and α is coefficient of thermal expansion.

Crack width in numerical simulation was also measured in 3 points which was same within the experimental work. First crack on the surface can be identified using appearing of crack pattern on it. After that, crack width can be calculated according to displacement between evaluated two nodes. Mass loss in simulation can be computed according to equation 2 and 3.



a. Front view b. Side view

Figure 5. Meshing of specimen

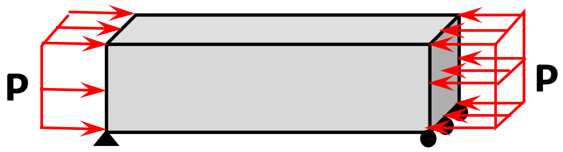


Figure 6. External compressive loads

C. Modeling of penetration of corrosion product into concrete

Since the space around steel bar and porous zone are filled fully, induced stresses on the inner concrete cover by expansion of corrosion products is started. By the time corrosion product increase and at certain time stresses generated on concrete exceed tensile strength. Consequently, micro crack occurs on the inner concrete cover. When the micro cracks appear on concrete, a part of corrosion product infiltrates in the micro cracks while another part is employed to generated stress on concrete cover until the micro crack reach on the outer surface of concrete cover. All of corrosion product which penetrates into space around steel bar, porous zone and micro crack does not produce stress on concrete cover.

The expansion of corrosion product modeled using elastic expansion in numerical simulation cannot cover the penetration of corrosion product in concrete. To minimize this phenomenon, an apparent expansion model such as equation 7 is proposed to correlate strain of corrosion expansion as a function of amount of corroded steel bar.

$$_{exp,app} = \sqrt{1 + W_{loss,app}\frac{(\ \ -1)}{r_0^2\ \ _s}} - 1 \quad (7)$$

$$W_{loss,app} = A\,(1 - \exp(-B * W_{loss})) + C * W_{loss} \quad (8)$$

Where, $W_{loss,app}$ is W_{loss} in apparent expansion model (gr/mm^2), A is a constant determined based on difference between W_{loss} penetrated in concrete by experimental and numerical result, B is a constant determined based on experimental result, C is a constant determined based on experimental result.

IV. RESULTS AND DISCUSSIONS

A. Apparent expansion model considering penetration of corrosion product

Based on experimental result of corroded steel as a function of corrosion crack width, constant in equation 8 can be determined such as Table 4. After inputting the constant in the equation, Figure 7 and 8 is obtained to express relationship between amount of corrosion product and strain. According Figure 7 and 8, two different apparent expansion model is applied which are for RC and PC member. This is due to the penetration of corrosion product in RC and PC member is not equal. Consequently, development of corrosion crack is also affected by this phenomenon.

Table 4. Constant of equation 8

Specimen	Constant		
	A	B	C
RC	4.24	50	1.2
PC	3.75	50	1.2

Curve of apparent expansion in Fig. 7 and 8 consist of two stages of line. First stage the W_{loss} ranged from zero to 4 gr/mm^2 has zero of strain. This stage illustrates that penetration of corrosion product into concrete does not produce any stresses on concrete cover. The next stage, W_{loss} as a function of strain is linear. It means that Increasing of W_{loss} affects the development of strain in concrete. Furthermore, crack is generated up to surface of concrete cover.

By comparing curves of elastic expansion and apparent expansion, strain in elastic expansion is higher than strain in apparent expansion in same level of $W_{loss.}$ It also shows that amount of corrosion product needed to build up crack width on concrete by apparent expansion model is higher than elastic expansion. Crack width by apparent expansion is calculated based on elastic expansion strain. For example by inserting W_{loss} is equal to 2 gr/mm^2 in equation 8, value of 7.3 gr/mm2 is obtained for $W_{loss,app}$ and strain in elastic expansion is about 18µ. Corrosion crack width caused by 7.3 gr/mm^2 of corrosion product in apparent expansion is computed when the strain of elastic expansion reach 18µ. Whole result of crack width by apparent expansion can be confirmed using Figure 10 and 12.

