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RILEM TC RECOMMENDATION

Recommendation of RILEM TC 269-IAM: damage assessment in consideration of repair/retrofit-recovery in concrete and masonry structures by means of innovative NDT

Methods for damage assessment of concrete members utilizing active elastic wave measurements

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Abstract This recommendation specifies a method for measuring active elastic waves and assessing damage to concrete members such as decks and girders. The method uses elastic waves propagating inside the concrete member. Elastic waves generated near a surface of the concrete member are detected by acoustic emission sensors installed on the opposite side of the member. Elastic waves propagating in concrete are attenuated or diffracted by damage such as cracks and voids, resulting in fewer AE sources than that of intact areas. Thus, it is possible to distinguish a damaged region from others with density of the observed AE source distribution.

Keywords Internal damage · Non-destructive testing · Source location · AE sensor · Crack

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1 Background

A large number of civil infrastructures, especially concrete structures, were constructed during the period of rapid economic growth, and their deterioration over time is becoming apparent. On the other hand, it is also inevitable not only in Japan but other developed countries that labor population as well as skilled engineers will remarkably decrease and resultant tax revenue will shrink, so that efficient maintenance of such ageing infrastructures has become a social requirement. The transition from the corrective maintenance, in which repairs are performed after the damage becomes apparent, to the preventive

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maintenance, in which repairs are performed while the damage is minor, is a basic approach to address this issue. In the case of concrete members, it is well recognized that in order to realize preventive maintenance, it is necessary not only to make judgments based only on surface information such as cracks but also to evaluate the potential internal damage through proper investigations and prognosis methods. Thus, effective technology that enables early-stage damage detection would be highly expected. On the other hand, even in corrective maintenance, there is an apparent requirement for technology that can quantify any existing damage, which makes it possible to contribute to a rational large-scale repair program. In addition, structures that are damaged and need repair should be evaluated in consideration of internal deterioration. To address these issues, this recommendation is proposed for evaluating damage such as cracks inside concrete members by measurement using AE sensors installed on the surface of the members. Elastic waves propagating in concrete are attenuated or diffracted by damage such as cracks and voids. Thus, it is possible to estimate damaged regions from the density of the observed source distribution [1]. This recommendation refers to several standards established or published in the references [2–6].

This recommendation specifies a method for measuring active elastic waves and assessing damage of concrete members such as decks and girders.

2 Definition of technical terms

For the purposes of this document, the terms and definitions given in ISO 16836 [4], ISO 16837 [5] and the following terms and definitions apply.

2.1 AE source

Source of AE in concrete members caused by crack occurrence, coalescence or the like.

2.2 Active elastic wave

Elastic wave generated artificially by external impacts, such as hammering and droplets due to sprinkling, and natural phenomena such as raindrops on the surface of the concrete member. The active elastic waves are not caused by cracks in the concrete member.

2.3 Elastic wave source

Source of active elastic waves.

2.4 Elastic wave source distribution

Distribution of elastic wave source locations obtained by AE source identification.

2.5 Elastic wave source density

Number of located elastic wave sources per unit area.

2.6 Elastic wave source density map

A map of the spatial distribution of elastic wave source density.

2.7 AE measurement

Measurement of AE activity using AE sensors.

2.8 Damage

A general term for deterioration or defects, including cracks, corrosion, spalling, delamination, and other signs of instability that affect the structural integrity and performance.

3 Measurement system

3.1 Test equipment

A schematic representation of measurement system is illustrated in Fig. 1.

3.1.1 AE sensor

The AE sensor shall be calibrated for absolute sensitivity, and the frequency with the maximum sensitivity shall be in the range of 20–100 kHz, and the maximum sensitivity shall be 53 dB or higher, where 1 V/(m/s) corresponds to 0 dB and 0.45 kV/(m/s) corresponds to 53dB*. In addition, each AE sensor shall

