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SYSTEM FOR THE GLOBAL MONITORING AND EVALUATION OF DAMAGE PROCESSES DEVELOPING WITHIN CONCRETE STRUCTURES UNDER SERVICE LOADS

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Abstract. In this paper, a global monitoring system based on the measurement of acoustic emission (AE) due to active deterioration processes is presented. This allows to examine the entire volume of an element and to locate (with an accuracy of the measuring zones) and identify the type and the dynamics of deterioration processes under service conditions. The resulting data are used to determine and locate the damage processes that are dangerous in construction and to assess the general condition of the structure as well as the degree of risk.

Keywords: destructive process, prestressed concrete, AE model database for damage processes, service load.

1. Introduction

To ensure the reliability and safety of engineering structures throughout their service life, it is important to control them and determine their current condition. This is especially important due to the following:

- a large percentage of concrete structures are now reaching the designed lifetime or are at the age at which there is an increased risk of failure; this may be the case for reinforced concrete bridges or large panel system buildings.
- due to changes in the fire safety code, sanitary code and environmental regulations, higher living and working standards, etc., most existing buildings and non-building structures should be reconstructed, extended or modernized.
- according to the building codes, it is important that each structure be properly designed and constructed to maintain reliability throughout its service life without excessive maintenance costs by accounting for all of the loads and other external effects encountered during construction and use.

Controls are implemented as a result of periodic inspections conducted by professional engineers and experts, and the procedures are similar in many countries.

For example, regulations concerning the assessment of the safety of reinforced concrete structures issued by the Polish Building Research Institute defines three types of inspection:

- a periodic inspection to verify the serviceability of the structure,
- an emergency inspection after the occurrence of considerable abnormality in the performance of the structure,
- a target-oriented inspection conducted in conjunction with a modernization or a change in function.

A diagnosis of bridges in Poland was performed in accordance with the building code instructions issued by the General Directorate for National Roads and Highways and included:

- current inspections,
- annual inspections – basic maintenance,
- periodic inspections at five year intervals – extended surveys,
- detailed surveys, and
- expertise.

Current and periodic inspections primarily rely on visual observation, and the procedures applied in European countries and the US are similar, except that a different damage classification system is used: in Poland a six-step scale classification is used; in France a four-step scale; in the US a ten-step scale; and in the UK a five-step scale and the level of damage is also subject to an assessment of its extent. The extent of damage and its level are considered together (Woodward 1999).

The analysis only reveals visual external damage at locations where observation is possible. This type of

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assessment is subjective in nature and depends on the experience of the individual.

Detailed surveys, expertise and emergency or target-oriented inspections require experts, and an assessment of the structural condition should be performed according to certain principles. Advanced testing techniques are listed as follows:

- destructive, non-destructive and semi-destructive testing methods to define the properties of concrete, the size and character of cracks, extent of corrosion, etc.;
- chemical and electrical methods for an assessment of the degree and extent of damage to the structural materials and the particular elements.

These techniques are used in addition to a visual assessment.

Due to the nature of those methods (ultrasonic, radiography, thermograph, *X*-ray, impact echo, etc.), the tested area includes only a very limited volume of the inspected element that must be precisely pointed out. It is not possible to establish whether the detected defects are the only ones within the structure and if they are active (progressive) in character, which determines if they pose a threat to the structural integrity of the object.

Hence, when developing a system for an objective assessment of the structural integrity of a concrete object (bridges, buildings, etc.), it is important to consider the following issues:

- tests focusing on the detection and location of damage should be performed for the entire structure or at least the crucial part;
- the system should work under the service and actual loads of the object;
- the system should accurately and spatially locate damage and its nature;
- it should be possible to establish whether the damage is active (progressive) or passive (non-progressive) in character; in many cases, cracks that appear to be dangerous may be the after-effects of some initial deformations that resulted in stress redistribution followed by the propagation of defects to other areas.

A passive monitoring system that is capable of addressing the above mentioned issues base on the measurement of acoustic emission (AE) generated by active (progressive) damage processes is presented in this paper.

