Acoustic emission method for facilitating decision making about the safety of structures being elements of smart cities

G Świt1, A Adamczak1,*, A Krampikowska1

1 Kielce University of Technology, Faculty of Civil Engineering and Architecture, Aleja Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland

E-mail: aadamczak@tu.kielce.pl

Abstract. Smart City concept is called the concept of the future and it relates to the so-called intelligent cities. Currently, it is the most promising idea aiming at their development, as well as to the development of local economy. Smart City is a response to the changes that have been occurring in the whole world, relating to both expansion and functioning of the cities that become more intelligent every year. Modern agglomerations should use the newest information and communication technologies in such a manner that they increase the interactivity and the effectiveness of urban infrastructure, but also in order to raise the awareness of the residents. Every city that wants to become smart should include numerous aspects connected with urban life in its development plan. One of the factors ensuring the effectiveness of city functioning is Smart Building, which is an intelligent, environmentally friendly construction, and most of all, it is safe for people. Ensuring the safety of the construction requires performing a series of diagnostic operations in all phases of construction object's life cycle. As the result of the influence of external factors on the structure, including environmental factors, and as the result of useful loads that change during long-time exploitation, the objects are subject to degradation. Early and precise detection of damages that occurred during the use allows to take reasonable measures, including repairs, ensuring uninterrupted exploitation of the object. Therefore, especially in the recent period, a lot of attention has been paid to the topic of diagnostics and monitoring of the structures being exploited, and it is connected with the issue of durability and assurance of reliability of these structures.

The article presents the application of acoustic emission methods for monitoring the condition of the construction. Complete usefulness of the AE method applied in monitoring the destructive processes in structures was confirmed, especially that it allows to assess the occurring destructive processes in the conditions of real exploitative loads. It was shown that the presented method is a successful diagnostic tool enabling effective and safe functioning of intelligent city.

1. Introduction

The dynamics of economic development of countries is highly dependent on the efficiency and reliability of transport network. It can also be stated that transport network development, including the one on highly urbanized areas, is necessary for ensuring proper economic and social life functioning. A significant problem in the development of road networks is the technical condition of bridges that are located within these roads. Average main assessment of bridges and flyovers on Polish national roads, on the basis of the so-called bridge economy system, on a scale 1-5 (1 - emergency
condition, 5 - perfect condition), is 3.64 [1]. The cause of the significant degradation of technical condition of these objects is both increasingly higher effort, caused by the increase of: the weight of the vehicles, car axle load and traffic intensity, and the failure in their current maintenance, resulting from the lack of funds for repairs. The repairs of the bridges and flyovers have most often been based on re-profiling of the holes or they were reinforced in order to allow for increased traffic and vehicle weight. Structural solutions of bridges, as well as their effort in the conditions of permanent growth of traffic volume, cause further uncontrolled increase of destructions on them [2].

Temporary exclusion of flyover or bridge from the exploitation causes the occurrence of significant economic, social and environmental losses, thus many activities are now oriented on the development of technologies and procedures of proper maintenance of road structures, as well as the methods of their monitoring and diagnostics. Monitoring systems should focus on recording two issues, i.e. the changes that occur in the structure of load and the accumulation of damages. Properly conducted monitoring and diagnostics of bridges should help the road management with managing these structures and with prolonging the exploitation time, thus it should make it possible to optimize the time of realization and the range of possible renovation, repair or reinforcement, and in the case of stating that there are damages posing danger to the safety of the structure, it should help with ensuring justified exclusion of the structure from exploitation [3-5].

The article presents the example of monitoring with the use of acoustic emission (AE) method [6], showing the signs of deterioration of technical condition of a road bridge in Sandomierz. Monitoring included three spans of the structure (Figure 1).

![Figure 1. View of the three test spans of the bridge from the side.](image)

2. Materials and methods

2.1. Materials

The test was conducted on the selected supporting elements of the structure. The evaluation of the level of structure damage was carried out on the basis of the analysis of acoustic emission signals parameters registered during the load on the bridge or structure. Damages generating AE signals were detected by zone or surface localization method.

As the result of the examination of the bridge structure, the occurrence of surface corrosion on the majority of steel elements of the bridge was found out. The corrosion is intensified on the top surfaces of the structural elements of the bridge, in particular in the area of the bottom chords, cross-members and longitudinal members and bottom nodes of the trusses. It was also stated that there is corrosion in the contact area of the profiles and metal sheets of multi-branched elements, i.e. bars, cross-bracings and chords, as well as in the place of connection of angle members with metal sheets of webs and chords of cross-members and longitudinal members. Moreover, it was noted that there
is improper drainage of steel orthotropic plates that constitute the bridge floor, and this leads to the occurrence of additional centers of corrosion.

