DAMAGE DIAGNOSIS OF RAILWAY CONCRETE STRUCTURES BY MEANS OF ONE-DIMENSIONAL AE SOURCES

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Abstract

Damage of railway concrete structures has been evaluated using acoustic emission technique. In the technique quantitative assessments of damage can be conducted from three-dimensional (3D) AE activity induced by active live load with train passage. To obtain the 3D AE activity, however, it needs multiple AE sensors together with longer analysis time. In order to get the technique into widespread use, in this paper, linear AE source location, requiring two AE sensors, are applied for the damage evaluation. After comparison was made with 3D results it was concluded that the damage estimated by linear AE source location accorded well with those of 3D, and therefore the damage assessment of railway concrete structures can be reasonably evaluated using linear AE source location.

Keywords: Railway structures, damage assessment, Calm ratio, RTRI, linear source location

Introduction

Among modern infrastructures, railway structures have been constructed earlier than others, experiencing a variety of damage due to weathering, earthquakes and so forth. The upper part of railway structures can be investigated visually. It is difficult to conduct diagnosis for foundations like piers, except for general evaluation with natural frequency [1, 2]. In order to obtain the damage characteristics of lower parts, we have applied acoustic emission (AE) techniques, and showed that train-induced AE activity can be used to evaluate the damage of concrete structures. In this technique extant defects/damages contribute to the so-called secondary AE generation. Only identified AE sources with the source location algorithm are selected for a damage related AE activity. From the obtained AE sources such damage indices as Calm ratio, RTRI and b-value are obtained. Those damage indices show the degree of damage reasonably well when they are compared with actual damage conditions. The final goal of this study is to attain the state of widespread use of the AE technique and to establish reliable AE criteria for defining the degree of damage. In this paper, we report AE monitoring during the cyclic damaging of a full-scale railway concrete pier. To examine the potential of the simplest way of AE source identification, linear AE source location is used for determining the damage indices. The resultant damage is verified with 3D results. The applicability of linear AE source location for the damage evaluation of concrete is discussed.

Damage Evaluation with AE Activity

In concrete subjected to incremental cyclic loads, AE activity can be classified into four different levels with the progress of damage. The damage levels are: intact; almost intact; slight damage; and heavy damage. As shown in Fig. 1, during the second cyclic load, AE signals are
generated at the load level of the maximum prior load. This is known as Kaiser effect. This material is intact or almost intact. In the third cyclic load, in which the material is slightly damaged, the onset of AE appearance is at a lower level than before. Decrease of effective areas against the external load or accumulation of microcracks within the material plays a significant role to show this behavior. Considering the AE activity to the stress level experienced, such damage indices as Felicity ratio [3], CBI ratio [4], and Load ratio [5] have been proposed. Also the AE activity during unloading processes is important for the damage characterization [6]. With damage evolution to heavy damage, not only the AE activity during uploading but that during unloading becomes more intense. Accumulation of shear-type cracks seems to induce this phenomenon. The ratio of the accumulated AE activity during unloading to that during the entire loading process, is referred to as Calm ratio [5].

The ratios mentioned previously may be difficult to apply for in-situ monitoring since the maximum stress that the materials have experienced is not readily estimated. Thus, we have proposed an RTRI ratio instead [7]. The RTRI ratio is defined by the following procedure: the onset of AE activity is estimated on the basis of whichever measured parameters, such as stress/load, strain/deformation and so forth, and the ratio is obtained as the ratio of the parameter’s value corresponding to the onset of the AE activity to the maximum value (or peak value) during the whole inspection period. The latter is used instead of the maximum stress that the structure has experienced.

