TOWARD HYBRID-NDE FOR REBAR CORROSION IN REINFORCED CONCRETE WITH ACOUSTIC EMISSION

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Abstract: For non-destructive evaluation (NDE) of corrosion in reinforcing steel-bars (rebar), a half-cell potential and a polarization resistance of the electrochemical methods are currently available. Since these techniques, however, evaluate surface values of concrete over rebars, it has been reported that the measured values are considerably affected by conditions of concrete cover. In this study, therefore, a procedure to estimate the potential distributions on rebars is developed by applying the boundary element method (BEM). An accelerated-corrosion experiment is conducted in a concrete–slab specimen. In order to monitor the corrosion process, acoustic emission (AE) measurement is performed during the test. Based on half-cell potentials and polarization resistances measured on the surface of the slab, potential distributions on rebars are estimated at the stages of high AE activities. Results are compared with direct observation of rebars, which are removed from the specimen. Thus, a great promise for a hybrid-NDE technique to quantitatively evaluate the corrosion process in reinforced concrete at an early stage is demonstrated.

1 INTRODUCTION

Corrosion problems of reinforcing steel bar (rebar) in reinforced concrete (RC) by salt attack have been widely reported through-out the world. Basically, concrete provides a good durable condition for embedded rebar with high alkaline environment by forming a passive film on the surface of rebar. Due to ingress of chloride ions through concrete, the passive film is destroyed and corrosion is initiated.

In order to avoid harmful damages, many monitoring methods have been developed to evaluate the corrosion before reaching the critical level [1]. One effective method could be nondestructive evaluation (NDE). NDE techniques are practical and useful in both a laboratory test and on-site measurement. So far, such electrochemical techniques as half-cell potential, polarization resistance and so forth are widely employed. Recently, acoustic emission (AE) is introduced for detecting both the onset of corrosion and the corrosion-induced cracks in concrete [2].

In this paper, we apply simplified inversion of the boundary element method (IBEM) based on the 3-dimensional BEM for the potential distribution of half-cell potentials. These results are compared with results of AE activity. Then, we propose the Hybrid-NDE to precisely evaluate rebar corrosion.

2 ANALYTICAL METHOD

In the case that concrete is referred to as homogeneous, potential $u(x)$ at an internal point x is obtained by the boundary integral equation [3],

$$u(x)=\int_S\left\{G(x,y)\frac{\partial u}{\partial n}(y)-\frac{\partial G}{\partial n}(x,y)\cdot u(y)\right\}dS \quad (1)$$

Here points y are located on the boundary S surrounding the concrete. $G(x,y)$ is the fundamental solution.

From Eq. (1), internal potentials at the interface between concrete and rebar are discretized as,

$$u(x)=\sum_{j=1}^{N}G(x,y_j)\frac{\partial u}{\partial n}(y_j)S_j-\sum_{j=1}^{N}\frac{\partial G}{\partial n}(x,y_j)u(j)S_i \quad (2)$$

Setting all variables at the boundary elements as discretized values, Eq. (2) is further simplified as,

$$u_i=\sum_{j=1}^{N}G_{ij}\frac{\partial u}{\partial n_j}S_j-\sum_{j=1}^{N}\frac{\partial G_{ij}}{\partial n}u_jS_j \quad (3)$$

where u_j and S_j are the half-cell potentials at the concrete surface and the area of electrode section of measurement, respectively. $\partial u/\partial x_j$ represents the corrosion currents and has a relation with the polarization resistances I_j as,

$$\frac{\partial u}{\partial n_j}\propto\frac{B}{I_j} \quad (4)$$

Substituting two coefficients C_1 and C_2 into the potential term and the current term for compensation in Eq. (3), we have,

$$u_i=C_1\left(\sum_{j=1}^{1}\frac{\partial G_{ij}}{\partial n}u_jS_j\right)+C_2\left(\sum_{j=1}^{N}G_{ij}\frac{1}{I_j}S_j\right) \quad (5)$$

