- Technical Paper -

ANALYSIS OF CORROSION-INDUCED CRACK PROPAGATION OF RC MEMBERS MODELING BY CORROSION EXPANSION PRESSURE AROUND BEAM ELEMENT

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ABSTRACT

This study proposed a method to simulate crack propagation due to rebar corrosion based on Rigid-Body-Spring Method (RBSM) in which rebar is modeled by beam element in order to reduce computational cost for the analysis of structural level. The effects of local corrosion around the rebar as well as penetration of corrosion products into cracks were taken into consideration in the model. The applicability of the method was verified by comparing with experiment using single-rebar specimens with different rebar diameters, cover thicknesses and specimen sizes. Analytical results showed a good correlation with experimental ones not only in terms of crack propagation tendency but also crack width values.

Keywords: corrosion-induced crack, 3D-RBSM, beam element, local corrosion, corrosion product penetration

1. INTRODUCTION

When crack propagation due to rebar corrosion is simulated, the rebar is usually modeled by solid element in order to consider expansion pressure from rebar or combination between rebar and concrete accurately. A number of researches based on this method has been published and the results showed reasonably well in comparison with experiment [1, 2, 3]. For instance, the authors proposed three-phase material corrosion expansion model including rebar, corrosion products and concrete, as shown in Fig.1. The merit of the model is that the properties of corrosion products are directly assumed and corrosion expansion behavior is introduced in corrosion products layer.

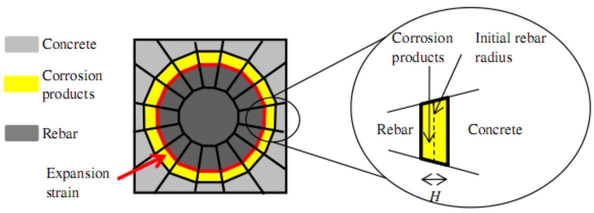

Fig. 1 Three-phase corrosion expansion model [3]

Nevertheless, the modeling of rebar by solid element is not practical to solve the structural level due to the reason that the simulation requires more complex modeling, huge amount of elements and much computational time. Even if solid element is employed, the model will not be consistent for both corrosion-induced crack analysis and structural analysis since rebar is usually modeled by beam element in structural analysis. Therefore, a method which can reasonably simulates both corrosion-induced cracking behavior and structural behavior with corrosion damages of RC member would be essentially needed.

In this study, a method to simulate crack propagation due to rebar corrosion based on Rigid-Body-Spring Method (RBSM) in which rebar is modeled by beam element is proposed. In the method, corrosion pressure is modeled by concrete strain expansion in virtual rebar's area around beam element considering the effect of critical corrosion amount. Moreover, the effects of local corrosion around the rebar and penetration of corrosion products into cracks are also taken into account. By using single-rebar specimens with different rebar diameters, cover thicknesses and specimen sizes, the applicability of proposed method is verified.

2. MODELING OF CORROSION EXPANSION PRESSURE AROUND BEAM ELEMENT

2.1 Three-dimensional RBSM

In the analysis, three-dimensional RBSM was employed [4]. The RBSM as a discrete numerical approach represents a continuum material as an assemblage of rigid particles interconnected by zero-length springs along their boundaries as indicated in Fig. 2. The particles elements are randomly generated with Voronoi diagram. Each of the elements has six degrees of freedom at its nucleus.

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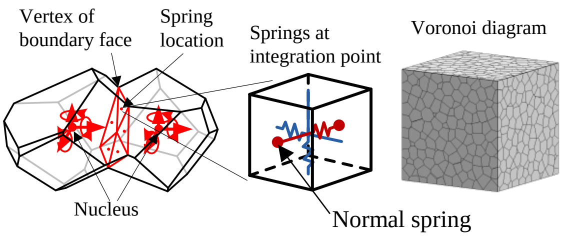


