EXPERIMENTAL AND ANALYTICAL STUDIES ON CRACKING DUE TO CORROSION IN REINFORCED CONCRETE SLAB

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ABSTRACT

This paper aims to present both experimental and analytical studies of reinforced concrete (RC) slabs embedded with multiple reinforcing bars. Crack initiation patterns and crack propagation due to the corrosion of rebar were investigated for RC slabs. The rebar spacing of specimens in this study was 60mm, 120mm and 240mm. Results from electrolytic corrosion experiments, revealed that crack initiation patterns were influenced by concrete depth and rebar spacing. Additionally, crack propagation was more dominant in the horizontal direction than the occurrence pattern. The corrosion weight loss of rebar for initial crack growth cracks was approximately 50 mg/cm^2 in this study. For crack initiation patterns and crack propagation, similar results were obtained by numerical analysis.

Keywords. corrosion, concrete slab, multiple reinforcing bars, crack propagation, delamination

INTRODUCTION

Steel bars embedded in concrete normally do not corrode because the alkaline environment of concrete surrounding reinforcing steels results in the formation of a passive film on the steel surface, which in turn, can protect the steels from corrosion.

However, Japan is an island country surrounded by the sea on all sides. Chloride ions from marine environments penetrate into the concrete and break the protective film on the reinforcing steels causing the steels embedded in the concrete to corrode.

Corrosion often leads to cracking and spalling of concrete due to the production of rust, which occupies a greater volume than the steel that produced it. If the concrete covering the rebars is relatively   shallow, and/or the rebars are widely spaced, cracks form perpendicular to the concrete surface (Figure 1a). However, if the concrete covering the rebars is relatively deep, and/or the rebars are closely spaced, cracks form parallel with the concrete surface (Figure 1b)[1),2)]. Figure 2 shows the propagation of cracks that follow the line of rebar in a concrete beam. The cracks are due to a thin cover of concrete at the bottom of the beam and are expected to expand over time.

Concrete delamination however, occurs from the propagation of horizontal cracks between the rusted rebar and an obvious lack of concrete cover in the case of a slab (Figure 3). The propagation of horizontal cracks is dominant even with a wide spacing of rebars and a slight cover of concrete (Figure 4). TRAN et al (2012) analyzed crack propagations due to multi-rebar corrosion using a discrete numerical analysis method[3)]. An analyzed model with 200 mm interval of rebar, and 40 mm caver depth, was delaminated due to propagation of internal cracks between the reinforcing bars. On the one hand, an experimental study using a concrete slab embedded with multiple reinforcing bars was not conducted.

In this study, experimental and analytical parameter studies were carried out for reinforced concrete slabs in order to investigate crack initiation and crack propagation due to corrosion.
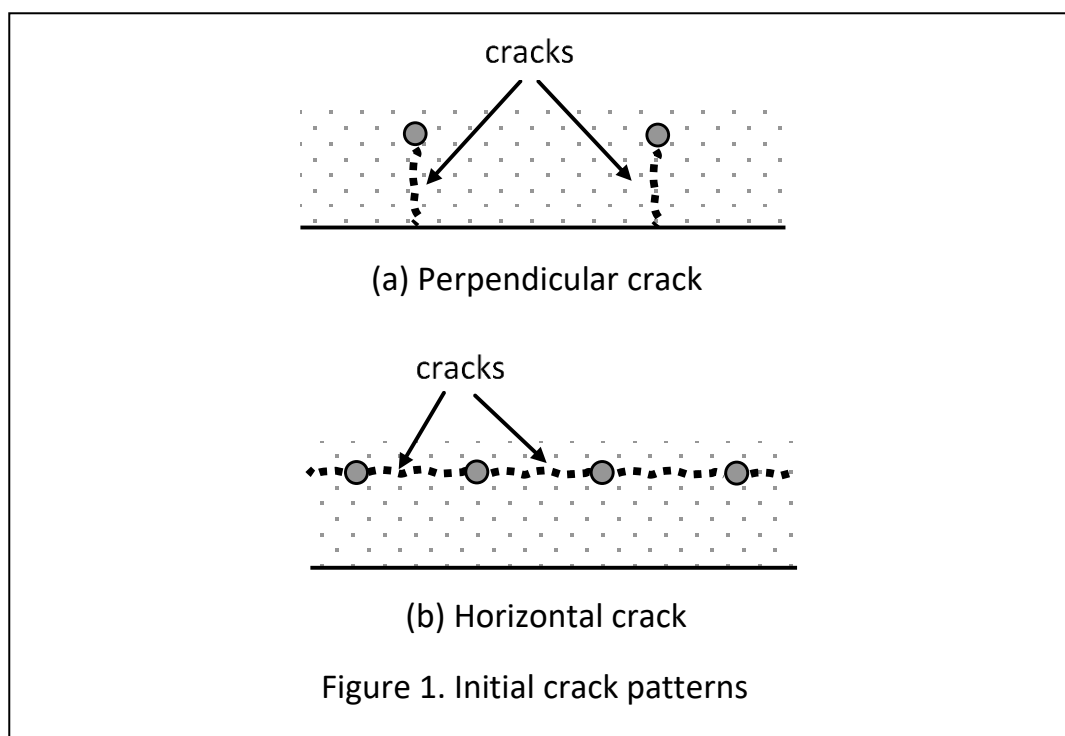