In the experiment, potentials and resistances were measured at two locations x_1 and x_2. Two relations are derived from Eq. (5),

$$\begin{aligned}u_1&=C_1\left(\sum_{j=1}^{N}\frac{\partial G(x_1,y_j)}{\partial n}u_jS_j\right)+C_2\left(\sum_{j=1}^{N}G(x_1,y_j)\frac{1}{I_j}S_j\right)\\u_2&=C_1\left(\sum_{j=1}^{N}\frac{\partial G(x_2,y_j)}{\partial n}u_jS_j\right)+C_2\left(\sum_{j=1}^{N}G(x_2,y_j)\frac{1}{I_j}S_j\right)\end{aligned} \quad (6)$$

After determining the coefficients C_1 and C_2 from Eq. (6), half-cell potentials at the rebar surface can be calculated by Eq. (5).

3 EXPERIMENT

Configuration of a specimen is illustrated in Fig. 1. One RC slab of dimensions 1000 mm x 570 mm x 100 mm was made. A deformed rebar of 13 mm nominal diameter is embedded with 20 mm cover-thickness. Ordinary

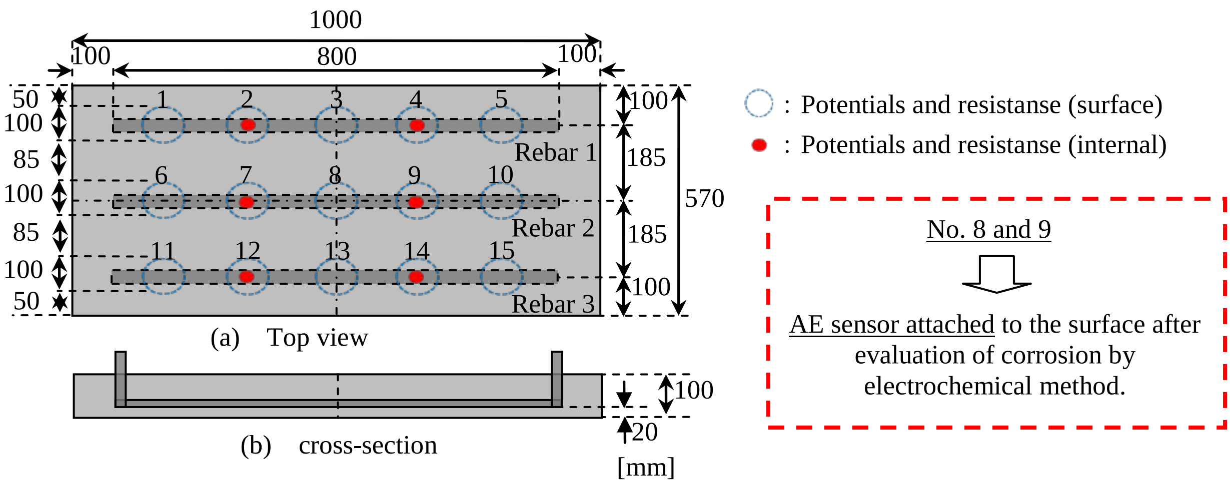


Figure 1: RC slab tested and the location of NDE.

Portland cement (OPC) was used. Coarse aggregate (gravel) was granite, of which the maximum gravel size is 10 mm. Concerning mixture proportion, the ratios of water, cement, sand, and gravel were 0.55, 1.0, 2.57, and 3.01 by weight. The slump value and air content of fresh concrete were controlled by admixture as 80 mm and 5.0 %, respectively. To accelerate corrosion of rebar, 0.704 kg/m^3 NaCl was mixed in water.

Following water curing for 28 days, a corrosion process due to salt attack was simulated by a cyclic wet and dry test. The specimen was cyclically placed into a container filled with 3% NaCl solution for a week and subsequently taken out of the container to dry under ambient temperature for another week.

AE measurement was continuously conducted using AE measuring system (DiSP, PAC). Two AE sensors of 150 kHz resonance are attached to the surface of the specimen as shown in Fig. 1. The frequency range of the measurement was 10 kHz to 2 MHz. AE signals were amplified with 40 dB gain in a pre-amplifier and 20 dB gain in a main amplifier. For ringdown-counting, the dead-time was set to 2 msec and the threshold level to 40 dB gain.

