AE-SiGMA ANALYSIS IN BRAZILIAN TEST AND ACCELERATED CORROSION TEST OF CONCRETE

MASAYASU OHTSU and YUMA KAWASAKI
Graduate School of Science and Technology, Kumamoto University
2-39-1 Kurokami, Kumamoto 860-8555, Japan

Abstract

The moment tensor analysis of AE waveforms has been developed and is available for identifying crack kinematics of a location, a crack-type and a crack orientation in a material as the SiGMA (Simplified Green’s functions for Moment tensor Analysis) analysis. Mechanisms of cracking can be visually and quantitatively studied at the meso-scale in concrete. Since the tensile strength of concrete is normally evaluated by the Brazilian test, mechanisms of macro-scale tensile failure in concrete are examined as the cracking process at the meso-scale using the SiGMA analysis. Evolution of the fracture process zone under the combination of tensile and compressive stresses is discussed. In the corrosion process of reinforced concrete, high AE activities are observed twice during the corrosion process at the onset of corrosion in rebar and the nucleation of cracking in concrete. The SiGMA analysis is applied to an accelerated corrosion test of a reinforced concrete beam. Kinematics of corrosion-induced cracks in concrete is identified and applicability to early warning of corrosion damage in reinforced concrete structures is discussed.

Keywords: AE-SiGMA analysis, concrete, Brazilian test, corrosion-induced cracking in reinforced concrete

Introduction

AE source mechanisms in engineering materials can be kinematically identified by applying the moment tensor analysis of AE signal-based methods (Grosse and Ohtsu, 2008). One powerful technique for the moment tensor analysis was developed as SiGMA (Simplified Green’s functions for Moment tensor Analysis) analysis, by which crack kinematics of locations, crack types and orientations are quantitatively determined (Ohtsu, 1991). The SiGMA analysis was successfully applied to fracture tests of reinforced concrete specimens to visualize the cracking mechanisms (Ohtsu, et al., 1998; Ohno and Ohtsu, 2007). Because the SiGMA analysis is closely associated with AE source modeling, a relation with such force models as a dipole force and a couple force is discussed. In addition, another relationship with linear fracture mechanics in concrete is briefly summarized.

As applications of the SiGMA analysis, results of two experimental studies are discussed. In the first application, the fracture process of the Brazilian test was observed. In concrete, the tensile strength of concrete is normally evaluated by this test, where a cylindrical specimen is compressed in the diametral direction, and macro-scale tensile failure is observed. A relation between the generation of macro-scale tensile cracks and the accumulation of meso-scale cracks is studied. In the second application, continuous AE measurement is conducted to monitor the corrosion process in reinforced concrete specimens. During cyclic wet-dry tests, kinematics of corrosion-induced cracks in concrete is identified, and an early warning for the corrosion damage in concrete is discussed.
AE-SiGMA Analysis

Although the generalized theory of AE was published (Ohtsu and Ono, 1984), AE source for a tensile crack is still mistakenly modeled by a single dipole force. In principle, AE source can be modeled by the dislocations, which are not referred to as crystalline motions, but discontinuities of displacements in a material (Eshelby, 1973). As is well known, the moment tensor is defined,

\[
M_{pq} = \int_S C_{pq} n_k b_j (y,t) dS = C_{pq} n_k l_j \int_S b(y,t) dS = C_{pq} n_k l_j \Delta V.
\]

Here, vector \(l\) is the unit vector of crack motion and \(\Delta V\) is the crack volume, corresponding to the integration of crack motion \(b(y,t)\) over the crack surface \(S\). Since \(n_kb_j\) corresponds to the eigen-strain in micromechanics (Mura, 1982), the moment tensor as the product of the elastic constants with strain is equivalent to stress as the second-rank tensor. It is noted that the physical unit is the moment as the elastic constants \([N/m^2]\) times the crack volume \([m^3]\). From Eq. 1, it is derived that AE source for a tensile crack is modeled by three normal components of the stresses. These components are equivalent to three dipole forces, which are decomposed into the compensated-linear vector dipoles (CLVD) defined by Knopoff and Randall (1970) and the hydrostatic components. In the case of a shear crack, AE source for a shear crack is modeled by shear stresses, which are equivalent to double-couple forces in the equilibrium state.

