Evaluation of Damage in RC Bridge Decks Reinforced with Steel Plates by AE Tomography

Yiming Feng, Tomoki Shiotani, Yoshikazu Kobayashi, Takahiro Nishida, Hisafumi Asaue, Katsufumi Hashimoto, and Shigeru Kayano

Abstract The aging of infrastructures has been one of the serious problems around the world, and innovative maintenance systems are desired. In Japan, an enormous budget is going to be paid for renewal projects of civil engineering structures, which were constructed during the period of high economic growth in 1960s. Some of severe cases are found in the RC bridge decks, peculiarly reinforced by steel plates on the bottom, as their conditions are difficult to be evaluated by the visual inspection or conventional NDEs. In order to implement an appropriate maintenance or renewal for this type of bridge decks, an accurate and practical damage evaluation system for RC bridge decks reinforced with steel plates should be established.

In present study, internal damages of RC bridge decks reinforced by steel plate were evaluated by the analysis of the acoustic emission (AE) activities and AE tomography to contribute to the decision-making if they shall be repaired, reinforced, or replaced. Through the results of AE tomography, it is concluded that the elastic wave velocity can represent the internal damage condition which cannot be confirmed by visual observation. Thus, the AE measurement and the tomographic approach could evaluate the existent or developing damages inside the RC bridge decks with steel plates.

Key words RC bridge decks · Steel plate reinforcement · AE source location · AE tomography · Internal damages

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1 Introduction

Load-carrying capacity and durability of reinforced concrete (RC) decks of road bridges in Japan constructed in old design standards are lower than that of today [1]. One of the most popular countermeasures for strengthening RC bridge decks was steel plate bonding. For example, urban highways in Kansai area in Japan have been strengthened by reinforced steel plates. As shown in Fig. 1, steel plates are attached under the RC decks through the attachment of anchor bolts and epoxy resin. Reinforced steel plates greatly improve bending rigidity and fatigue durability of bridge decks. In this case, however, damages on the decks cannot be visually observed from outside. Furthermore, moisture supplied to the road surface stays in bridge decks, which may sometimes accelerate internal corrosion or corrosion of steel plates. Therefore, the effective detection method for internal damage or surface cracks in RC bridge decks reinforced with steel plates is demanded.

Acoustic emission (AE) is an elastic wave generated due to crack occurrence, growth, and nucleation, which are referred to as primary AE activity, while the emissions due to existent cracks' reversible motion induced by internal stress distributions are referred to as secondary AE activity [2]. In this study, secondary AE activities generated in RC bridge decks were detected and analyzed by parameters such as wave velocity and, as for the elastic wave velocities within bridge decks, the area of lower velocities indicated as the deterioration or damage of the concrete.

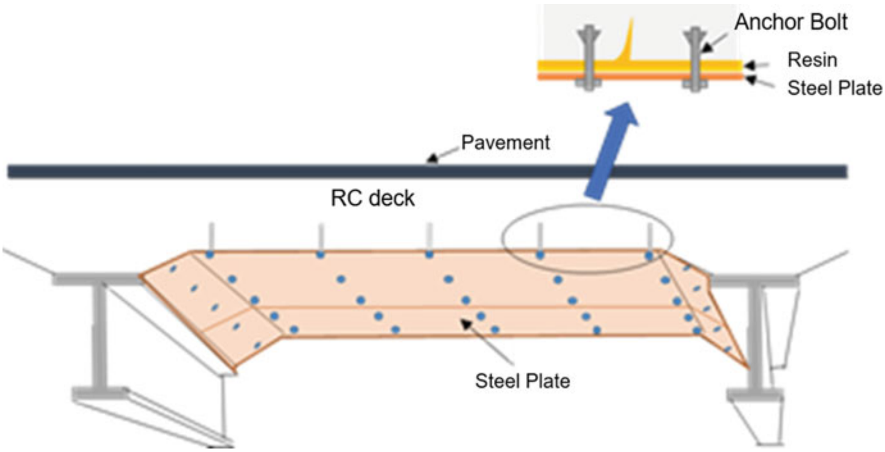

Fig. 1 Reinforced steel plates and anchor bolts bonded on the bottom of RC deck

2 AE Tomography

2.1 AE Tomography Method

AE tomography technique is developed by Shiotani and Kobayashi [3, 4, 9, 10]. In AE tomography, the region analyzed is divided into finite-element meshes. The slowness (reciprocal of the velocity) is calculated and assigned to each mesh, and finally a contour of the velocity distribution is obtained. In other words, slowness is given to each element of the model, and the internal soundness of the targeted area can be estimated.