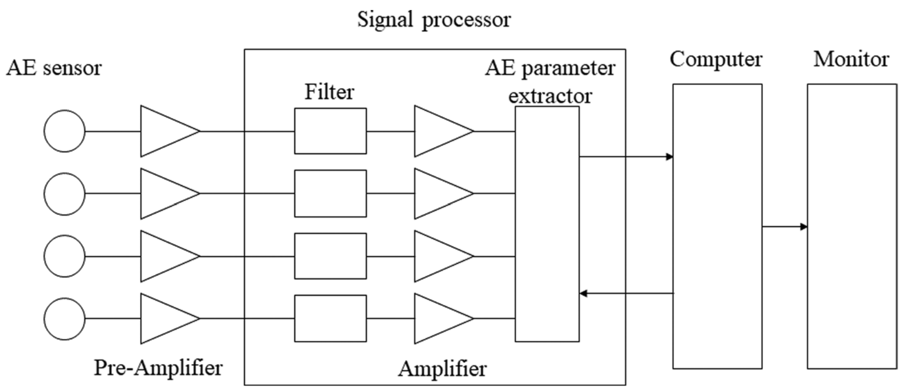

Fig. 1 Schematic representation of measurement system

be of the same model, and the variation among their maximum sensitivities shall be within 6 dB.

*Note: The value of 1 V/(m/s) indicates that the voltage output from the AE sensor is 1 V when a vibration velocity of 1 m/s is detected. The value in logarithmic scale is expressed in dB and converted by the equation, logarithmic value (dB) = 20 log10 (A_1/A_0), where A_1 represents a detected signal in V/(m/s) and A_0 equals to 1 V/(m/s).

3.1.2 Requirements for test equipment

The test equipment shall have a sufficient number of AE sensors and measurement channels to monitor all or specific areas of the target member. In addition, the test equipment shall be able to record the following information regarding the signal of AE waves and elastic waves.

a. AE or elastic wave arrival time at AE sensors
b. AE signal amplitude or alternative quantities

3.1.3 Pseudo AE source

A pseudo AE source shall be reproducible and has a frequency band of at least from 20 to 100 kHz. Either a mechanical method such as pencil lead break, or an electric pulse generator, which can produce the same 20–100 kHz frequency band connecting to an AE sensor may be used.

3.2 Arrangement of AE sensors

The AE measurement shall identify the AE sources over the area of interest detected by at least the minimum number of AE sensors required for the calculation of the AE source location adapted. The sensor spacing and its frequency range shall be set so that it has sufficient resolution for the scale of damage assumed to be detected. In addition, the sensor spacing shall be set in consideration of the degree of attenuation of elastic waves in the member of interest in the corresponding frequency band of the sensor to be used.

4 Test procedure

4.1 AE sensor setup

Figure 2 shows an example of AE sensor arrangement on the member of interest. Multiple sensors shall be placed on one side of the member of interest and detect elastic wave signals generated on the opposite side and propagated through the member. The planar area of interest shall be surrounded by the sensors.

4.2 Confirmation of the installation status on AE sensor

The acoustic coupling of the AE sensor to the member of interest shall be confirmed by the following procedure [3–6]. It is also preferable to perform the same procedure immediately after the end of the test.

Figure 3 shows the procedure to confirm the AE sensor installation. A pseudo AE source shall be used as the artificial acoustic source for checking the sensor installation. Pseudo AE shall be generated multiple times in the vicinity* of each AE sensor. The signals caused by the pseudo AE sources shall be detected by the AE sensor and the average value of