cracks

(a) Perpendicular crack

cracks

(b) Horizontal crack

Figure 1. Initial crack patterns

Figure 2. Cracks of a beam

Figure 3. Delamination of a slab

Figure 4. Horizontal cracks

EXPERIMENTAL PROGRAM

Reinforced Concrete Slab Description

The test specimens were 400 mm long slabs with 900x180 mm^2 rectangular cross sections. 19mm deformed steel bars were embedded in the slabs with varied spacing (Figure 5). Two or three 16mm deformed steel bars were set at right angles to the reinforcing bars (Figure 6). The distance between the undersurface of the rebar and the bottom face of the slab was 30 mm and the distances between the steel bars were 60 mm, 120 mm and 240 mm (Figure 7). The mixture proportion of the concrete used is summarized in Table 1. The compressive strength was 36.9 MPa (28 days). For the 120mm spacing and the 240mm spacing, two identical specimens were casted.

Accelerated Corrosion Tests

An applied current was used to accelerate the corrosion of the rebars. The RC slab was placed in a PVC tank containing an alkaline salted solution (30 g/L NaCl), and the bars were polarized anodically using a counter electrode to enhance corrosion (Figure 8). The counter electrode, made from a stainless steel plate, was placed at the bottom of the slab using a rigid sponge.
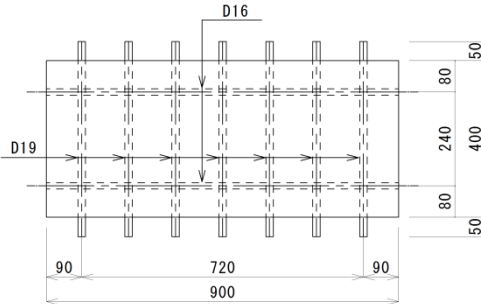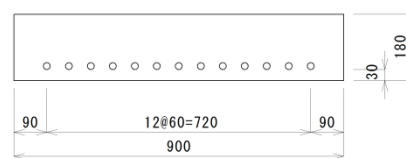

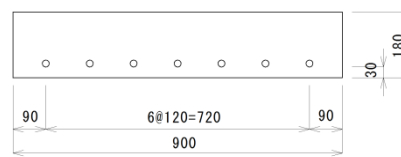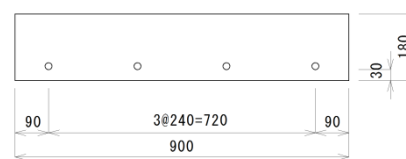
Figure 5. Specimens

Figure 6. Size and details of specimens (Plane view, unit: mm)

(a) 60mm Spacing

(b) 120mm Spacing

(c) 240mm Spacing

Figure 7. Size and details of specimens (Sectional view, unit: mm)

Table 1. Mixture proportion

G.max	W/C	Slump	Air content	s/a	Unit weight (kg/m^3)					AE-Water Reducing Agent	AE Entrainewr
					Cement	Water	Fine Aggregate 1	Fine Aggregate 2	Coarse Aggregate		
(mm)	(wt%)	(cm)	(vol%)	(wt%)						C×(%)	C×(%)
20	54	8±2.5	4.5±1.5	45.2	282	155	610	262	1056	0.6	0.003

A power supply delivered a constant current density of 1.0 mA/cm^2 between the reinforcing bars and the counter electrode. Insulating the crossing rebar was implemented to ensure that only the embedded reinforcing bars were affected. A schematic representation of the accelerated corrosion testing setup is depicted in Figure 9.

