Acoustic Emission-Based Decision Support for Bridge Safety in Smart Cities

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ABSTRACT

This paper presents an acoustic emission (AE) based Identification of Active Anomalies (IAA) system, using signal clustering, image recognition, and machine learning, for monitoring the condition of a highway overpass near a large urban agglomeration. The monitoring results provide the basis for assessing the structural condition of the asset and for the automated load (traffic) control necessary to ensure its safe operation. Acoustic emission (AE) signals recorded during service loads undergo multi-parametric signal analysis using pattern recognition and are assigned classes corresponding to specific anomalies in the material or structure. Each class is associated with a level of structural hazard, ranging from safe operation to loss of safety. Corresponding traffic control measures, including vehicle speed and weight limits, ensure safe operation. The method was experimentally applied to monitor an A2 highway overpass, part of the Łódź city transport hub, facilitating north-south and east-west travel in Poland. This enables highway administration services and agencies to prevent sudden, unforeseen structural failures proactively. The IAA system proves to be an effective diagnostic tool for the efficient and safe operation of a Smart City, enabling the rational allocation of funds for road infrastructure maintenance

INTRODUCTION

Efficient transportation is vital for economic growth and social and economic activity. Bridges, crucial to this system, face increasing strain from heavier traffic and neglect, impacting Smart City functionality. Smart Cities aim for intelligent urban development, where "Smart Building" emphasizes safe and environmentally friendly construction. Structural safety requires continuous diagnostics to detect

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degradation from loads, enabling timely maintenance and ensuring operation. Bridge closures cause significant economic, social, and environmental losses, highlighting the need for effective monitoring and diagnosis to optimize maintenance and extend lifespan. Consequently, reliable methods for monitoring bridges are being sought. Acoustic emission (AE) as a diagnostic method is under development due to its broad coverage, ability to detect active damage under real loads without disruption, and advanced analysis tools. This paper presents the application of our AE-based Identification of Active Anomalies (IAA) system for continuous monitoring of cable-stayed concrete bridges under operational loads, enabling automatic traffic control for safety by identifying hazards. Developed between 2023 and 2025 under the RID II governmental research project, the IAA method allows in-service measurements. It provides objective assessments, paving the way for a more efficient and reliable bridge monitoring system.

IAA - IDENTIFICATION OF ACTIVE ANOMALIES SYSTEM

Basics

The loading of materials causes deformation, leading to destructive processes that generate detectable acoustic emission (AE) waves. These waves result from the rapid release of stored energy due to micro-damage, such as crack growth and dislocation movement. Various parameters, including count, peak amplitude, duration, rise time, amplitude, energy, strength, and frequency, describe AE waves. Analysis of these parameters enables classification into groups corresponding to specific destructive processes. A reference database for cable-stayed and prestressed concrete elements, integrated within the IAA (Identification of Active Anomalies) method, was developed from laboratory and in-situ tests, with signal designations and classes outlined in Table 1.

A processor records AE signals and compares them to a pre-established reference database. Through pattern recognition, these signals are classified into anomaly categories, aiding in the assessment of the tested element's condition. Reference databases were created using material samples, specialized tests, and validated during

TABLE I AE SIGNAL CLASSES, SYMBOLS, AND CODES

Symbols	⬭	□	◆	▼	▲	●	✚	✖
Classes	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7	No. 8
Degree of danger	5	4	3	3	2	2	1	0

Class 1 Initiation of micro-cracking in the grout
Class 2 Initiation of micro-cracking at the grout-aggregate interface and development of microcracks
Class 3 Initiation of micro-cracks on the component surface
Class 4 Growth of cracks
Class 5 Loss of adhesion in the crack vicinity and prestressing cable corrosion
Class 6 Buckling of compression bars
Class 7 Crushing of compressed concrete
Class 8 Fracture of prestressing strand/cable or rupture of reinforcing bar.

