ASSESSMENT OF CRACK ACTIVITY BY ACOUSTIC EMISSION IN CONCRETE STRUCTURES

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Abstract

Concrete and steel are the most widely used major materials for constructing civil structures such as bridges, dam, and buildings. From the acoustic emission (AE) point of view, contrary to steel itself, a lot of AE signals are acquired in concrete itself under service loads whether the crack is active or not. This paper aims to identify the differences of AE event patterns caused by developing cracks from those of a normal or safe state, and also to suggest a new algorithm for assessing the integrity of concrete structures using acoustic emission method. AE event patterns under various loading conditions were investigated experimentally for two types of reinforced concrete beams. Significant differences of AE event patterns between normal and damage developing states were observed in acoustic emission parameters like total number of hit, hit rate, differences of primary and secondary AE peak, and relative AE hit rates from sensors at different locations. Finally, based on the key parameter analysis, a new algorithm for practical AE diagnosis was suggested for assessing the conditions of damage and distress in concrete structures. From this study, it is revealed that AE monitoring can be applied to estimate whether the damage is active or not and can announce the signs of failure of concrete structures earlier.

1. Introduction

In the area of civil engineering, concrete is a structural material that is most widely used for civil structures. The development of non-destructive techniques to evaluate deterioration of concrete structures is one of the most important issues for an effective maintenance.

Since the early 1980's, there has been an increasing awareness and emphasis on the deterioration and lack of performance of civil infrastructure system (CIS), both at service and damage limit-states, especially in relation to natural disasters [1]. The people have recognized the importance of noble maintenance and innovative management, and the needs for new tools such as nondestructive evaluation. For instance, there are various techniques such as infra-red thermal method for delamination detection of concrete bridge-deck, ground penetration radar (GRP) for pavement inspection, acoustic inspection of concrete bridge deck, conventional NDE method like visual testing, etc.[2-5] However, current NDE system for testing concrete structures are usually expensive, slow, or tedious.

Acoustic emission (AE) is defined as the class of phenomena whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material [6]. In comparison with other non-destructive techniques, acoustic emission technique has two important advantages: one is that AE technique can give valuable information what's going on inside of the material, and the other one is that it gives a capability of on-line monitoring during in-service of structures or facilities. So, the AE technique has emerged as a powerful non-destructive tool to detect or evaluate damages in the field of safety of civil structures.

Since acoustic emission the process associated with the emission and propagation of strain waves, resulting from localized modifications of materials. In concrete, micro-cracking and crack growth are the principal sources of emission. Previous most of AE researches on concrete have been focused on characterizing the failure mechanisms in cement-based materials [7, 8] and on evaluating integrity of concrete structures [9, 10].

This study aims to identify the differences of AE event patterns caused by developing cracks from those of a normal or safe state, and also to suggest a new algorithm for assessing the integrity of concrete structures using acoustic emission method. In this study, the patterns and characteristics of AE hits of reinforced concrete beam under various loading conditions were investigated experimentally.

2. Acoustic Emission Sources and Behavior of Concrete Beam under Loads

To understand the damage behavior and failure criterion of reinforced concrete beams is essential to applying the AE technique to the structural integrity assessment. The moment-curvature diagram of a reinforced concrete beam is shown in Fig. 1 [11]. Failure behavior of reinforced concrete beam can be simplified in 3 stages. The typical crack patterns, strain and stress distributions of each stage are shown in Fig. 2. At first stage (stage A) in Fig. 1, the tensile part of the concrete doesn't have cracks because the applied loads are too small. Point B in Fig. 1 indicates a starting point of tensile yielding. The second stage (stage C) in Fig. 1 is a range of normal service loads. In this range, flexural cracks which are the cracks in tensile part of the concrete would be developed. Consequently, neutral axis would move slightly upward and only the reinforcement would be burdened with the tensile stress. Flexural cracks in reinforced concrete beams are normal and unavoidable because concrete has the inherent property of weak tensile strength. Point D in Fig. 1 indicates a limit of elastic range, and from this point, the third stage (stage E) in Fig. 1 begins. The third stage shows a series of progress of failure. Strains would increase rapidly, diagonal tension cracks would be developed by shear force at each end of the beam, and finally, the beam would fail with compressive yield at the center of the beam.