The described destructions are caused by corrosion factors as a consequence of precipitation water retention. The way of constructing the nodes, namely the lack of proper grades, as well as reverse grades that are created when the bridge is sagging, and the lack of openings in the place of connection of bars with bottom chord aid the retention of water, and with the lack of proper anticorrosive layer that should be on all steel components of the bridge, it aids quick growth of corrosion and destruction of the material structure.

![Figure 2.](image)

(a). The connection of the bottom chord of the truss with cross-bracings and the bar, advanced surface corrosion of elements is visible.
(b). The view from the inside of the top node, the surface corrosion of construction elements of the truss, as well as the corrosion on the contact areas of the connected profiles is visible.
(c). The view from the inside of the top node, surface and pitting corrosion of longitudinal members, cross-members and orthotropic plats is visible.
(d). The node with the signs of pitting and surface corrosion of metal sheet and rivets.

2.2. Methods

The fundamental tests of the objects and elements made of steel (beams, roof girders, bridges, flyovers) with the use of acoustic emission method (monitoring) are conducted on the structures under the load during standard exploitation of the structure (in unusual situations under test load) [7-10]. In the case of the bridge in Sandomierz, the monitoring was conducted during standard exploitation of the object.

The purpose of the tests during standard exploitation of the structure is:

- to determine whether there are active destructions in the analyzed object, i.e. destructions that grow (develop) in the conditions of exploitation,
- to identify and localize the destructions,
• to estimate the level of danger that the destructions pose to the structure,
• to determine the level of danger to the safety of the object in the conditions of standard exploitation.

The evaluation consisted in the analysis of the intensity of acoustic emission generated in particular areas of specified components of the structure. The registered AE signals were grouped into classes that included various destructive mechanisms that occurred during the use of the analyzed structures [11-13]. The amount of the registered parameters of AE signals has to be consistent with the parameters used for the construction of the base of standard signals.

Grouping and classifying the AE signals was conducted with the use of the method based on pattern recognition.

The level of danger that is created by the processes generating within one class are specified by the so-called destructive processes intensity code. These processes are presented in the best way by scatter plots where each AE signal has one point. The color and the shape of the point indicate the class to which a given AE signal belongs. The discussed classes, symbols and codes are presented in Table 1.

| COLOR | NUMBER OF CLASS | CODE OF THREAT |
|-------|----------------|----------------|
|       | 0              | 4              |
|       | 1              | 3              |
|       | 2              | 2              |
|       | 3              | 1              |
|       | 4              | 5              |

Table 1. Classes, symbols and codes of AE.

The signals of class 4 are generated by disturbances. On the other hand, classes 0, 1, 2 are generated by single destructive mechanisms:

0 - steel yielding on the top of the crack,
1 - crack initiation,
2 - crack development,
while class 3 gathers signals that are the result of overlapping of the waves generated by more than one destructive process and crack surface friction.

The presence of every class during the monitoring can be assumed as another level of the code determining the influence of the defects on the technical condition of the structure.

Their occurrence signals the presence of dangerous destructive processes in the components of the structure, and they are determined as:

| COLOR | NUMBER OF CLASS | RISK OF THREAT |
|-------|----------------|----------------|
|       | 0              | low            |
|       | 1              | medium         |
|       | 2              | high           |
|       | 3              | very high      |
|       | 4              | no danger      |

Table 2. Danger levels.
In the evaluation of the extent of the destruction, the results of zone localization and the classification of AE signals in zones were used.

3. Results

The results of the measurement of acoustic emission signals with data processing for the selected groups of elements are presented below.

The bottom chord of the truss (span 1): on the basis of the registered AE signals that were analyzed with the use of the base of standard signals, it can be observed that signals of all classes occur in the analyzed chord. Duration of these signals is diversified and it is up to 350 000 µs, moreover, the energy emitted during the development of the signals is low and its value is 20 000 eu (Figure 3). Single signals reach slightly higher values. Acoustic emission signals are not generated in a constant manner, but they are initiated by the passing vehicles of particular features (truck tractors with dump semitrailer moving with the speed higher than 60 km/h or lorries moving in convoy with the speed higher than 60 km/h). It has a particular relationship with the condition of dilatation on the structure and with the development of dynamic loads that cause the initiation of AE signals within the anchoring of cross-bracings and bars in gusset plates. The developed signals suggest that there is growth of stresses in the riveted and welded joints because of significant surface corrosion, and in some places even pitting, slight loosening of rivets and their movement. The number of signals describing the yielding and development of cracks is low and it is focused in three zones of the tested chord, and these signals occur only at the moment of passing of the above mentioned lorries that are over-speeding.

