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On-Site Measurement of Corrosion of Steel Bars in Concrete by Acoustic Emission

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ABSTRACT

The mechanisms of corrosion-induced cracks and evaluation methods for diagnosis are under development in concrete engineering. In order to develop AE techniques to be applicable to on-site measurement for infrastructure, hybrid nondestructive ealuation (NDE) is under investigation. Thus, an accelerated corrosion test of a reinforced concrete (RC) slab was conducted. To monitor the corrosion process, AE measurement is applied, along with measuring half-cell potentials and polarization resistances at the surface of the slab. Here, in order to identify the corroded area in rebar, the potential inverse BEM (PiBEM) analysis is developed and applied. Toward on-site measurement by NDE, it is demonstrated that the hybrid NDE is practically applicable to damage identification due to salt attack.

Keywords. Acoustic Emission, PiBEM, Corrosion-induced cracks, Electrochemical methods, NDE

INTRODUCTION

In order to avoid harmful damages due to corrosion-induced cracks in RC structures, many monitoring methods have been developed to evaluate the corrosion before reaching the critical level (Dubravka et al., 2000). One effective method could be nondestructive evaluation (NDE). So far, such electrochemical techniques as a half-cell potential, a 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 (Kawasaki et al., 2010). Recently, to identify the corroded area in rebar, the potential inverse boundary element method (PiBEM) was proposed (Kobarai et al., 2012). According to their results, potential values analysed were dramatically fluctuated. So, improvement is definitely needed.

In order to develop the hybrid-NDE for rebar corrosion applicable to on-site measurement, further study is conducted by conducting an accelerated corrosion test of an RC slab. AE measurement and electro-chemical techniques are performed. Results estimated by NDE are confirmed by visual observation of corroded rebars.

ANALYTICAL METHOD - PiBEM

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 (Brebbia, 1987),

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

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,

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

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

$$u_i = \sum_{j=1}^{N} G_{ij}\frac{\partial u}{\partial n_j}S_j - \sum_{j=1}^{N}\frac{\partial G_{ij}}{\partial n}u_j S_j \tag{3}$$

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,

$$\frac{\partial u}{\partial n_j} \propto \frac{B}{I_j} \tag{4}$$

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

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

In the experiment, potentials and resistances were measured at two locations x_1 and x_2 by embedded sensors. Thus, the potentials at the two locations are derived from Eq. 5,

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

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.

EXPERIMENTAL PROCEDURE

Configuration of a specimen is illustrated in Fig. 1. One RC slab of dimensions 1000 mm x 570 mm x 75 mm was made. A deformed rebar of 13 mm nominal diameter is embedded with 20 mm cover-thickness. Ordinary Portland cement (OPC) was used. Coarse aggregate (gravel) was granite, of which the maximum gravel size is 10 mm. Concerning mixture proportion, the ratio of water : cement : sand : gravel is 0.55 : 1.0 : 2.57 : 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). 8 AE sensors of 60 kHz resonance (R6) and 150 kHz (R15) are attached to the surface of the specimen as shown in Fig. 1. In order to compare the difference of the frequency range, both R15 and R6 are used at the center of the slab. 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 discontinued to measure the half-cell potentials and polarization resistances. The potentials of the surface of the specimen were measured by using a portable corrosion meter, (SRI-CM-II) (Yokota, 1999), and C. S. E. values were estimated on the basis of ASTM C876 standard (ASTM, 1991). In order to avoid large fluctuation of the results of BEM, 12 measurement points are added as shown as green circles.