Crack Initiation Tests

After starting the electric corrosion test, crack patterns were observed on the bottom surfaces and sides of the specimens. The corrosion weight loss of the embedded rebar was measured when the crack initiation was located.

Measurement of Corrosion Amount
After the accelerated corrosion test, the concrete of the specimen was crushed and the embedded rebars were taken out to measure weight loss. The reinforcing bars were cleaned with 10% diammonium hydrogen citrate solution to ensure that all corrosion products were washed away, then weighed. A sound rebar without corrosion was also weighed as a control.
The weight loss was calculated as follows,

$$\Delta W = \frac{W_0 \cdot L_r - W_1}{A_r} \tag{1}$$

Where ΔW is the weight loss of corrosion rebar (mg/cm^2), W_0 is the weight per unit length of sound rebar without the protective oxide layer on the rebar (mg/cm), W_1 is the measured weight of the corrosion rebar after removal of corrosion products (mg), L_r is the rebar length (cm) and A_r is the surface area of the rebar (cm^2).

Crack Propagation Tests
Specimens under the same conditions used in the crack initiation tests, were viewed for crack propagations without a break. After confirmation of crack propagation, the weight loss of the rebar in the specimen was measured.
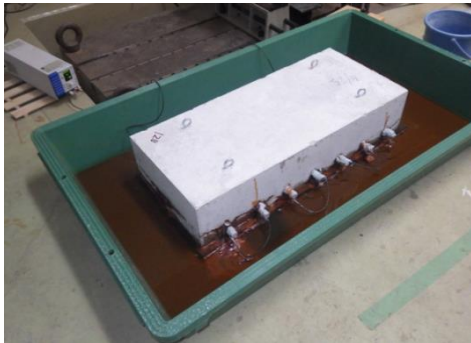

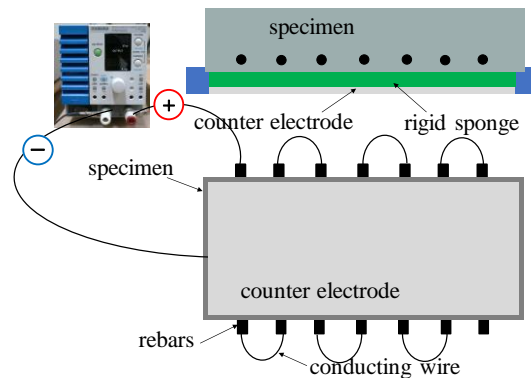Figure 8. Electric corrosion test

Figure 9. Scheme of the accelerated corrosion set up

EXPERIMETAL RESULTS

Crack Initiation Results
Due to the swelling caused by corrosion products, cracks appeared from the steel/concrete interface and propagated in different patterns (Figure 10). For the specimen with 60 mm spacing, cracks initially appeared in the horizontal direction between the bars (Figure 10a). For specimens with 120 mm and 240 mm spacing, cracks initially appeared in the vertical direction below some bars at the bottom of the specimen (Figure 10b and Figure 10c). The weight loss of the rebar after corrosion is