Fig. 2 Three-dimensional RBSM

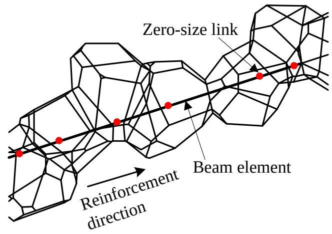


Fig. 3 Reinforcement arrangement

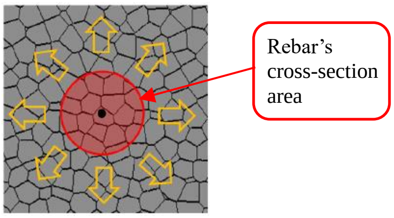


Fig. 4 Corrosion expansion model

Three springs, one normal and two shear springs, are defined at the center point of each triangle formed by the center of gravity and the vertices of the boundary between two elements. Nonlinear material models of concrete were introduced into the springs. The response of the spring model provides an understanding of the interaction between particles instead of the internal behavior of each element based on continuum mechanics [4].

2.2 Reinforcement model

Fig.3 shows the reinforcement model, which is formed as a series of regular beam elements. In this model, the reinforcement can be freely positioned within the members, regardless of the mesh size of the concrete [4]. At each beam node, two translational and one rotational degree of freedom are defined by means of the springs. The reinforcement is attached to the concrete particles by zero-size link elements.

2.3 Corrosion expansion model

In order to simulate corrosion-induced crack propagation, modeling of real rebar's parameters such as diameter and surface are obviously important since the cracking pattern and surface crack width are strongly influenced by the ratio of cover thickness and rebar diameter as well as local corrosion area around the rebar. However, as beam element which is used for modeling of rebar does not have real area like solid element, we propose the virtual expansion area which is similar as cross-section area of the rebar (Fig. 4). In such an area of concrete, initial strain is set in normal spring which is located on boundary surfaces between Voronoi elements. Initial strain is calculated based on expansion pressure U which dependent on corrosion amount [3]:

$$U = \frac{W_r\,(\alpha_{cor}-1)}{\rho_s} \tag{1}$$

where,

W_r : corrosion amount (mg/cm^2)

α_{cor} : volume-expansion ratio of corrosion products, assumed 2.5 in this study.

ρ_s : rebar density (7.85 x 10^3 mg/cm^3).

Due to the use of elastic modulus of concrete instead of that of corrosion products in real structure for calculating of corrosion expansion stress; therefore, the stress of concrete in the model would increase faster than in real structure. Moreover, due to the difference between real area of rebar in real structure and virtual area of rebar in the model; therefore, U would be modified by adding modification factor β:

$$U_{md} = \mathrm{U}.\,\beta \tag{2}$$

The effect of β on expansion pressure will be illustrated in later section.

Furthermore, since the elastic modulus also influence on crack initiation point, critical corrosion amount (CCA) would be considered. CCA is defined as accumulated amount of corrosion that can create surface cracks [5]. CCA in this study is set to be 25 mg/cm^2. Before reaching CCA, each analysis step will be given ΔU equal to nearly zero, otherwise ΔU will be applied as same as calculated in Eq. (2).

2.4 Modeling of local corrosion around the rebar

It has been known that the chloride diffusivity through cracked concrete is much more than through un-cracked concrete. Experimental results showed that local corrosion can be observed near the vertical crack [3]. In this study, HALF corrosion model will be applied in a way that only a half of rebar area is given an incremental expansion strain, as shown in Fig. 6. Several assumptions are applied in this study:

- Rebar is locally corroded when a vertical crack above the rebar exceeds 0.2mm width.

- The total corrosion amount in local corrosion model is similar to that in uniform corrosion model (Fig. 5) at the same corrosion amount.

2.5 Modeling of penetration of corrosion products into cracks

When cracks in concrete structure occur due to corrosion, penetration of corrosion products into cracks will be started and may results in the reduction of internal expansion pressure on concrete. Experimental results showed that penetration of corrosion products into cracks could be observed in vertical cracks in concrete cover thickness [3].

