GLOBAL MONITORING OF CONCRETE BRIDGE USING ACOUSTIC EMISSION

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Abstract

Global monitoring of civil structures is a demanding challenge for engineers. Acoustic emission (AE) is one of the techniques that have the potential to inspect large volumes with transducers placed in strategic locations of the structure. In this paper, the AE technique is used to characterize the structural condition of a concrete bridge. The evaluation of AE activity leads to information about any specific part of the structure that requires attention. Consequently, more detailed examination can be conducted once the target area is selected. In this study, surface wave investigation was subsequently performed to detail the condition of the target area.

Keywords: Concrete structures, damage assessment, global monitoring, surface wave velocity.

Introduction

The deterioration of civil infrastructure worldwide calls for effective methods for damage evaluation. One of them, AE monitoring technique, uses signals generated within the structure, which are due to crack growth under stress, as well as secondary emissions due to friction of crack interfaces. This unique monitoring technique parameterizes the fracture/failure process, and distinguishes it from other nondestructive tests. This is the only one capable of real-time mapping of fracture processes. In addition to real-time source identification from the acquired AE signals, the energy level or "magnitude" of the detected signals can be evaluated, and provides immediate evidence of the degree of damage. A particular engineering advantage of the AE technique is its efficiency for global monitoring since a large and complex structure can be monitored with a limited number of sensors. Consequently, the most crucial part of the structure can be targeted with a more detailed AE monitoring for quantification of AE indices [1-4], or using other suitable techniques [5]. Results obtained from the AE testing depend highly on many external parameters such as the applied load and loading rate, the properties of the material and the type of structure. These factors restrict the development of comprehensively applicable tools. Additionally, due to the complex composition of most civil structures, AE waveforms depend on their propagation path from the source to the sensors [6]. However, in any case, valuable information can be extracted concerning which part of the structure has sustained the most severe deterioration.

In the specific case presented herein, a 45-m bridge span is under examination. Preliminary investigations of surface-crack observation and physical tests of excavated cores did not reveal any extensive damage. The cores can characterize only the area where they were extracted and the surface observation cannot reveal internal damage. Therefore, further monitoring was conducted with AE technique. The AE testing was performed by moving a heavy vehicle over the bridge. Based on the AE activity the part of structure more likely to exhibit higher degree of damage than the other areas in the longitudinal direction was selected for the detailed investigation. A similar application on a much smaller scale was reported in [2]. A surface ultrasonic examination, which is indicative of the quality [7, 8], followed in order to investigate the pulse velocity of concrete at the area of interest.

Experimental Procedure

For the AE monitoring, 28 sensors were attached in all to the bottom surface of the bridge using a wax. They were placed on the longitudinal axis of the bridge with a separation of 1.4 m as shown in Fig. 1. Specifically, the sensitive AE sensors to concrete structures, R6 of PAC, were used. These sensors exhibit nominally the maximum sensitivity at 60 kHz and are widely used for concrete monitoring. The detected AE signals were pre-amplified by 40 dB and acquired by two synchronized data acquisition systems, namely a 16-channel DiSP and a 12-channel Mistras of PAC. Strain gauges were also placed in three locations on the top surface of the bridge, as shown in Fig. 1.