Firstly, each element of the area is given a homogeneous elastic wave velocity distribution of 4000 m/s as an initial value. Then source locations of AE activities are performed based on the arrival time difference of AE waves among sensors, and the elastic wave velocity distribution is identified by using the results of AE source locations. By iterating this process until the difference between observation arrival time and theoretical arrival time become sufficiently small, the results of elastic wave velocity distribution can be obtained. In the elastic wave velocity distribution, lower-velocity areas are regarded as those of severe deteriorated condition, while higher-velocity area shows sound condition.

2.2 AE Measurement in RC Bridge Decks

In general, it is considered difficult to install the sensors and measure on the concrete of RC decks reinforced with steel plates directly, because air gaps between reinforcing steel plate and concrete is sometimes observed, resulting in difficulty to install the sensors onto the steel plate reinforced. In this study, anchor bolts, which are transitionally used until the time to confirm the adhesiveness between the concrete slab and the steel plate, are utilized as a wave-guide to detect AE generated in RC decks, and sensors are installed at the ends of anchor bolts by screws and magnets. Figures 2 and 3 show the outline of fixing and installing the sensors. Thus, the secondary AE activities, which are generated inside the RC bridge decks by traffic loads, are detected by accelerometers put on the edge of anchor bolt placed on the bottom surface of the steel plate. Then the elastic wave velocity distribution will be obtained by the AE tomography method.

In this study, 32 piezoelectric accelerometers (707IS, TEAC) and two wideband recorders (WX-7000, TEAC) are used for measuring a part of the RC bridge deck in urban highway in Kansai area. The outline of the targeted bridge deck and the arrangement of sensors are shown in Fig. 4. The sampling rate is set as 200 kHz, while the range of the frequency response of sensors is from 3 Hz to 20 kHz. Since the measurement system is based on a streaming method, the process of extracting meaningful AE waves from the raw data is necessarily conducted. Firstly, the data is converted to text, and when the amplitude of waves exceeds the set threshold value, a

Fig. 2 Installation of sensors to the anchor bolt

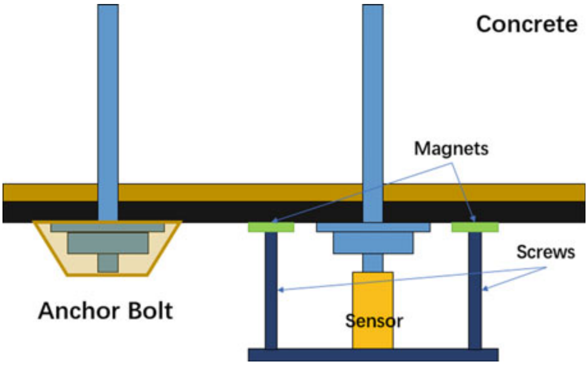

Fig. 3 The picture of sensors installation

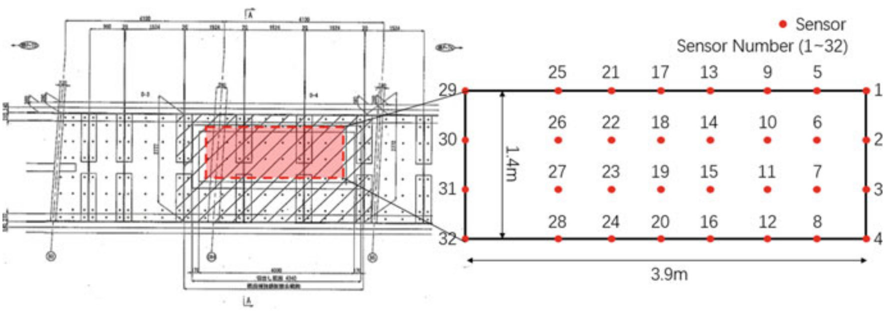

Fig. 4 The measured in-situ bridge deck and the arrangement of sensors

waveform of 5 ms centered the time of threshold- crossing will be extracted. Secondly, the arrival time is picked up by means of AIC [5] from the waveform. This process is done for each sensor, and then the arrival time of an AE hit is extracted entirely. Thirdly, by grouping AE hits whose differences of arrival time (AE event duration) is within 1 ms as AE events, the final data is obtained. In this way, sets of input data for the AE tomography is prepared as the AE sources and the arrival time contributin the each of AE sources in every potential combinations of the sensors.

