Hybrid NDE for Rebar Corrosion in Reinforced Concrete

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ABSTRACT: To maintain concrete structures in safe and healthy conditions, nondestructive evaluation (NDE) for corrosion damage is recently in critical demand. Conventionally, NDE for corrosion of reinforcing-steel bars (rebars) has been performed by electro-chemical techniques of half-cell potential and polarization resistance. Although these could be useful for estimation of rebar corrosion, results measured are marginally successful because of uncertainty, depending on many factors associated with the measuring conditions.

A great promise is realized for an applicability of acoustic emission (AE) techniques to monitoring the rebar corrosion. High AE activities are observed twice during the corrosion process, corresponding to the onset of corrosion (1st stage) and the nucleation of corrosion cracking (2nd stage). It is reported that AE location analysis and SiGMA analysis provide visual information of damaged areas inside concrete in the 2nd stage.

In the present paper, practical NDE for the rebar corrosion in concrete structures is studied for developing a reliable early-warning system. Continuous AE monitoring was performed, combing with the electro-chemical techniques. Thus, a hybrid NDE is proposed. The 1st stage is readily identified from the decrease in the polarization resistance with the 1st high AE activity. The 2nd stage is determined from the 2nd high AE activity, keeping the half-cell potentials more negative than -350 mV (C. S. E.) and decreasing in $I_b$-values of AE amplitude distribution.

1 INTRODUCTION

Corrosion of reinforcing-steel bars (rebars) is one of critical de teriorations in reinforced concrete (RC) located in marine environment or subjected to ingress of chloride ions. When the chloride concentration at rebar exceeds the critical threshold value (Nygard and Geiker, 2005) a passive film on the surface of rebar is destroyed and corrosion is initiated. Then the electrochemical reaction continues with supplying oxygen and water. Corrosion products on surfaces of rebars grow with time and nucleate micro-cracks in concrete. In order to maintain concrete structures in healthy and safe conditions, therefore nondestructive evaluation (NDE) for early warning of rebar corrosion is in critical demand.

We have demonstrated that high AE activities are observed twice during the corrosion process (Ohtsu and Tomoda, 2008). According to the phenomenological model of reinforcement corrosion in marine environments (Melchers and Li, 2006), evolution of a typical corrosion loss is modeled as four phases as shown in Fig. 1. At phase 1, the corrosion is initiated and the corrosion loss increases. The rate of the corrosion process is controlled by the rate of transport...
of oxygen. As the corrosion products build up on the corroding surface of rebar, the flow of oxygen is eventually inhibited and the rate of the corrosion loss decreases at phase 2. The corrosion process involves further corrosion losses at phases 3 and 4 due to anaerobic corrosion.

In reinforced concrete, it is demonstrated that the 1st high AE activity results from phase 1 of the onset of corrosion in rebar. During phases 3 and 4, corrosion-induced cracks could be generated in concrete due to expansion of corrosion products in rebar, and eventually the 2nd high AE activity is observed.

It is also found that AE sources at the 2nd high AE activity are large enough to be identified by AE-SiGMA analysis as shown in Fig. 2 (Ohtsu and Kawasaki, 2010). Therefore, evolution of corrosion cracking in concrete could be visually detected by AE analysis. In practical cases, however, this kind of multi-channel observation is not always available. In addition, the detection of the 1st stage is definitely necessary for early-warning. Consequently, the next step of research should be development of a reliable technique for practical detection of the 1st stage of the corrosion.

In the present paper, continuous AE monitoring was performed in a reinforced concrete-slab specimen, combing with the electro-chemical techniques. Based on results, a hybrid NDE of AE measurement and the electro-chemical techniques is proposed for the rebar corrosion in concrete structures, as a reliable and practical early-warning system.

![Figure 1. Corrosion process and four phases.](image1)

![Figure 2. Results of SiGMA analysis in reinforced concrete (Ohtsu and Kawasaki, 2010).](image2)
2 NDE TECHNIQUES

2.1 Electro-chemical measurement

Half-cell potentials and polarization resistances were measured by an embedded mini-sensor shown in Fig. 3 (General Building Research Corp., Japan). These sensors were directly bonded to rebars. Then, values of half-cell potentials and polarization resistances measured were recorded by a portable corrosion meter (SRI-CM-II, Shikoku Soken, Japan).