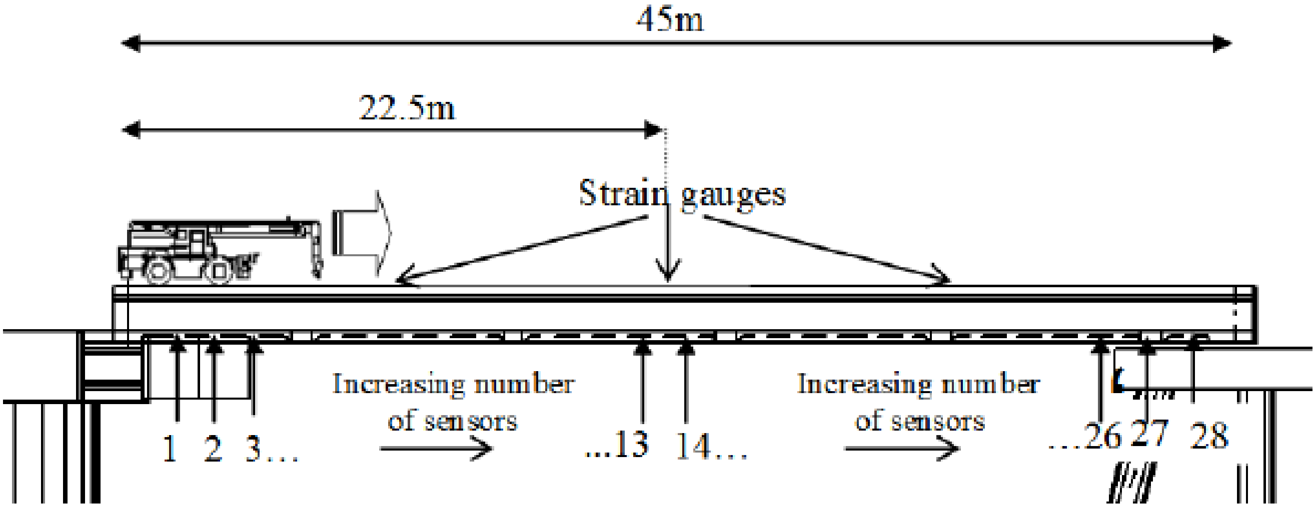

Fig. 1. Representation of the crane passing over the bridge and sensor location.

Acoustic Emission Activity

Damage indices

The interpretation of the detected AE activity is not always easy. This is the reason why different indices have been suggested and applied for the purpose of damage quantification. As stated earlier, when a material or structure is stressed, AE is produced. Additionally, the behavior during unloading is also crucial. In case the material is intact (or the applied load is low), the AE activity during unloading is of low intensity. For damaged material, the emission continues even during unloading. The number of AE hits during unloading divided by the number of hits during the whole cycle is defined as the Calm ratio and values near zero indicate intact material condition [2, 4, 9].

Another index comes from the analysis of the amplitude distribution of AE events, or so called the improved *b*-value analysis [1, 4]. Although a large-scale fracture in general corresponds to large AE peak amplitude, the use of the amplitude solely can be misleading. This is because the accumulated damage increases the materials' attenuation rate due to scattering at the cracks. Therefore, even a high amplitude signal will be severely attenuated before being recorded by the sensors. In this respect, the amplitudes are studied through their cumulative distribution that uniquely changes as the damage is accumulated. Specifically, the gradient of the distribution is calculated. With the evolution of damage, this slope decreases, meaning simply that the ratio of the large energy AE events to that of the small relatively increases in the total population of AE events. It has been confirmed that at the moments of extensive cracking, the I*b*-value exhibits severe drops [10-14].

AE monitoring results

The load for the AE monitoring was applied by a 20-ton crane vehicle, which passed three times over the bridge with a constant speed of approximately 0.5 m/s, as seen in Fig. 1. As the crane moved over the bridge, the strain and stress fields changed. The compressive strain measured on the top surface of the bridge at the mid-span can be seen in Fig. 2. The maximum strain was recorded at 88 s, when the vehicle was in the middle of the span, suggesting the highest tensile stress at the bottom layer of the structure. In the same figure, the cumulative number of AE hits recorded by all the sensors is depicted for one passage. It can be seen that the rate of AE hits was more intensive before the crane reached the center of the bridge at 88 s. Up to that moment, more than 70% of the total number of hits was recorded, implying that more active sources were located in the first half of the bridge.