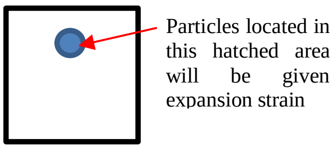


Fig. 5 UNIFORM corrosion model

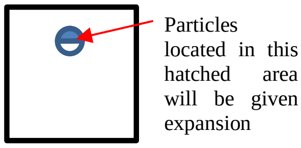


Fig. 6 Local corrosion HALF model

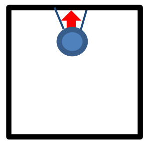


Fig. 7 Modeling of penetration of corrosion products into cracks

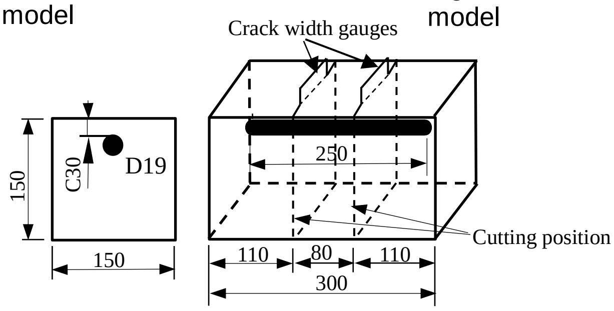


Fig. 8 Specimen outline

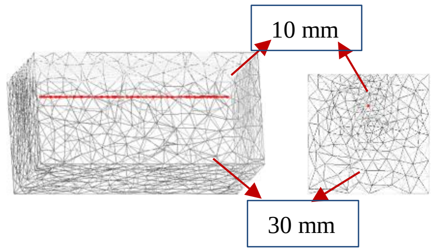


Fig. 9 RBSM model

The merit of 3D-RBSM model is that crack width and crack volume can be directly calculated during the analysis. Hence, this effect can be simulated in the 3D-RBSM and the reduction of internal expansion pressure due to penetration of corrosion products is calculated as below [3]:

$$\Delta U_{real} = \Delta U - \frac{\Delta V_{crk}}{2\pi . r . L} \qquad (3)$$

where,

ΔU_{real} : real increment of the free increase

ΔV_{crk} : increment of volume of cracks

r : radius of rebar

L : rebar length.

Several assumptions should be taken into account when considering this effect:

- Only vertical cracks above the rebar will be considered (Fig. 7).
- Corrosion products can only penetrate into cracks and fully occupy the crack volume if crack width exceeds threshold value of crack width 0.2 mm.
- The free increase U is uniformly reduced around the rebar and then the HALF model in Section 2.4 is applied to redistribute the internal expansion pressure.

3. VERIFICATION OF ANALYTICAL MODEL

Specimen outline is indicated in Fig. 8 which was conducted by Tran et al. [3]. The specimen is arranged with single D19 rebar and concrete cover is 30 mm. Surface crack width was measured by crack width gauges set in specimen's surface. After each test was completed, the specimen was cut at the positions shown in Fig. 8 to enable observation of the internal crack patterns. Analytical RBSM model is shown in Fig. 9. In order to be able to simulate structural level, the analytical model is arranged with large enough mesh size. In this study, the mesh sizes of the Voronoi particles are 10 mm in the area near the rebar as well as concrete cover, and 30 mm for other areas.

We analyzed specimens with various values of modification factor β and determine the effect of each value. Moreover, the effect of local corrosion HALF model blended with effect of penetration of corrosion products into cracks were applied in the analysis.

3.1 Effects of modeling

(1) Effect of modification factor β

By changing β from 0.1 to 1.0, we found that with the same corrosion amount, the higher β value is, the higher surface crack width. In addition, surface crack width propagation curve in case of β equal to 0.3 agrees well with experimental result at stage of just after initiation of surface crack, as indicated in dashed circle in Fig. 10.