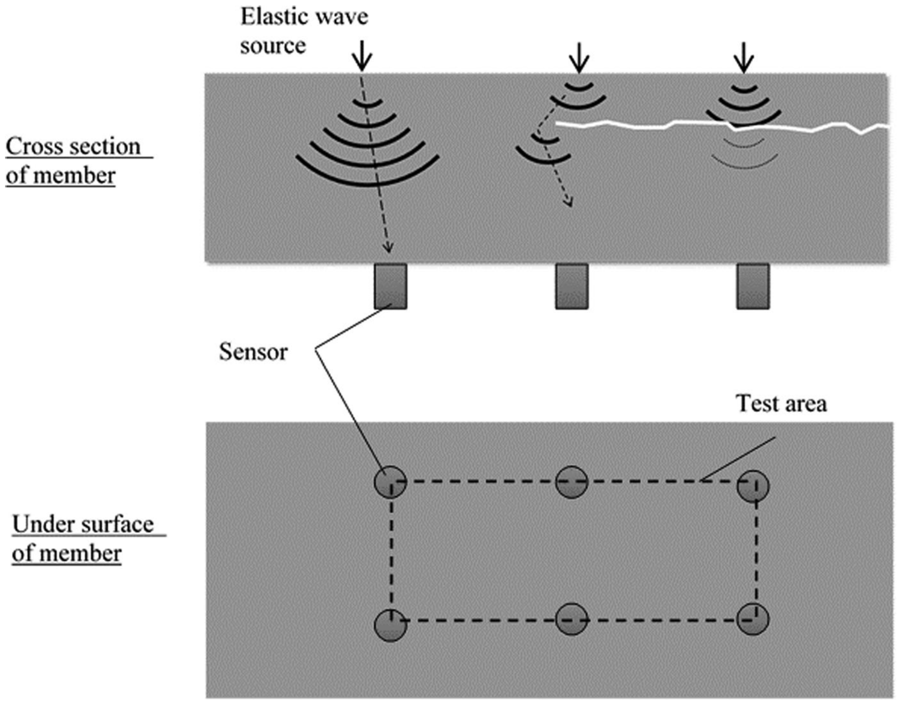

Fig. 2 Example of AE sensor arrangement

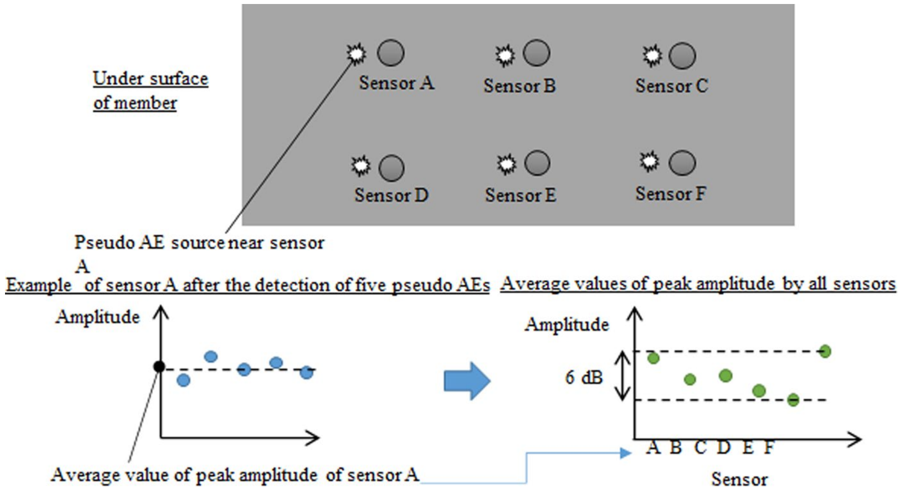

Fig. 3 Procedure of confirmation of the AE sensor installation

the peak amplitudes shall be obtained. This operation shall be performed for all AE sensors and the difference among all the obtained average values shall be within 6 dB. The voltage threshold during AE measurement and the allowable accuracy of AE source location shall be set in advance based on the characteristics of known AE sources.

*Note: Here, "vicinity" includes the meaning of a position that does not have a damaged part such as cracks between the pseudo AE source and the sensor. Since the elastic wave generated by the pseudo AE source is attenuated when passing through the damaged part, the maximum amplitude value of the detection signal shall be confirmed in a position where there is no influence of the damage. If the influence of the damage cannot be avoided and a decrease in the maximum amplitude value is observed, it is recommended to change the sensor position.

4.3 Environmental noise

The intensity of background noise (peak voltage value) for all channels used shall be measured and recorded in the test. When there is a strong source of noise, measures shall be taken to mitigate it. In the case of measuring concrete bridge deck, it is desirable to measure the noise when there are no vehicles traveling on the bridge in order to eliminate the effect of structural vibrations and electrical noises or the like.

4.4 Adjustment of threshold value

The voltage thresholds of all channels used in the test shall be adjusted so that they do not respond to the background noise.

4.5 AE measurement

Elastic waves shall be generated through mechanical impacts placed on the surface of target structure, and the elastic wave propagated through the structure shall be measured by AE sensors. It is desirable to generate a large number of elastic waves with a uniform distribution within the test area. The elastic wave may be generated actively by using an instrument such as a hammer, or an impact caused by a natural phenomenon such as rainfall. AE measurement shall be performed until sufficient number of data is accumulated for analysis.

5 Measurement and damage assessment

5.1 Procedure of measurement and damage assessment

The flow of damage assessment is illustrated in Fig. 4.

5.2 Elastic wave source location

The position of the elastic wave source shall be calculated using the propagation velocity of the elastic wave and the difference in arrival time among the sensors, and by implementing this procedure for the all of the acquired AE data, the elastic wave source distribution shall be finally obtained. In addition to two-dimensional source distribution, it is also possible to use one-dimensional or three-dimensional source distribution depending on the dimension of interest as well as forms of target structure, by the corresponding array of the sensors. For the propagation velocity of the elastic wave, the velocity in the target member in a sound region shall be used.