3 Results of Wave Velocity Distribution Due to AE Tomography

As described, in this study, anchor bolts are inserted into the concrete on the back side of reinforcing steel plates. And the elastic waves, which are generated inside the bridge decks, propagate through various paths until they are detected by the sensors that are installed at the end of anchor bolts. Therefore, it is considered difficult to analyze how anchor bolts affect the propagation of elastic waves in three dimensions. This study thus only aims to evaluate the plane of RC bridge decks by two-dimensional AE tomography and focuses on planar spread of internal cracks.

The result of elastic wave velocity distribution analyzed by AE tomography method is shown in Fig. 5. From the figure, the area of the velocity smaller than 2250 m/s of velocity was identified, and this area was considered as a severe damaged area. On the other hand, AE source locations were also calculated and shown in Fig. 5 as blue plots. The amount of AE sources, which are generated from cracks' friction, might be illustrated as the progress of the degradation of bridge decks.

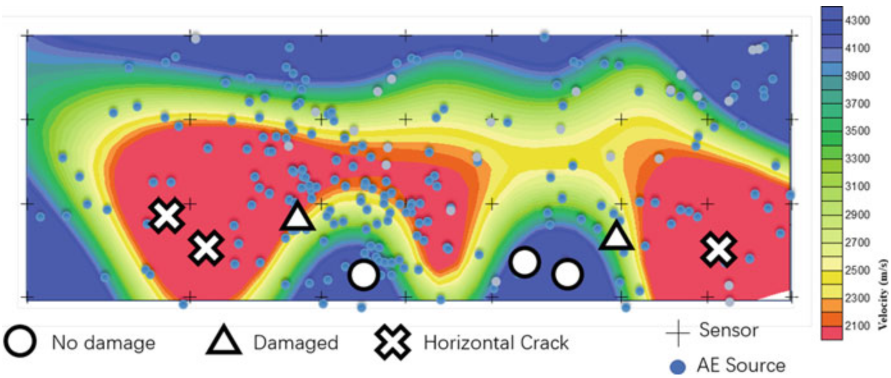

Fig. 5 AE source locations and the velocity distribution by AE tomography

Fig. 6 Observed horizontal cracks of the cutoff deck

4 Verification of Damage in RC Bridge Deck

After the measurement of the RC bridge deck reinforced with steel plates by AE tomography, the deck (1.5 m × 4.1 m) was cut off. As shown in Fig. 6, horizontal cracks were confirmed at the left-side surface and bottom-side surface of the cutoff bridge deck, which is roughly in agreement with the low-velocity area shown in Fig. 5.

In order to verify the result of the AE tomography, the damage of the actual cutoff bridge deck was examined by cored holes injected by red epoxy resin [6]. Specifically, a holes of 5 mm in diameter was drilled in eight places as shown in Fig. 5 for the first, and red resin was injected in these holes. After hardening of the resin, a larger holes then previously were drilled at the same eight places (three places are 9 mm in diameter, five places are 10.5 mm in diameter), and the resin injected area was regarded as cracked by high-resolution endoscope in the concrete deck. Figure 7 shows the example of the confirmation of the horizontal cracks by the endoscope. As the results, it was confirmed that large amount of injected resin has entered into existent horizontal cracks and has been observed in all three holes of low-velocity area. This result matches quite well the result of AE tomography. On the other hand, any injected resin was not confirmed at three places of high-velocity area illustrated by the velocity distribution.