Every week, AE measurement was temporarily stopped to conduct the half-cell potential measurement. The potentials of the surface of the specimen were measured by using a portable corrosion meter, (SRI-CM-II) [4], and C. S. E. values were estimated on the basis of ASTM C876 standard [5].

4 RESULTS

4.1 Activities of electrochemical techniques

Results of half-cell potentials at rebar 1 (measurement areas are 3 and 4) and rebar 2 (measurement areas are 8 and 9) are shown in Fig. 2. The internal potentials and the results of BEM analysis are included in Fig. 2. From both results, the half-cell potentials at rebar 1 increased until 105 days elapsed. It is found that the potentials drastically decreased after 105 days elapsed. At 133 days elapsed, the potentials became lower than -350 mV which indicates 90 % corrosion possibility.

However, in the case of results of rebar 2, the half-cell potentials increased until 21 days elapsed. Then, at 49 days elapsed, the potentials became lower than -350 mV. Thus, the potentials at the surface of concrete at rebar 2 suggested so early as evaluated the corrosion possibility than rebar 1. After the potentials became more negative than -350 mV, the potentials were stabilized. At the period, corrosive stains were observed on the bottom surface at rebar 2-8. From these results, it is realized that corrosion activities due to half-cell potentials are different from the beginning. The corrosion process at rebar 2 is more active than that of rebar 1.

According to results of the internal

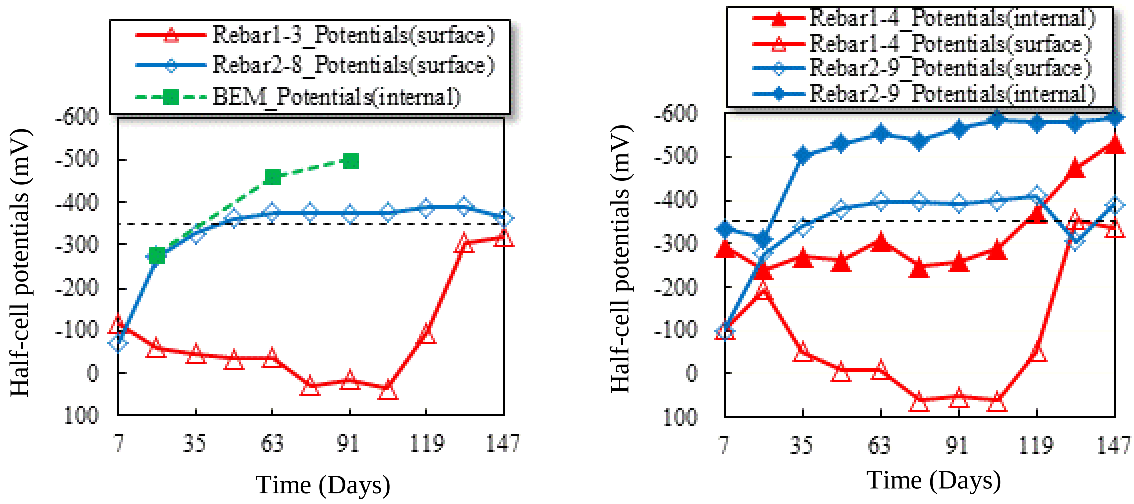


Figure 2: Halfcell-potentials of rebar 1 and rebar2 (rebar-measurement area).

potentials at rebar 1-4 and rebar 2-9, those potentials are lower than results of the surface potentials. It implies that the potentials at the surface of rebar are very important to electrically evaluate the corrosion initiation.

CEB recommendation of polarization resistance and results of those at rebar 2 are given in Table 1 and 2, respectively. The resistances of all measured points become quite low from the beginning. The corrosion rates from middle to high are observed at 35 days elapsed.

From these results, we assumed that the corrosion started from about 35 days. Then, two AE sensors were attached to the surface of the specimen at rebar 2-8 and rebar 2-9, and AE monitoring was conducted until 147 days.