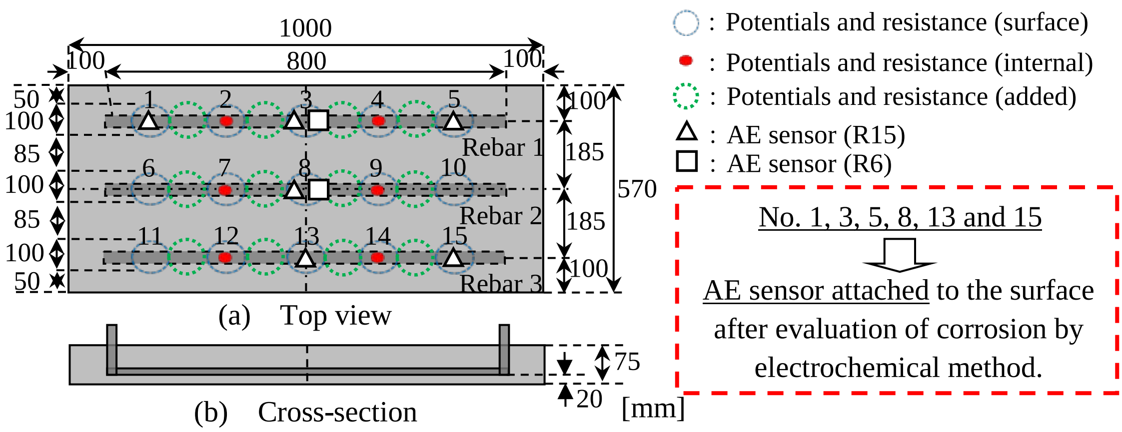


Figure 1. RC slab tested and the location of NDE

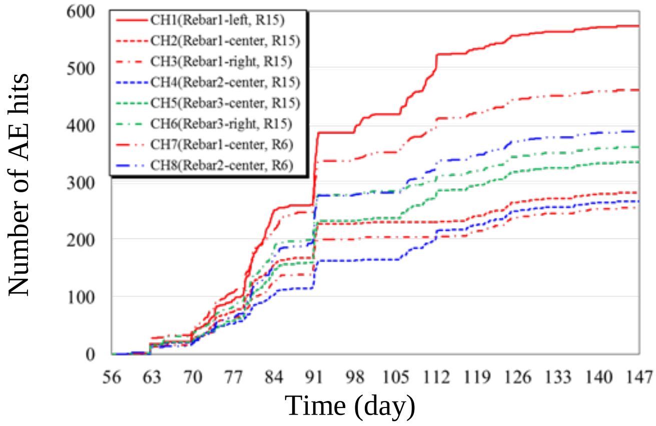
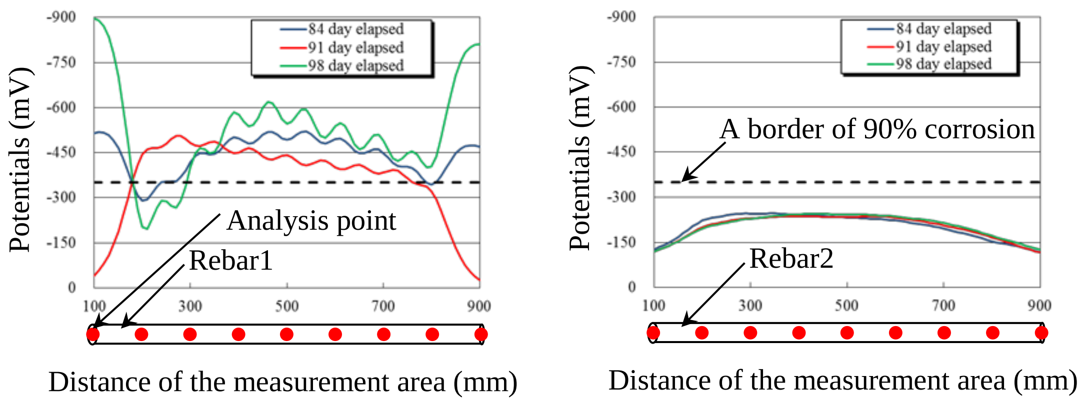


Figure 2. AE activities at all CH

Results of the AE activities are shown in Fig.2. The largest number of AE hits is observed at ch1. The fluctuation range of AE hits of all sensors becomes large with increasing the elapsed time, especially from 77 days. It is realized that the evolution of the corrosion seems to be started from 63 days, and thus the corrosion-induced cracks could be initiated. At rebar 1, it is observed that AE activity due to the corrosion is the highest, comparing AE activities of all sensors. In particular, the left part of rebar 1 is to be actively corroded.