Signal class	Destructive process	Hazard level
Class No. 1	Initiation of micro-cracking in the grout	No hazard
Class No. 2	Initiation of micro-cracking at the grout-aggregate interface and development of micro-cracks	No hazard
Class No. 3	Initiation of micro-cracks on the element surface	Low hazard
Class No. 4	Growth of cracks	Moderate hazard (durability)
Class No. 5	Loss of adhesion in the crack vicinity	Moderate hazard (load capacity)
Class No. 6	Buckling of compression bars	High hazard (load capacity)
Class No. 7	Crushing of compressed concrete	Very high hazard
Class No. 8	Prestressing strand/cable fracture or reinforcing bar rupture.	Failure/crash

Table II Destructive processes, corresponding signal classes, and assigned hazard levels

in-situ operation. Statistical signal analysis was conducted with NOESIS v.12.0 software, using both Unsupervised and Supervised Pattern Recognition systems to develop a "black box" for the IAA system. Structural damage criteria were established based on the analysis of destructive process classes, as crack advancement significantly impacts service life (Table II).

TESTS AND THE RESULTS OF THE IAA SYSTEM APPLICATION FOR VIADUCT CONDITION ASSESSMENT

Selected structural elements of the WA252 road viaduct on the A1 highway's left carriageway (km 302+952.10 to 303+117.80) were investigated. This structure carries a large animal ecological corridor and the "L" class communal road No. 106309E (Moskwa-Plichtow) under the A1. Six-span continuous slab-girder structures, each featuring three main prestressed concrete girders, were utilized for both traffic directions. The girders are 1.34 m high, with a minimum width of 0.8 m and a spacing of 6 m. The deck slab has a minimum thickness of 0.28 m. Abutments are massive, reinforced concrete structures, separated at the median strip, with wings parallel to the structure's longitudinal axis, founded on a DSM column-reinforced soil. Intermediate supports are reinforced concrete piers, consisting of three 1.2 x 1.2 m rectangular columns in each, founded on piles with 3.30 x 2.70 m pile caps, connected by beams. A general view of the structure is shown in Figure 1. The central beam of the left (eastbound) carriageway was investigated in the areas above supports No. 2 (km 302+979.35) and No. 6 (km 303+090.55), with support numbering according to the viaduct's design documentation. The locations of the investigated areas and the arrangement of the AE sensors are shown schematically in Figures 2 and 3. The investigations included the measurement of AE signals generated by the physical processes associated with the structure's behavior under traffic load and trial loads. A 24-channel SAMOS acoustic emission processor with cabling and flat response sensors in the range of 20-120 kHz, VS-30, was used for the tests. Sixteen sensors were linearly arranged on the bottom of the beams. The distance between

Figure 1. General view of the viaduct in Plichtow.

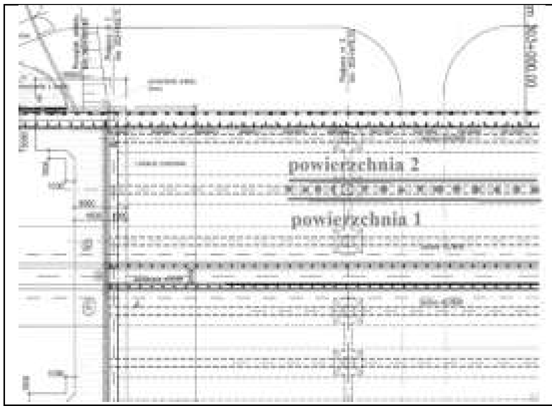

Figure 2. Arrangement of AE sensors on the beam above support No. 2

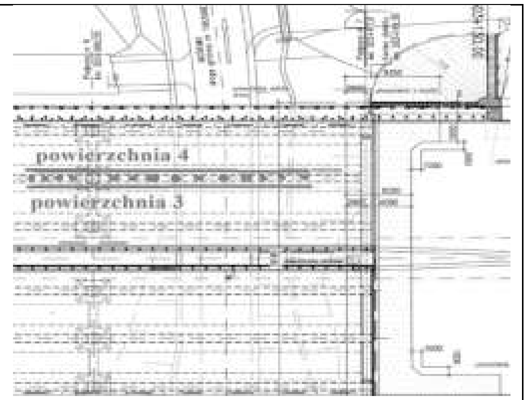

Figure 3. Arrangement of AE sensors on the beam above support No. 6.