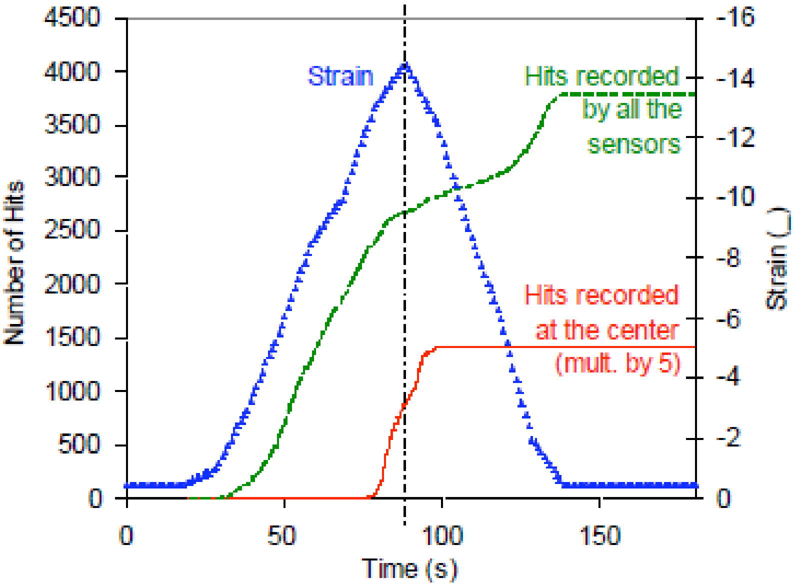

Fig. 2. Time history of strain at the center and cumulative AE hits during crane passage.

As stated, in order to calculate the Calm ratio, the AE activity should be correlated with a measured mechanical parameter. In this case, this was conducted using the measured strain at the middle point and the AE activity of the center part, recorded by the two sensors placed closest to the center (13 and 14 of Fig. 1). The activity of these sensors and AE hits of all sensors combined are plotted in Fig. 2. For clarity, the middle sensor hits are multiplied by a factor of 5. The hits of the middle sensors started at 74.5 s as the crane was approaching, and the last hit was recorded 10 s after the crane had passed over the bridge center, showing the intensive AE activity even during unloading. The number of hits for three different trips of the crane and the resulting Calm ratios are presented in Table 1. The Calm ratios concerning the center part of the bridge range from 0.3 to 0.45 for any individual passage of the crane, indicating serious damage according to past studies [2, 11, 12, 16, 17].

After location of the events, interesting conclusions can be drawn about the attenuation of the structure. In Fig. 3(a), the amplitude of the hits of all events is depicted vs. the distance from the source. The average first hit stands at amplitude of 54 dB. In Fig. 3(b), the linear fits to the amplitude of each individual event are plotted. Attenuation was calculated from the slope of each line. Averaging of the slopes of all the events results in -7.02 dB/m, which is representative for the attenuation of the whole structure. It is seen that hits of the weakest events still propagate 1.5 m before being reduced below the threshold level (40 dB). Therefore, they are recorded by at least 2 sensors. This shows that the separation of the sensors in this case allows source location. In general for the average amplitude of 54 dB at the source, 2 m for the sensor separation would provide a reasonable detection in this bridge. In any case, it is a crucial parameter that should be seriously taken into consideration since, in monitoring of most large structures, compromises must be made between the available number of sensors, time restrictions for measurement preparation and the desirable degree of detail of examination. Attenuation is a key parameter to make an adequate decision.

Concerning the Calm ratio, mentioned above, taking into account the measured attenuation and the fact that the Calm ratio is based on the results of two neighboring sensors (with separation of 1.5 m), the events should originate within a span of 4 to 5 m in the middle of the bridge. Thus, conclusions about material degradation based in this Calm ratio concern this zone.