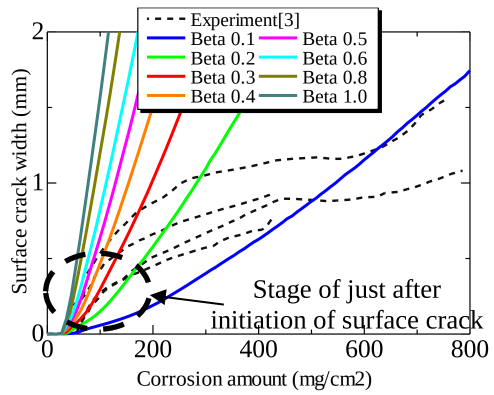


Fig. 10 Surface crack width propagation with various values of modification factor $\boldsymbol{\beta}$

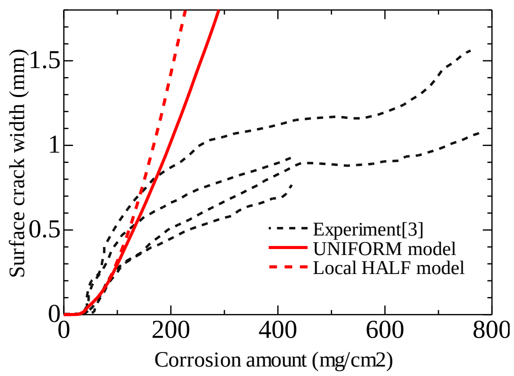


Fig. 11 Effect of local corrosion model

Therefore, we used modification factor β of 0.3 for following analysis. However, at later stages, all cases appeared to be significantly over-estimated experimental results. The reason of over-estimation will be mentioned in Section 3.1(3).

(2) Effect of local corrosion

The effect of local corrosion, which was discussed in Section 2.4, is represented in Fig.11 in which β equal to 0.3 is used. Due to the concentration of corrosion expansion pressure in top-half of rebar's cross-section area, the surface crack width at this case seems to be higher than uniform case.

(3) Effect of penetration of corrosion products into cracks

Fig. 12 illustrates the analytical surface crack width propagation considering the effect of penetration of corrosion products into cracks in comparison with the experimental results. The curve of without penetration case as well as different threshold values cases of modification factor β of 0.3 are also plotted in the figure. It can be clearly observed that without penetration effect, the internal expansion pressure is highest and it causes widest cracks at the same corrosion amount.

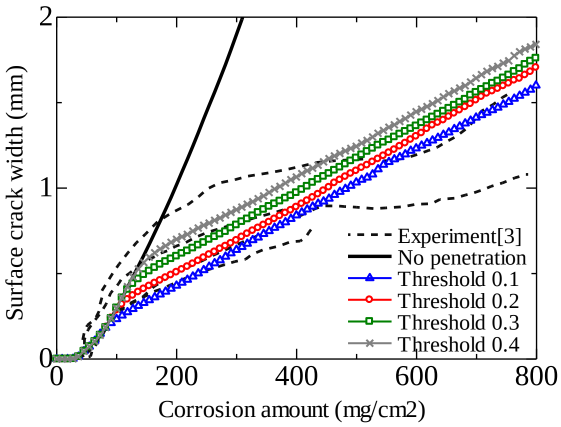


Fig. 12 Effect of penetration of corrosion

When penetration effect is taken into account, the surface crack width curves change drastically due to the reduction of expansion pressure caused by penetration effect. In case of threshold value 0.2 mm, the analytical result shows well correlation with experimental one not only in terms of crack propagation trend but also in surface crack width value.

3.2 Analytical results

(1) Surface crack propagation

The analytical surface crack width propagation is compared with the experimental results, as shown in Fig. 13. The analytical result shows a good agreement with test results indicated in [3] in both crack width values and propagation tendency. It also showed the same tendency with analytical results obtained by [3]. That is surface crack width initiates at certain corrosion amount, around 40 mg/cm^2 and then propagates rapidly due to increase of corrosion amount. At surface crack width around 0.3 mm, the effect of penetration of corrosion product into cracks make the expansion pressure reduces their values and as a results, surface width propagation curve is decreased its slope.