![Figure 3.](image)

**Figure 3.** Graph of energy in time for the bottom chord of the truss in the span number 1.

Nodes 1-3 (span 1): on the basis of the registered AE signals that were analyzed with the use of the base of standard signals, it was stated that signals of all classes occur in the analyzed nodes. Duration of these signals is short and it does not exceed 50 000 µs, moreover, the energy emitted during the development of the signals is low and its value is 2 500 eu (Figure 4). Single signals reach slightly higher values. Acoustic emission signals are not generated in a constant manner, but they are initiated by the passing vehicles of particular features and they are caused by the work of element working binominally, as well as by compressed element. It should be interpreted in such a way that the change of the value of the stresses will cause slight movements within riveted joints and within the joints of gusset plates with the top chord of the truss. The registered signals are indicative of the work of the elements within the elastic range, and the single signals are indicative of local phenomena of yielding and corrosion within these nodes.
Figure 4. Graph of energy in time for the node number 1 in the span number 1.

Longitudinal members 1-6 (span 1): on the basis of the registered AE signals that were analyzed with the use of the base of standard signals, it is stated that signals of all classes occur in the analyzed longitudinal members. Duration of these signals is high and it reaches the value of 360 000 µs, and the energy emitted during the development of these signals reaches the value of up to 40 000 eu (Figure 5). Single signals reach slightly higher values of energy of up to 60 000 eu. Acoustic emission signals of high parameters are not generated in a constant manner, but they are initiated by the passing vehicles of particular features (truck tractors with dump semitrailer moving with the speed higher than 60 km/h or lorries moving in convoy with the speed higher than 60 km/h). Localized and registered signals are mainly based in the central zone of the tested longitudinal members. High rise time of the signals, 25 000 µs, suggests that the signals derive from corrosion processes and friction occurring close to the top chord of the longitudinal member and the orthotropic plate of the bridge. The formed signals suggest that the corrosive processes are advanced, and that the dynamic loads lead to the occurrence of the cracks delaminating within the corroded surfaces and their friction between each other. The number of signals of higher classes no. 1, 2, 3 is not significant and it suggests that these processes do not pose a danger to the tested bridge, but strong corrosive processes and the occurrence of fatigue micro-cracks have started, and with the lack of repair, it can lead to the occurrence of fatigue cracks on the tested components, and thus it can weaken the whole structure.
Figure 5. Graph of energy in time for the longitudinal member number 2 in the span number 1.

Longitudinal members 7-8 (span 2): on the basis of the registered AE signals that were analyzed with the use of the base of standard signals, it was stated that signals of all classes occur in the analyzed longitudinal members. Duration of these signals is low and it reaches the value of 15 000 µs, and the energy emitted during the development of these signals reaches the value of up to 2 500 eu (Figure 6). The rise time of the signals on the level of 4 500 µs indicates that the work of the tested components within the elastic work is correct.

Figure 6. Graph of energy in time for the longitudinal member number 8 in the span number 2.

4. Discussion

After the conducted analysis, it should be noted that:

1. Acoustic emission signals are not generated in a constant manner, but they are initiated by the passing vehicles of particular features (truck tractors with dump semitrailer moving with the speed higher than 60 km/h or lorries moving in convoy with the speed higher than 60 km/h). It has a particular relationship with the condition of dilatation on the structure and with
the development of dynamic loads that cause the initiation of AE signals within the anchoring of cross-bracings in the analyzed node.

2. The developed signals suggest that there is growth of stresses in the riveted joints within the center of the node, and because of significant surface corrosion, and in some places even pitting, slight loosening of rivets and their movement. It makes it possible for slight fatigue micro-cracks within the openings, and they are not dangerous now, but they have to be monitored in order to preclude their possible development into fatigue cracks. The number of signals describing the yielding and development of cracks is low and it is focused in the zone of the central gusset plate, and these signals occur only at the moment of passing of the above mentioned lorries that are over-speeding.

3. Localized and registered signals are mainly in the central zone of the tested longitudinal members. The signals mainly derive from corrosive processes occurring close to the top chord of the longitudinal member and the orthotropic plate of the bridge.