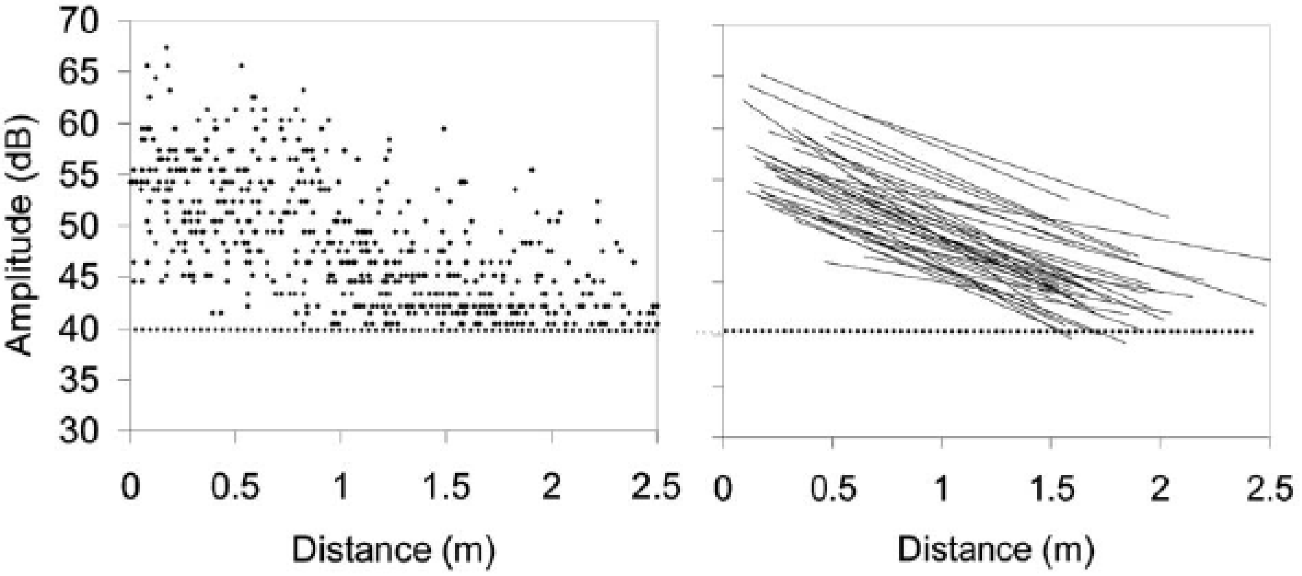

Fig. 3. (a) Hit amplitude vs. distance from event source, (b) individual attenuation slope for different events.

Table 1. Number of AE events for different stages of loading and Calm ratios.

Trip	Loading	Unloading	Calm ratio
1	175	146	0.455
3	409	179	0.304
5	295	208	0.414

Ib-value analysis

In Fig. 4, the *Ib*-values based on the AE events located at different zones of the bridge are plotted for the three different passages of the crane. The span was divided into 12 zones of 3 m each, in order to allow the number of events for the *Ib*-value calculation. Specifically, the total number of events to be considered for the calculation of the *Ib*-value should be above 50 [1, 10-14]. The number of events for the same zones is also shown in the chart. It is evident that some areas of the structure exhibited larger number of events than others as seen in Fig. 4 and the *Ib*-value is calculated for the zones only exhibiting more than 50 events. Focusing on the *Ib*-values, it is seen that they vary between 0.05 and 0.13. According to established correlations, values above 0.2 imply the intact condition, between 0.1 and 0.2 suggests the moderate damage and it is becoming more intense as the *Ib*-value decreases below 0.1 [1, 2, 12]. This shows that a large part of the structure is deteriorated. While the limited AE activity of the rest does not allow the evaluation of this parameter, there were not many active sources in that area.