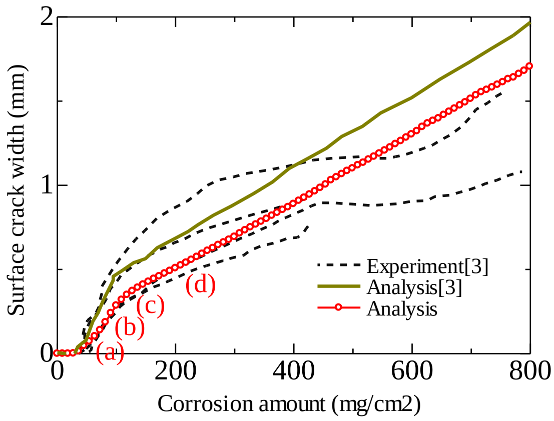
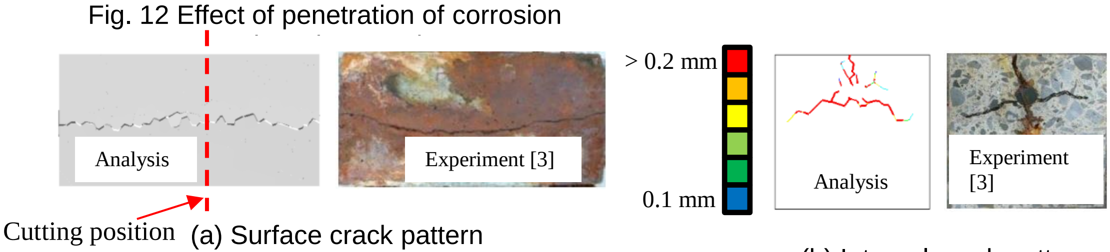


Fig. 13 Surface crack width propagation



(a) Surface crack pattern

(b) Internal crack pattern

Fig. 14 Crack patterns compared with experiment

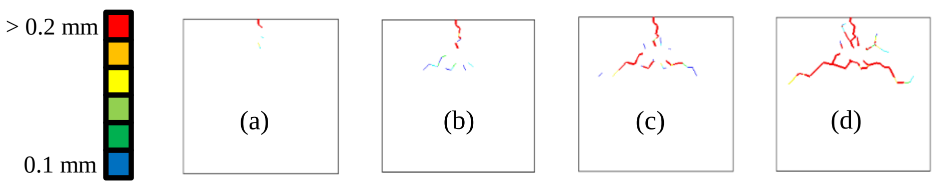


Fig. 15 Internal crack propagation

(2) Crack patterns

Fig. 14 shows the cracking behavior of analytical model. Internal crack pattern was observed from cutting position shown in Fig. 14(a) and the color of cracks illustrates the classification of crack width. It is indicated that crack patterns in analytical model reasonably agree with those of experimental ones.

Fig. 15 indicates internal crack propagation process at cutting position shown in Fig. 14(a), corresponding to the marked points (a) to (d) shown in Fig. 13, which is first crack occurs on the surface due to surface deformation caused by expansion pressure (Fig.15a). After that, vertical crack propagates to the rebar and then lateral crack starts increasing (Fig. 15b). Vertical and lateral cracks increase their widths and lengths corresponding to the increase of corrosion amount (Fig. 15c). Vertical crack continues to increase but reduces its speed due to penetration of corrosion products effect (Fig. 15d).

5. APPLICABILITY OF PROPOSED CORROSION MODEL

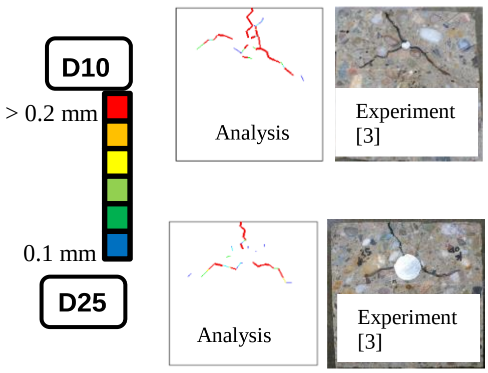
The proposed model is applied to simulate single-rebar specimens which were carried out by Tran et al. [3]. The authors made with different series to figure out the effect on corrosion-induced cracking behavior. In the first series, basic specimen dimension is illustrated in Fig. 8, but the changing parameters are rebar diameter and cover thickness. On the other hand, in the second series, the author carried out the corrosion test with different sizes of single-rebar specimens. The analytical results obtained from proposed model will be discussed in the following sections.