Research work on the use of AE to detect defects in concrete components has been reported in many research centers (Beck *et al.* 2003a; Blanch *et al.* 2002; Gołaski, Świt 2005; Gołaski *et al.* 2006; Kalicka 2009; Tinkey *et al.* 2002; Goszczyńska *et al.* 2012a, 2012b). Research was carried on the development of a methodology to apply the AE method to enable the non-destructive testing of concrete elements (Hadzor *et al.* 2011; Shah, Ribakov 2011).

The present work focused mainly on the study of localization and registration of AE signals generated by individual damages in the structure (Tinkey *et al.* 2002).

In the papers (Anastsopoulos 2007; Gołaski *et al.* 2009; Suzuki *et al.* 2002; Tinkey *et al.* 2002), criteria for evaluating the structure were developed, in which a single parameters of AE were linked with the occurrence of visible defects on the test element (width of opening cracks, load value, the intensity of damages).

Another works (Anastsopoulos 2007; Beck *et al.* 2003b; Ohtsu *et al.* 1998; Yuyama *et al.* 1995) were focused on the possibility of predicting the formation and direction of cracks propagation. For this purpose the AE signals recorded during the destruction of the beam to determine the constant components of Green's function were used. This allowed to develop the program for evaluation of cracks appearance probability and its direction of propagation.

Until now, pattern recognition method to create a comprehensive monitoring system throughout the structure was not used. Laboratory tests were conducted using the AE in the study of individual elements (beams) (Colombo *et al.* 2002) or destructive processes (corrosion, crack) (Diederichs *et al.* 1983; Ing *et al.* 2005). It is difficult to apply such results to diagnose large and complicated structures such as bridges, where different damage processes affect each other.

2. Acoustic monitoring – deterioration processes in prestressed concrete structures

During AE monitoring, AE sensors detect signals (elastic waves) that are generated by a rapid release of energy that is related to fracture process in a material (microcracks growth, movement of vacancies and dislocations, dislocation glide at the aggregate-cement paste interface, overlapping dislocations, crack initiation and development, and crystalline phase transitions). The attenuation of acoustic waves is the result of absorption, which is the conversion of elastic energy into thermal energy.

The generation of AE is thus a signal of the degradation of the properties of the material (and a given structural element). Accordingly, the AE phenomenon indicates the deterioration of the material or the element that consists of the material.

Elastic AE waves generated by cracks are registered by sensors placed on a structure. The sensors are typically piezoelectric sensors with a range of operation from 0.1 to 2.0 MHz which determine the frequency range of the received wave.

Fig. 1 shows an idealized AE signal.

The signals that are recorded are described qualitatively by the following (12) parameters: counts, counts to peak, duration, rise time, amplitude in mV or dB, energy, strength, root mean square, mean level, mean frequency, reverberation frequency and initial frequency.

The processes that generate AE signals accompany only active damage which is created or developed during a measurement. These signals are not generated by defects that are physically present in the facility, but there is no development process. Therefore, the damage process registered during AE measurements pose a threat to the structural integrity.

The deterioration phenomena (AE sources) found in prestressed concrete structures (Gołaski *et al.* 2005) include:

- microcracking (Ohtsu 1999),
- friction between crack faces,
- initiation and growth of cracks,
- cracking at the concrete-reinforcement interface,
- concrete spalling,
- friction at the concrete-reinforcement interface,
- corrosion,
- plastic deformation and cracking of cables and other reinforcement.

The primary goal of the proposed system is to group the registered AE signals into classes that correspond to deterioration phenomena and to establish the model database. To create such database it was necessary to conduct laboratory-based strength tests using laboratory scale samples (short beams), full-scale samples (girders) and in-situ measurements of the entire structure (bridges) or its vital elements (Świt 2009, 2011). The values of twelve AE signal parameters where taken into account for grouping using NOESIS system (Gołaski *et al.* 2006).

The model database that enables identification of the deterioration phenomena (and related to the deterioration process – threat to the safety of a structure) was established and recorded (Kalicka 2009; Świt 2009):

Class 1 – Micro cracking at the interface between the fine aggregate (∅ ≤ 2 mm) and the cement paste.