In order to improve results of the PiBAM analysis, the measurement points of the electrochemical techniques increased from 5 locations to 9 locations. Results of PiBEM at rebar1 and rebar2 are shown in Fig.3. Here, if the potentials became lower than -350 mV, it indicates 90 % corrosion possibility. In the case of rebar 1, fluctuations of the analytical values are large while the fluctuations of that are negligible at rebar 2. It is clearly observed that rebar 1 should be corroded after 84 days elapsed. In contrast, it is estimated that no corrosion occurs in rebar 2 even after 98 days elapsed. It is noted that the half-cell potentials of rebar 1 become more negative at the left part.



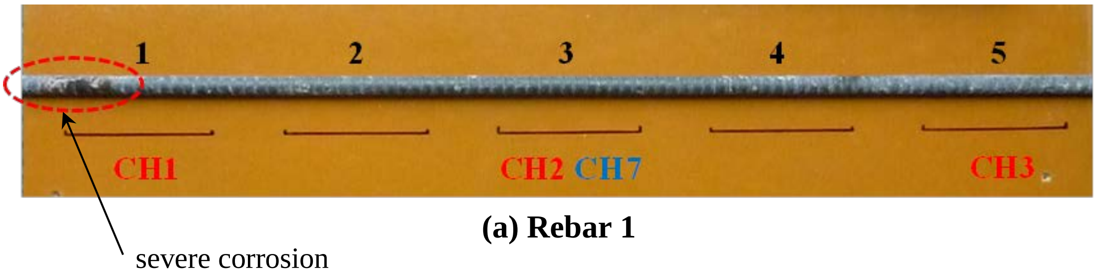
(a) Rebar 1 **(b) Rebar 2**

Figure 3. Fluctuation of the analytical values

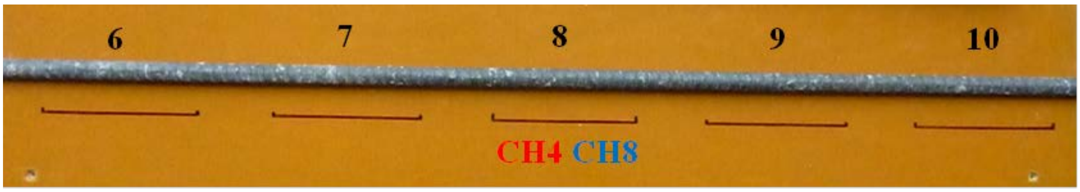
Consequently, the increase in AE activity from 77 days shown in Fig. 2 is confirmed by the potential distribution in Fig. 3. It demonstrated that results of AE measurement are quantitatively analysed by the PiBEM analysis. By the method, the corrosion activity and the corroded area are reasonably evaluated as the corrosion process at rebar 1 is more active than that of rebar 2.

All rebars were removed to observe visually the corrosion state after the cyclic test. Two rebars removed are shown in Fig. 6. Here, red circles indicate the location where the rust is found.

Slightly corroded areas in the both rebar 1 and 2 are visually observed. In rebar 1, severe corrosion is found at the left part where AE measurement shows high activity. All the results really confirm an applicability of AE measurement and the PiBEM analysis as the hybrid NDE.



(a) Rebar 1



(b) Rebar 2

Figure 4. Visual observation

CONCLUSIONS

AE techniques and a numerical analysis by using electrochemical techniques are applied to monitor the corrosion process in the RC slab for the development of on-site measurement. The corroded area of rebar is quantitatively estimated by the PiBEM analysis, based on the electro-chemical techniques of the half-cell potentials and the polarization resistances.

From the results of PiBEM analysis, the internal potentials at the all points estimated in RC slab are in good agreement with AE activities observed. These results are in remarkable agreement with the results of the visual observation. It implies that the electrical evaluation inside concrete can be done by the analysis.

The imperceptible difference of the corrosion phenomena, which is difficult to be detected only in the electrochemical measurement, can be detected by collaborating with AE techniques. AE activities are in remarkable agreement with PiBEM analysis and visual observation. Thus, it demonstrated that the state of the rebar corrosion in RC can be quantitatively evaluated by using the hybrid-NDE technique of AE techniques and the electrochemical techniques with numerical analysis toward on-site measurement.

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