5.1 Single-rebar specimens with different rebar diameters

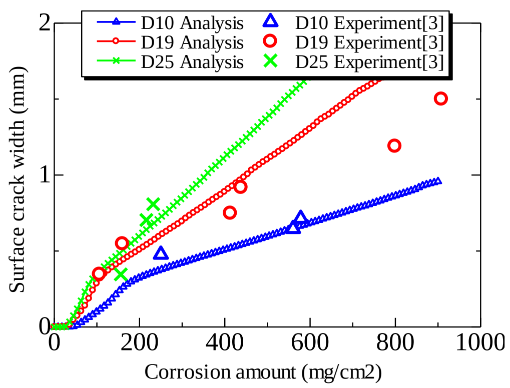
Specimen outline in this case is similar as shown in Fig. 8. However, specimens are arranged with different rebar diameters, specifically D10 and D25. The crack patterns and surface crack width propagation are finally obtained and plotted in Fig. 16. It can be seen that analytical results in these cases show a good correlation with experimental ones not only in terms of crack patterns but also surface crack width propagation.

5.2 Single-rebar specimens with different cover thicknesses

Specimens indicated in Fig. 8 was used again but the changing parameter was cover thickness, from 30 mm to 15 mm and 45 mm. The results are illustrated in Fig. 17. In general, crack patterns acquired from analysis are agreed with experiment. Regarding surface crack propagation, specimens which have smaller cover thickness will have larger surface crack value at later stage.

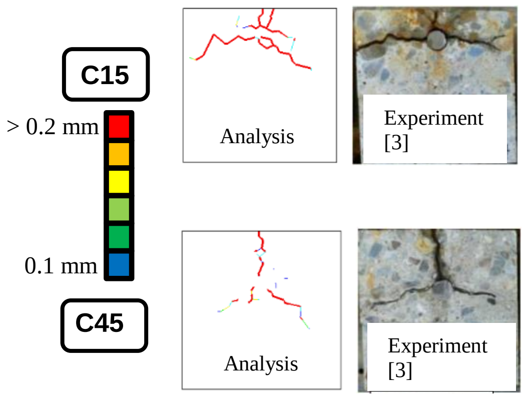


(a) Crack patterns

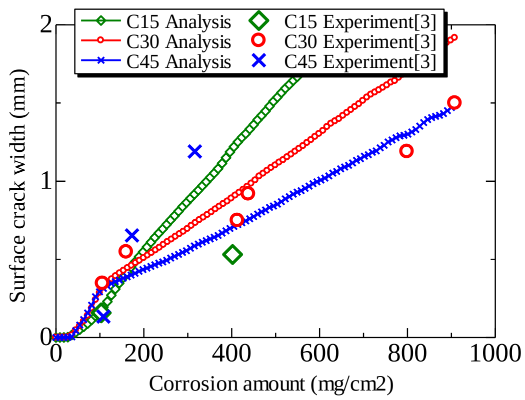


(b) Surface crack width propagation

Fig. 16 Results of different rebar diameters



(a) Crack patterns



(b) Surface crack width propagation

Fig. 17 Results of different cover thicknesses

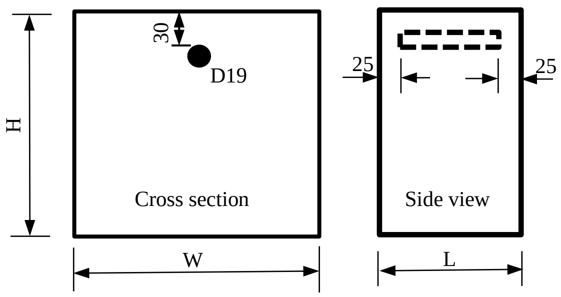


Fig. 18 Specimen set-up (various sizes)

It seems not to match the experimental results due to the fact that in smaller cover thickness cases observed from experiment, corrosion products not only penetrated into cracks but also moved to outside of specimen. In the analysis we assumed that corrosion products only penetrate into cracks. However, other research pointed out that smaller cover thickness specimens will appear to have higher surface crack width [6], which is agreed with simulation results in this study. This study, therefore, needs to be studied further in future research.