Class 2 – Micro cracking at the interface of fine aggregate and medium aggregate (∅ ≤ 8 mm).

Class 3 – Crack initiation and growth in the concrete tension zone – indicate a potentially dangerous condition.

Class 4 – Crack growth and friction at the interface between the coarse aggregate and the cement paste (∅ = 8–16 mm) – indicate a progressively dangerous deterioration.

Class 5 – Cracking at the concrete–reinforcement interface – indicates a progressively dangerous deterioration.

Class 6 – Plastic deformation of steel and concrete – indicates particularly dangerous deterioration processes.

Class 7 – Concrete delamination – indicates particularly dangerous deterioration processes.

Class 8 – Rupture of prestressed tendons – indicates particularly dangerous deterioration processes.

Classes were marked as shown in Table 1.

For example, a signal corresponding to Class 1 signifies the existence and development of micro cracks in the concrete at the interface between the fine aggregate and the cement paste.

The occurrence of certain signals determines the type deterioration and indicates a threat to the safety of a structure as follows:

Class 3 signal – indicates a potentially danger condition;

Class 4 and 5 signals – indicate a progressively dangerous deterioration;

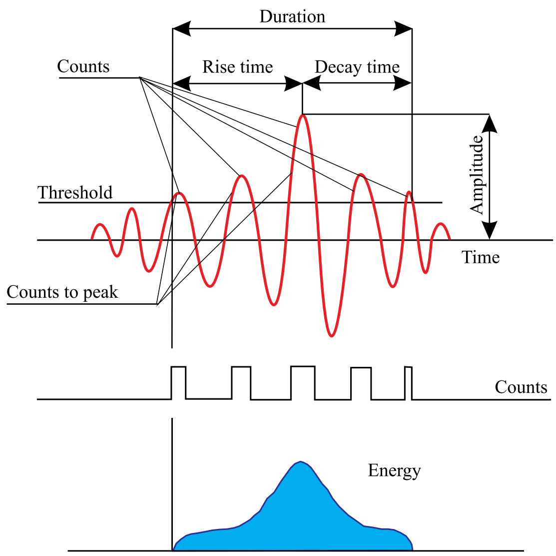

Fig. 1. An idealized AE signal

Table 1. Classes and corresponding marking

Shape/color	□ (red)	◆ (blue)	● (green)	▼ (black)	○ (pink)	▲ (purple)	+ (grey)	X
Class number	No 1	No 2	No 3	No 4	No 5	No 6	No 7	No 8

Class 6, 7 and 8 signals – indicate particularly dangerous deterioration processes.

By measuring AE signals and applying the model database, one identify the processes of active deterioration occurring in an element tested and its nature. With the proper placement of AE sensors, it is possible to measure AE signals within an entire element (or structure) and locate the emission sources (areas of deterioration).

3. Detection and location of defects – arrangement of the sensors

An AE wave released during a destructive process is registered by sensors placed on the structure, and their measuring surface is assumed to be a spherical cap with radius *a* (Fig. 2) which magnitude is dependent on the signal

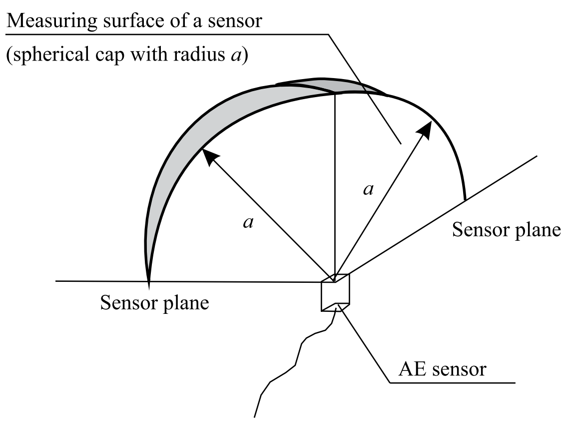

Fig. 2. Sensor measuring surfac

strength, attenuation and sensor sensitivity (which determined experimentally by using a model wave and assuming certain wave attenuation – to define radius *a,* experiments were carried out assuming wave attenuation ≤ 10 dB).

