EVALUATION OF REINFORCEMENT IN DAMAGED RAILWAY CONCRETE PIERS BY MEANS OF ACOUSTIC EMISSION

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Abstract

We focus on a particular case of concrete piers, in which the damaged state and repaired state can both be investigated. In order to know the precise damage condition within the piers, boreholes are excavated, followed by internal wall observation with a borehole camera. Cracks within the retrieved core samples are examined with impregnation of fluorescent epoxy. In AE monitoring, active loads with train passage are utilized to induce AE signals. AE sources are only extracted from the detected raw AE data set using 3D source location. On the basis of the extracted AE events only, the damage quantification is performed along with an analysis of AE peak amplitude distribution. The AE monitoring is additionally performed in the structure after repair works have been completed, and the repair work is evaluated with AE activity. Through the AE monitoring in comparison with several observation techniques, it is concluded that the degree of damage can be quantified with the AE amplitude distribution reasonably well and the effectiveness of repair works can be evaluated with the distribution.

Keywords: Railway structures, Damage quantification, Fluorescent epoxy impregnation, Borehole observation, Reinforcement/Repair, Seismic prospecting

1. Introduction

In Japan the number of civil structures of older than 50 years will rapidly increase from 2005 on, and the maintenance and renewal cost is expected to exceed that of new construction in 2022. Determining the priority of structures to be maintained, for example, the damage assessment for the structures is essential. Thus, the damage quantification of civil structures to assess the structural integrity is in strong demand. In general, crack density as well as crack widths have been treated as damage indices so far; however, those cracks are conventionally evaluated visually and all information on cracks is based on the surface observation only. In evaluating damage degree the method, which can show the inside condition of the structures, is highly sought. An AE testing seems to give a reasonable resolution for such demand since active cracks only generate AE activity under in-service condition. Paying attention to the secondary AE activity, generated from existing cracks, the present authors have studied damage quantification in comparison with actual damage condition. In this paper, the AE testing is both applied for damaged and repaired state of railway concrete piers. Combining a variety of observation results with the findings of AE testing, damage degree as well as repair effect can be assessed.

2. Monitoring Site and Testing Procedure

Three railway concrete-piers, located in Chiba Prefecture, were examined in this study. Figure 1 shows the side view of the piers. The piers were made of plain concrete, have been used for
over 70 years, and have sustained, due to long-term weathering as well as earthquakes, a variety of damages. Degree of damage, severe (P3), intermediate (P4) and intact (P2), was each estimated by impact vibration tests [1, 2]. Figure 2 shows surface cracks observed. No visible cracks were found in P2, but a serious crack in a horizontal direction, which corresponds to the construction joint of concrete, was found in both P3 and P4. These cracks are generated by a recent earthquake. In P3 especially, a part of concrete was already separated from the stem of pier.

The monitoring protocol is shown in Fig. 3. Acoustic emission was carried out for three piers: two damaged and one intact, followed by seismic prospecting. In order to quantify the internal damage and cracking condition of the pier, three boreholes in a lateral direction and one borehole in a diagonal direction were made only in P3. This pier is employed as a representative of the piers. A borehole CCD camera was subsequently inserted into the boreholes to record the crack distribution precisely. In regard to the core retrieved, not only core observation but also impregnation of fluorescent epoxy [3] was performed. With impregnation of fluorescent epoxy, crack width smaller than 1 \( \mu \text{m} \) and air voids can be revealed under ultraviolet light.

3. Repair Works

The damaged piers, P3 and P4, were repaired using an injector specifically designed for repair work (Konishi Co.) under a constant pressure of 0.05-0.10 MPa with a pair of elastomer
The pressure varied depending on the amount of injection agent. In order to evaluate the repair agent, organic repair agent was used for P4 and inorganic agent with fine cement particles was selected for P3. Before injecting with the repair agent, all visible surface cracks on the piers were sealed with caulking material. Note that additional injection was made only for P3 using the borehole in a diagonal direction, where no pressure was given during the injection.

### 4. Damage Evaluation

Non-destructive techniques such as AE and seismic prospecting can provide rough locations of damaged/cracked areas; however, the details of crack geometry cannot be deduced through those tests. In contrast, destructive techniques with core retrieved, such as visual and microscopic crack observation, can give better insight in terms of crack distribution/geometry. In practice, however, applications with those destructive techniques are limited only to a part of the structures tested. Furthermore even when the destructive techniques were implemented, the findings are limited only to a partial condition of the structures. Thus, non-destructive techniques have been used as so-called *global health monitoring*, and the results of non-destructive techniques would be subsequently verified by the destructive techniques, which are locally conducted. Therefore, in this study, AE and seismic prospecting are performed in order to monitor the piers globally, whereas a variety of observation is conducted to follow up the findings obtained from the non-destructive techniques.

