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ACOUSTIC EMISSION DISCRIMINATION OF CRACK TYPES IN REINFORCED CONCRETE BEAMS

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Abstract

In this study, acoustic emission (AE) technique was investigated to distinguish the crack types occurring in reinforced concrete (RC) beams such as bending cracks, shearing cracks and bond cracks between reinforcing steel bars and concrete.

First, several model tests were performed to characterize AE signals caused by these cracks. According to the results of the moment tensor analysis for these model tests, the objective type of cracks could be observed dominantly in each model test. Then, in order to establish a simpler distinction method, AE waveform parameters were employed as an evaluation index. As a result, it was found that the maximum amplitude and the average frequency of AE signals detected were effective for discriminating the crack types.

Next, in order to verify the validity of the results of model tests, AE measurement was carried out during the bending tests of the mock-up of RC beams. Consequently, various types of cracks occuring during the failure process of RC beams could be distinguished clearly by the two AE waveform parameters.

Key words: Acoustic emission, concrete, crack, amplitude, frequency, discrimination

1 Introduction

Concrete structures in general are doomed to be vulnerable to cracking, which causes various troubles, such as the decrease in the strength and rigidity of members, penetration of deleterious substances from outside, and corrosion of reinforcing steel. It is therefore of paramount importance to grasp the state of cracking accurately, in order to maintain concrete structures properly. In case of important structures and those in severe environments, it is also necessary to evaluate the changes in the state of cracking over time by the crack monitoring.

In this study, the authors investigated a technique for monitoring cracks by acoustic emission (AE), particularly the discrimination of crack types in regard to reinforced concrete (RC) beams. Bending cracks, shearing cracks, and bond cracks between reinforcing steel bars and concrete were analyzed as typical cracking modes in RC beams. The investigation was begun by the model tests to induce these cracks, during which AE was measured. Next, the relationship between crack types and AE characteristics obtained was investigated by the moment tensor analysis and the waveform parameter analysis. From these results, AE parameters effective in discriminating crack types were clarified. Finally, the validity of this discrimination technique was verified through AE measurement during the bending tests on the mock-up of RC beams.

2 Experiment procedure

2.1 Specimens and test methods

2.1.1 Bending crack model test

The cylinder splitting test on mortar was conducted as a bending crack model test. The geometry of specimen and sensor layout are shown in Fig. 1. Mortar cylinders 150 mm in diameter and 300 mm in length were used for this splitting test. The W/C and S/C of the mortar used were 0.50 and 2.27, respectively.

2.1.2 Shearing crack model test

The shearing test was conducted as a shearing crack model test. The geometry of specimen and sensor layout are shown in Fig. 2. Prismatic specimens of mortar 150 by 150 by 70 mm were used for this test. The mortar used was the same as before. The load was applied so that the shearing plane was 15 degrees to the vertical, in consideration of the stability of loading and the ease of shear failure. Sufficient grease was applied between the specimen and the loading jig to eliminate noise due to the friction between them. The state of the test is shown in Fig. 3.

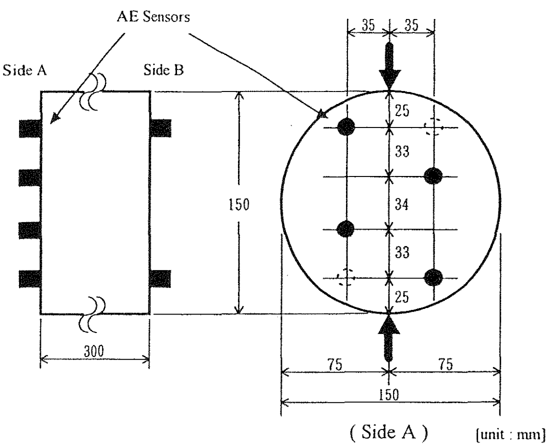


Fig. 1 Model test for bending crack

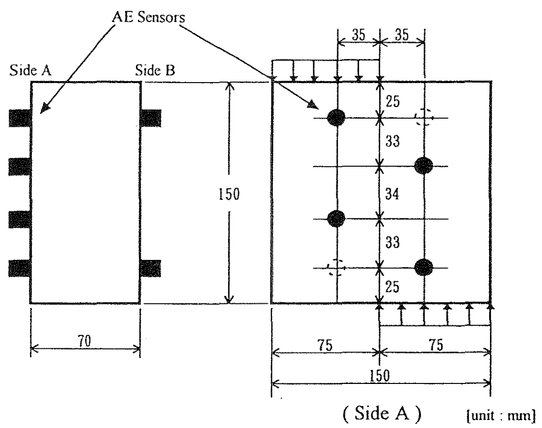


Fig. 2 Model test for shearing crack

2.1.3 Bond crack model test

The direct tension test on the reinforced concrete was conducted so that bond cracks between reinforcing bars and concrete occurred dominantly. The shape and size of specimen and sensor location are shown in Fig. 4. The reinforced concrete specimens 100 by 100 by 400 mm in size were used. A round steel bar of 25mm diameter was placed in the center of the concrete part with both ends protruding. The W/C and s/a of the concrete used were 0.50 and 0.47, respectively. The concrete portion was restrained with a steel jig as shown in Fig. 4 to prevent tensile cracks in concrete during loading.