In addition to these indices, AE peak amplitudes are also known to be closely associated with the fracture scale, or the degree of damage. Accordingly, the peak amplitude might be larger with the progress of fracture. However, it was found that the damage evaluation was difficult from only the peak amplitude; i.e., as the fracture develops an apparent mechanical property of the structure decreases as well and this causes higher attenuation rates of the propagation medium resulting in smaller amplitude of AE signals at the sensor even while higher-energy AE signals were produced at the sources. Thus, in our study the peak amplitudes have been studied as their distributions, namely improved b-value (Ib-value) [8, 9].
Cyclic Fatigue Test of a Full-Scale Concrete Pier

Experimental Condition

To characterize the AE activity corresponding to damage evolution, a railway RC pier (5.87 m high) was subjected to incremental cyclic loads. This pier was demolished after the test to modify underground structures for subway construction. The cyclic test was controlled by the lateral displacement from the south-to-north direction with step-wise increments of 1, 2, 4, 8, 16, 32, 64, and 128 mm, where the load was applied by means of two hydraulic jacks (maximum capacity of 392 kN). The tested pier and the sensor configuration are shown in Fig. 2. 16 AE sensors (60-kHz resonance) covered the whole area of the pier, and additional 12 AE sensors (60-kHz resonance) were placed locally onto the area where stress concentration was expected. The former outputs were processed and recorded with a DiSP AE system and the latter with a
Mistras AE system (both by Physical Acoustics Corp.). Four strain gauges were attached to the lower four sides, and displacements on two sides, namely the north and the east side, were measured with laser displacement meters. To estimate the internal stress condition, strain gauges were also attached to rebars located at the four corners. A set of four strain gauges was each placed in three different heights: 400, 1800 and 3200 mm from the ground.

**Results**

Figure 3 shows the applied load and the lateral displacement as a function of elapsed time where the onset, peak, and termination of each step are indicated with solid lines, broken lines, and solid lines, in order. The load variation corresponds well to the response of the lateral displacement up to 15 ks; however, from 16 ks showing the step of 128 mm lateral displacement, the load decreased slightly whereas the displacement was constant. This implies fracture occurred either in the pier or in the ground support.

Figure 4 shows measured strains in the rebar at the height of 400 mm, where strain gages #1 and #2 were installed in the south and strain gages #3 and #4 in the north. Note the displacement was given by force from the north. Both strains of #3 and #4 gages showed negative values indicating compression, while the strains of #1 and #2 gages showed positive values or tensile state. These trends agreed with the expected stress conditions. Special note is given for strain gage #2 (showing the value in the right vertical axis), where a sudden jump is found at 16.35 ks denoted by a chain line. Tensile tests of rebar showed the yield point at 1500-1600 µε and the tensile strength was reached at 2200-2300 µε. The strain at 16.35 ks stood at 2274 µε already, suggesting that the rebar with strain gage #2 had yielded during the previous step; namely, 64-mm displacement, and the sudden jump at 16.35 ks coincided the time when the stress had reached the tensile strength.

Figure 5 shows the cumulative AE events and the lateral displacement with respect to elapsed time. The AE events are defined as located AE sources in three dimensions with a source location algorithm. The AE events started to be active from 16-mm displacement (around 4 ks), and
intensive AE activities during unloading (or decrease of displacement) were observed from 32-mm displacement (11 ks). Using the onset of AE activity and the accumulated numbers of AE events during unloading to those during a whole loading process in every stage, RTRI and Calm ratios were calculated.

![Cumulative AE and lateral displacement](image)

**Fig. 5** Cumulative AE and lateral displacement. The number of unloading AE events at each stage is given in the figure, ranging from 1 to 146 events.

Figure 6 shows 3D AE source locations on the eastern surface for 32-mm (left) and 64-mm (right) displacements. The crack traces are also drawn in this figure and in Fig. 7. As shown the figure, AE sources at around 1.0 m height, corresponding to the observed vertical crack, were started to be active from 32-mm displacement. At this displacement, AE activity can be found in the foundation as well (see below 0.0 m). At 64-mm displacement, both AE sources at 1~1.5 m height and those at 2~2.3 m developed further and became more concentrated.