shown in Table 2. The weight of the protective oxide layer on the sound rebar was 22.77 mg/cm^2. The weight of the corroded rebar was 42.91~50.52 mg/cm^2.
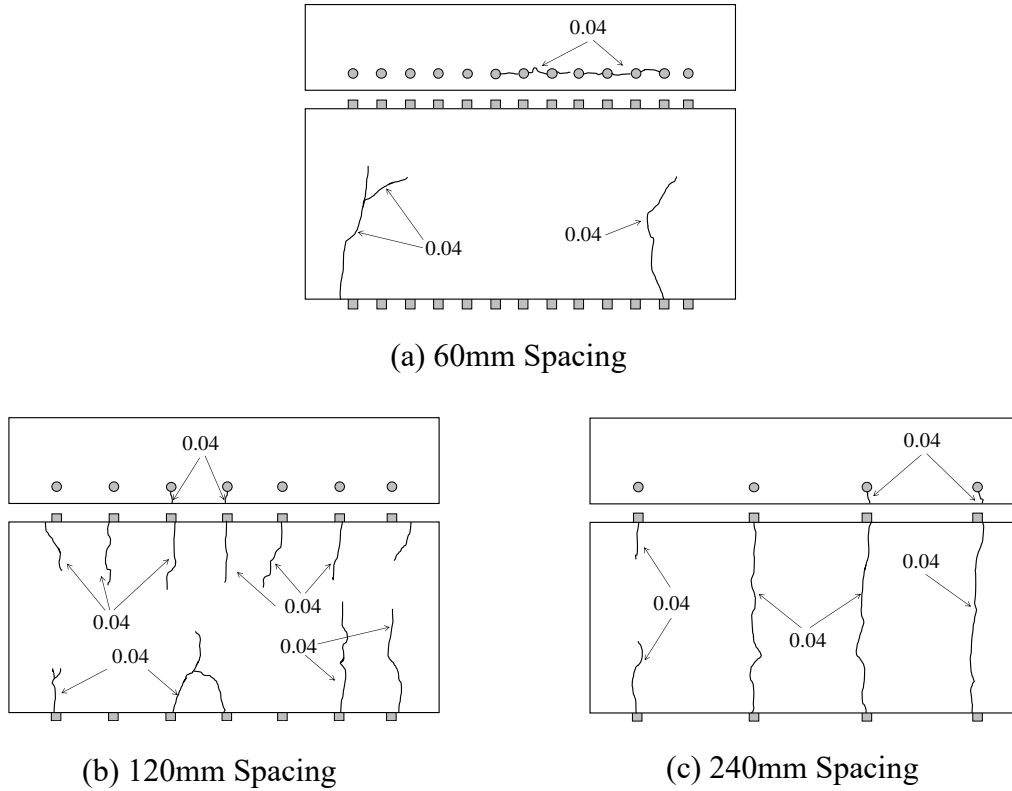

(a) 60mm Spacing

(b) 120mm Spacing

(c) 240mm Spacing

Figure 10. Sketches of the initial crack patterns and crack widths (unit: mm)

Table 2. Weight loss of corrosion reinforcing bars

(mg/cm^2)

|	D19ctc60	D19ctc120	D19ctc240
Measured value	72.58	73.29	65.68
Protective oxide layer	22.77		
Weight loss of corrosion rebar	49.81	50.52	42.91

Crack Propagation Results

The accelerated corrosion test was conducted for 670 hours at 1.7A. The rebars were numbered 1~7. Figure 11 shows crack patterns on the specimen with 120 mm spacing. Sketched crack patterns and crack widths are shown in Figure 12. On the end surface, cracks initially appeared in the vertical direction, followed by horizontal cracks propagating between the bars. Slight inclined cracks were observed at bars 1 and 7 which propagated towards the side surfaces of the concrete (Figure 12a). The width of the horizontal cracks ranged from 0.20 mm ~ 0.85 mm. On the bottom surface, the

largest crack width along rebars 1 and 7 was 1.50 mm. Crack widths along rebars 2~6 however, did not exceed 0.15 mm.
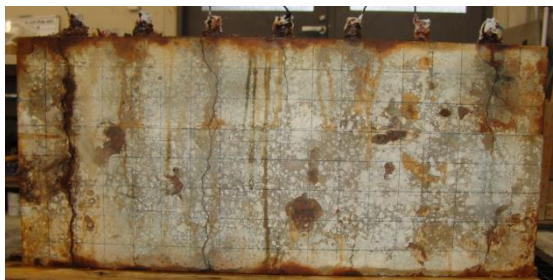
Figure 13 shows crack patterns on the specimen with 240 mm spacing. The accelerated corrosion test was continued for 857 hours at 1.0A The rebars were numbered 1~4. Sketched crack patterns and crack widths are shown in Figure 14. We were not able to measure the crack width on the end surface because it peeled off (Figure 13). The crack patterns were similar to the specimen with 120 mm spacing in that the initial vertical cracks did not widen. However, the horizontal cracks extended along the bars with corrosive progression.
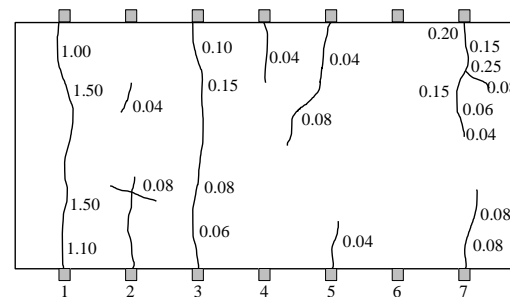