4. The formed signals suggest that the corrosive processes are advanced, and that the dynamic loads lead to the occurrence of the cracks delaminating within the corroded surfaces and their friction between each other. The number of signals of higher classes no. 1, 2, 3 is not significant and it suggests that these processes do not pose a danger to the tested bridge, but strong corrosive processes and the occurrence of fatigue micro-cracks have started, and with the lack of repair, it can lead to the occurrence of fatigue cracks on the tested component, and thus it can weaken the whole structure.

5. Conclusions

On the basis of the information presented in the article, it is stated that AE method allow for the evaluation of the occurring destructive processes, including the accumulation of the damages, in real conditions of operational loads, and it proves its full usefulness for monitoring the objects. This method allows for full control of and possible respond to new destructive processes that occur during exploitation, as well as for the evaluation of the vulnerability of the structure to destructions and the extent of these destructions. It enables the maintenance of well-functioning transport infrastructure, which is the basis of the activity of the Smart City concept, because the dynamics of the economic growth is significantly dependent on the efficiency and reliability of the transport network, and the development of the transport network itself is necessary for ensuring proper functioning of economic and social life.

References

[1] Flaga K, 2010 Diagnostics, modernization and revitalization of bridge structures from concrete
Materials of the 56th Krynica Conference 2010 pp 123-156 (in polish)
[2] Alampalli S, Ettouney M, 2007 Results of workshop on structural health monitoring in bridge
security The 3rd International Conference on Structural Health Monitoring of Intelligent
Infrastructure pp 13-16
[3] Inaudi D, 2009 Structural Health Monitoring of bridges: General Issues and Applications
Structural Health Monitoring of Civil Infrastructure Systems
[4] Zhou H F, Ni Y Q, Ko J M, 2011 Structural Damage Alarming Using Auto-Associative Neural
Network Technique: Exploration of Environment-Tolerant Capacity and Setup of Alarming
Threshold Mechanical Systems and Signal Processing 25(5) pp 1508-26
[5] Olaszek P, Świt G, Casas J R, 2010 Proof load testing supported by acoustic emission. An
example of application Bridge Maintenance, Safety and Life-Cycle Optimization, Taylor &
Francis Group London pp.472-79
[6] Goszczyńska B, Świt G, Trąmpczyński W, 2015 Analysis of the microcracking process
with the Acoustic Emission method with respect to the service life of reinforced concrete
structures with the example of the RC beams BULLETIN OF THE POLISH ACADEMY
OF SCIENCES-TECHNICAL SCIENCES 63(1) pp 55-63
[7] Goszczyńska B, Świt G, Trąmpczyński W, 2013 Monitoring of active destructive processes as a diagnostic tool for the structure technical state evaluation Bulletin of the Polish Academy of Sciences, Technical Sciences 61(1) pp 97-108

[8] Goszczyńska B, Świt G, Trąmpczyński W, 2014 Assessment of the technical state of large size steel structures under cyclic load with the acoustic emission method – IADP Journal of Theoretical and Applied Mechanics 52(2) pp 289-99

[9] Świt G, Krampikowska A, Minh Chinh L A, 2016 A Prototype System for Acoustic Emission-Based Structural Health Monitoring of My Thuan Bridge Proceedings of 2016 Prognostics and System Health Management Conference (PHM-Chengdu) pp 624-30

[10] Świt G, 2004 Evaluation of Compliance Changes in Concrete Beams Reinforced by Glass Fiber Reinforced Plastics Using Acoustic Emission Journal of Materials in Civil Engineering Volume 16(5) pp 414-18

[11] Goszczyńska B, Świt G, Trąmpczyński W, 2016 Application of the IADP acoustic emission method to automatic control of traffic on reinforced concrete bridges to ensure their safe operation ARCHIVES OF CIVIL AND MECHANICAL ENGINEER 16(4) pp 867-875

[12] Minh Chinh L, Adamczak A, Krampikowska A, Świt G, 2016 Dragon bridge - the world largest dragon-shaped (ARCH) steel bridge as element of smart city E3S Web of Conferences 10 pp 1-5

[13] Goszczyńska B, Świt G, Trąmpczyński W, Krampikowska A, 2014 Application of the acoustic emission method of identification and location of destructive processes to the monitoring of concrete bridges Proceedings of 7-th International Conference of Bridge Maintenance, Safety and Management (IABMAS 2014, Shanghai, China) pp 245-46