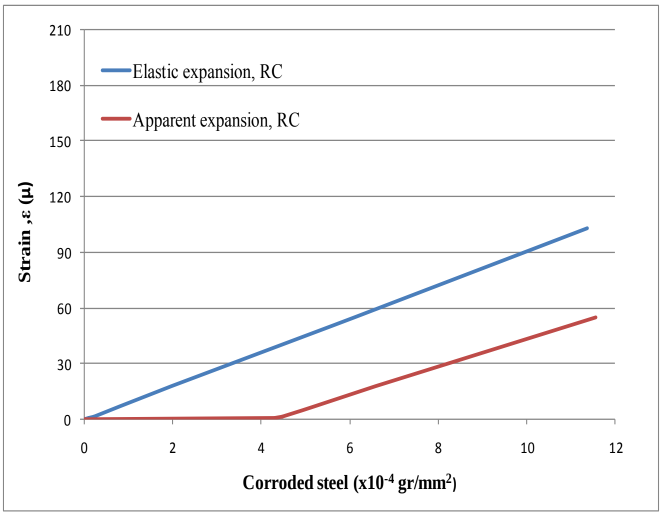


Figure 7. Corrosion expansion in RC member

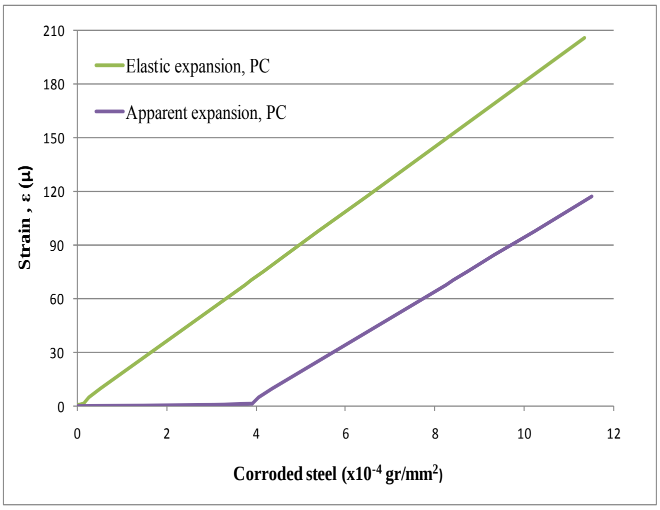


Figure 8. Corrosion expansion in PC member

B. *First crack on surface of RC cover*

Amount of corroded steel when the first crack occurs on the surface of concrete is presented in Table 5. Regarding to Table 6, all of the methods can cover penetration of corrosion product into concrete. Though, elastic expansion method still have high gap compared to the experimental result. On the other hand, method of elastic expansion with considering some penetration of corrosion products into concrete show a good result corresponds to the experimental one. Nevertheless, it should be confirmed based on it propagation of crack width after the first crack on surface of concrete cover. This clarification is needed to judge that the method is matching completely to the experiment result.

Pattern of the first crack can be seen in the Fig. 9. Both in the experimental and the analytical crack appears on the center of the beam. In the experiment, the first crack on surface can be seen with naked eye, but its width is as small as 0.05 mm which is the minimum of scale used. Red, blue and green color in the Figure 8b indicate crack width of the concrete after cracks occur on the surface which have range value of 0 – 0.0026 mm, 0.0026 mm - 0.0173 mm, and 0.0173 mm - 0.0321 mm consecutively.

