QUANTITATIVE AE ANALYSIS OF DIAGONAL-SHEAR FAILURE IN REINFORCED CONCRETE BEAMS

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Abstract
Disastrous damages due to massive earthquakes in Japan draw a great attention to diagonal-shear failure in reinforced concrete (RC) structures. In RC beams, it is known that the failure type depends on the ratio of the shear span to the effective depth (a/d), and the diagonal-shear failure occurs in the case that a/d<2.7. In this study, RC beams with 1.97 a/d ratio were tested under 4-point bending. AE source mechanisms on crack location, crack type and crack orientation were investigated by applying the SiGMA procedure to detected AE waves. Since classification of crack mechanisms could be performed by AE parameter, results of AE parameter analysis and those of SiGMA analysis were compared. Concerning the discrepancy between these two classified results, the criterion for classification is discussed. In the tests, three stages in AE generating behaviors are identified, and an accumulation process of microcracks in the shear span is found in advance to nucleation of the final diagonal-shear failure plane.

Keywords
Acoustic Emission, Parameter Analysis, SiGMA Analysis, Diagonal-Shear Failure, Concrete
1. INTRODUCTION

After the Hanshin-Awaji Earthquake in 1995, it has become urgently important to investigate the failure mechanisms of concrete structures in Japan. In particular, a variety of shear failures in reinforced concrete (RC) structures were reported [1]. Since it was demonstrated that the diagonal-shear failure could lead to the serious damage, the diagonal-shear failure of RC members has drawn a great attention. So far, it is well known in concrete engineering that the occurrence of the diagonal-shear failure in the RC beam depends on the ratio of the shear span to the effective depth (a/d). In the case where the ratio a/d is smaller than 2.7, it is found that the diagonal-shear failure occurs at the final stage. Yet the mechanisms of the diagonal-shear failure in RC beams have not been fully clarified.

Because the number of aged concrete structures increases continuously in Japan, the damage assessment and repair of a concrete structure are important in order to prevent from serious disaster due to disastrous earthquakes, corrosion and weathering. Acoustic Emission (AE) method has been applied to nondestructive evaluation for concrete structures [2-4]. The advantage of AE techniques, which allow passive observation of crack growth and internal defects, is to monitor the damage process during the entire load history. AE sources physically correspond to the micro-fracture in a material. Thus, information on the micro-fracture mechanism is included in AE waves. To identify the mechanisms of AE sources, SiGMA (Simplified Green’s functions for Moment tensor Analysis) procedure has been developed [5]. Based on the moment tensor analysis, crack location, crack type and crack orientation are readily identified from recorded AE waveforms.

In this paper, AE method is applied to four-point bending test of RC beams with the ratio a/d =1.97. To monitor primarily micro-cracks of the diagonal-shear failure, AE sensors are arranged as surrounding an area of the shear span. Detected AE waveforms are analyzed by the SiGMA procedure. Since classification of crack mechanisms could be performed by using AE parameter [6], results of the AE parameter analysis are compared with those of the SiGMA analysis. Concerning the discrepancy between these two classified results, the criterion for classification is discussed.

2. AE-SiGMA ANALYSIS

In the SiGMA code, AE waveform is represented by taking into account only the amplitude of first motion A(x),

\[ A(x) = C_s \frac{\text{Ref}(t, \gamma)}{R} \cdot \frac{\gamma_p T_q}{\gamma} M_{pq} \cdot DA, \]

where \( C_s \) is the calibration coefficient of the sensor sensitivity and material constants. The reflection coefficient \( \text{Ref}(t, \gamma) \) is obtained as \( t \) is the direction of sensor sensitivity. \( DA \) is area of crack surface, \( M_{pq} \) is the moment tensor and \( \gamma \) is the direction vector of distance \( R \) from the source to the observation point \( x \).

In the case of an isotropic material, the moment tensor \( M_{pq} \) is defined as,

\[ M_{pq} = (\lambda l_k n_k \delta_{pq} + \mu (n_p n_q + n_p n_q)) \Delta V, \]

where \( \lambda \) and \( \mu \) are Lame constants. \( l \) is the unit direction vector and \( n \) is the unit normal vector to the crack surface. \( \Delta V \) is the crack volume. Since the moment tensor \( M_{pq} \) is symmetric and of the second order, the number of independent unknowns \( M_{pq} \) is six. A multi-channel
observation of the first motions at more than six sensor locations can provide sufficient information to solve equation 1.

Prior to solving the moment tensor, the source (crack) location $x'$ as shown Figure 1 is determined from the arrival time differences $t_i$ between the observation point $x_i$ and $x_{i+1}$, by solving equations,

$$R_i - R_{i+1} = |x_i - x'|- |x_{i+1} - x'| = v_p t_i.$$  

Here $v_p$ is the velocity of P-wave.