Table 1: CEB recommendation

Resistance Rct ($k\Omega cm^2$)	Corrosion rate
130<Rct≤260	No corrosion or very low rate
52<Rct≤130	Low ~ middle rate
26<Rct≤52	Middle ~ high rate
Rct≤26	Very high rate

Table 2: Results of resistance

	Rebar 2-8	Rebar 2-9
7 days	46	46
21 days	37	37
35 days	30	29
49 days	31	35
63 days	32	35
91 days	38	36

4.2 BEM analysis

Results of BEM analysis at rebar 2 are given in Fig. 3. In order to analyze, half-cell potentials at the surface are considered as the input date. In the figure, results at 3 periods (21 days, 63 days and 91 days) are shown.

Comparing all measurement points (6 ~ 10), the fluctuation range of both the potentials of point 8 through 10 at 21 days and the potentials of same points at 63days and 91 days are more negative than that of the points 6 and 7. It implies that the corrosion activity at points 8 to 10 is higher. Furthermore, comparing the points 8 to 10, the half-cell potentials at point 10 are the most negative. This implies that the corrosion at point 10 more progressed than at points 8 and 9 in rebar 2. From these results, it indicates that the corrosive location could be readily evaluated by BEM analysis.

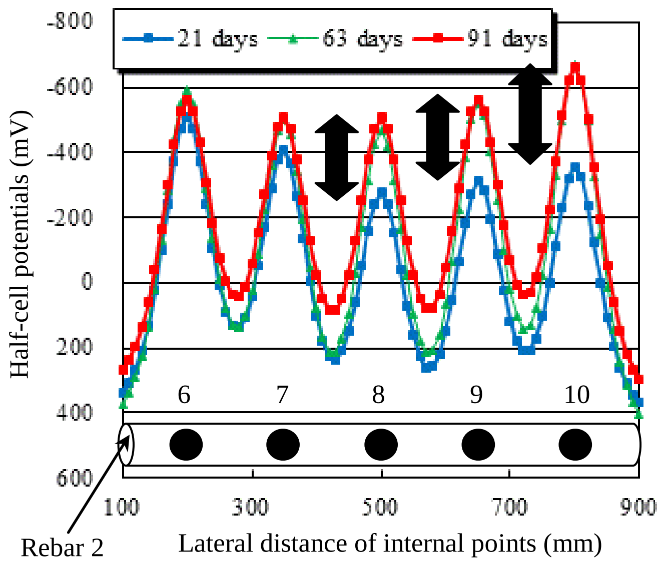


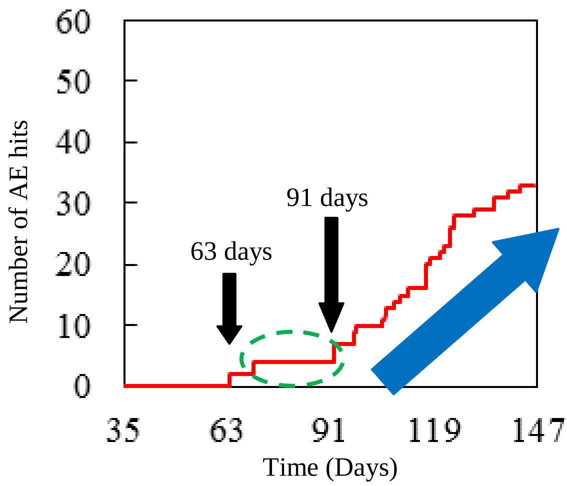
Figure 3: Results of BEM analysis at rebar 2.

4.3 AE activities

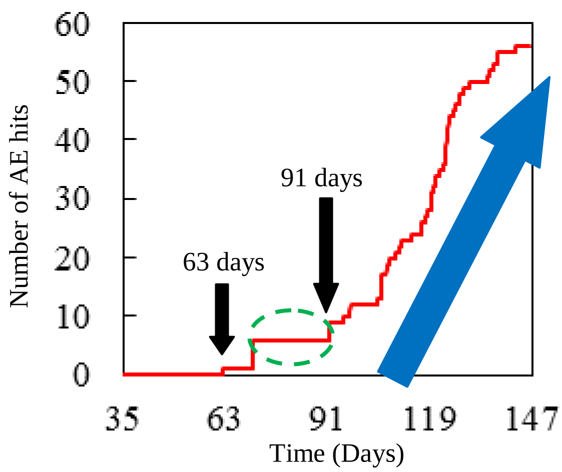
Results of AE activities are shown in Fig. 4. It is noted that the periods of both “the onset of corrosion” and “the nucleation of corrosion-induced crack” could be evaluated by AE monitoring [6].