Figure 4. 24-channel AE measurement system with cabling and VS-30 sensors installed on selected elements of the viaduct.

the sensors was 200 centimeters. This distance was sufficient to register all AE signals from the investigated beams. A view of the monitored beams with the arranged sensors is shown in Figure 4. During the investigation, the so-called linear location method was used. Before and after the measurement, sensor calibration was performed by generating a standard Hsu-Nielsen wave source. The signal amplitude for the sensors ranged from 98 to 99 dB.

The measurements were taken during the regular operation of the structure and a proof load test (Figure 5).

Figure 5. View of the structure under load.

Results

Analysis of the results in Figures 6 and 7 shows that in beam No. 2, Classes 1-4 signals are present across all measurement zones, indicating microcracks at the cement paste-aggregate interface and the growth of existing cracks. While these signals do not pose an immediate hazard, they affect durability. Though immediate intervention is not required, crack injection should be conducted soon, or the structure should be monitored periodically using the IAA system.

Analysis of the graph in Figures 8 and 9 for beam No. 6 reveals Class 5 signals in one zone, Class 4 in three zones, and Class 3 in the remaining zones. Similar anomalies related to microcracks are observed. Class 1-4 signals indicate no immediate danger but impact durability, necessitating future monitoring. Class 5 signals indicate a potential threat to load capacity, requiring immediate alternative testing and periodic monitoring. The IAA system for automatic monitoring of the technical condition of cable-stayed/ suspension bridges is designed to support decision-making in response to changes in the durability and load-bearing capacity of structures.

The IAA system aids in monitoring the technical condition of cable-stayed/suspension bridges, facilitating decision-making regarding durability and load capacity.

MEASUREMENT OF AE SIGNALS - THE BEAM ABOVE SUPPORT NO. 2 (KM 302+979.35) – UNDER REGULAR TRAFFIC.

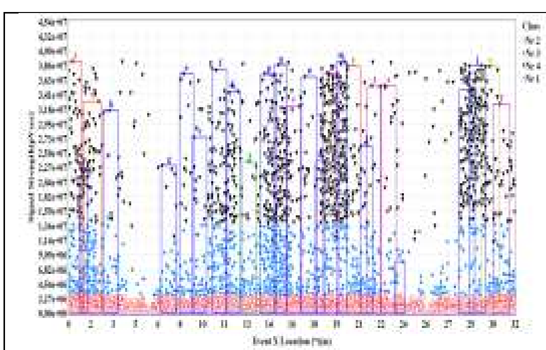

Figure 6. Scatter plot of signal strength as a function of location (beam length)

Figure 7. Measurement zones with anomaly codes

MEASUREMENT OF AE SIGNALS OF THE BEAM ABOVE SUPPORT NO. 6 (KM 303+117.80) – UNDER REGULAR TRAFFIC.

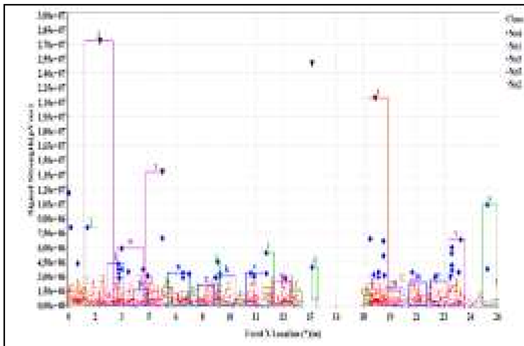

Figure 8. Scatter plot of signal strength as a function of location (beam length)