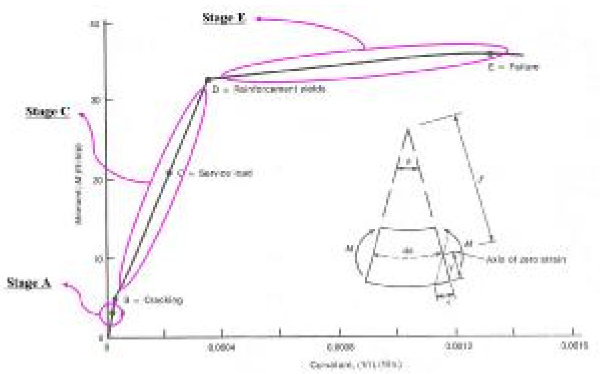
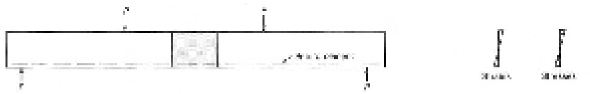


Fig. 1. Moment curvature diagram of RC beam

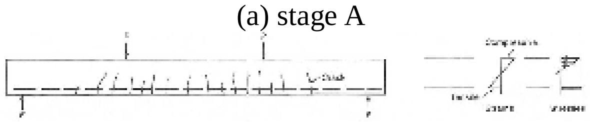
Generally, AE sources in concrete are known as three major causes: crack development, friction between concrete and reinforcement, and break of fibers in fiber reinforced concrete [12]. To evaluate concrete damage using AE technique, it is necessary to subdivide AE sources from crack development, considering flexural behavior of reinforced concrete, since some kinds of cracks were unavoidable and allowed naturally in reinforced concrete beams. Therefore, AE signal sources caused by concrete cracks can be subdivided as a development of micro cracks, the flexural cracks, the diagonal tension cracks, and the friction of existing crack surfaces.

If a flexural load under allowable range were applied for the first time to the beam that has never been loaded, micro cracks and flexural cracks would develop. With friction of existing crack surfaces, development of these cracks would generate much more AE events. But if cyclic loads of the same amplitude were applied repeatedly, AE signals from crack propagation would decrease as development of the cracks was completed. Finally, the signals from friction of existing crack surfaces would be the primary sources of the AE events. After that, if a bigger load than previous load is applied to the beam, flexural cracks would be propagated again and it would cause AE generation to be more active. Consequently, AE signals by friction and micro cracks can be considered as normal, and the signals by diagonal tension cracks and compressive failure can be considered as abnormal. In most of the previous studies, AE signals caused by friction were considered as noise although it is hard to separate from the signals caused by crack propagation [13]. In this study, the signals from the friction of crack surfaces were considered as normal signals, and in the field application point of view, we tried to find new criteria to estimate normal and abnormal signals through a series of experiments.

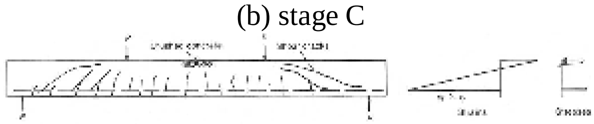
From the previous work, it was found that RC beams have unique AE behavior called secondary peak [14] which is generation of AE hits during unloading. This phenomenon didn't occurred in case of concrete beam without reinforcement, That is, this secondary peak is presumed to be caused by friction while cracks or interfaces with discontinuity are closing, and it is expected that the ratio of primary and secondary peak would be useful for evaluating integrity.



(a) stage A



(b) stage C

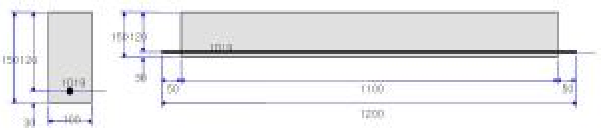


(c) stage E

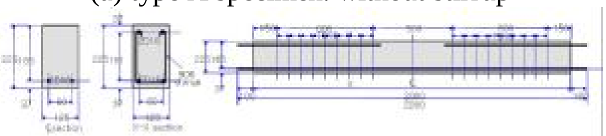
Fig, 2 Typical crack patterns, strain and stress distributions of each stage

3. Experiments

A series of four points bending tests for two types of reinforced concrete beam specimens was carried out to obtain AE event patterns under various loading conditions. To confirm the repeatability of the test results, the same series of loading tests were repeated for three specimens for each type of beam. Fig. 3 shows the drawings of two types of specimens used for the tests. Concrete was designed to have 23.5 MPa of compressive strength and steel reinforcement which has 294.3 MPa of tensile strength was embedded in concrete. Nominal ultimate flexural moment and design limit load (DLL) for four point bending test were 7,100 N-m and 36 kN for type A and 16,000 N-m and 60 kN for type B respectively.