After solving equation 3, the reflection coefficient $Ref(t, \gamma)$, the distance $R$, and direction vector $\gamma$ are readily obtained to solve equation 1. The amplitude of the first motions at more than six channels are substituted into equation 1, and all the elements of the moment tensor are determined. To identify source kinematics, a unified decomposition of eigenvalues of the moment tensor has been proposed [5]. In general, crack motion on the crack surface consists of slip motion (shear components) and crack-opening motion (tensile components), as illustrated in Figure 2 [7]. Then, the eigenvalues are decomposed uniquely into those of a shear crack, the deviatoric components of a tensile crack and the isotropic (hydrostatic mean) components of a tensile crack. Eventually the decomposition leads to relations,

$$1.0 = X + Y + Z$$

the intermediate eigenvalue / the maximum eigenvalue = 0 - $Y/2 + Z$  

the minimum eigenvalue / the maximum eigenvalue = -$X - Y/2 + Z$

In the present code, AE sources of which the shear ratios $X$ are smaller than 40% are classified as tensile cracks. AE sources of the shear ratios $X$ greater than 60% are referred to as shear cracks. In the case of the ratios between 40% and 60%, AE source is classified as mixed-mode.

After determining the crack type, the direction of crack motion is derived from the eigenvectors. From the eigenvalue analysis, three eigenvectors $e_1, e_2, e_3$ are also obtained. Theoretically, these are derived as,
\[ e_1 = l + n \]
\[ e_2 = l \times n \]
\[ e_3 = l - n \]

Here \( \times \) denotes the vector product, and the vector \( l \) and \( n \) are interchangeable. In the case of a tensile crack, the vector \( l \) is parallel to the vector \( n \). Thus, the vector \( e_1 \) could give the direction of crack-opening, while the sum \( e_1 + e_2 \) and the difference \( e_1 - e_3 \) give the two vectors \( l \) and \( n \) for a shear crack.

3. EXPERIMENTAL PROCEDURE

Mixture proportion of concrete is given in Table 1. Mechanical properties of hardened concrete are summarized in Table 2. In order to generate the diagonal-shear failure, the ratio \( a/d \) of an RC beam was set to 1.97. RC beam of dimensions 150 mm \( \times \) 250 mm \( \times \) 2000 mm with 400 mm shear span were designed as shown figure 3. No stirrup reinforcement was arranged in the right-hand shear span, as the diagonal-shear failure could be localized. In Figure 3, the diameter of D10 reinforcement bars is 10 mm and D13 represents 13 mm diameter, the yield stress of those bars are 295 N/mm\(^2\).

The RC beams were tested under four-point bending, recording AE waves. To monitor selectively micro-cracks of the diagonal-shear failure, eight R15 (150 kHz resonance; PAC) sensors were attached using wax on the surface of the RC beam as shown in Figure 4. AE signals were amplified with 40 dB gain by a pre-amplifier and 20 dB gain by a 8-channel system (DiSP, PAC). AE waveforms were recorded at 1 MHz sampling frequency. During the test, vertical displacements on two sides were measured with displacement-transducers.
4. RESULTS AND DISCUSSION

4.1 AE Parameter Analysis

The ultimate load of one RC beam was 96.1 kN and the diagonal-shear failure surely occurred in the shear span of the target as shown in Figure 5. Figure 6 shows the loads and total AE hits as a function of time. During the loading the number of AE hits increased, and then the hits were obtained acceleratedly near the ultimate load. As seen in Figure 7, slope of the load-displacement curve is changed at about 25 kN, then AE hits were actively detected.

AE parameter analysis can classify cracks into two types of tensile mode and shear mode (JCMS-III B5706-2003 code) [6]. Here, average frequency (AE ring-down count/the duration time) and RA value (the rise time/the maximum amplitude) were applied to the analysis. In this analysis, there does not exist any definite criterion on the proportion of the average frequency to RA value for crack classification. In this study, the proportion of the average frequency to RA value was set to 1:4 as shown in Figure 8. As a result, 53.53 % AE hits were classified into tensile cracks. For each sensor, however, the ratio of tensile cracks and shear cracks are different as shown in Figure 9. It is interesting that the ratio of shear cracks seem to be approximately similar in each sensor, regardless of sensor locations. In contrast, the ratios of tensile cracks at channels 1CH and 5CH are higher than those of other sensors.

The loading process is divided into three stages based on a variation of AE hits as shown in Figure 6. At the stage 1, the number of AE hits was a few. Bending cracks at the bending span were not visually observed on the surface yet. At the stage 2, a lot of AE hits were obtained,
and bending cracks were observed at the center-bottom of the beam. The number of AE hits (per minute) became the largest at the stage 3 and the diagonal-shear failure occurred in the final moment. Figure 10 shows results of AE parameter analysis at the three stages. In the stage 1 and stage 2, the ratio of the tensile cracks at channels 1CH, 2CH, 4CH and 5CH are higher than those of other sensors. As these four sensors were located at near the bending span, AE signals due to initiation of bending cracks might be detected selectively.