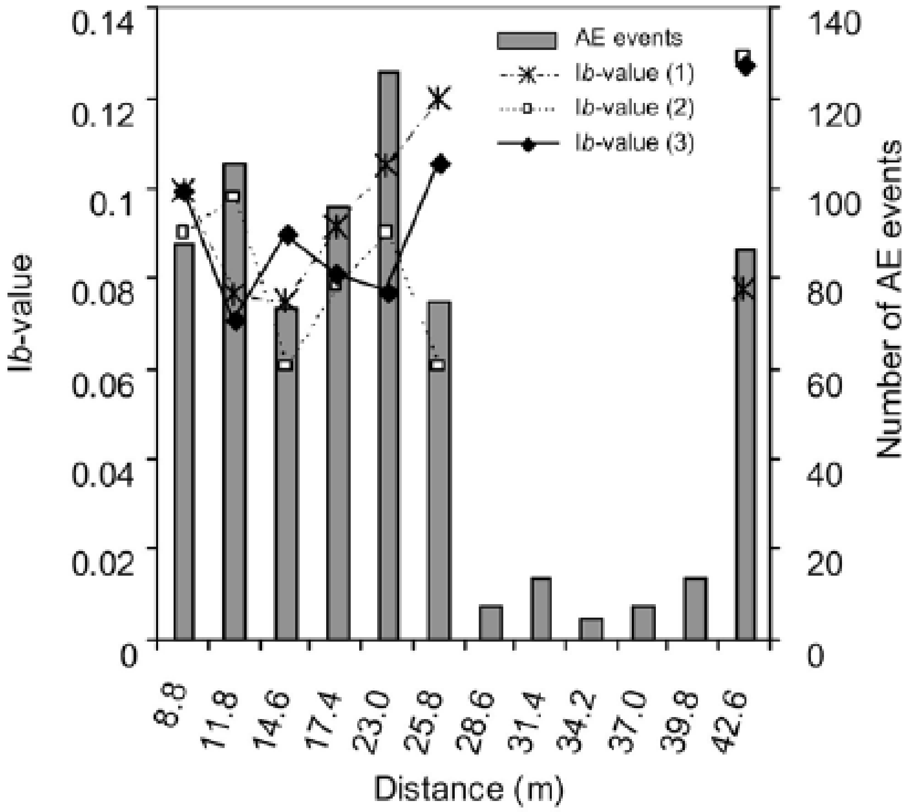

Fig. 4. *Ib*-values for three different trips of the crane and indicative AE events for the first trip.

Velocity measurements

In order to make a more detailed examination of the active area of AE activity, wave velocity measurements were made. Velocity has been established as an indicator of concrete quality for many decades and it is accepted that velocity above 4000 m/s indicates high quality, while below 3000 m/s suggests poor quality [7, 17].

For the velocity measurement, nine AE sensors were used in an arrangement of three parallel arrays of three. The separation distance was 1.5 m, resulting in an examined area of 3 m by 3 m, see Fig. 5. The excitation was conducted by pencil-lead break near the location of each transducer. Therefore, each time, one sensor was used as trigger for the acquisition and eight as receivers. In this way, a number of intersected paths were examined, and the results can be considered more representative of the area and more reliable than single measurement between two points. The velocity was measured by the time of the first detectable disturbance of each waveform, which corresponds to the onset of longitudinal waves.

The transit times of the individual paths, along with the sensor positions were supplied to a suitable tomography program [18]. This way the visualization of the velocity structure was obtained and the information of which parts of the surface area exhibit lower velocity than others was obtained as shown in Fig. 5. From this figure, considerable discrepancies of the wave velocity were found within the area of 9 m^2. Specifically, a zone approximately in the center of the selected area exhibited velocities close 2500 m/s, while other areas had velocity higher than 4000 m/s.