5 Evaluation of Fatigue Damage by Wheel Loading Test

5.1 Wheel Loading Program

In order to simulate cracks actually observed in the cutoff RC bridge deck due to fatigue, repeated loadings with a steel wheel was conducted as shown in Fig. 8. As

Fig. 7 Horizontal cracks observed by high-performance endoscope

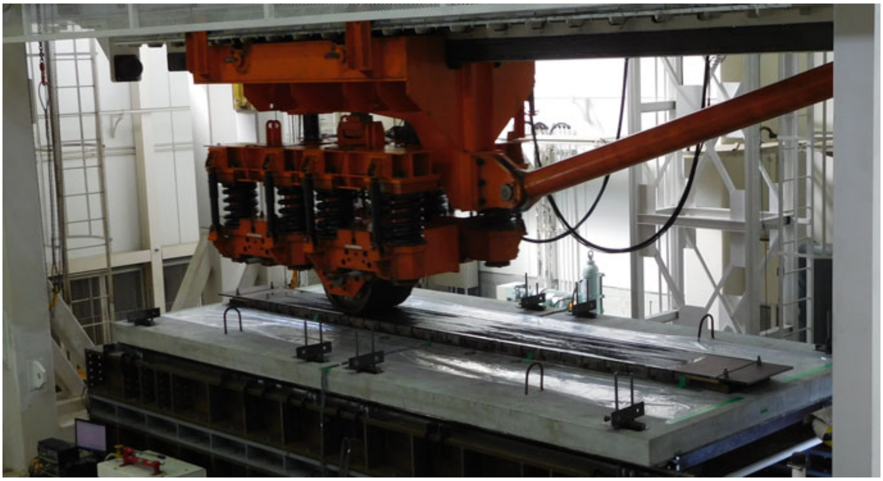

Fig. 8 Wheel loading apparatus

shown in Fig. 9, dimensions of the cutoff RC deck are 2690 mm in length, 950 mm in width, and 170 mm in thickness. And new concrete with the same condition as the cutoff RC deck was placed surrounding the cutoff RC deck, whose resultant dimensions are 5460 mm in length and 2060 mm in width. The steel wheel with 560 mm width and 300 mm in diameter can be applied with the load up to 400 kN in the case of repeated loading and 400 kN in the case of static loading [7, 8]. The steel wheel runs at the center of the span repeatedly, of which the repetition rate is set at 15 rpm in this experiment. In this study, stepwise cyclic loadings are conducted based on the