Table 5. Amount of corrosion when crack appears on the surface of reinforced concrete

Type of analysis	Corroded steel (10^{-4} gr/mm^2)
- Numerical simulation with elastic expansion	0.195
- Numerical simulation with apparent expansion	4.471
- Experimental	4.432

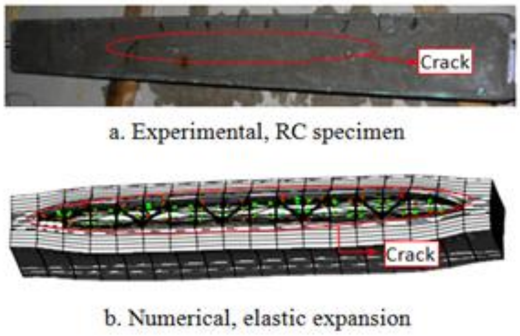


Figure 9. First crack on surface of RC beam

C. *Development of crack width on RC structure*

Based on Fig. 10, development of crack width on surface of RC cover can be identified. Numerical simulation with elastic expansion has a similar slope of crack width development compared to the experimental work. Graphic of numerical simulation shows that after first crack appear on surface of RC cover, crack width increase sharply. After that, relationship between corroded steel and crack width grow proportionally such its propagation before. At the end point, this method still has a great difference with the experimental. Even though a great gap took place at the propagation of crack width on surface, slope of them seem equal in tendency.

Numerical simulation with apparent expansion to consider penetration of corrosion product into concrete shows that it is match to the experimental result. The satisfied fulfillment is not only in the describing of penetration of corrosion product into concrete before the first crack but also its development of crack width on the surface of RC cover. Furthermore, after stress was started to induce on concrete, it was simulated as its real properties.

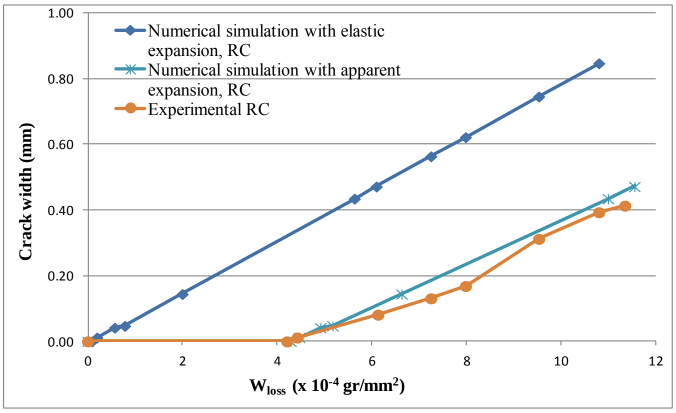


Figure 10. Relationship between corroded steel and crack width of RC beam

D. *Verification of the reliability of the numerical simulation with apparent expansion in PC members*

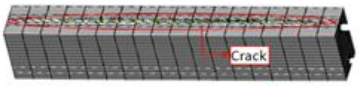
Table 6 shows amount of corroded steel when first crack appear on surface of PC cover.

Table 6. Amount of corrosion when crack appears on the surface of PC cover

Type of analysis	Corroded steel (10^{-4} gr/mm^2)
- Numerical simulation with elastic expansion	0.137
- Numerical simulation with apparent expansion	3.909
- Experimental	3.886

Numerical simulation with elastic expansion has great gap with the experimental result, but the great difference can be minimized after apparent expansion is adopted in the numerical simulation. Corroded steel which is evaluated using numerical simulation with apparent expansion has a good agreement with the experimental result. Accuracy of the method was more than 99%. This evidence is also supported by Figure 11. Appearance of first crack pattern on surface of PC cover takes place at the center and parallel with the corroded steel. The tendency in numerical simulation was exactly matching to the experimental one.

Figure 12 illustrates crack width on surface of concrete cover PC beam as a function of corroded steel. It shows that propagation of crack width on surface of PC can be approached perfectly using numerical simulation with apparent expansion to consider the penetration of rust into concrete.