Figure 7 shows 1D AE sources on the same eastern surface. The 1D AE sources were obtained using the sensor array for wide area monitoring (see Fig. 2). In the figure, the crack trace and AE events are drawn at every step-wise lateral displacement with different colors. AE sources both in upper and intermediate areas started to appear from 8-mm displacement (see the red traces). Specifically numerous AE sources were observed during 64-mm displacement. AE sources under unloading are actively generated during 128-mm displacement and the locations of AE sources are almost identical to those of observed cracks.

Figure 8 shows RTRI on each surface obtained from 3D AE sources as well as 1D AE sources. It is noted that since the RTRI obtained in each step of displacement explained the damage condition in the previous stage, the horizontal axis can only show the damage up to 64 mm; i.e., the RTRI obtained based on 128-mm displacement shows the actual damage during 64-mm displacement. Except for the first drop from 2 mm to 4 mm since the values of more than 1.0 showing the intact state, the remarkable decrease can be found during 32-mm displacement. Regarding the trend of 3D and 1D, both showed the same variation as a function of lateral displacement, irrespective of the direction of surface. This suggests that one-dimensional sources can provide the same useful damage information as those of 3D.
Figure 9 shows similar results as Fig. 8 but for Calm ratio. Besides the RTRI, the Calm ratio can evaluate the damage up to 128-mm displacement. The Calm ratios in the chart obtained during 128-mm lateral displacement were calculated using three different parameters: lateral displacement; applied load; and rebar strain. The Calm ratio became active from 32-mm displacement and increased further at 64 mm. This trend agreed well to that of RTRI. However, at 128-mm displacement, the Calm ratio gives different values depending on the employed parameter; i.e., considerable increase was found in rebar, a slight increase for load and remaining constant for displacement. The parameter, which can evaluate the damage condition properly, will be discussed next.
Discussion

Effective Structural Behaviors in Association with AE Activity

As shown in Fig. 4, one of the rebars evidently yielded during 64-mm displacement stage and it reached the tensile strength during 128-mm displacement. Thus, the internal damage of the pier apparently developed intensively beyond the lateral displacement of 64 mm. Figure 10 shows the
surface concrete strains of the pier on all of directions. In sound or minor damage condition, the strain variation would follow that of applied deformation. However, both surface strains on the east and west walls decreased even during the up-deformation process (see 64 mm displacement or between 13 ks and 15 ks), implying that the pier had already lost the load bearing capacity. Furthermore, from the crack observation, distinct shear-type cracks could not be developed in the pier through the test. Accordingly, the damage evolution of the pier seemed to be terminated during 64-mm displacement and further development of the damage would not be introduced by the subsequent stage, namely 128-mm lateral displacement. Considering those findings, the Calm ratio on the basis of the rebar-strain overestimate the damage (see Fig. 9). Thus, the Calm ratio based on either the load or the displacement better evaluates the actual damage.
Damage Quantification of AE Damage Indices

Figure 11 shows a chart consisting of Calm ratio and RTRI. In the map, damage criteria reported [10] are overlaid with broken lines. H, I and M in the chart show the damage level: heavily, intermediate; and minor damage, respectively. Since the RTRI during 128-mm displacement could not be obtained, the plots up to 64-mm in the lateral displacement are shown. Using the reported criteria, the minor damage was estimated when 4-mm displacement was given. The intermediate damages were indicated both during 8- and 16-mm displacement, and from 32-mm displacement heavily damage in the pier was indicated. Conclusively, these evaluations were in good accordance with other findings as well as actual damage.

Conclusions

A full-scale railway concrete pier was cyclically loaded and damaged with AE monitoring. Main findings obtained through the test are as follows:

1) Damage indices obtained from AE activity in combination with structural behaviors showed a good agreement with actual damage. Among structural parameters used, internal strains measured on rebars showed overestimation for the actual damage. The applied load or the deformation is more appropriate parameter when evaluating the structural integrity quantitatively.

2) Since the aforementioned issue was both found in 3D and 1D AE sources, it can be concluded that structural integrity of railway concrete structures is potentially evaluated by using the simplest array of AE sensors, namely 1D AE sources.
References