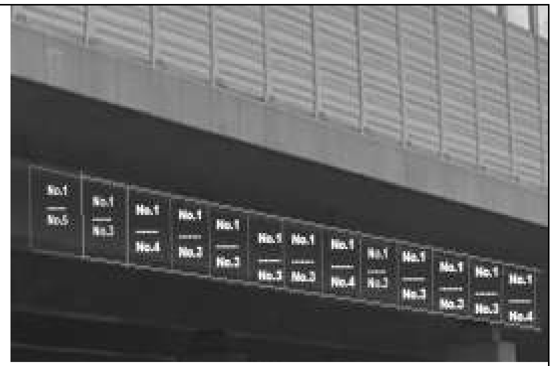

Figure 9. Measurement zones with anomaly codes

Acoustic sensors are strategically placed to monitor critical elements continuously or during peak traffic. If Class 4-6 signals are recorded, the system reduces vehicle speed and weight limits. For Class 7 signals, only vehicles under 3.5 tons are permitted, and Class 8 signals warrant a complete traffic closure.

In the event of Class 7 and Class 8 signals, an expert assessment and additional investigations using other methods should be commissioned in emergency mode to confirm the technical condition.

This method has been successfully used to assess the technical condition of over 180 bridge structures, as well as to monitor the passage of oversized transports.

IAA SYSTEM FOR AUTOMATIC IDENTIFICATION OF ACTIVE ANOMALIES TO ENSURE SAFE BRIDGE OPERATION

The IAA system is modular, comprising several key modules: **M1**, which contains historical investigation data and documentation; **M2**, which includes calculations and simulations of the current structure, highlighting stressed or vulnerable areas. AE sensors 1-5 are mounted on test elements and connected to the AE signal analysis module **M3**, which identifies the types and locations of anomalies (Classes 1-8). **M3** relays destructive process information to the **M4** module for hazard analysis and to the **M6** module for administrator signaling. In **M4**, data is assessed to determine hazards that lead to load restrictions (e.g., limiting vehicle speed and weight) and to define measurement intervals. Additional modules can be integrated to monitor conditions like temperature, humidity, and vibrations. Decisions based on these readings are communicated to the **M5** module for allowable load levels, which displays traffic restrictions via stoplights and no-entry signs. The **M6** module shows hazard levels and restriction messages on a monitor. Overall, the system works together to ensure structural safety through continuous monitoring and timely decision-making (Table III).

TABLE III INFORMATION SENT TO THE MODULE ENSURING SAFE OPERATION **M5** AND THE STRUCTURE ADMINISTRATOR REGISTRATION AND SIGNALING MODULE **M6**

Signal class	Hazard level	Information for the permissible load level signaling module – **M5**	Information for the structure administrator registration and signaling module – **M6**
class 1	None	No information – green light	No information
class 2	None	No information – green light	No information
class 3	Low (durability)	No information – amber light	**Warning** Crack formation in zone X…..
class 4	Moderate (durability)	Limit the permissible speed to 50 km/h for vehicles exceeding 12 t – amber light	**Durability hazard** Crack formation in zone X…. the permissible speed to 50 km/h for vehicles with a weight exceeding 12 t
class 5	Moderate (load capacity)	Limit the permissible load capacity of the structure to 10 t – amber light	**Load-bearing capacity hazard** Loss of reinforcement bond in zone X ... the permissible speed to 50 km/h for vehicles with a weight exceeding 12 t... Limit the permissible load capacity of the structure to 10 t
class 6	High (load capacity)	Limit the permissible load capacity of the structure to 20 t – amber light	**Load-bearing capacity hazard** Plastic deformation of compressed concrete in zone X ... limit the permissible speed for vehicles with a weight exceeding 12 t to 50 km/h. Limit the permissible load capacity of the structure to 20 t
class 7	Very high (load capacity),	Limit the permissible load capacity of the structure to 3.5 t + public transport – amber light	**Load-bearing capacity hazard.** Plastic deformation of compressed concrete in zone X ... limit the permissible speed to 40 km/h. Limit the permissible load capacity of the structure to 3.5 t
class 8	Failure or catastrophe	Closure of the structure to traffic – red light	**Failure of the structure**

In the given example, the system is activated for one hour at set time intervals, e.g., every two hours, and measurements are performed in a loop. The registration of a given destructive process occurs upon the tenth recording of signals of a specific class in a consecutive measurement interval.