Fig. 3 shows the measuring surfaces for an element the cross-section of which is "a narrow rectangle" ($a >> g$) where $d < 2a$; the measuring surfaces overlap and form the measuring zones.

The sensor measuring zone is an area where the distance of an arbitrary point *e* to a given sensor is less than or equal to *a* and is not greater than the distance to the other sensors. This is illustrated in the measuring zone for sensor 1 at an arbitrary point *e*: $e_1 \le e_2 \le e_3 \le e_4 \le a$, as shown in Fig. 3.

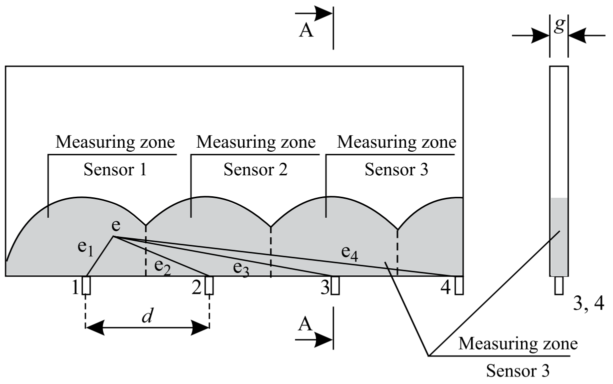

Fig. 3. Overlapping measuring surfaces – measuring zones

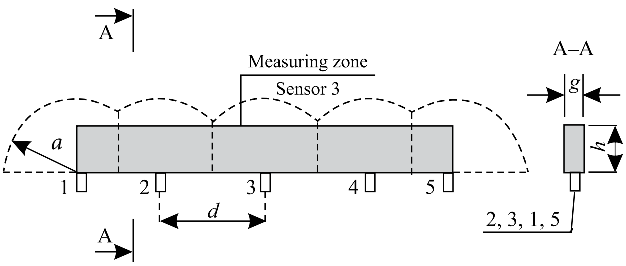

Fig. 4. Measuring zones covering the entire element: *d* – distance between sensors, cm; *g* – element thickness, cm; *h* – height of the element, cm; *a* – radius of a sensor measuring surface, cm

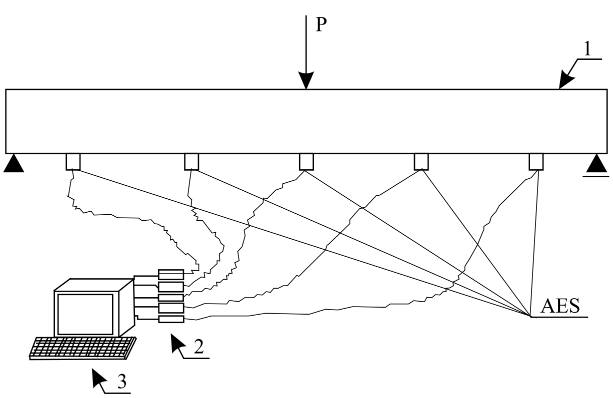

Fig. 5. Diagram of the acoustic emission measuring system

The sensors should be arranged in such a way that their measuring zones cover the entire or the selected part of the measured element.

For instance, if the element is rectangular in cross-section (where $g < a$) and the arrangement of the sensors is uniform over the bottom surface, then the measuring zones of the sensors cover the entire volume of the element with height *h* (Fig. 4), where:

$$h \le \sqrt{\left(a^2 - \left(\frac{g}{2}\right)^2 - \left(\frac{d}{2}\right)^2\right)}, \tag{1}$$

where *a* – radius of a sensor measuring surface, cm; *d* – distance between sensors, cm; *g* – element thickness, cm; *h* – height of the element, cm.

By applying Eq (1), it is possible to determine the max distance between the sensors, d_{max}, for an element with a pre-determined height *h* and width *g*.

If an element is more complex in shape then the sensors should be arranged in such a way that the whole volume of this element is covered by the measuring zones.