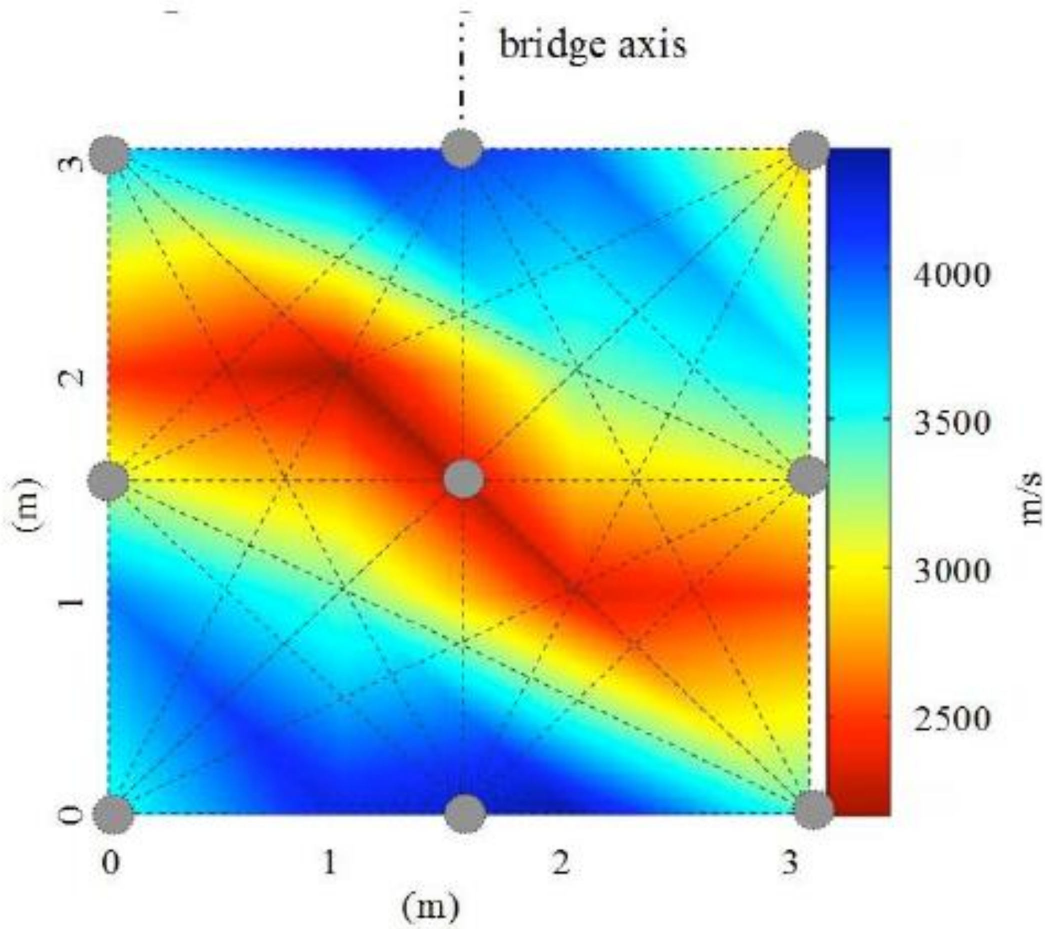

Fig. 5. Velocity structure of the bottom surface of the concrete bridge. The positions of the transducers are indicated by circle and the examined wave paths are drawn by dashed lines.

It is noted that no visual defect was observed on the surface. Therefore, the low velocity zone is attributed to a subsurface defect. The depth cannot be easily determined though. Concerning Rayleigh waves, it is accepted that the penetration depth is approximately similar to the wavelength [19]. In this case, however, the first arrival used to measure velocity corresponds to the longitudinal wave, which is in any case faster than Rayleigh or shear waves. Therefore, it is not straightforward how deep is the surface layer characterized by this velocity. Concerning Rayleigh propagation, typical velocities for the bottom part of Fig. 5 were around 2500 m/s, corresponding to the longitudinal velocity certainly higher than 4000 m/s. Although this implies good quality, the determination of Rayleigh velocity was not always possible due to severe attenuation and distortion of the waveform, especially for paths at the top of Fig. 5. This was because there was no characteristic point to use as reference for Rayleigh wave measurement [20]. This again shows that the continuous path was disrupted by a discontinuity. Using the Rayleigh velocity of 2500 m/s and the major frequency component of 150 kHz the wavelength is calculated to approximately 17 mm. Therefore, since the Rayleigh component was not visible at some areas, this should be due to a weak material zone (discontinuity) that extends very close to the surface (even closer than 2 cm), because if it was deeper the Rayleigh would not be influenced. It is mentioned that the frequency of 150 kHz is measured by waveforms recorded 1.5 m away from the excitation. Close to the excitation the frequencies are higher, while for propagation of 3 m the major frequency component is just below 50 kHz. This complicates the quantification of the penetration depth, since the frequency content is not constant but is downshifted with propagation due to concrete damping. The characterization depth using surface wave examination (including Rayleigh and longitudinal components) needs further study, which is currently undertaken.

As to the AE events observed, concrete cracks, delaminations of different layers (e.g. asphalt on concrete) or friction between the tendon ducts and matrix concrete are possible origins. Follow-up investigations focusing on this weak area will clarify the source, while this sequential investigation, which started with AE activity and followed by detailed measurements of ultrasonic velocity is useful in characterizing the quality of large-scale concrete structures, leading to contribute to the rehabilitation program of aging infrastructures.

Conclusions

In this paper, the suitability of acoustic emission to monitor large concrete structures is presented. The AE technique was initially used to select the most deteriorated area based on the number of AE events and the values of quantification indices like the Calm ratio and I*b*-value. The subsequently conducted ultrasonic examination exhibited very low velocities confirming that the area indicated by AE activity was actually deteriorated. This shows the potential of AE testing as a global monitoring for examination of large volumes using a limited number of sensors. Even if AE indices or parameters cannot be directly correlated with the degree of damage, they suggest which part of the structure needs further and detailed investigations. Subsequently, wave velocity measurements were conducted allowing a more general evaluation through the reported correlations between velocity and concrete quality. It is suggested that the combination of such stress wave techniques as AE and surface wave examination can assess the degree of damage of large civil structures that so far has been difficult to attain.