AE hits are detected from 63 days at both measurement areas. In between 70 days and 91 days, there is no progress of AE hits. Then, AE hits drastically increase at 91 days, and the rate of increase at rebar 2-9 is higher than rebar 2-8. From these results, it is confirmed that the corrosion process at rebar 2 is earlier than rebar 1, as these are in remarkable agreement with results of BEM analysis.

On the other hand, comparing with the half-cell potentials at the surface of rebar 2-8 and 2-9 in Fig. 2, any difference was not found in both measured points. It implies that the imperceptible difference of the corrosion

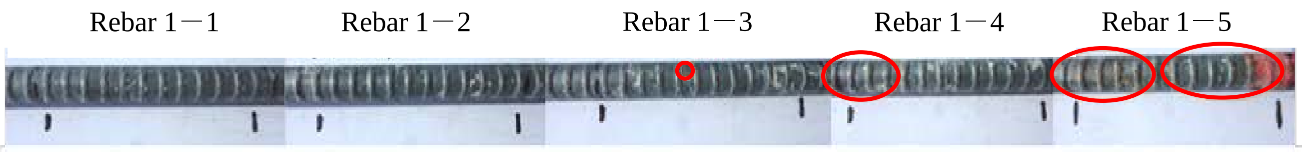


(b) Measurement area 8

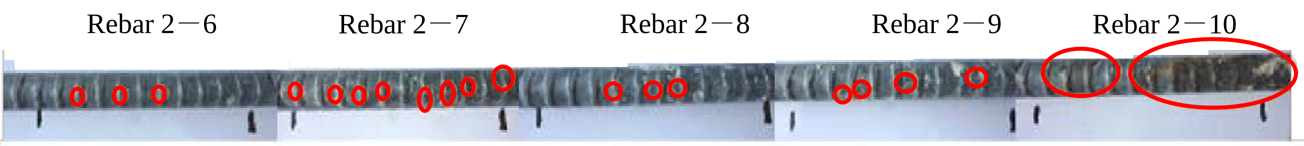


(a) Measurement area 9

Figure 4: Results of AE activities.



(b) Rebar 1



(a) Rebar 2

Figure 5: Results of visual observation of removed rebar.

phenomena, which might be difficult to be detected in the electrochemical measurement, can be detected by AE monitoring.

4.4 Visual observation

All rebar was removed to observe visually the corrosion state after the cyclic test. These removed rebar are shown in Fig. 5. Here, red circles indicate the location where the rust was found.

Corroded areas in the both rebar 1 and 2 are visually observed. In the rebar 2, the rust stain was found at all measured points, and the high corrosion was identified at point 10. Also in the point 8 and 9 where AE measurement was conducted, definitive corrosion was confirmed. This result is in remarkable agreement with results of the half-cell potentials in Fig.2 and results of the AE activities in Fig. 4.

5 CONCLUSIONS

AE techniques and electrochemical techniques are applied to evaluate the corrosion process in the RC slab. Corroded areas are estimated by IBEM analysis, compensating the half-cell potentials. The results are summarized as follows:

1. In the half-cell potential measurement, evaluation of the initiation periods of corrosion in RC is possible. However, because the half-cell potentials at the

surface of the rebar are distinctly more negative than that of the surface of the specimen, the electrical evaluation at the surface of the rebar is very important.

2. From the results of BEM analysis, the internal half-cell potentials at the all points were estimated in RC slab. These results are in remarkable agreement with the results of the visual observation. It implies that the electrical evaluation inside concrete is effective.

3. The imperceptible difference of the corrosion phenomena which is difficult to be detected in the electrochemical measurement can be identified by using AE techniques. AE activities are in remarkable agreement with BEM analysis and visual observation. Thus, it demonstrated that the state of the rebar corrosion in RC can be quntitatively evaluated by using hyblid-NDE techniques of AE techniques and the electro-chemical techniques with numerical analysis.

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