(a) End surface
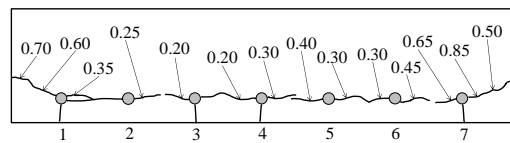
(a) End surface
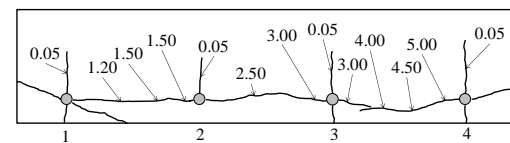

(b) Bottom surface

(b) Bottom surface

Figure 11. Crack patterns of the specimen with 120 mm interval

Figure 12. Crack sketches and crack widths of the specimen with 120 mm interval (unit: mm)
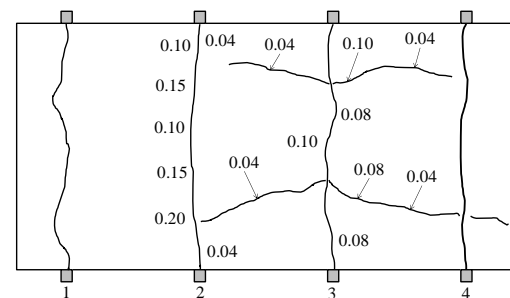

(a) End surface

(a) End surface

(b) Bottom surface

(b) Bottom surface

Figure 13. Crack patterns of the specimen with 240 mm interval

Figure 14. Crack sketches and crack widths of the specimen with 240 mm interval (unit: mm)

EXPERIMENTAL DISCUSSION

Results from the crack initiation tests confirmed that rebar spacing affects crack initiation patterns in cases of multi-rebar corrosion. If the rebars are closely spaced such as the specimen with 60 mm spacing, the initial cracks form parallel with the concrete surface. If the concrete cover depth is relatively shallow, and/or the reinforcing bars are widely spaced such as the specimens with 120 mm and 240 mm spacing, the initial cracks are aligned with the reinforcing bars and are perpendicular with the concrete surface. Moreover, the corrosion amount at occurrence of corrosion cracks was approximately 50 mg/cm^2 in this study.

The crack propagation tests revealed that propagation was dominant in the horizontal direction between the reinforcing bars. The internal radial stress caused by rust expansion acted on the concrete around the reinforcing bars. The reinforcing bars at the left and right ends have no binding force to counteract a lateral force of corrosion expansion. Therefore, it is easier to expand the widths of crack perpendicular to the concrete surface. Conversely, for the central rebars, a lateral force due to corrosion expansion is suppressed in the surrounding concrete. As a result, a vertical action due to corrosion expansion dominates, thus horizontal cracks occurred between the reinforcing bars.

NUMERICAL ANALYSIS

In order to confirm the experimental results, a numerical analysis was examined on corrosion cracks of the specimens.

