IDENTIFICATION OF MACROSCOPIC LATERAL DAMAGES IN RC SLABS WITH RAINY INDUCED ELASTIC WAVE ACTIVITY

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ABSTRACT

Efficient inspection techniques for ageing infrastructures are in great demand. In this study, rainy induced acoustic activity, which has so far been treated as a nuisance event for acoustic monitoring, is ambitiously utilized to identify damages of RC slabs. Specifically, in-situ AE measurements of RC bridge slabs are conducted for a week. First, internal damages of the slabs are evaluated by both of AE activity and elastic wave velocity by means of AE monitoring and AE tomography. As for some representative locations showing each different damage estimated by the AE activity and the velocity, core samples are taken for the verification. In addition, AE activity induced by rain droplets in a short period of minutes are identified by an AE source location algorithm. Through the evaluations, it was found that the distribution of AE sources induced by precipitation could reflect internal damage of RC slabs i.e., dense areas of source locations imply the intact or minor damage, while sparse areas of source locations suggest serious damage of RC decks. With this finding, the prompt decision making if the decks shall be replaced, repaired or left, which could not so far be readily implemented by other inspection techniques, would be reasonably conducted.

Key words: acoustic emission, damage identification, raindrops, lateral damage, RC slabs

1. Introduction

It is generally recognized that preventive and proactive maintenance works are necessary for such important infrastructure as bridges and tunnels. For reinforced concrete (RC) members,
essential issues include establishing a maintenance system with the appropriate measures prior to the extensive damage and failure.

As a result of budgetary restrictions, preventive and proactive maintenance of infrastructure are desired, and inspections by non-destructive testing (NDT) methods must be applied. In terms of the damage assessment and estimation of repair and retrofit recovery in concrete structures, in addition to current NDT, innovative methods must be established.

The authors are thus studying tomography techniques based on elastic waves and acoustic emission (AE) to visualize three dimensional internal defects in concrete. The basic analytical procedure and the applicability of these techniques have already been reported as elastic-wave tomography [1-3] and AE tomography [4-6].

Through the tomography technique, internal conditions are obtained using elastic wave parameters such as amplitudes and elastic wave velocities. In this study, elastic wave velocity is used as the parameter. In elastic wave tomography, both the location of the excitation and the excitation time are known, whereas they are unknown for AE tomography. Specifically, the tomography can evaluate the elastic wave velocity in each set-element over the structure, which is theoretically associated with the modulus of elasticity. Because of the presence of such internal defects as cracks and voids, the elastic waves are reflected, diffracted, and scattered inside media with anomaly such as voids and cracks. The effect results in a decrease in elastic-wave velocity. Thus, it can reasonably be assumed that the areas exhibiting lower elastic-wave velocity correspond to those of serious deterioration. Accordingly, the distribution of wave velocities can be referred to as a good indicator of the internal condition of concrete structures.

2. AE activity measurement and AE tomography

2.1 Estimation of wave velocity distribution

In in-situ RC Bridge decks, secondary AE activities, generated by friction among existing crack interfaces due to traffic loads can be measured. Therefore, the evolitional damage area can be visualized and specified when plotting AE sources through the measurement period; while the tomography can estimate internal velocity distributions of the structure, of which the velocity value can correspond to the quality of the concrete. The basic analysis procedure is shown as follows. Some AE sensors can record arrival time of elastic wave when the wave is generated by an AE source or artificial excitations such as hammering. After each arrival time is obtained, the propagation velocity through the propagation path of elastic wave is calculated by both of the distance from the excitation point to the receive point and $T_{obs}$ (observed propagation time)

$$T_{cal} = \frac{T_{s} - T_{o}}{T_{obs}}$$

where $T_{s}$ is the excitation time and $T_{o}$ is the arrival time. In the algorithm of the tomography, the inverse of velocity which is specifically referred to as the “slowness” is given as an initial parameter of each element as shown in Fig. 1. Next, $T_{cal}$ (theoretical propagation time) is obtained, which is the total of the propagation time calculated by the slowness and the distance in each element (refer formula (2)), where $s_{j}$ is the slowness of each element and $l_{j}$ is the length crossing each element. $\Delta T$ is defined by observed propagation time ($T_{obs}$) and theoretical propagation time ($T_{cal}$) as shown in formula (3):