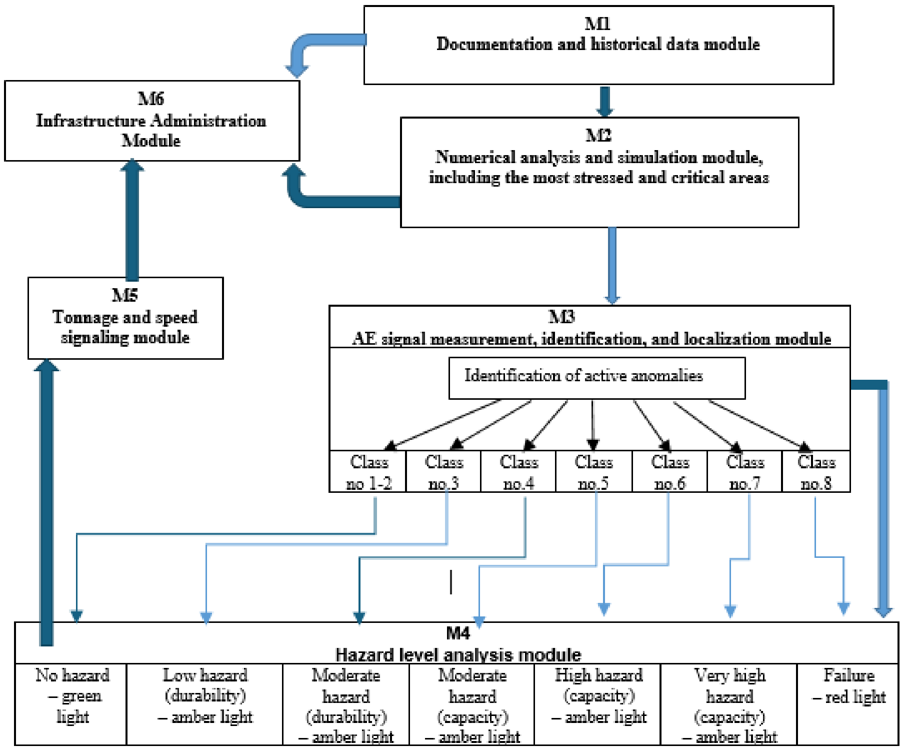

Figure 10. Block diagram of the IAA system operation

DISCUSSION

- Defects from static and dynamic loading were observed in the beams.
- Visible cracks in the support areas are likely due to prestressing inaccuracies; however, no further increase in width was observed. These cracks currently do not impact the structural capacity but pose a corrosion risk; therefore, resin injection is recommended.
- During testing of the beams under traffic and trial loads, the locations of crack initiation and their propagation were identified. Currently, the cracks have a width in the range of 0-0.1mm and do not affect the load-bearing capacity or durability of the structure. However, due to the identified defects in the concrete (voids, insufficient vibration) and large dynamic loads caused by transit traffic on the structure, it is recommended to perform AE tests at least twice a year (April and September) to monitor the increase in the number of cracks and their propagation intensity.
- Crack propagation was noted above support No. 2 under dynamic loads, while the beam over support No. 6 showed propagation during proof load testing.
- The location of anomalies and the identification of destructive processes support the suitability of the AE method for assessing the technical condition of bridge structures.
- The use of reference signal database analysis helps evaluate the mechanisms occurring in the investigated elements, including crack initiation, crack growth,

and the lack of further growth under service loads, as well as potential corrosion processes.

SUMMARY

This article demonstrates the suitability and effectiveness of the AE method in assessing ongoing destructive processes, including damage accumulation, under actual service load conditions and in structural health monitoring. This method enables complete control and potential response to new destructive processes that may occur during operation, as well as the evaluation of the structure's susceptibility to damage and the extent of that damage. By doing so, it supports the maintenance of efficient transport infrastructure, which is crucial to the Smart City concept. The efficiency and reliability of the transport network are vital for economic growth, making the development of this network essential for a prosperous economic and social life.

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Poland

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