As well known, the half-cell potentials are applied to estimate the probability of corrosion, while the intensity of corrosion current was estimated by the polarization resistance.

![Figure 3. Sketch of embedded mini-sensor.](image)

2.2 AE measurement

In order to estimate AE activity, one counting method of a hit was employed. AE hit corresponds to one AE transient at a given AE channel detected and processed. The accumulated number of AE hits was obtained during the corrosion process. In addition to the hit, the amplitude distribution of AE hits was analyzed. A relationship between the number of AE hits, \( N \), and the maximum amplitudes, \( A \), of AE hits is statistically represented as,

\[
\log_{10} N = a - b \log_{10} A
\]

where \( a \) and \( b \) are empirical constants. The latter is known as \( b \)-value. Instead of the seismic \( b \)-value, an improved \( b \)-value (\( Ib \)-value) has been proposed (Shiotani et al. 1994), which is suitable for AE applications to concrete and rock. It is important to determine the \( b \)-value as to apply the constant number of data to calculation. To improve the calculation of the \( b \)-value, the number of AE data is formulated by,

\[
\int_0^\infty n(a)da = \beta
\]

where \( n(a) \) is a number of AE at \( da \) and \( \beta \) is a number of AE data. 100 of \( \beta \) value was employed in the \( Ib \)-value analysis.

It is well known that in the case that \( Ib \)-values are large, small AE events are mostly generated. In contrast, the case where \( Ib \)-values become small implies active nucleation of large AE events.
3 EXPERIMENTS

3.1 Specimens

Mixture proportion of concrete is given in Table 1. In order to accelerate the rebar corrosion, NaCl solution was added to mixing water. At the age of 28 days after moisture curing, a cylindrical specimen of 100 mm diameter and 200 mm height was sliced into 5 mm-thick disks. They were crushed and concentrations of chloride ions were determined by the potentiometric titration method. The concentration was found to be 0.097 % per cement weight, which was suggested to being equivalent to the onset level of chloride ions.

A slab specimen of dimensions 1000 mm x 570 mm x 75 mm was made. After 28-day moisture curing, AE sensors and embedded sensors for corrosion monitoring were attached as shown in Fig. 4. At the center, two deformed rebars of 13 mm nominal diameter are embedded in 20 mm cover thickness from the bottom. Two AE sensors of 150 kHz resonant frequency (R15, PAC) are attached by using wax, at the top surface right over rebars. In order to study the effect of cover thickness on rebar corrosion, two holes are bored until 10 mm from the bottom at one-side rebar area as shown in the figure. Thus, the penetration depth of concrete is varied as 10 mm and 20 mm. The mini-sensor is bonded to each rebar at the top side of which was grounded to flat, before casting concrete.

Table. 1 Mixture proportion of concrete

<table>
<thead>
<tr>
<th>Max. size of aggregate (mm)</th>
<th>Slump (cm)</th>
<th>W/C (%)</th>
<th>Air content (%)</th>
<th>s/a (%)</th>
<th>Weight per unit volume (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>8</td>
<td>55</td>
<td>5</td>
<td>48.6</td>
</tr>
</tbody>
</table>

![Figure 4. Sketch of slab specimen tested.](image-url)
Single-reinforced concrete specimens of dimensions 400 mm x 100 mm x 100 mm were also made with 20 mm cover thickness. Under the same condition as the slab specimen, chloride concentration and corrosion degree of rebar were estimated.

### 3.2 Measurements

A cyclic wet-dry test was performed. The specimens were cyclically put into a container filled with 3% NaCl solution for a week and subsequently dried under ambient temperature for another week.

AE measurement was continuously conducted, by using DiSP system (PAC). Frequency range of the measurement was 10 kHz-2 MHz and total gain was 60 dB. For AE counting, the dead-time was set to 2 msec. with 40 dB threshold.

### 4 RESULTS AND DISCUSSION

#### 4.1 AE activity and half-cell potentials

Results of AE activity (the number of AE hits) and those of half-cell potentials are compared in Fig. 5. At rebar of 10 mm cover thickness, half-cell potentials become more negative than -350 mV (C. S. E.) after 28 days elapsed. According to ASTM criterion (ASTM, 1991), the rebar must be corroded with more than 90% probability. Earlier than 28 days elapsed, the number of AE hits clearly starts to increase.