#### 4.1 Acoustic Emission

12 AE sensors of 60 kHz resonance were placed on the pier surface as shown in Fig. 4. AE sensors were placed at four height levels in a set of three. The vertical spacing between AE sensors was 1 m for P2 and P3, and 0.5 m for P4 pier. AE monitoring was performed when passing trains pass over the bridge and AE signals are induced by the live load due to train passage. These were detected and amplified by 40 dB within the sensor. The AE signals over threshold of 40 dB (100 μV at the amplifier input) were recorded for their AE parameters as well as AE waveforms with an AE monitoring system (Mistras, Physical Acoustics Corp.). Besides AE activity, acceleration with accelerometers (ASW-2A, max acceleration 2g, Kyowa Dengyo Corp), displacements with π-shaped displacement meters (PI-2-50, Kyowa Electronic Instruments) and strains with strain meters (PL-120, Kyowa Dengyo Corp) were each measured in the piers, where the data was sampled at 1 kHz and stored in a data logger (DRA-101B, Tokyo Sokki Kenkyujo).
4.2 Seismic Prospecting

Seismic prospecting was performed only in P3 for three sections as shown in Fig. 5. In each section, 12 piezoelectric accelerometers (SAF51, Fuji Ceramics Corp.), symmetrically arranged were placed onto the pier surface spaced by 50 cm. In the seismic prospecting, elastic waves were excited by impacting a steel ball of 5 cm in diameter. Elastic wave velocities in the section were estimated by means of ray-tracing and simultaneous iteration methods.

4.3 Observation of Boreholes and Sampled Cores

In order to better evaluate the crack condition, four boreholes were excavated as shown in Fig. 6. Three boreholes (No. 1-3) were made in the lateral direction and one (No. 4) in a diagonal direction. In particular, No. 1 and No. 4 boreholes were set so as to penetrate cracks observed on the surface. For the wall of boreholes excavated, optical images were recorded with BIPS (borehole image-processing system [4]). The BIPS enables us to obtain quantitative/qualitative results by projected/unfolded image data, along with valuable color data and oriented and non-disturbed borehole wall images. Besides the borehole image monitoring, cores retrieved were carefully observed visually to quantify the damage.
4.4 Impregnation of Fluorescent Epoxy

It is difficult to distinguish real cracks from all of the observed cracks, in the study of the damage/cracks of concrete material with various observation techniques. This arises due to the limitation of picture-resolution or disturbance of sampling and therefore it is essential to separate real cracks from apparent cracks. This is possible by means of impregnation technique with fluorescent epoxy. In this study, the bulk cores retrieved were placed into an impregnation chamber filled with fluorescent epoxy, under a reduced pressure (9.3 Pa) using a vacuum pump. By sectioning, cracks distributed within the core can be visualized under the ultraviolet light. Note that sectioning was conducted after the impregnation and no additional cracks are introduced.

5. Results

5.1 Observation in Damaged Condition

As a typical case the developed borehole image of No. 4 borehole is shown in Fig. 7. At 1.4 m depth, a crack smaller than 0.5 mm can be seen. Here, the depth of 1.4 m corresponds to that of the construction joint of concrete. Beside the observed crack and a void at 0.4 m depth, no other crack was found. Core samples retrieved at No. 4 borehole are also shown in the figure at right. A large number of ruptures, especially below 1.6 m depth, were obtained. Cracks corresponding to the depth of ruptures were not observed in the borehole image. These are likely to be produced by the excavation.

In order to study unidentified damage from the above observations, further examination was conducted by means of fluorescent epoxy impregnation. The core samples ranging from 1.1-1.6 m were subjected to the impregnation, and cuts were made at four locations representing 1-4 as shown in Fig. 7. Results are given in Fig. 8; one side of the cross-section at No. 1 and No. 4 are both shown. Under ultraviolet light, No. 1 section includes voids of large area. At No. 4, which is located close to the casting joint, a distinct macro-crack and branched cracks were detected. These findings imply that even for the bulk core/un-ruptured core, large scale of cracks and large area of voids existed, so that it is most likely that these critical cracks can readily generate AE activity due to a live load.
5.2 Acoustic Emission

In the damaged condition, AE sources in three-dimension are shown in Fig. 9, where the diameter of AE source reflects the average of peak amplitude of AE hits contributing to the AE source/event. No significant AE sources were obtained in P2. In contrast to P2, substantial AE sources both in P3 and P4 were found, not only along the existing joints but within the whole monitoring area. These AE activities appear to agree well to the damage condition already evaluated from impact vibration tests and damage observation. Paying attention to the scale of AE sources in P3 and P4, AE sources ranging from small to large average peak amplitude were observed in P3, while in P4 such differences in peak amplitude among AE sources were small.