In order to classify crack type, the eigenvalue analysis of the moment tensor was developed (Ohtsu, 1991). The eigenvalues of the moment tensor are to be composed of the combination of the shear crack and the tensile crack. The decomposition leads to the shear component (X), the deviatoric tensile component (Y), and the hydrostatic component (Z) of the tensile crack. The last two components correspond to CLVD and the equivalent stresses to the crack volume \(\Delta V\) in Eq. 1. In the present SiGMA code, AE source with the shear ratio \(X > 60\%\) is classified as the shear crack, one with \(X < 40\%\) as a tensile crack and one with \(40\% < X < 60\%\) as a mixed-mode crack. The crack-motion vector \(l\) and the normal vector \(n\) in Eq. 1 are determined from three eigenvectors. Results are visually displayed, by using a graphic software (LightWave 3D, NewTek). Three models of these cracks are illustrated in Fig. 1. Cracks are classified into three types of shear, mixed-mode and tensile, and their crack planes normal to vectors \(n\) are illustrated by circles and directions of crack motions \(l\) are shown by arrows.

![Fig. 1 Models for tensile crack, mixed-mode crack and shear crack.](image)

It is worth noting a relationship with the modes in linear fracture mechanics. Although the crack classification of the tensile crack and the shear crack in the SiGMA analysis was referred to as identical to mode I and mode II in fiber-reinforced concrete (Carpinteri et al., 2007), the
treatment is not rational. Rigorously speaking, the crack classification by the moment tensor is based on crack displacements (motions) on the crack surface at the meso-scale. In contrast, the modes in fracture mechanics represent crack propagation from the crack-tip at the macro-scale in composite materials. In case that crack orientation $\theta$ is taken into account for crack propagation, the modes can be calculated from the criterion on the crack extension (Erdoğan and Sih, 1963),

$$K_I \sin \theta + K_{II} (3 \cos \theta - 1) = 0,$$

and

$$\cos \frac{\theta}{2} (K_I \cos^2 \frac{\theta}{2} - \frac{3}{2} K_{II} \sin \theta) = K_{IC}.$$ (3)

Here $K_I$ and $K_{II}$ are the stress intensity factors of mode I and mode II, respectively. $K_{IC}$ is the critical stress intensity factor of mode I. Referring to the propagation angle $\theta$ as the angle between consecutive AE sources determined from normal vectors $\mathbf{n}$, the extension of tensile cracks due to volumetric expansion in concrete was studied, applying Eqs. 2 and 3 (Ohstu and Uddin, 2008). It was found that the extension of the tensile cracks at the macro-scale is predominantly governed by mode I failure, even though all the types of tensile, mixed-mode and shear cracks were observed at the meso-scale in the SiGMA analysis.

In the SiGMA analysis, the determination of the two parameters of the arrival time and the amplitude of the first motion is essential and previously carried out by visual and hand-picking methods. To improve these enormous efforts for the analysis, we have currently developed an automated detection method based on AIC (Akaike Information Criteria) (Ohno and Ohitsu, 2010).

**Brazilian Tests**

**(1) Tensile strength of concrete**

The Brazilian test is also known as a split-tensile test for the tensile strength of concrete. Later, a direct tensile test was alternatively applied, because the test is conducted under compression. Currently, it is found that the difference between the strengths determined by the Brazilian test and those by the direct-tensile test is within 10%. As a result, the Brazilian test is usually applied to estimate the tensile strength of concrete.

As is well-known in elasto-statics, stresses at the center of a disk of diameter $d$ and unit thickness under compressive load $P$ in the diametral direction is known (Timoshenko and Goodier, 1970) as,

$$\sigma_{xx} = \frac{2P}{\pi d} \quad \text{and} \quad \sigma_{yy} = -\frac{6P}{\pi d},$$

where $\sigma_{xx}$ is the tensile stress in the horizontal direction and $\sigma_{yy}$ is the compressive stress in the vertical direction. $\sigma_{xx}$ is the maximum tensile stress, and stresses near loading plates are even more compressive than $\sigma_{yy}$ in the cross-section. This implies that a tensile crack at the macro-scale could start from the center of the disk, but experimental observations suggest that the crack starts from the areas near the loading plates.