$$T_{cal} = \sum s_{j} * l_{j}$$

$$\Delta T = T_{obs} - T_{cal}$$
Then the slowness in each element is revised in order to reduce $\Delta T$. The slowness correction amount and the revised slowness are obtained by formula (4) and (5), respectively:

$$s'_{i} = s + \Delta s_{i}$$

(5)

where $L_{i}$ is the total distance of the wave in the $i$-element. The iteration calculation from formula (4) to (5) enables to obtain the accurate slowness and finally the velocity in each element corresponding to the observed propagation time of multiple waves over the structure, resulting in forming the tomogram of the elastic wave velocity over the target area [1]. Through these steps, velocity distributions were determined in the structure. It is noted that in the AE tomography, the AE source identification and velocity distributions are both unknown and therefore they are calculated iteratively using AE tomography algorithm [4].

2.2 AE measurement and analysis

A real RC bridge deck was selected as the study target which has deterioration such as rebar corrosion due to salt attack and fatigue failure due to mobile loads. The AE measurement was carried out with AE sensors, set on the bottom side of RC bridge decks. Resonance frequency of the AE sensor is 30 kHz, arranged on the RC deck as shown in Fig. 2. Thickness of the RC bridge decks is 235 mm. Serious damage could be expected for the deck as large cracks with water leakage trace has been already confirmed. Threshold value of LUCY (location uncertainty) is set on 300 mm, about half space of two adjacent sensors in this study. LUCY means source location accuracy and is the root-mean-square of the difference between calculated and observed distances between the source and the sensor [7].
Dotted lines of parallelogram in Fig. 2 shows the cut-off specimen to study precise evaluation with the AE tomography, where three-dimensional analysis is carried out to estimate velocity distributions inside of the panel. AE sensor array for the tomography analysis is also shown in Fig. 3.

![Sensor arrangement in random hammering for AE tomography](image)

**Fig. 3:** Sensor arrangement in random hammering for AE tomography

### 2.3 AE tomography

12 sensors of 60 kHz resonance were newly set on the bottom of panel. Random excitations with a hammer of a \( \phi 11 \) mm curvature edge were carried out for exciting elastic waves on the top surface of the panel. Appropriate input sources were carefully selected on the following conditions: the case that the number of hits for an AE event is more than five by one hammering and the other is that LUCY is under 300 mm. As the results, the number of input sources for the tomography were 51. Results of AE tomography are shown in Fig. 4.

![Velocity distributions from the top to the bottom of RC deck with AE source location and peak amplitude of the first arrival of the AE event](image)

**Fig. 4:** Velocity distributions from the top to the bottom of RC deck with AE source location and peak amplitude of the first arrival of the AE event

In general for the AE activity, the more intensive AE activity is obtained, the more damage than of lees is expected in the media. As for the velocity, the area showing large velocity namely 4000 m/s suggests intact condition whereas small velocity of less than 3000 m/s roughly implies serious damage. As shown in Fig. 4, however, the area showing small velocity exhibits less AE activity while the area showing large velocity denotes the intensive AE activity. Some representative locations were subsequently selected and those core samples had been excavated and compared with the results both from the AE activity and the velocity. As a result, the followings were found: the area exhibiting small velocity with less AE activity showed serious damage existed inside of the deck, intensive AE activity with large velocity suggested in progress damage condition, and less AE activity with large velocity implied intact condition [6].
3. Rain-induced AE activity

3.1 AE activity with rain drops

AE hits per half an hour for 135 hours is shown in Fig. 5. An intensive AE activity were acquired from 120 to 130 hours. Besides, rain droplets are also known as a factor generating AE activity when it impacts on a solid material [8]. As considered factors of AE activity in the panel, some of the AE activity, shown in Fig. 5, might be generated as the resultant impacts of rain droplets on the surface of RC deck.