A signal is considered to belong to a given measuring zone by measuring the differences in time in which the AE source signal reaches the sensors. As shown in Fig. 3, the signal generated at point *e* will reach sensor 1 sooner than sensors 2, 3 and 4. Once the signal is registered by sensor 1, the apparatus will automatically cut off the signal (hereby preventing sensors 2, 3 and 4 from registering it). Thus, the signal belongs to the measuring zone for sensor 1. Hence, by identifying a deterioration process, one is able to locate its occurrence by attributing it to a particular measuring zone.

The behavior of a structure is monitored and assessed either globally (if the entire load-bearing element is analyzed) or locally (if a selected area called a "*hot spot*" is measured).

4. Application of the acoustic emission system to inspect and assess reinforced concrete structures

Diagram of the acoustic emission measuring system applied to the loaded beam (1) is shown in Fig. 5.

It consists of: AES – acoustic emission sensors SE-55-R (55 kHz); 1 – loaded beam; 2 – pre-amplifiers PAC gain 40 dB; 3 – computer system SAMOS with the following software: AEwin, NOESIS 4.0 (Trąmpczyński *et al.* 2012).

4.1. Monitoring a road bridge over a railway line under normal service conditions

The structure under consideration (Fig. 6) is a three-span bridge in which the outer spans are butt-joined prestressed concrete beams supplemented with concrete topping. The static diagram shows the simply supported outer spans measuring 9.70 m in length. The acoustic emission method was applied to analyze the condition of the two outer span beams and piers 1 and 2.

Fig. 6 illustrates the linear arrangement of seven 55 kHz resonance sensors along the bottom surface of an outer-span beam which divides the area into seven measuring zones. The distance between the sensors was 140 cm which satisfies the conditions of Eq (1) for a given cross section of the beam (Fig. 7) and an experimentally determined radius of the measuring surface a = 110 cm.

The classes of signals registered in the particular zones of the beam are presented in Table 2. Fig. 7 illustrates the measured signals in Zone 7 located in the area where the beam rests on the pier cap.

The signals registered in Zone 7 indicate that the deterioration processes are dangerous (Class 4 signals correspond to the crack growth and friction at the interface between the coarse aggregate and the cement paste) and potentially dangerous (Class 3 signals) to the structure.

Observation made during the visual inspection confirms the measurement results; deterioration covered approx 30% of the surface area of the beam around the anchorage and the support on the pier. The deterioration processes caused the initiation of cracks up to 0.1 mm in width, corrosion of the cable anchorage, and a lack of sliding friction in the bearings.