Recently, fracture mechanics has been applied to the tensile test of concrete (Akita, 1998). It is realized that the fracture process zone is nucleated prior to final failure in the direct tensile test. So, observation of the fracture process in the Brazilian test could provide a new insight for cracking mechanisms at the meso-scale in concrete.
(2) Experiments
Cylindrical specimens of 150 mm diameter and 100 mm height were made. The compressive strength of concrete at 28 days under the standard curing was 37.2 MPa and the velocity of P wave was 4410 m/s. AE measurement was performed by employing AEWin SAMOS (PAC). Eight sensors of 150 kHz resonance (R15I-AST) were attached to the specimen. The frequency range was 10 kHz to 2 MHz and total amplification was 60 dB gain. Three specimens were tested to confirm the reproducibility of results.

Prior to the test, the sensor array was determined by a simulation analysis. As shown in Fig. 2, AE sources are assumed at lattice points with 5 mm grid at five cross-sections, C1 to C5, at 5 mm apart. The velocity of P wave was set to 4000 m/s and arrival times were estimated with 1 µs sampling. It was found that computational errors of the source locations were the minimum within 1.6 mm in the case of the sensor array shown in Fig. 3 and their coordinates given in Table 1.

Table 1 Optimal sensor array determined.

<table>
<thead>
<tr>
<th>Sensor coordinates</th>
<th>x (m)</th>
<th>y (m)</th>
<th>z (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel 1</td>
<td>0.065</td>
<td>0.025</td>
<td>0.113</td>
</tr>
<tr>
<td>Channel 2</td>
<td>0.065</td>
<td>0.075</td>
<td>0.038</td>
</tr>
<tr>
<td>Channel 3</td>
<td>-0.065</td>
<td>0.075</td>
<td>0.113</td>
</tr>
<tr>
<td>Channel 4</td>
<td>-0.065</td>
<td>0.025</td>
<td>0.038</td>
</tr>
<tr>
<td>Channel 5</td>
<td>-0.040</td>
<td>0.000</td>
<td>0.120</td>
</tr>
<tr>
<td>Channel 6</td>
<td>0.040</td>
<td>0.000</td>
<td>0.030</td>
</tr>
<tr>
<td>Channel 7</td>
<td>0.040</td>
<td>0.100</td>
<td>0.120</td>
</tr>
<tr>
<td>Channel 8</td>
<td>-0.040</td>
<td>0.100</td>
<td>0.030</td>
</tr>
</tbody>
</table>

Fig. 2 Source locations assumed in a simulation analysis.

(3) Results and discussion
Because all results of the SiGMA analysis are similar among three specimens, those of two specimens A and B are shown in Figs. 4 and 5. At the beginning (1st) stage, AE sources are
observed only near two loading plates in the diametral direction. Although a few events are identified, dominant cracking-modes are tensile and mixed mode. This suggests that tensile cracks in the meso-scale are generated due to contact between the loading plates and the cylindrical specimen under compressive loading in the diagonal direction. In all three specimens, it was demonstrated that AE sources were observed near the loading plates at the 1st stage.

At the 2nd stage, AE sources of all kinds are distributed near the final tensile failure-plane. In the elevation view, AE sources are concentrated near the failure plane at the macro-scale, while they are distributed widely at the cross-section in the side view. It is noted that no visual
cracks were found at this stage in the test. In total, all events are plotted and compared with the macro-scale tensile cracks finally observed at the surface. Agreement between AE clusters and the final failure surfaces is reasonable. At the macro-scale, tensile-type cracks are observed, while all kinds of tensile, mixed-mode and shear cracks are identified at the meso-scale. These results suggest that the fracture process zone is nucleated around the diagonal cross-section, and these meso-scale cracks are coalesced to create macro-scale tensile cracks. This fact is in good agreement with detailed observation in the direct tensile test (Akita, 1998). Thus, in the both Brazilian test and direct-tensile test, the fracture process zone is, in advance, nucleated around the final failure surface. Coalescing process of meso-scale cracks identified by the SiGMA analysis results in the fact that the tensile strengths estimated by both tests become comparable.