(a) type A specimen: without stirrup



(b) type B specimen: with stirrup

Fig. 3 drawings of two types of specimens

Multi-channel commercial AE system, MISTRAS 2001 (Physical Acoustics Corp.) was used to analyze AE signals. A digital oscilloscope model 9354A (LeCroy) with four channels was used to store and analyze the waveforms (Fig. 4). Three AE sensors having 150 kHz resonant frequency (R15) were used to acquire AE signals with the sensor arrangement shown in Fig. 5. Ch. 2 monitored signals mainly from flexural cracks and Ch. 1 and Ch. 3 monitored signals mainly from diagonal cracks. Acquired signals were amplified 40 dB by using pre-amplifier. 500 kN hydraulic actuator (MTS) and the controller (FlextestIIm, MTS) were used to control loads.

Cyclic loads of 1,000 cycles were applied at each loading step to obtain stabilized normal AE signals after being completed development of micro and flexural cracks. Fig. 6 shows the cyclic loading condition and their terminology. Table 1 indicates the overall loading schemes for the whole tests.

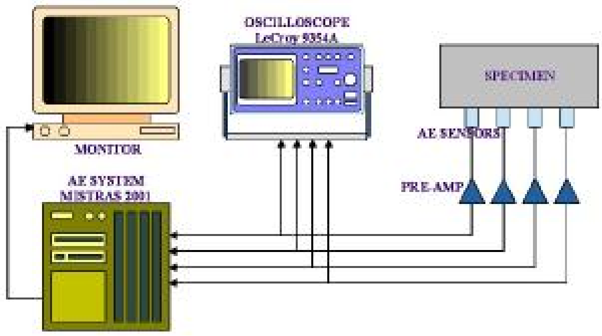


Fig. 4 acoustic emission data acquisition system

Fig. 5 AE sensor arrangement

Fig. 6 cyclic loading condition and its terminology

Table 1 overall loading schemes for the whole test

4. Results and Discussions

Fig. 7 shows typical AE hit versus time graphs acquired by constant amplitude cyclic loading test and failure test. In Fig. 7 (a), a relatively large number of AE hits occurred at an early stage, and as the cyclic load repeated, the number of AE hits were decreased and finally stabilized to a constant level. From a structural behavior point of view, there would not be any crack propagation at the latter stage because it was considered that flexural cracks had already been developed at an early stage. Therefore, it could be presumed that the AE hits at the latter stage were caused by friction sources between crack surfaces and caused by the friction sources between concrete and reinforcement. The high AE hit rate at the early stage can be explained as the result of additional AE hits caused by crack development including of original AE hits from friction sources. The above results considering friction of crack surfaces can be explained in Fig. 7 (b) too. The first row of Fig. 7 (b) indicates the applied loading scheme during stepwise cyclic loading test. In the first four cycles, the applied load levels were under the range of maximum previous load, and in the last three cycles, the applied load levels exceeded the maximum previous load. As a result, more rapid increase of AE hit rate was observed between fourth and fifth cycle due to the transient of loading condition. Therefore, the AE signal patterns at the early stage of Fig. 7 (a) and at the right column of Fig. 7 (b) were considered as crack developing condition. On the other hand, the AE signal patterns at latter stage of Fig. 7 (a) and at left column of Fig. 7 (b) were considered as normal condition.

(a) cyclic load test (b) stepwise cyclic load test

Fig. 7 AE hit-time according to the crack activity

Now, in order to compare the AE hit occurrence level quantitatively, AE hit rate was defined as the number of AE hits during one loading cycle. Fig. 8 shows the calculated AE hit rates, the number of hits per cycle, according to each applied load ranges for various specimens. Each symbol in the Fig. 8 (a) and (b) indicates an absolute value of AE hits rate for each specimen. However, Fig. 8(c) indicates the averaged value of AE hit rates at each loading step for Type B specimen especially. As shown in Fig. 8 (c), there is an obvious gap of AE hit rates between normal and crack developing conditions. In this case, some criterion which defines a certain AE hit rate, H_{cycle}, could be suggested for the evaluation of damage condition. It implies that the AE hit rate can be utilized as an effective indicator to estimate the activity of cracks in reinforced concrete structures.

Fig. 9 represents the magnified views of AE hit-time graph for only three cycles among the entire loading cycles. The first row of the figure shows the number of AE hits and the second row shows the applied three cyclic loads. Fig. 9 (a) and (b) shows AE hits acquired for the first three cycles of the test and for three cycles at the stabilized latter stage, respectively. As well as the differences of AE hit rate, another distinct differences between normal condition (a) and crack developing condition (b) was observed.