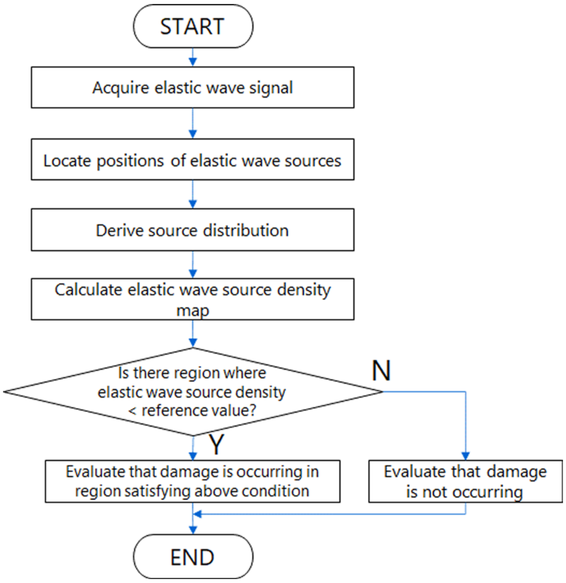

Fig. 4 Flow of damage evaluation

5.3 Elastic wave source density map

The elastic wave source density map shall be generated from the elastic wave source density, which is calculated from the elastic wave source distribution. Figure 5 shows an example of elastic wave source density map. In the example, the test area is divided into cells, and the number of elastic wave sources located in each cell is counted, and then the elastic wave source density for each cell may be obtained. An elastic wave source density map may be generated by plotting the elastic wave density obtained for each cell. A recommended range of the cell size could be from 1/5 to 1/10 of the maximum sensor distance.

The procedure for generating an elastic wave source density map may not be limited to the above. For example, an index equivalent to the elastic wave source density, such as the kernel density, may be used.

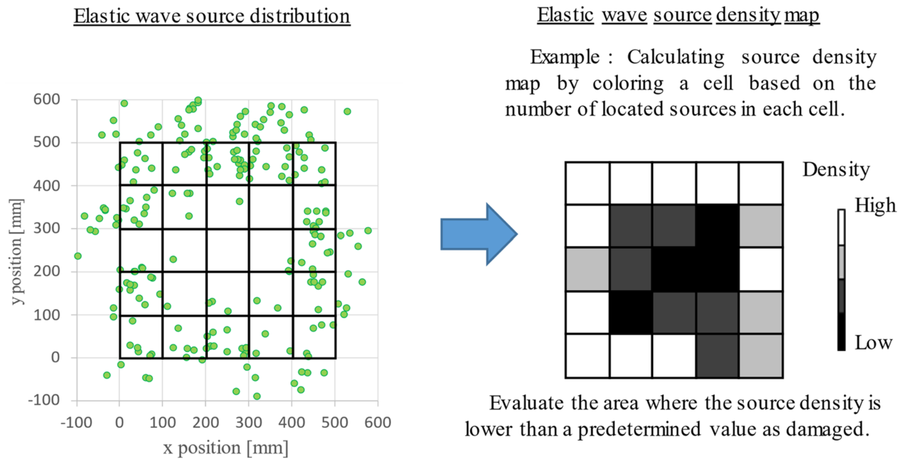

Fig. 5 Example of creating an elastic wave source density map

5.4 Damage assessment

The soundness of the target shall be evaluated according to the source density at the target position to be assessed with respect to the reference value of the elastic wave source density. A high elastic wave source density shall be evaluated as sound, and a low elastic wave source density shall be evaluated as damaged.

The reference value shall be determined in consideration of the applied active elastic wave source density and the attenuation in the path in which the elastic wave propagates from the elastic wave source to the sensor.

For example, when an elastic wave is excited by hitting a known point, the excitation points and their distribution is known, and the reference value is set according to the assumed elastic wave source distribution in consideration of the attenuation in the member. When the position of the elastic wave source is not known, for example, when a high-density impact with a uniform distribution is applied, such as raindrops due to heavy rainfall, the obtained elastic wave source density becomes high on average, so the reference value may be reasonably set high. On the other hand, if the elastic wave sources are expected to be relatively few, or if a large attenuation is expected due to the structure and characteristics of the member, the elastic wave source density may be low as a whole, so the reference value may be set low accordingly. If it is possible to perform a test using the target member or a test piece equivalent to it, measurement in a sound area may be performed to obtain the elastic wave source density in the sound part, and set a reference value accordingly. Note that the elastic wave source density may be affected by the sensor arrangement, so special consideration may be required.