**Accelerated Corrosion Test of Reinforced Concrete**

(1) **Corrosion process**

In concrete structures, reinforcing steel-bars (rebars) normally do not corrode because of a passive film nucleated on the surface of rebar in concrete of high pH. Corrosion of embedded rebars arises when a reinforced concrete structure is located in marine or salt environment. When the chloride concentration at rebar exceeds the critical value (Peterson, 1992), a passive film on the surface of rebar is destroyed and the corrosion is started. The electrochemical reaction continues with a supply of oxygen and water. Due to the expansion of corrosion products, corrosion-induced cracks are generated in concrete. In order to avoid these harmful cracks, an early warning by nondestructive evaluation (NDE) is desirable. It was reported that by applying AE technique, micro-cracks were readily detected (Yoon et al., 2000).

According to a phenomenological model of reinforcement corrosion in marine environments (Melchers and Li, 2006), a typical corrosion loss is illustrated as shown in Fig. 6. At stage 1,
the corrosion is initiated. 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 stage 2. The corrosion process involves further corrosion loss as stages 3 and 4 due to anaerobic corrosion. Thus, two-step corrosion losses are modeled. As physical phenomena, the periods of the onset of corrosion in reinforcement and that of the nucleation of cracking in concrete are to be identified for inspection. So far, these stages are normally defined by the chloride threshold (Nyggaard and Geiker, 2005). This is because NDE techniques presently available are marginally successful for identifying the two periods.

Recently, we have demonstrated that high AE activities are observed twice during the corrosion process (Ohtsu and Tomoda, 2008). It is found that a curve of total AE hits (counts) is in remarkable agreement with the curve shown in Fig. 6. Thus, in reinforced concrete, the first high AE activity at stage 1 reasonably corresponds to the onset of corrosion in reinforcement. During stages 3 and 4, corrosion-induced cracks in concrete could be generated due to expansion of corrosion products in reinforced concrete, and the second high AE activity is observed.

Based on these findings, continuous AE measurement was conducted to monitor the corrosion process in a reinforced concrete specimen in laboratory. During cyclic wet-dry tests, the SiGMA analysis is applied, and kinematics of corrosion-induced cracks in concrete are investigated.

(2) Experiment

For the accelerated corrosion test, reinforced concrete specimens of dimensions 100 mm × 75 mm × 400 mm were made. One deformed rebar of 13-mm diameter was embedded with 20 mm cover-thickness from concrete surface. Configuration of the specimen is illustrated in Fig. 7. The rebar was coated by epoxy except for a target area. NaCl solution was employed as mixed-water. After the standard curing, chloride content was measured and found to be 0.175 kg/m³ in concrete volume. The compressive strength of concrete at 28 days of the standard curing was 43.9 MPa, and the velocity of P wave was 4330 m/s.

To simulate the corrosion process in a typical seawater environment, a cyclic wet-dry test was carried out. The specimens were submerged into 3%-NaCl solution up to the height of the
rebar in the container for a week, and subsequently taken out of the solution to dry under ambient temperature for another week. In one specimen, AE measurement was continuously conducted, by using AE measurement system (DiSP, PAC) and six AE sensors (R15, PAC). The sensor array is also shown in Fig. 7. These six sensors were arranged so that the target area was reasonably covered, because the simulation analysis was difficult in reinforced concrete. The frequency range of the measurement was also 10 kHz to 2 MHz and total amplification was 60 dB gain. For event counting, the dead-time was set to 2 ms and the threshold level was set to 40 dB_{AE}.

Fig. 7 Reinforced concrete specimen and AE sensor array for corrosion test.

![Fig. 7 Reinforced concrete specimen and AE sensor array for corrosion test.](image)

(3) Results and discussion

During the cyclic wet-dry test, a numerical simulation predicted that chloride concentration at rebar reached the lower-bound threshold for corrosion of 0.3 kg/m$^3$ after 28 days. At approximately 70 days elapsed, the chloride concentration at rebar became higher than 1.2 kg/m$^3$, which is known as the nominal corrosion-trigger level of chloride concentration. Accordingly, at 28 days elapsed and 70 days elapsed, rebars were removed from the specimens and inspected by scanning electron microscopy (SEM).