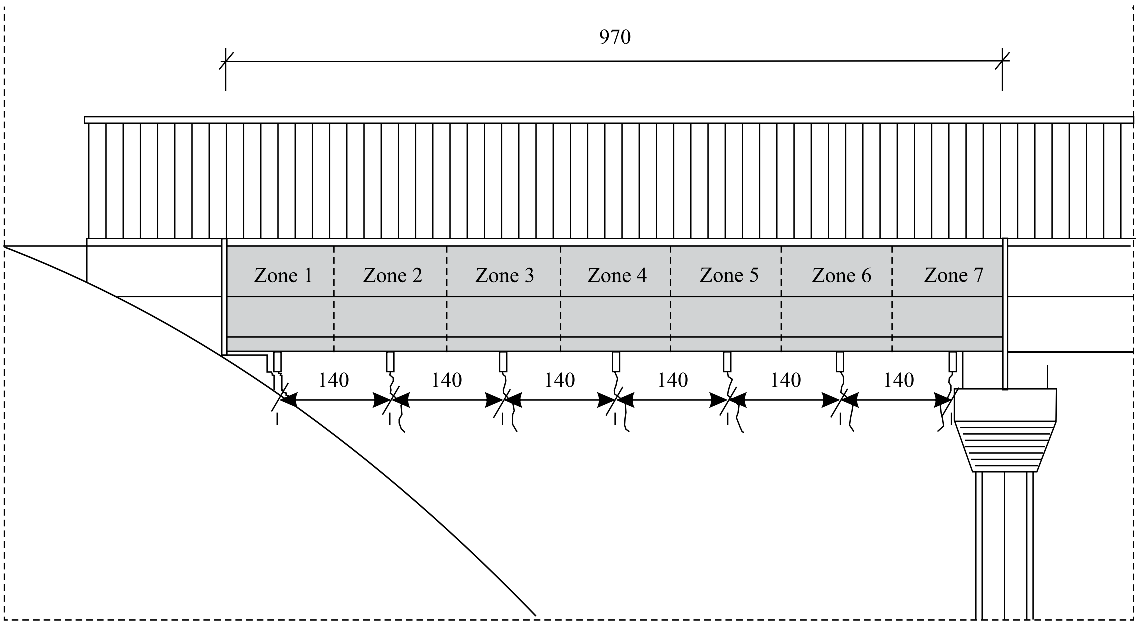

Fig. 6. The structure under consideration and arrangement of the AE sensors along one of the beams (measurements in cm)

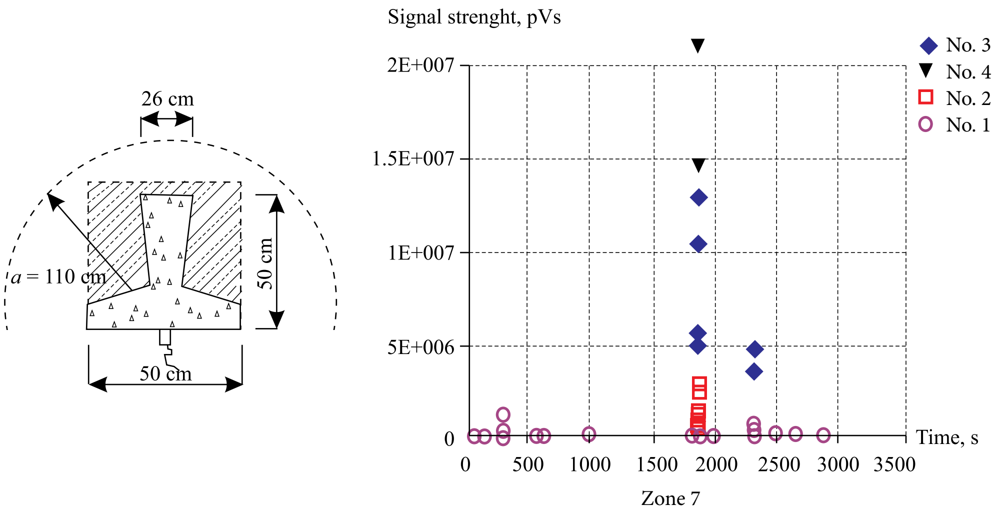

Fig. 7. Max range of the measuring surface and the AE signals registered in Zone 7

Table 2. Classes of signals (damage processes) registered in different measuring zones of one of the bridge beams under service load

	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8
Zone 1								
Zone 2								
Zone 3								
Zone 4								
Zone 5								
Zone 6								
Zone 7								