4.2 SiGMA Analysis

In the SiGMA analysis, AE event definition time (EDT) is set to 120 µsec. 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. In this case of P-wave velocity 4230 m/s and sampling rate 1 MHz, the error of source location would be smaller than 5 mm. During the
test, locations of 372 events were determined by 8 AE sensors, and these events were analyzed. Results of the SiGMA analysis at the three stages are shown in Figure 11. By employing the Light Wave 3D software (New Tek), a tensile crack is indicated with a yellow disk, directing an opening orientation with an arrow. A mixed-mode crack is denoted with a green disk and a shear crack is shown with a blue disk.

At the stage 1, only four AE events are plotted. These events are located mostly near the bending span of the beam. At the stage 2, large number of AE events are observed in the middle of the shear span. It is realized that as the load increases, the area of AE cluster starts to concentrate close to the failure plane in Figure 11(g). At the stage 2, the diagonal-shear failure was not visually found on the surface of the beam. As seen in the figure, however, large number of micro-cracks are observed in the shear span. At the stage 3, locations of tensile cracks are mostly observed near the loading point and the support. It suggests that the mechanisms that the diagonal-shear failure is initiated at the central area and extends to both ends as tensile cracks are first generated, and then the shear cracks follow.

To discuss the detail at stage 1, AE sources are evaluated again only with using the specified sensors as of 1CH to 5CH under the condition of EDT of 200 µs. Figure 12 shows results of AE source locations at stage 1. AE sources are concentrated at from 0.5 m to 0.6 m. At the stage 1, time history is divided into two stages from positions of AE source. The early
(stage is the period when AE sources are localized around the loading point until 40 minutes elapsed. The locations of AE sources move to the bottom of the beam near the bending span at the late stage in the stage 1. It is found that locations of AE sources are changed even during the stage 1 of a few AE hits. The "improved $b$-value ($I_b$-value)" analysis is applied to AE hits detected at all 8 channels during the stage 1. Results are shown in Figure13. Generally, a large scale fracture corresponds to AE waves of large amplitudes. However, AE amplitude is known to be not an appropriate parameter because the attenuation increases due to damage accumulation. It has been suggested that deterioration is possibly estimated by the decrease in the $I_b$-value [8, 9]. As can be seen in Figure 13, three remarkable drops of $I_b$-values are observed at the early stage in the stage 1. The $I_b$-values at the later stage are generally smaller than those of the early stage. Furthermore, the $I_b$-value often dropped below 0.05 in the late stage. The smaller values than 0.05 are known to suggest an extensive damage [8-10]. According to the $I_b$-value analysis, the severe damage of RC beam is suggested even at the stage 1.

4.3 Comparison between AE parameter Analysis and SiGMA Analysis

Comparison between results of AE parameter analysis and those of the SiGMA analysis are given in Figure 14 and 15. Most of micro-cracks are classified as tensile cracks in Figure 14, although the number of shear cracks is dominant in Figure 15. The difference between AE parameter analysis and the SiGMA analysis could result from the fact that AE parameter analysis was carried out for all AE hits, while the SiGMA analysis applied to only AE events. In addition, AE parameter analysis might include AE events generated in middle of the specimen. This could be a reason why the ratios of the tensile mode are always high in AE parameter analysis. To focus on AE events for comparison, AE parameter analysis is applied to detected AE events by SiGMA analysis. In addition, the proportion of the average frequency to the RA value was set to 1:2. Results of AE parameter analysis are shown in Figure 16. By referring to the mixed-mode cracks of the shear ratios X < 50% as belonging to shear mode, the ratios of shear cracks and tensile cracks in Figure 16 are in reasonable agreement with those of shear cracks and tensile cracks in Figure 17.
5. CONCLUSIONS

AE monitoring was applied to the four point bending test of an RC beam and the diagonal-shear failure process was studied. Results obtained are concluded, as follows;

- Three stages of AE generation behaviors are identified. Cracking mechanisms are visually clarified by the SiGMA analysis. It suggests the mechanisms that the tensile cracks first generated, and then the shear cracks follow, creating AE cluster around the final failure plane.

- According to AE parameter analysis, the ratio of shear cracks seems to be similar in each sensor, regardless of sensor locations. Dominant cracking modes of the diagonal-shear failure were found to be tensile cracks in AE parameter analysis. From the SiGMA analysis, however, dominant cracking modes in the shear span were of the shear crack. Because AE parameter analysis was applied to all AE hits, AE sources outside the shear span might be included. This could be a reason why the ratios of the tensile cracks at the stage 2 were higher than those of other stages in AE parameter analysis.

- By modifying the criterion, classified results of AE sources by AE parameter analysis are in reasonable agreement with those of the SiGMA analysis.
ACKNOWLEDGEMENTS

The authors thank to Dr. Yuichi Tomoda, Kumamoto University, for conducting experiments. It is noted that research achieved in this paper is financially supported by Kumamoto University 21st Century Center of Excellence (COE) Program: Pulsed Power Science and Its Applications.

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