2.1.4 Bending test on mock-up of RC beams

The bending tests were performed on relatively large RC beams 300 by

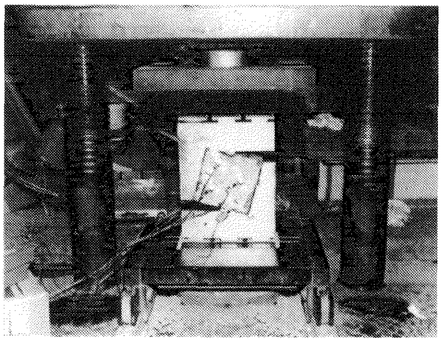


Fig. 3 Shearing test

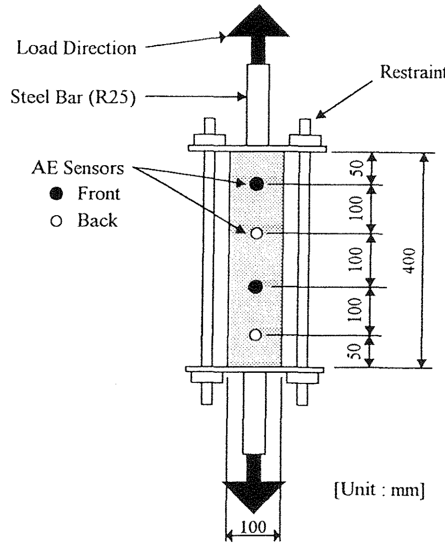


Fig. 4 Direct tension test

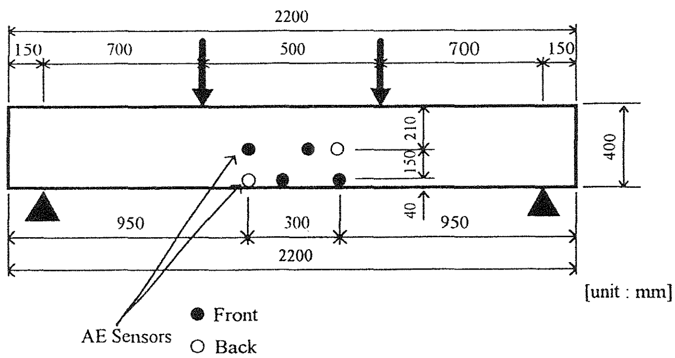


Fig. 5 Bending test on mock-up of RC beams

400 by 2200 mm in size as shown in Fig. 5. The W/C and unit water content of 0.70 and 210 kg, respectively, were adopted to make the bleeding under reinforcing bars more, causing bond cracking between the reinforcement and concrete. The s/a of the concrete was 0.50. Two deformed steel bars were placed on the tension side, and ten stirrups were set at 175 mm intervals excepting the bending zone. The depth of concrete cover was 70 mm.

The bending force was applied initially to the cracking load (45 kN) and then the cyclic loading was carried out with an increment of 10% of the breaking load (500 kN) up to approximately 60% of the ultimate.

2.2 AE measurement

A system manufactured by Physical Acoustics Corporation was used for the measurement of AE. AE signals detected by 150-kHz resonant

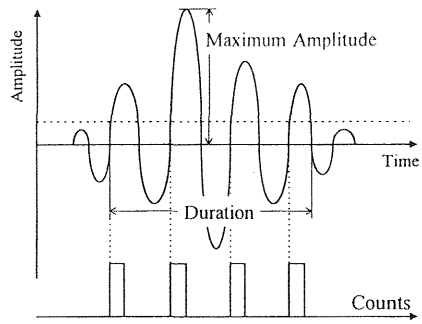


Fig. 6 AE waveform parameters

sensors were amplified with the pre-amplifier by 40 dB and main-amplifier by 40 dB, so that the total gain was 80 dB. The threshold level was set at 50 dB and 44 dB in the model tests and the bending tests on RC beams, respectively, taking into consideration the noise level in each test. The detected AE signals were analyzed and recorded in terms of not only the waveform but also various waveform parameters as shown in Fig. 6. When measuring AE, rubber pads and teflon sheets were inserted appropriately between the specimens and the loading and supporting points to eliminate noise due to the friction.