References

1) T. Shiotani, K. Fujii, T. Aoki, K. Amou, Evaluation of progressive failure using AE sources and improved b-value on slope model tests, *Prog. Acoust. Emiss VII*, (1994), JSNDI, Tokyo, pp. 529-534.

2) M. Ohtsu, M. Uchida, T. Okamoto, S. Yuyama, Damage assessment of reinforced concrete beams qualified by acoustic emission. ACI Structural Journal, **99**(4), (2002), 411-417.

3) C. Grosse, H. Reinhardt, T. Dahm. Localization and classification of fracture types in concrete with quantitative acoustic emission measurement techniques. NDT&E Int, **30**(4), (1997), 223–230.

4) T. Shiotani, Evaluation of long-term stability for rock slope by means of acoustic emission technique, NDT&E Int, **39**(3), (2006), 217-228.

5) V. M. Malhotra, N. J. Carino (Eds.), *CRC Handbook on Nondestructive Testing of Concrete*, (1991), CRC Press, Florida.

6) B. Schechinger, T. Vogel, Acoustic emission for monitoring a reinforced concrete beam subject to four-point-bending, Construction and Building Materials, **21**(3), (2007), 483-490.

7) T. R. Naik, V. M. Malhotra, The ultrasonic pulse velocity method, in: Malhotra, V. M., Carino N. J., (Eds.), *CRC Handbook on Nondestructive Testing of Concrete*, (1991), CRC Press, Florida.

8) T. Gudra, B. Stawinski, Non-destructive characterization of concrete using surface waves, NDT&E Int, **33**, (2000), 1-6.

9) S. Colombo, M. C. Forde, I. G. Main, M. Shigeishi, Predicting the ultimate bending capacity of concrete beams from the "relaxation ratio" analysis of AE signals, Construction and Building Materials, **19**, (2005), 746-754.

10) T. Shiotani, M. Ohtsu, K. Ikeda, Detection and evaluation of AE waves due to rock deformation, Construction and Building Materials, **15**(5-6), (2001), 235-246.

11) T. Shiotani, Y. Nakanishi, X. Luo, H. Haya, T. Inaba, Damage evaluation for railway structures by means of acoustic emission, Key Engineering Materials, **270-273**, (2004), 1622-1630.

12) T. Shiotani, Y. Nakanishi, X. Luo, H. Haya, Damage assessment in deteriorated railway sub-structures using AE technique, Journal of Acoustic Emission, **22**, (2004), 39-48.

13) J. H. Kurz, F. Finck, C. U. Grosse, H. W. Reinhardt, Stress drop and stress redistribution in concrete quantified over time by the *b*-value analysis, Structural Health Monitoring, **5**, (2006), 69-81.

14) S. Colombo, I. G. Main, M. C. Forde, Assessing Damage of Reinforced Concrete Beam Using "*b*-value" Analysis of Acoustic Emission Signals, Journal of Materials in Civil Engineering-ASCE, **15**(3), (2003), 280-286.

15) T. Shiotani, D. G. Aggelis, Damage quantification of aging concrete structures by means of NDT, *Proc. of Structural Faults and Repair-2006*, June 13-15, Edinburgh, (in CD).

16) T. Shiotani, X. Luo, H. Haya, Damage diagnosis of railway concrete structures by means of one-dimensional AE sources, Journal of Acoustic Emission, **24**, (2006), 205-214.

17) M. F. Kaplan, The effects of age and water/cement ratio upon the relation between ultrasonic pulse velocity and compressive strength. Mag. Concr. Res., **11**(32), (1959) 85– 92.

18) Y. Kobayashi, H. Shiojiri, T. Shiotani, Damage identification using seismic travel time tomography on the basis of evolutional wave velocity distribution model, *Proc. Structural Faults and Repair-2006*, June 13-15, Edinburgh. (in CD).

19) D. G. Aggelis, T. Shiotani, "Repair evaluation of concrete cracks using surface and through-transmission wave measurements", Cement and Concrete Composites, **29**, (2007), 700-711.

20) L. Qixian, J.H. Bungey, "Using compression wave ultrasonic transducers to measure the velocity of surface waves and hence the dynamic modulus of elasticity of concrete". Construction and Building Materials, **10**(4), (1996), 237-242.