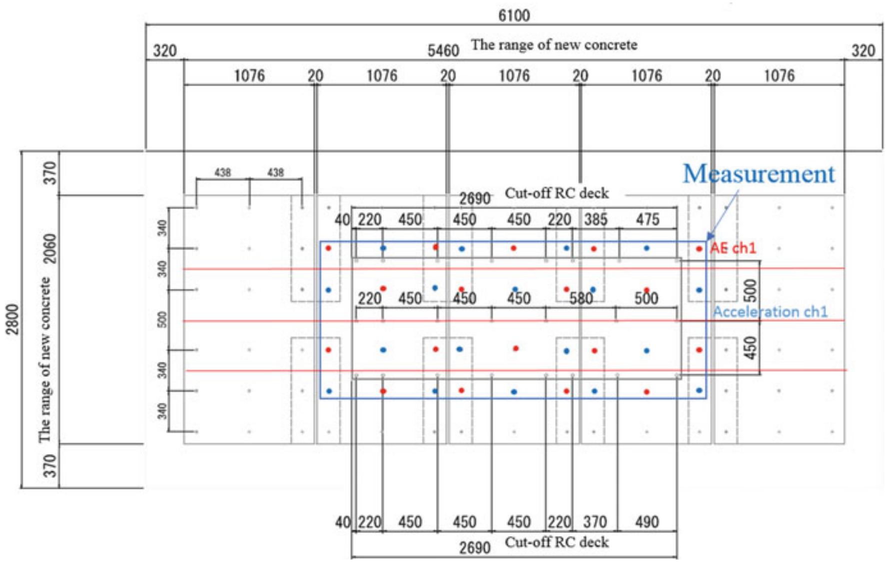

Fig. 9 Dimensions of specimen and locations of sensors

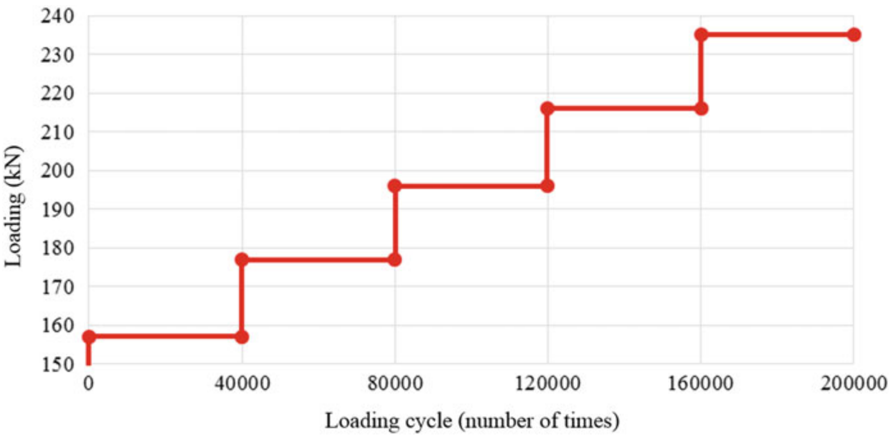

Fig. 10 Loading program

loading program as shown in Fig. 10. In the loading program, the loads of 157, 177, 196, 216, and 235 kN were repeatedly applied for each 40,000 times running, respectively.

Fig. 11 AE sensors installation

5.2 Measurement Conditions

In this study, the AE tomography analysis is again applied by employing elastic wave excitations. As illustrated in Fig. 9, 18 AE sensors of 60 kHz resonance and 18 piezoelectric accelerometers are installed at 36 locations alternately on the bottom of the specimen. The AE sensors' installation is shown in Fig. 11. In this experiment, the excitations were driven by hammers of 10 mm and 30 mm in diameter, respectively, at random locations on the top surface of the specimen. The wheel loadings were applied at the center area of 560 mm × 4600 mm between the red lines as shown in Fig. 9.

5.3 Results of Wheel Loading Test

In order to analyze the velocity distributions of the specimen after 40,000 time cycles on each load, AE tomography analysis was conducted in the region of 3.2 m × 1.2 m of the specimen, which is shown as the blue rectangle in Fig. 9. The results of elastic wave velocity distributions of the RC bridge deck specimen after the wheel loading test on each load step, are shown in Fig. 12. From the figure, it is apparent that the areas of the velocities lower than 2750 m/s are progressing as the applied loads' increase, especially intensively observed at the area of left side of the measurement region. After 40,000 time cycles of 196 kN load, the areas of velocities lower than 2250 m/s are remarkably observed.

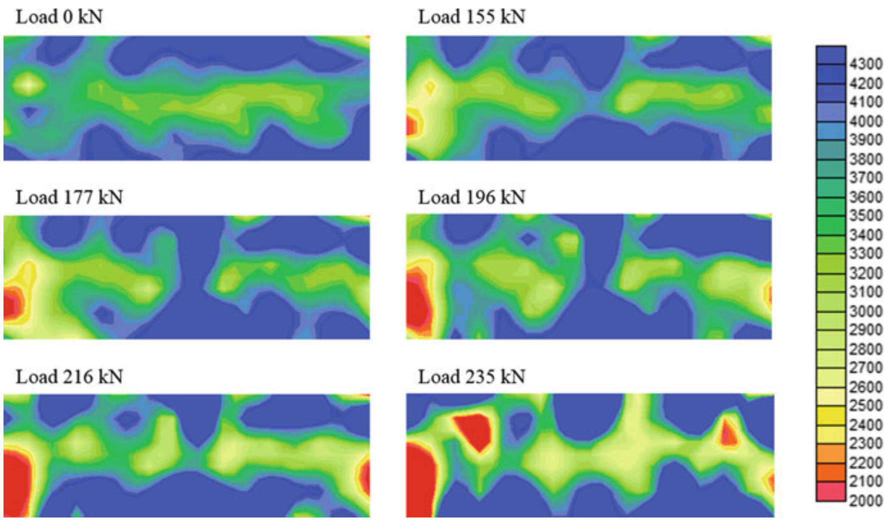

Fig. 12 Velocity distributions during the wheel loading test

6 Conclusions

It was confirmed that AE source location and AE tomography detected the damaged area in concrete decks reinforced with steel plates, which was difficult to find by visual inspection or conventional NDTs. In addition, the reliability of the above method was confirmed by comparing the results of observing the internal damage from cutoff bridge decks by core drilling test. And with the AE tomography method, the change of velocity distributions and the progress of fatigue damage due to wheel loading test are able to be demonstrated clearly.

In the future, the effective sensor arrangement and improvement of resolution of AE tomography results will be investigated.

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