Figure 8 shows SEM photographs; At left, no corrosion is identified after 28 days from the cross-sectional view, although some exfoliation of the oxide film is observed at the surface. At 28 days, only the surface of rebar is slightly corroded due to penetration of chloride ions. At 70
days (shown at right), rust and loss of the oxide film are clearly observed. The corrosion started to penetrate inside rebar, nucleating corrosion-induced cracks in concrete due to expansion of corrosion products. Thus, the growth of corrosion products is confirmed after 70 days.

In the SiGMA analysis, AE event definition time (EDT) is set to 100 $\mu$s. EDT is applied to recognize AE waves occurring within the specified time from the first-hit wave and to classify them as part of the current event. Results of the SiGMA analysis at stage 1 and at stage 2 are shown in Fig. 9. At the stage 1 (at 28 days elapsed), only 6 AE events are determined. These events are located mostly near the top of the specimen, as it is realized that these events are not directly related to the onset of corrosion. This is because only large AE sources can be analyzed in the SiGMA analysis. Some shrinkage cracks might be responsible for these events in an early age of concrete.

![Elevation view](image1)

![Side view](image2)

(a) Stage 1

![Stage 2](image3)

(b) Stage 2

![Total](image4)

(c) Total

Fig. 9 Results of SiGMA analysis in reinforced concrete beam.

At stage 2 of 70 days elapsed, 49 AE events are analyzed by the SiGMA analysis. These events are located, surrounding the rebar, especially at the left portion of the specimen. Because expansion of corrosion products is suggested and generation of corrosion-induced cracks in concrete is expected, these results suggest that the final crack could progress mostly at the left portion of the specimen. In addition, some cracks (AE sources) are located from the rebar
toward the bottom of the specimen, of which AE sources are mostly classified into tensile cracks and mixed-mode cracks. These results clearly suggest that corrosion-induced cracks extend outward from the rebar. Shear cracks were dominantly observed in the later part of the stage. Thus, the mechanisms in the corrosion process are indicated as follow: tensile and mixed-mode cracks start to be first generated around the rebar. Next, coalescing and connecting of these cracks lead to the nucleation of shear cracks. This finding is useful for early warning of corrosion damage in reinforced concrete structures.

Conclusions

The SiGMA analysis is applied to the Brazilian test of concrete cylinders, and corrosion-induced cracks in a reinforced concrete beam during the cyclic wet-dry test. The following conclusions are derived.

(1) A relation between macro-scale tensile failure and nucleation of AE sources in the meso-scale is clarified in the Brazilian test for the tensile strength of concrete. In the macro-scale, tensile-type cracks are only observed, while all kinds of tensile, mixed-mode and shear cracks are identified at the meso-scale. During propagation of tensile cracks at the macro-scale, other types of AE sources of mixed-mode and shear cracks were actively identified. Thus, nucleation of the fracture process zone is confirmed around the final failure surface. This is a reason why the tensile strengths estimated by the Brazilian test are comparable to those by the direct-tensile test, although stress distributions are quite different.

(2) It is found that high AE activities are observed twice during the corrosion process, which correspond to the onset of corrosion in rebar and the nucleation of cracking in concrete due to expansion of corrosion products. In relation to the 2nd AE activity, the generating mechanisms of corrosion-induced cracks are studied in reinforced concrete. Concerning the mechanisms in the corrosion process, it can be summarized that tensile and mixed-mode cracks start to be generated around the rebar, and coalescing and connecting these cracks, shear cracks are nucleated at the meso-scale. This implies that the SiGMA analysis is useful for early warning of corrosion damage in reinforced concrete structures.

Acknowledgement

The research conducted was supported by Kumamoto University Global COE (Center of Excellence) Program: Global Initiative Center for Pulsed Power Engineering. To perform experiments and analyses, the assistance of technical associate, Dr. Yuichi Tomoda was valuable. The authors wish to deeply thank the program and his support.

References


Peterson K. (1992),"Corrosion Threshold Value and Corrosion Rate in Reinforced Concrete,” Swedish Cement and Concrete Research Institute, CIB report 2.