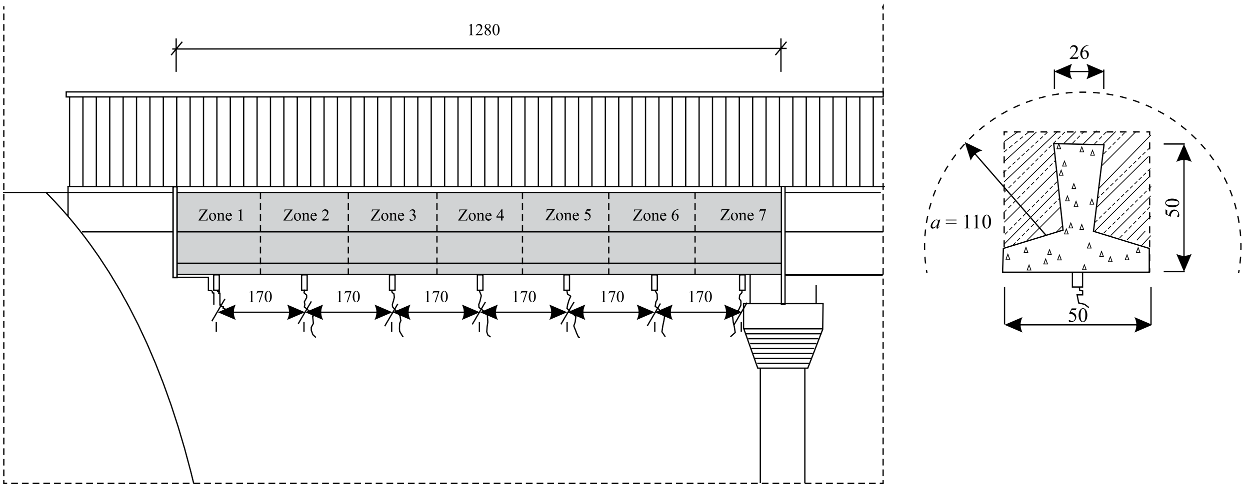

Fig. 8. Arrangement of the AE sensors on the surface of the beams and the max range of the measuring surface (measurements in cm)

Table 3. Classes of signals (damage processes) registered in different measuring zones of one of the bridge beams under normal traffic load

	Class 1	Class 2	Class 3	Class 4	Class 4	Class 5	Class 6	Class 7
Zone 1								
Zone 2								
Zone 3								
Zone 4								
Zone 5								
Zone 6								
Zone 7								

4.2. Monitoring the behavior of the road bridge during the passage of an overloaded truck

The structure is a two-span bridge measuring 25.65 m in length and 9.96 m in width. The bridge consists of prestressed concrete beams (Fig. 8). The inspection was conducted under normal traffic loads and during the passage of overloaded trucks (with an excessive mass). The load-bearing elements of the bridge were monitored and assessed using the acoustic emission method.

Fourteen 55 kHz resonance sensors were placed over the bottom surface of the two beams (Fig. 8). The distance between the sensors was 170 cm which satisfied the conditions of Eq (1) for the given cross-section of the beam (Fig. 8) and the experimentally determined radius of the measuring surface (a = 110 cm).

Table 3 shows the classes of the signals registered in particular zones of a selected beam under normal traffic loads, whereas Table 4 shows the classes of the signals registered during the passage of an overloaded truck. Fig. 9 shows the measured AE signals that were obtained from Zone 6.

The signals that were registered in Zones 5 and 6 under normal traffic loads demonstrate the occurrence of dangerous deterioration processes (Class 4 signals) and potentially dangerous (Class 3 signals) to the structural integrity.

Table 4. Classes of signals (damage processes) registered in different measuring zones of one of the bridge beams during the ride of an overloaded truck

	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8
Zone 1								
Zone 2								
Zone 3								
Zone 4								
Zone 5								
Zone 6								
Zone 7								

During the ride of an overloaded truck, the signals registered in Zones 1, 2 and 6 show deterioration processes that are potentially dangerous (Class 3 signal).

This confirms that the deterioration processes observed during the ride of an overloaded truck do not pose a greater threat to the integrity and reliability of the structure than those present under normal service conditions. This is due to the high-speed passage of several trucks together during service traffic that causes additional dynamic loads and rapid deterioration of the structure.

4.3. Monitoring of a reinforced concrete frame building exposed to strong acids and bases

Long-term monitoring of a production building made of reinforced concrete was performed in course of four years.

Four 55 kHz resonance sensors were placed on the surface of a selected element with a separation distance of 1.5 m, as shown in Fig. 10. The conditions of Eq (1) are satisfied for the given cross-section of the beam (Fig. 10) and the experimentally determined radius of the measuring surface is a = 110 cm. The tests were conducted under normal service conditions.

The classes of the signals registered in each zone on the beam are presented in Table 5 for the years 2009–2005.

By comparing the most recent data with the data obtained in 2005 and 2007, one conclude that there have been no significant changes in the intensity of the deterioration processes that occurred within the analyzed element.