To clarify the fact of precipitation, relative humidity at the bridge is shown as in Fig. 5 as well as AE activity. After 120 hours, humidity increased to 100% in accordance with the high AE activity. In the weather record, precipitation was also confirmed at that period. Thus, the peak of AE activities is considered to be caused by heavy rainfall. It indicates that the impacts of raindrops on the road surface caused AE activity, and some AE activity reached the sensors attached on the bottom surface of the deck. Those concentrated AE activities were not directly correlated to the traffic load and could not be considered that they were produced from cracks inside the bridge decks. Therefore, those signals are in general considered not to reflect the deterioration of the deck, leading to be treated as noise. However, a unique distribution of AE sources induced by rain droplets was found, the following discussion would be developed to inspect the bridge decks.

![Fig. 5. AE activities and relative humidity during measurement](image.png)

3.2 Source location of rain induced AE hits

The AE data was extracted during the rain peak and analysed the source locations. Fig. 6 shows the source locations of the measured panel. Here, the source locations considered to have low reliability has been filtered out. Enough amounts of AE sources for evaluating the distribution of AE sources were obtained only for 700 seconds. In the figure, a low-density area denoted by dashed lines can be seen on the panel. As the random AE events by the precipitation shall be resulted in homogeneous distribution of AE sources over the bridge deck; however, heterogeneity of the source distribution exhibiting an empty area of the source distribution is obvious, and therefore this low-density area is attributed from extremely high attenuation of AE sources.
wave propagation in the propagation media, suggesting the suspect to be heavily deteriorated. In consideration of velocity distribution as well as visual inspection by actually excavated core samples it has been concluded that the area of less AE activity accorded well to the laterally damaged or cracked locations. Accordingly it was found that rainy induced AE activity had a potential to determine the area of serious deterioration in the concrete decks.

![Fig. 6: Result of AE source location analysis](image)

Specifically by calculating the AE source locations, the density of the AE sources would reveal the damage condition inside the deck. In addition, since all AE sources generated by raindrops are on the same surface of the road surface, instead of 3D, simple 2D source locations can be readily conducted. As the short-term heavy rain could generate a large amount of AE hits on the road, providing reasonable interpretation on the specification of the internal damage, the damage assessment of the decks induced by rain droplets has a great potential to realize in-situ damage inspection with great efficiency.

### 3.3 AE tomography by rainy induced AE sources

As expected, a sufficient number of rainy induced AE events has been obtained, the wave velocity distribution by means of AE tomography in this panel has also been conducted using rainy induced AE sources and the results are presented in Fig. 7 with core samples taken out from the deck to verify the results. The deck after core excavation can be found as in Fig. 8.
As shown in Fig. 7, the lateral damage was observed in the cores showing small velocity and vice versa. Nevertheless, this is not exactly true for the core samples C11 and C13 which are both located at the border between a low velocity zone and a medium velocity zone. These small inaccuracies may simply be due to the fact that the fineness of the mesh determining elements of analysis does not allow for such a precise evaluation or secondary damage produced during cut-off work. In the left chart of Fig. 9, the velocity distributions obtained by using internal AE events is shown for the comparison to that obtained by using rainy induced AE events. The tomogram obtained by means of rainy induced AE events is almost compatible to that obtained by the internal AE events, suggesting AE events produced by the precipitation in a short-term provides a reasonable result, being equivalent when using secondary AE events in a long-term.
4. Summary

The elastic waves generated by the rain droplets could be an AE activity contributing to the AE tomography. The results of AE tomography with rainy induced AE activity in a short term was compatible to the results of AE tomography with using secondary AE activity generated inside of the concrete deck in a long term. With the AE source distribution due to precipitation, the serious damage as to be developed lateral cracks could be estimated for the low-density area of the distribution. With this finding, the prompt decision making if the decks shall be replaced, repaired or left, which could not so far be readily implemented by other inspection techniques, would be reasonably conducted.

6. References