Finite Element Modeling
The aim of the numerical simulation is to estimate the propagation of cracks from concrete with different rebar spacing. Analyzed specimens were modeled as shown in Figure 15. Due to the limitation of numerical computation, the specimen's length is 5 mm utilizing it as a plane strain model in this analysis. The specimens are simply supported on the other side of the concrete cover (Figure 16). The analysis uses a concrete material model whereby the tensile behavior of concrete up to the tensile strength is modeled as linear elastic (Figure 17). A bilinear softening branch is assumed after cracking, in which f_t is tensile strength and G_F is tensile fracture energy.
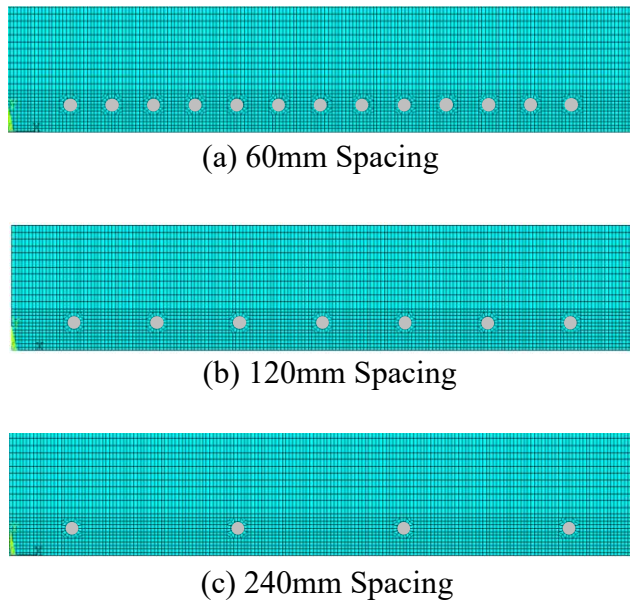
(a) 60mm Spacing

(b) 120mm Spacing

(c) 240mm Spacing

Figure 15. Analytical models of specimens
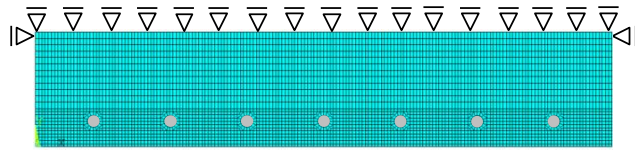
Figure 16. Specimen supports
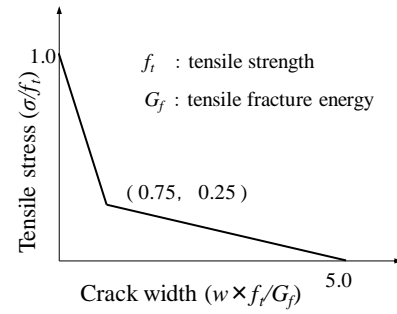
Figure 17. Concrete model

Table 3. Material property

【Concrete】	
Elastic modulus E_c (GPa)	15
Poisson ratio v_c	0.2
Tensile strength f_t (MPa)	2.75
Compressive strength f'_c (MPa)	36.9
【Reinfocing bar】	
Elastic modulus E_s (GPa)	200
Poisson ratio v_s	0.2
Diameter of steel φ (mm)	19

Material Property

Table 3 shows the material properties that are used in the analysis. The parameters of concrete material were identified from the experimental measurements performed on concrete specimens. To consider creep deformation, the elastic modulus of concrete is as follows:

$$E_{cr} = \frac{1}{1+C_r} E_r \qquad (2)$$

Where E_{cr} is the elastic modulus of concrete for this analysis, E_c is the elastic modulus of the experimental result, and C_r is the creep factor, set at 1.0.
The shear transferring capacity at the cracked interface is taken here as a transfer coefficient.

Corrosion Expansion Model

Rust expansion occurred by applying heat to the steel rebar. The thermal expansion coefficient of the reinforcing bar was 1.0×10^{-5} /°C. The input temperature was gradually increased in increments of 0.2 °C.

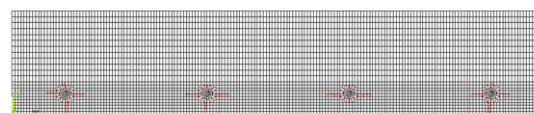**Analytical Crack Initiation Results**

Crack patterns occurred at an early stage for the specimens with 60 mm, 120 mm and 240 mm spacing (Figure 18). The dotted lines in the figures represent the areas where the stress in the concrete reached the tensile strength, due to the inflation pressure. For the rebar spacing of 60 mm, cracks occurred initially in the horizontal direction between the bars (Figure 18a). For the rebar spacing of 120 mm and 240 mm, cracks appeared initially in the vertical direction below some bars (Figure 18b and Figure 18c). These results were similar to the experimental results.
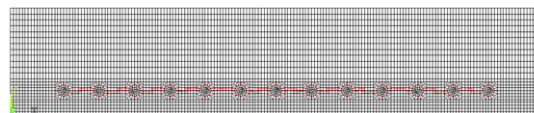
(a) 60mm Spacing (step=88)
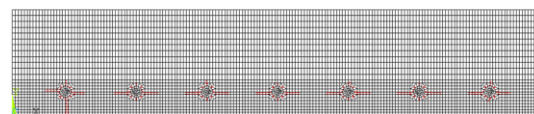
(b) 120mm Spacing (step=111)