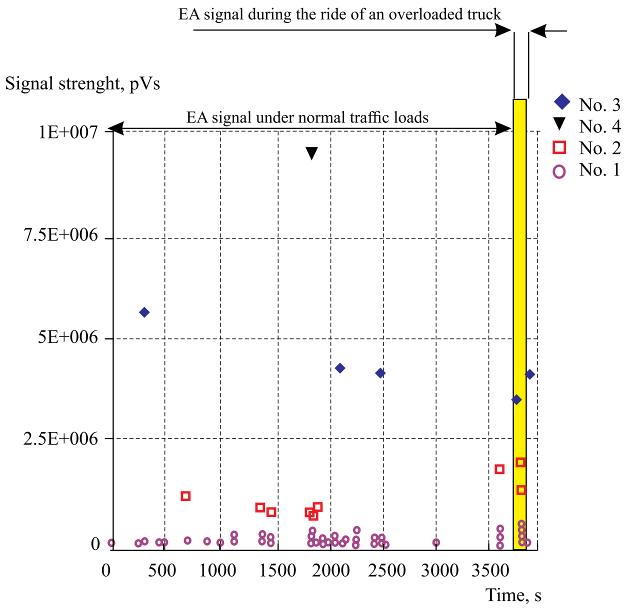

Fig. 9. Examples of the AE signals measured in Zone 6

5. Conclusions

In this paper, a monitoring system based on the measurement of acoustic emission due to active deterioration processes was presented. This allows to examine the entire volume of an element and to locate (with an accuracy

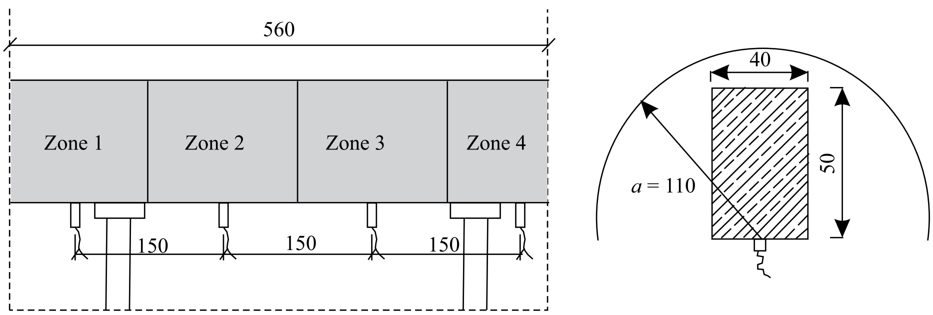

Fig. 10. Arrangement of the AE sensors on the surface of the rib and max range of the measuring zone (measurements in cm)

Table 5. Classes of signals (damage processes) registered in different measuring zones of one of the bridge beams under normal traffic load, 2005–2009

	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8
2009								
Zone 1								
Zone 2								
Zone 3								
Zone 4								
2007								
Zone 1								
Zone 2								
Zone 3								
Zone 4								
2005								
Zone 1								
Zone 2								
Zone 3								
Zone 4								

to the measuring zones) and identify the type and the dynamics of the deterioration processes under service conditions.

The resulting data were used to determine and locate the damage processes that are dangerous in construction and to assess the general condition of the structure as well as the degree of risk.

The system is used as follows:

- to monitor a concrete structure under normal service conditions,
- to register and classify the development of active processes of deterioration under service conditions,
- to determine the most dangerous processes and locate the most potentially dangerous areas,
- to assess the level of danger that the structure is exposed to,
- to assess the influence of the service conditions (water, frost, etc.) on the deterioration processes that are occurring in the structure.

The system is also useful for the following applications:

- to assess the effectiveness of maintenance activities, i.e., checking whether the detected damage in the structure has been removed (i.e., deterioration process has stopped),
- to assess the validity of decisions aimed at reducing the traffic over an object or decreasing its max load capacity in which the decisions are no longer conservative, i.e., subjective and unverifiable,
- to monitor the structural behavior of a bridge during the passage of large vehicles – for example, the slow passage of a considerably overloaded truck causes less damage than the simultaneous passage of three fast moving trucks with loads less than the max permitted values.

The system presented was successfully used for an examination of more than 70 full-scale structures (bridges, buildings, etc.)

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