In both figures of Figs. 4 (a) and (b), the number of AE hits increases in remarkable agreement with the corrosion loss in Fig. 1 as a two-step process. From the beginning, the number of AE hits increase as phase 1. During phase 2, AE activity slightly increases and the half-cell potentials keep more negative than -350 mV.

After experiments, rebars were removed from the specimen and the corrosion of rebar was confirmed, as indicated in the figure. AE activity further increases in phases 3 and 4, while the half-cell potentials keep more negative values than -350 mV (C. S. E.).

Consequently, it is suggested that the onset of rebar corrosion start from the beginning of the cyclic wet-dry test, and reach to phase 2 at around 28 days. The half-cell potentials at rebar of 20 mm cover thickness in Fig. 4 (b) start to decrease around at 56 days elapsed, suggesting that it takes more days to reach the critical level of chloride ions than at the case of 10 mm cover thickness. It is summarized that the decrease in the half-cell potentials along with the increase in AE activity could give information of early warning of phase 2, leading to the 2nd stage of corrosion-induced cracking in concrete.

![Figure 5. AE activity and half-cell potentials.](image)
4.2 **AE activity and polarization resistance**

Results of AE activity (the number of AE hits) and those of polarization resistances are compared in Fig. 6. At both rebars of 10 mm cover thickness and 20 mm cover thickness, the polarization resistance suddenly decrease at around 28 days. It implies the corrosion current actively flowed in rebars. Thus, agreement between the increase in AE hits and the decrease in the polarization resistances is remarkable. It is suggested that the sudden decrease in the polarization resistances along with the increase in AE activity could give reliable information of early warning for the 1st stage of the onset of corrosion. In the case of rebar at 10 mm cover thickness, the further decrease of the polarization resistance corresponds to high AE activity at the 2nd stage.

4.3 **Trend of Ib-value**

During the wet-dry cycles, $I_b$-values vary as shown in Fig. 7. The trend of decrease in $I_b$-values is slightly slower at rebar of 20 mm cover thickness than that of 10 mm cover. At both rebars, in particular, abrupt changes are observed at around 28 days. It suggests that sudden generation of large AE hits (high $I_b$-values) follows that of small AE hits. Thus, something definitely happens at 28 days. According to Figs. 5 and 6, 1st high AE activity is observed before 28 days elapsed, when both half-cell potentials and the polarization resistances decrease. So, all information of AE hits, $I_b$-values, the half-cell potentials and the polarization resistances clearly suggests that the onset of corrosion happens before 28 days elapsed. In a practical viewpoint, hybrid estimation of AE and electro-chemical techniques could give us good information of early warning of the rebar corrosion, resulting from phase 1 of the onset of corrosion.
All the results by electro-chemical measurements and AE data suggest the onset of corrosion at around 28 days. Therefore, a rebar was removed from the single-reinforced concrete specimens of dimensions 400 mm x 100 mm x 100 mm at the age of 35 days elapsed. Chloride concentration of the surface layer up to 20 mm was also measured. It was found to be 0.29% per cement weight, which is clearly higher than the threshold level for the rebar corrosion in concrete. A cross-section was examined by a scanning electron-microscope. A result is given in Fig. 8. It is observed that surface oxide layer (dark layer) is already delaminated from steel (gray area) and thus corrosion is initiated at rebar.

The corrosion process in real structures slowly proceeds, but hybrid results of AE data with the half-cell potentials and the polarization resistances provides reliable estimation of the rebar corrosion.

![Figure 8 SEM photo of rebar at 35 days.](image)

5 CONCLUSIONS

Practical NDE for rebar corrosion in concrete structures is studied for developing a reliable early-warning system. Continuous AE monitoring was performed, combining with the electro-chemical techniques.

Based on the results, a hybrid NDE is proposed, combining the electro-chemical techniques and AE analysis. The onset of corrosion is readily identified from the decrease in the polarization resistance with the 1st high AE activity. The stage leading to the corrosion-induced cracking is determined from the 2nd high AE activity, keeping the half-cell potentials more negative than -350 mV (C.S.E.) and decreasing in Ib-values of AE amplitude distribution.

References