a. Numerical simulation

b. Experimental work

Figure 11. First crack on surface of PC beam

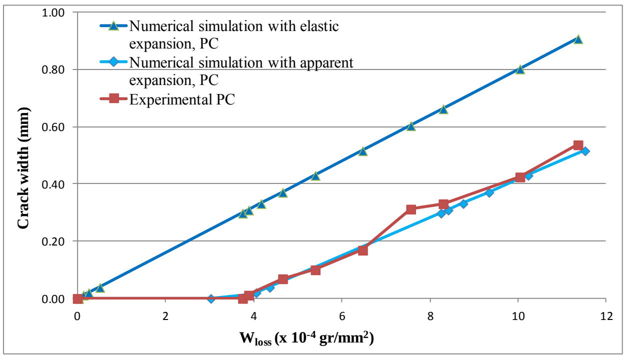


Figure 12. Relationship between corroded steel and crack width of PC beam

Not only appearance of the first crack but also slope of the development of crack width is able to simulate near the experiment result. The numerical simulation with apparent expansion can be utilized not only in RC structures but also in PC structures. Until this case, the reliability of the method can be proved that it has a good quality with the reality.

V. CONCLULSIONS

1. Elastic expansion model for corroded reinforcement in concrete overestimates width of corrosion crack on surface of concrete cover.
2. Apparent expansion model for corroded reinforcement in concrete, in which penetration of corrosion product into interfacial spaces around steel bars, pores and micro crack in concrete, can adequately simulate development and opening of corrosion crack on surface of concrete cover in RC and PC member.

Acknowledgments

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References

[1] C. Lu, W. Jin, R. Liu, Reinforcement corrosion-induced cover cracking and its time prediction for reinforced concrete structures, Corrosion Science 53 (2011) 1337-1347.

[2] Y. Zhao, H. Ren, H. Dai W. Jin, Composition and expansion coefficient of rust based on X-ray diffraction and thermal analysis, Corrosion Science 53 (2011) 1646-1658.

[3] C. Andrade, F. Tavares, L. Toro, J. Fullea, Observation on the morphology of oxide formation due to reinforcement corrosion, RILEM (2011) 179-193.

[4] P.Thoft, Christensen, Stochastic modeling of the crack initiation time for reinforced concrete structures, Structures Congress, Philadelphia (2000).

[5] Y.G. Du, A.H.C. Chan, L.A. Clark, Finite element analysis of the effect of radial expansion of corroded reinforcement, Computer and Structures 84 (2006) 917-929.

[6] Y. Zhao, A.R. Karimi, H.S Wong, B. Hu, N.R. Buenfield, W. Jin, Comparison of uniform and non-uniform corrosion induced damage in reinforced concrete based on a Gaussian description of the corrosion layer, Corrosion Science 53 (2011)2803-2814.

[7] A. Maryoto, Y. Kitazono, T. Shimomura, Numerical simulation of corrosion crack in reinforced concrete (RC) and pre-stressed concrete (PC) member, JSCE - Kanto Branch, Niigata Conference, Japan (2011) 378-381.

[8] K. Toongoenthong and K. Maekawa, Simulation of coupled corrosive product formation, migration into crack and propagation in reinforced concrete sections, Journal of Advance Concrete Technology, 3 (2005) 253-265.

[9] Anonim, Steel bars for prestressed concrete, Japan Industrial Standard G 3109, Japan, 2008.

[10] Anonim, Standard specifications for concrete structures – 2007, Material and Construction, Japan Society of Civil Engineers (JSCE), 2010.

[11] Y. Saitou and T. Shimomura, Effect of non-uniformity of corrosion of steel in concrete on criteria of corrosion crack, Proceeding of the Japan Concrete Institute, Vol. 30, No.1, Japan (2008) 1089-1094.

[12] F.J Molina, C. Alonso, C. Andrade, Cover cracking as a function of rebar corrosion : part 2 – numerical model, Material & Structures 26 (1993) 532-548.

[13] Comite Euro-International du Beton – Federation Internationale de la Precontrinte, CEB-FIP Model Code, Thomas Telford Ltd, London (1990).

[14] Diana, User's manual, Release 9.4.4, TNO DIANA, BV, Delft, The Netherlands, 2010

[15] H.W Reinhardt, Fracture mechanics of an elastic softening material like concrete, Heron 29, 2 (1984).