6 Appendix

6.1 Generating elastic wave source density maps using kernel density estimation

A kernel density distribution can be obtained by replacing the located elastic wave source with a kernel that indicates a probability distribution and integrating it. Figure 6 shows an overview of kernel density estimation. A located elastic wave source is replaced with a kernel function. The figure shows an example in which a Gaussian distribution is used as the kernel function. The Gaussian kernel function for the point (x_0, y_0) can be expressed as $K_h(x, y)$ in Eq. (1). The variable h in the formula indicates the bandwidth of the function.

$$\left(x_0, y_0\right) \rightarrow K_h(x, y) = \frac{1}{2\pi h^2} \exp\left(-\frac{\left(x - x_0\right)^2 + \left(y - y_0\right)^2}{2h^2}\right) \quad (1)$$

The integral value of the kernel function is 1, and the value of the function can be supposed as the probability that a located source exists at a certain position. The spread of the probability distribution can be defined by the bandwidth. When setting the

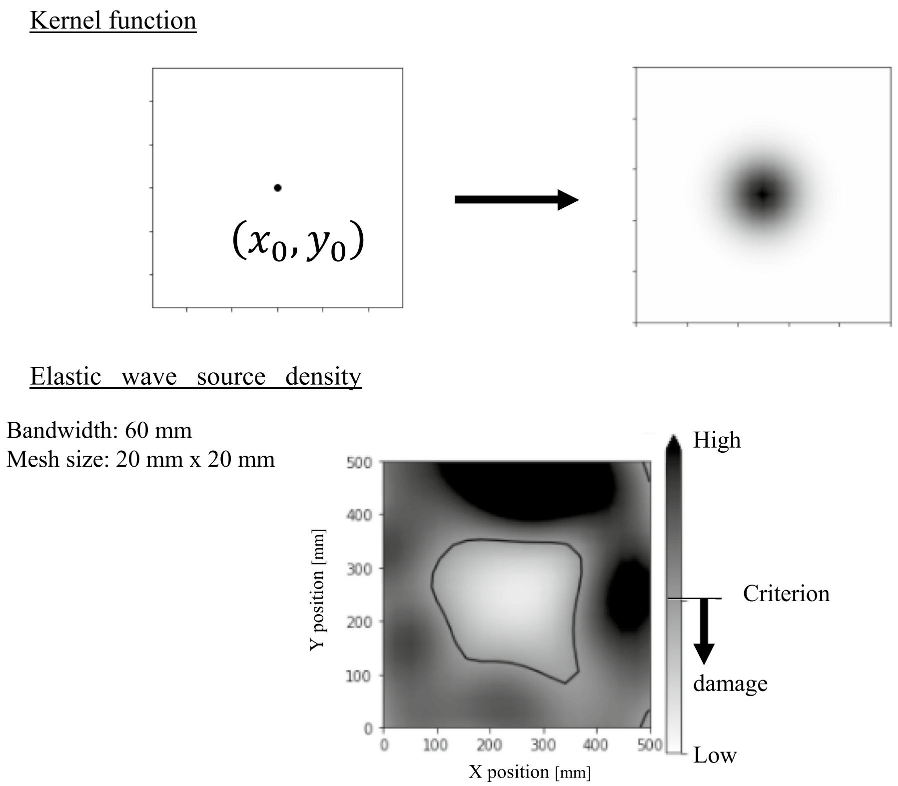

Fig. 6 Generation of elastic wave source density map using kernel density estimation

bandwidth, source location errors may be reflected, such as increasing the bandwidth when location accuracy is poor. As shown in Eq. (2), the overall elastic wave source density $f(x, y)$ can be obtained by adding up the kernel functions for all elastic wave sources. N in the formula indicates the total number of elastic wave sources.

$$f(x,y) = \frac{1}{N}\sum_{i=1}^{N} K_h\left(x - x_i, y - y_i\right) \tag{2}$$

The total density is normalized to 1 by dividing the total density by the number of located sources. In this case, the obtained density value is considered to correspond to the probability that one located source is observed at a certain position in the area of interest. A contour diagram of the function $f(x, y)$ illustrates an elastic wave source density map.

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