(a) normal (b) crack developing

(c) averaged value

Fig. 8 Number of AE hits during one loading cycle

In Fig. 9 (a), the number of hits generated during the increasing load was similar to or larger than the number of hits generated during the decreasing load. However, in case of normal condition as shown in Fig. 9 (b), the numbers of hits generated during the decreasing load were much higher than that of increasing load. Moreover, the maximum number of hits shows a peak at the around bottom of loads. This phenomenon occurring in the concrete with reinforcing steel is called as the secondary peak [14] and provides strong evidence in proving that most of the AE hits acquired at normal conditions were caused by friction sources between surfaces of completely developed cracks. At normal condition which means that development of allowable (micro and flexural) cracks are completed and there is not any crack activity, the allowable cracks in reinforced concrete would be opened with loading and closed with unloading by the elastic force of reinforcement. In this process, the maximum friction between crack surfaces would occur with the moment of completion of crack closure, as it coincides with secondary peak in Fig. 9 (b). Therefore, comparing both cases of the number of AE hits during increasing and decreasing load, the state of crack activity could be estimated. If the degree of crack activity in existing structures shows very high, it could be considered that the failure was progressing for any reason.

Fig. 10 shows the number of AE hits for each loading cycle during increasing load (H_i) and that of decreasing load (H_d). It was found that the difference between normal and crack developing condition was clearly shown in this graph. That is, H_i is slightly higher than H_d at the crack developing condition. On the other hand, H_i was much lower than H_d at the normal condition.

(a) crack developing (b) normal

Fig. 9 AE hits rate for 3 cycles for crack developing and normal conditions

(a) crack developing (b) normal

Fig. 10 Number of AE hits during loading and unloading for each loading cycle

One of the three specimens of type A failed during step 6 of the cyclic loading test. Fig. 11 shows typical trends of AE hit rate when the concrete beam undergoes failure process. Left column of Fig. 11 shows AE hit-time graphs acquired through normal condition of step 6, not failure. On the other hand, the right column of Fig. 11 shows AE hit-time graphs acquired during step 6 in failure. The failure occurred along with diagonal tension crack at the side of Ch. 1 sensor. Hence, AE signals from the Ch. 1 showed a sign of failure by sudden increase of AE hit rate about 300 cycles prior to failure.

In test of all the specimen under normal condition, AE hit rates at the beam center (Ch. 2) were always higher than those at beam ends (Ch. 1 and Ch. 3). The reasons why major AE sources come from friction sources and most of flexural cracks are distributed around the beam center. However, most of failures in the reinforced concrete beam occur at beam end along with diagonal tension crack. Consequently, the initiation and development of diagonal tension crack would be an indication of beam collapse, AE hit rate at the beam end would increase suddenly at the beginning of failure. As shown in the right column of Fig. 11, AE hit rate at Ch. 1 (failed part) gradually increased prior to failure while AE hit rate of the other channels maintained constant until just before failure. Therefore, by comparing AE hit rate of Ch. 1 and 3 with that of Ch. 2, the location of damage in the beam could be predicted. Fig. 12 shows the result of an additional analysis that confirms the above results. Especially, Fig. 12 (a) shows the number of hits per cycle when the failure occurred for the type A specimen during cyclic loading test. From the result of Fig. 12 (a), AE hit rates occurred during failure process showed sudden increases clearly while all other channels exhibited constant value. As mentioned before, in case of normal condition, AE hit rates at the Ch. 2 (center of the beam) was higher than other channels.

Fig. 11 AE hit rate for sensor position

Fig. 12 Number of AE hits for one loading cycle according to sensor position

Through the analysis of AE hit occurrence patterns obtained by a series of tests, it was found that three major differences in AE signal patterns between normal and crack developing condition were well defined, and those results showed a good repeatability at the same conditions. Three indices informing whether the crack is active or not could be summarized as follows: the number of AE hit (H_{cycle}), the ratio of H_i to H_d, and comparison of AE hit rate for the side and center channels. Consequently, these algorithms for judgment of damage conditions could be utilized to estimate crack activity or structural integrity of reinforced concrete structures.

5. Conclusions

A series of constant amplitude cyclic loading tests and stepwise load-hold-unload cyclic tests were performed through the four point bending test of the reinforced concrete beam by using acoustic emission method.

It was found that the AE hits at the normal condition were caused by friction sources between crack surfaces and by the friction sources between concrete and reinforcement. The high AE hit rate at the crack developing condition could be explained as the result of additional AE hits caused by crack development including of original AE hits from friction sources.

Significant differences of AE event patterns between normal and damage development states were observed in acoustic emission parameters like total number of hit, the ratio of hit rates generated from the loading and unloading process, and relative AE hit rates from sensors at different locations. Finally, based on those three key indices, a new algorithm for practical AE diagnosis was suggested for assessing the conditions of damage and distress in concrete structures.

6. References

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