5.3 Single-rebar specimens with different sizes

Specimens with various sizes were modeled to verify the applicability of the model. Specimen set-up is shown in Fig. 18. The height of specimens (H) are varied from 150 mm to 400 mm and the widths (W) are ranged from 150mm to 400 mm, the lengths (L) are 200 mm or 300 mm. Eventually, three specimens is assigned, named 150x150x300 (indicated in Fig. 8), 250x250x200 and 400x400x200. Fig. 19 shows typical analytical model of various sizes of specimens. The results obtained from analysis are plotted in Fig. 20.

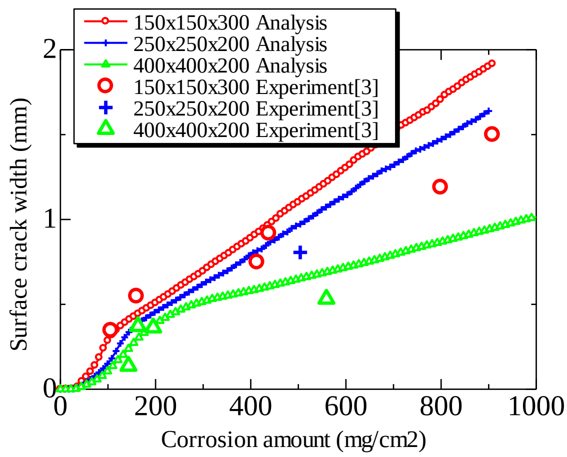


Fig. 20 Surface crack width propagation in cases of various sizes specimens

It is clearly observed that analytical results reasonably agree with experimental ones. Surface crack width in small width specimens appeared to have higher value than that in large width specimens, which is same as stated in [3].

6. CONCLUSIONS

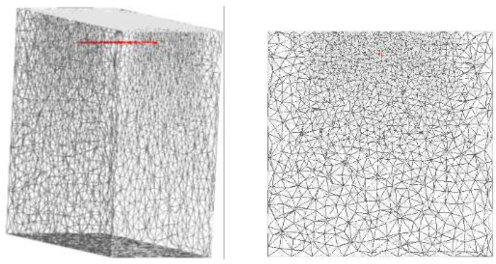


Fig. 19 Analytical model

(1) This study proposed a method to simulate cracking behavior due to rebar corrosion using 3D-RBSM in which rebar was modeled by beam element.

(2) Some parameters such as critical corrosion amount, modification factor were assumed to take into consideration the deviation between the model and real structure.

(3) The proposed method has successfully modeled the effects of local corrosion around the rebar as well as penetration of corrosion products into cracks.

(4) The results obtained from analysis showed good correlation with experiment and more importantly clarified the cracking propagation mechanism in single-rebar specimens. The proposed model could be a good tool to analyze the structural behavior of RC members with corrosion-induced damages.

REFERENCES

[1] Toongoenthong K. and Maekawa, K., “Simulation of Coupled Corrosive Product Formation, Migration into Crack and Propagation in Reinforced Sections”, Journal of Advanced Concrete Technology, 2005, Vol. 3(2), pp. 253-265.

[2] Ozbolt, J., Orsanie, F., Balabanie, G., “Modeling Damage in Concrete Caused by Corrosion of Reinforcement: Coupled 3D FE model”, Int J Fract, 2012, Vol. 178, pp. 233-244.

[3] Tran, K. K., “Study on Cracking Behavior of Concrete due to Rebar Corrosion”, Doctoral thesis of Nagoya University, 2012.

[4] Yamamoto, Y., Nakamura, H., Kuroda, I. and Furuya, N, “Analysis of Compression Failure of Concrete by Three Dimensional Rigid Body Spring model”, Journal of JSCE, 2008, Vol. 64, pp. 612–630. (in Japanese).

[5] Oh, B. H., Kim, K. H., Jang, B. S., “Critical Corrosion Amount to Cause Cracking of Reinforced Concrete Structures”, ACI Materials Journal, Jul.-Aug. 2009, Vol. 106, pp. 333-339.

[6] John, A. M., Mark, G. S., “Corrosion-Induced Cover Cracking: New Test Data and Predictive Models”, ACI Structural Journal, Jan.-Feb. 2011, Vol. 108, pp. 71-79.