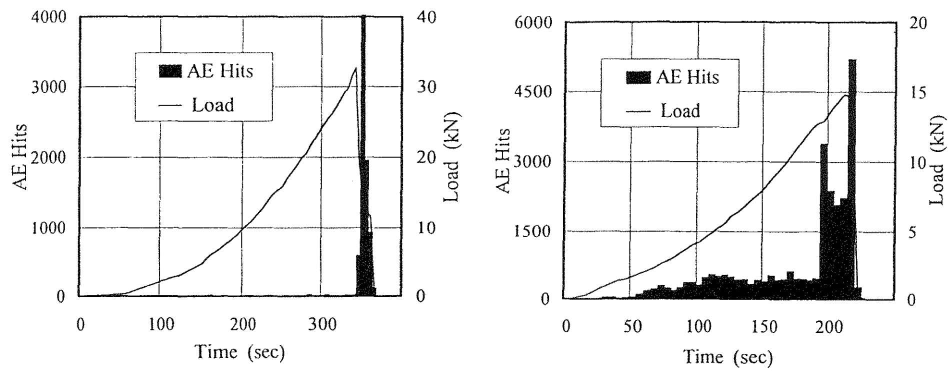
3 Results and discussion

3.1 Examination by moment tensor analysis

Kinematics of crack type and crack orientation are theoretically modeled by the moment tensor representation for analyzed AE sources. Ohtsu(1989) have developed the method for the moment tensor analysis. In this method, to identify crack types from the moment tensor components, three eigenvalues are obtained. And then, three eigenvalues are decomposed into X, Y and Z ratios, where a pure shearing crack corresponds to the case of X=100% and Y=Z=0%, while a pure tensile crack corresponds to the case of X=0%. In general, X is considered the contribution ratio of shearing type cracks.

In this study, crack types were investigated by above mentioned the moment tensor analysis in both model tests for bending cracks and shearing cracks. Then, in this investigation, AE events with X ratio lager than 60% are classified into the shearing type, and AE events with X ratio smaller than 40% are classified into the tensile type. Then, 40% < X < 60% is considered mixed type of shearing and tensile.

Fig. 7 shows the relationship between applied load and AE hits in bending crack model test and shearing crack model test, respectively. In case of bending crack model test, AE activity was very low up to the



(a) Bending crack model test (b) Shearing crack model test

Fig. 7 AE behavior during loading

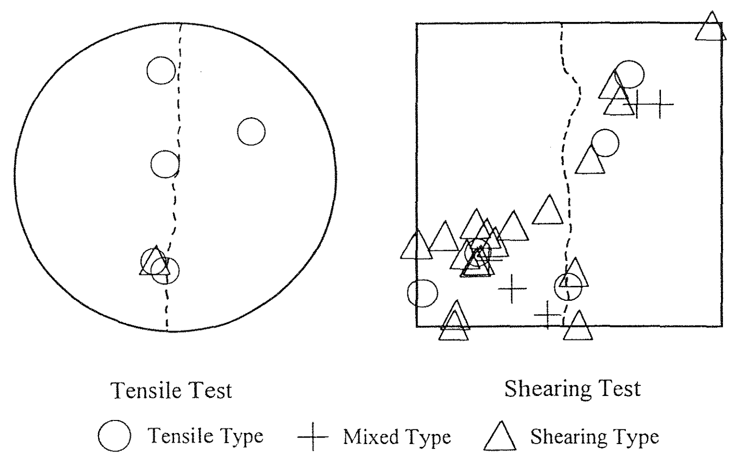


Fig. 8 Result of moment tensor analysis

maximum load and at the peak of load AE hits increased dramatically. On the other hand, in case of shearing crack model test, AE hits were observed constantly with the increment of load, and just before the maximum load AE hits rapidly went up and reached the peak at the breaking point of the specimen. From these results, in the limits of this experiment, it is considered that cracks occurring in bending crack model test showed brittle rupture and cracks in shearing model test gradually developed. One hundred sets of AE waveform data recorded around the maximum load by six sensors in both tests were analyzed using the moment tensor. Fig. 8 shows the calculated AE sources and those types of crack classified. It was confirmed that tensile type cracks were dominantly generated in bending model test and shearing type was mainly observed in shearing model test. Consequently, these model tests are considered suitable for modelling each type of cracks.