(c) 240mm Spacing (step=114)

Figure 18. Initial crack patterns

Analytical Crack Propagation Results and Discussion

Cracks developed at two stages for the specimens with 120 mm and 240 mm spacing (Figure 19). After vertical cracks initially appeared, cracks developed horizontally from each rebar with rust expansion (Figure 19a-1 and Figure 19b-1). The horizontal cracks eventually joined together between rebars (Figure 19a-2 and Figure 19b-2). Cracks to the left and right sides were different from the experimental crack propagation in that the cracks were parallel to the bottom of the specimen. As well, there were more vertical cracks. The progress of horizontal cracks between reinforcing bars was approximately similar to the experimental results. From the analytical crack propagations, it is apparent that cracks in the horizontal direction prominently progress after crack initiation due to rebar corrosion.
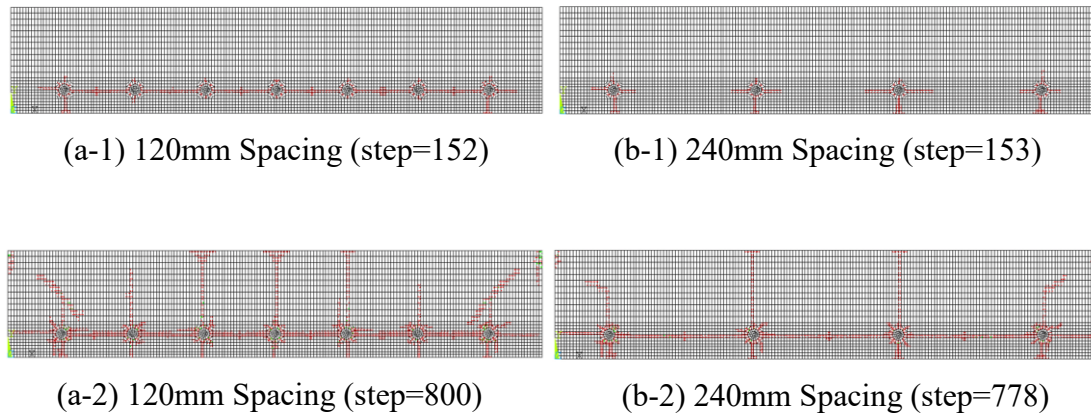
(a-1) 120mm Spacing (step=152)　　　　(b-1) 240mm Spacing (step=153)

(a-2) 120mm Spacing (step=800)　　　　(b-2) 240mm Spacing (step=778)

Figure 19. Crack development

CONCLUSION

Crack initiation patterns and crack propagation due to corrosion were investigated for reinforced concrete slabs embedded with multiple reinforcing bars with 60 mm, 120 mm and 240 mm spacing. Rebar corrosion was accelerated using an electric corrosion test. A numerical analysis was also carried out to verify the experimental results. From the experimental and analytical study, the following conclusions may be drawn:

1. Reinforcing bar spacing affects the crack initiation patterns. Small cover depth generates a vertical crack along the rebar. Narrow spaces between the rebar generates a horizontal crack.

2. A corrosion amount at occurrence of corrosion cracks was approximately 50 mg/cm2 in this study.

3. In crack propagation, the horizontal direction between rebar was dominant rather than the crack initiation patterns for reinforced concrete slabs. The progress of the horizontal crack makes it difficult to observe on the concrete surface. In the case of concrete slabs, it was considered that methods other than crack observation are necessary for long-term maintenance.

4. In order to apply the outcome of this study to a real structure, it is necessary to conduct an exposure experiment in a natural environment. However, this study may be useful for the maintenance of reinforced concrete slabs with multiple reinforcing bars.

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