The same 3D sources after repair are shown in Fig. 10. Comparing to the damaged condition (see Fig. 9), generally, no significant decrease of the scale of AE sources as well as the number of AE sources could be found in repaired piers. In P3, however, not so many large scale sources were found in repaired condition. With regard to the average of peak amplitude, they were 39.24 (39.82) and 38.29 (38.63) in P3 and P4, respectively, where the value in parentheses denotes the average peak amplitude in the damaged condition (Fig. 9). Thus, notable change/improvement due to repair could not be obtained also from the average of peak amplitude.
Fig. 8 Sections after the impregnation at No. 1 (top left) and No. 4 (bottom left), and the corresponding images under ultraviolet light. (No. 1: top right, No. 4: bottom right)

5.3 Seismic Prospecting

A typical distribution of elastic wave velocity on section II is shown in Figure 11 together with 3D AE sources projected to the section II. Comparison is made between damaged and repaired condition, where it is noted that the repair agent was poured into the borehole No. 4; i.e., no repair was performed in the range higher than 2.0 m since no pressure was applied when pouring. No improvement was observed at position higher than 2.0 m, which proves the accuracy of employed seismic prospecting. In the damaged condition, low velocity range of lower than 3000 m/s can be seen along the casting joint; however, after the repair work the elastic wave velocity in such low range becomes higher, suggesting the improvement of mechanical property in the pier. Effectiveness of repair work was thus verified with seismic prospecting. Note that the range of lower velocity could be found elsewhere except for the construction joint of concrete.

6. Discussion

6.1 Damage Condition Evaluated by Several Techniques

Except for P2, which was in the intact state, the predominantly evolved crack along the casting joint were found both in P3 and P4. These cracks could also be observed with borehole
observations. AE sources show, however, not only along the joint but in the range above the joint active AE sources were present. As shown in the core samples, many ruptures of core sample were obtained, implying that the numerous cracks obtained by the boring were generated when the pier was subjected to the torsion force due to the boring; i.e., the critical state of cracks as to grow macroscopic cracks with a slight stress had already existed within the pier. This fact was further verified by the observation results with fluorescent epoxy impregnation. Thus these findings lead to a conclusion that critical state of cracks had already been distributed within the
pier, although these could not be evaluated with conventional observations like borehole camera and unaided eyes, but could only be evaluated by AE activity.

Fig. 11 Elastic wave velocities estimated by seismic prospecting in P3. (left: before repair, right: repaired)

Fig. 12 Symmetric behavior of two π-shaped displacement meters along with AE activity due to train passage.

6.2 Quantification of Damage with AE Technique

In order to evaluate structural integrity, Calm ratio and RTRI have been proposed on the basis of train-induced AE activity, and they were successfully applied for damage evaluation of railway substructures [see 5]. When obtaining those two indices, structural behavior such as deformation is essentially incorporated with AE activity; i.e., a loading process as well as an unloading process should be defined when a train passes. As shown in Fig. 12, however, since the macroscopic crack had already existed in a horizontal direction along the casting joint and the pier showed rocking when a train passes. A variety of attempts to determine the processes were made, but no indices for the structures could be developed. AE amplitude distribution gives a unique
Fig. 13 Amplitude distributions in P3 (left) and P4 (right). The average amplitude of a set of AE hits contributing to an AE event is used to determine the distribution.

trend corresponding to the degree of damage and is used to quantify the damage. Cumulative amplitude distributions are shown in Fig. 13. To quantify the distribution, a gradient of the curve is extracted on the basis of improved $b$-value analysis [6, 7]. Note when comparing a seismic $b$-value, the improved $b$-value should be multiplied by a coefficient of 20.

As a typical result, the cumulative amplitude distribution in P3 is shown as in Fig. 13. In the state of before repair, or damaged condition, more AE events of large amplitude are generated, while in the after repair state, more small-amplitude events are generated. Such a difference of distribution can be seen in improved $b$-value; i.e., 0.0817 in the damaged condition and 0.2508 in the repaired condition. This difference is distinct enough to separate the two conditions. In Fig. 14, the $I_b$-values of the three piers are summarized in the left side along with the other results from I-site and K-site. In the present piers of P2, P3 and P4, damage recovery or repair effect can be illustrated by the variation of $I_b$-value. Considering other results, the degree of damage can be successfully classified with $I_b$-value;

- serious damage: $I_b$-value of 0 - 0.1,
- intermediate damage: $I_b$-value of 0.1 - 0.2, and
- intact or minor damage: $I_b$-value of > 0.2.

Accordingly, damage quantification was successfully carried out using the improved $b$-value analysis. The improved $b$-value analysis has already been applied to several railway structures and was successful in quantifying the degree of damage.

7. Conclusions

Damaged railway concrete piers before and after repair were investigated with AE technique. Details of damage condition were also studied with several observation techniques. Through those studies following findings are obtained:

1. AE activity monitoring reflects the actual damage of structures. Using improved $b$-value, damage quantification is possible. However, more data with a variety of damage should be systematically collected and evaluated.
2. It is difficult to quantify the damage only from visual observations and from borehole wall observation. Critical damage assessment could only be done by means of fluorescent epoxy impregnation, but this is impractical in field.

3. Non-destructive techniques as AE and seismic prospecting showed reasonable results corresponding to the damage obtained from all observations. Seismic prospecting can give the effectiveness of repair works as an increase of the wave velocity. AE results failed to show substantial changes in terms of the number of AE events or the scale of amplitude. However, improved $b$-value demonstrated the possibility to quantify the damage.

Fig. 14 Variations of improved $b$-value from various conditions of concrete piers.

References