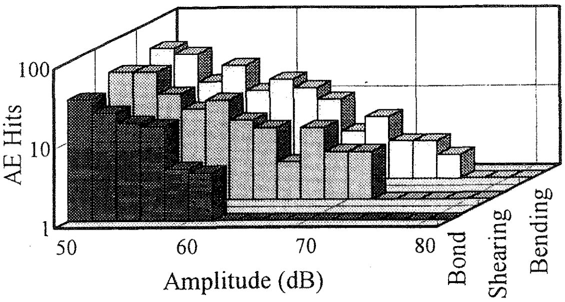


Fig. 9 Amplitude distribution

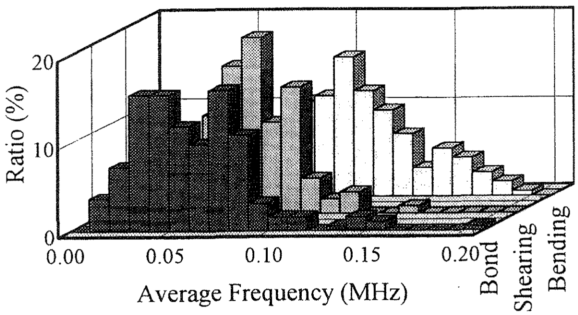


Fig. 10 Average frequency distribution

3.2 Examination by AE parameters

3.2.1 General

AE waveform parameters can be recorded and analyzed instantly in every AE measurement. Therefore, failure phenomenon in materials can be rapidly evaluated as a real-time monitoring. To discriminate crack types in the existing RC beams using AE waveform parameters is thought to have advantages compared with the moment tensor analysis because of its simpleness and speediness.

3.2.2 Investigation by amplitude distribution

Attention was focused on the maximum amplitude as an index whose effect had already been confirmed by Nagataki, et al.(1995), and it is thought to be related to the scale of micro-fracture in an AE source. Fig. 9 shows the amplitude distribution for every crack model test. This figure reveals that AE due to bending cracks have a higher maximum amplitude, on the other hand, the amplitude distributes around smaller values in case of shearing and bond crack model test.

3.2.3 Investigation by average frequency distribution

Out of the parameters shown in Fig. 6, the ratio of counts to duration was defined as "average frequency". Komai, et al. (1990) used this

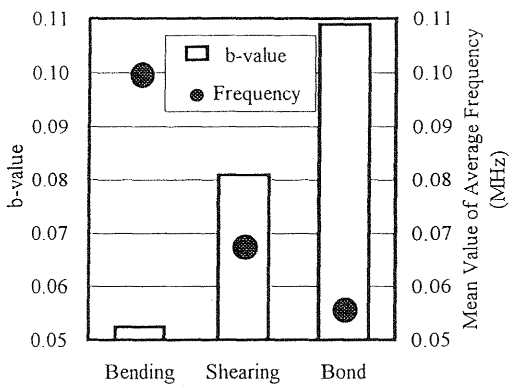


Fig. 11 Relationship between crack type and AE characteristics

defined ratio to investigate the fracture mechanism of carbon/epoxy composites and they obtained successful results. The average frequency is considered to have relation with the developing velocity of micro-fracture in an AE source. Fig. 10 shows the distribution of the average frequencies of AE signals generated during every crack model test. Whereas the average frequencies for bending crack model test distribute over 0.1 MHz, those for bond crack model test concentrate below 0.1 MHz.

3.2.4 Discrimination of crack types by AE parameters

Fig. 11 shows the results of model tests rearranged in terms of the slope of regression line obtained from the amplitude distribution and the mean value of the average frequency distribution. This figure represents that bending crack model test leads to a lower slope of the amplitude distribution and a higher average frequency than other model tests. When comparing shearing cracks and bond cracks, the latter causes a higher slope of the amplitude distribution and a lower average frequency. Accordingly, the types of crack occurring in RC beams can be discriminated by paying attention to the amplitude distribution and the average frequencies of AE signals.

3.3 Applicability of this discrimination technique to RC beams

AE measurement was conducted during the bending test on the mock-up of RC beams to investigate the applicability of the crack type discrimination technique proposed in the previous section to RC beams. Fig. 12 shows the relationship between the load and AE hits during the bending test. Fig. 13 shows the slope of the amplitude distribution and the mean value of the average frequencies during each loading step. This figure indicates that the slope is low and the average frequency is high at the loading step I, suggesting the occurrence of bending cracks.

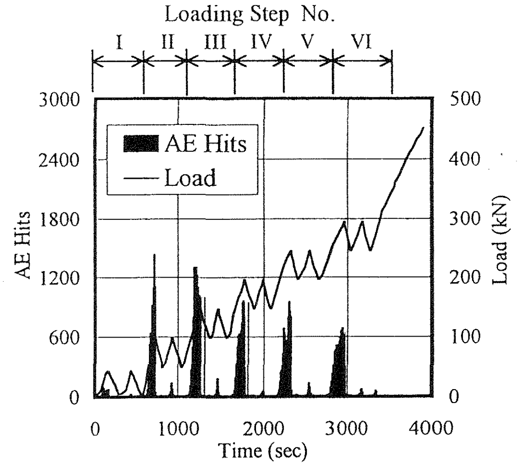


Fig. 12 Result of AE measurement for bending test

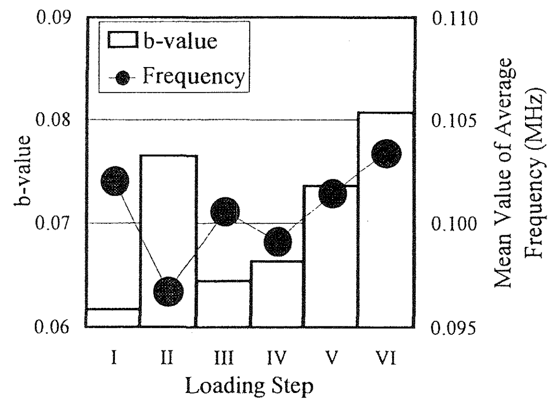


Fig. 13 Change in AE parameters during loading process

It agrees with the fact that, in this loading step I, the cyclic loading was made up to the load at which the bending cracks initiated.

Contrastly, at the loading step II, the slope of the amplitude distribution is highest and the average frequency is lowest among every loading step. It suggests that bond cracks between the main steel bars and concrete occurred following bending cracking. Fig. 14 shows the result of AE source location analysis during the loading step II. According to this figure, it is confirmed that calculated AE sources concentrate close to the reinforcement. In the latter half of the loading process, the slope of the amplitude distribution gradually increases, suggesting the characteristic of shearing cracks. It corresponds well with the result of the diagonal strain measurement in the shear zone shown in Fig. 15. Hence, the crack type discrimination technique by means of AE parameters is confirmed to be applicable to RC beams.

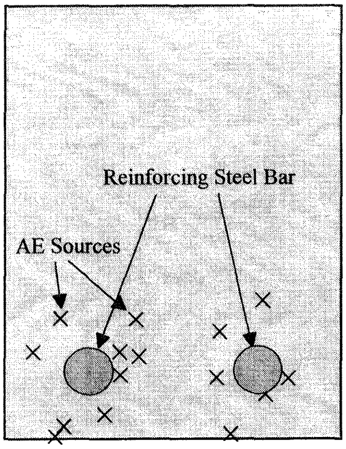


Fig. 14 Calculated AE sources around reinforcement

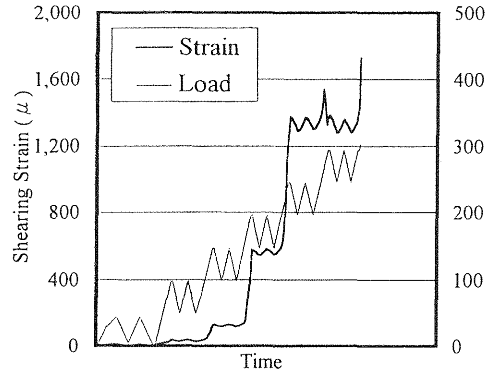


Fig. 15 Relationship between load and shearing strain

4 Conclusions

The authors conducted several tests modelling bending cracks, shearing cracks and bond cracks between reinforcing bars and concrete, and grasped the characteristics of AE signals induced by these cracks by using AE waveform parameters. These results agree well with the result of AE measurement during the bending test on the mock-up of RC beams, allowing accurate evaluation of the changes in the cracking situation in RC beams over time. Accordingly, the discrimination technique of crack types in RC beams by AE technique was found highly effective.

5 References

Komai, K., Minoshima, K. and Shibutani, T. (1990) Investigation of the fracture mechanism of carbon/epoxy composites by AE signal analyses. **Transactions of the Japan Society of Mechanical Engineers**, A-56(528), 72-79.

Nagataki, S., Otsuki, N., Kamada, T., Iwanami, M. and Kawashima, M. (1995) Evaluation of fracture types of concrete members by acoustic emission. **Proceedings of the Fifth East Asia-Pacific Conference on Structural Engineering and Construction**, Gold Coast, Australia, 15-20.

Ohtsu, M. (1989) Source kinematics of acoustic emission based on a moment tensor. **NDT International**, 22(1), 14-20.