

Acoustic emission for diagnosing cable way steel support towers

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Abstract. The paper reports results of the study on the possibility of using the acoustic emission method in diagnosing fatigue and corrosion damage in steel elements of the cable way support towers. The assessment of the sensitivity of the structure to the recorded destructive processes is based on the structural damage classification method using the patterns created as a result of statistical and mathematical processing of acoustic emission signals through image analysis and grouping methods.

1 Introduction [1-4]

The factors influencing the service life of steel structures include fatigue of the material, fatigue cracking and corrosion damage. Determining the durability of the structure through the modelling of these processes requires:

- defining the actual service loads [9],
- determining the external factors such as: humidity, aggressive media, temperature changes, etc.
- defining a material model that takes into account the external factors,
- locating the initiation point (damage) of the crack,
- determining the load around the defect after its formation and during its evolution (stress redistribution),
- defining the interaction between various types of damage.

In the case of large installations (cable way support towers, cranes, bridges, wheel excavators, guide frames or belt conveyors), the determination of all those items is very difficult or hardly possible.

The diagnosing and monitoring of technical condition of building structures is a very topical and socially important problem. The aging infrastructure and increasing service loads in engineering structures are the main stimuli for rapidly progressing research within the new interdisciplinary field called Structural Health Monitoring (SHM), closely related to the durability and safety of structural members.

The load is a typical random load, which is difficult to model in currently known fatigue calculation procedures, which are used for stationary, low-amplitude loads alone. The impact of the phenomena such as training and crack closure or corrosion processes at the crack tip on durability is evident at loads encountered in most structures due to an accidental sequence of considerably varied amplitudes. The presence of these effects is usually discovered in the

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post-failure analysis of damaged surfaces. Consequently, the calculation of fatigue life of steel structures using currently recommended procedures can provide only approximate information about the possibility of fatigue failure, and provided that information on the fatigue strength of the material is valid.

Where computational methods provide only a limited scope of information regarding fatigue life, the emphasis is on experimental research of the existing structures. Fatigue damage tests are carried out during inspections. Detected cracks are classified by the causes of their occurrence, and in the case of fatigue cracks, the speed of their evolution is assessed. These activities are, however, subjective, and in the case of large and complex structures ineffective, as the detection of, for example, a small fatigue crack under the layer of paint and in a hard-to-reach place is unlikely.

No objective and effective methods with field diagnostic capabilities exist for the detection and classification of fatigue damage in the material of structures.

The best solution for the in-situ evaluation problem is to develop an appropriate NDT-based monitoring system that will be able to signal the threat to the safety of the structure. Normally the portions examined by NDT methods constitute a small percentage of the structure. A number of risk zones are not surveyed mainly for economic and time-related reasons or due to their inaccessibility. Even if the damage is detected and described, the safety risk it poses may remain unknown. This is due to the random nature of the load, the lack of effective computational models for elements with defects, and the occurrence of stress redistribution.

Analysis of damage that poses a threat to the safety of the structure cannot be limited to the size of the defect but has to extend further to include "hot spots" or "process zones" in which destructive processes occur. Ultimately, the threat and risk are determined by:

- the location of dangerous sites,
- the size of the process zone,
- the impact of defects on the process zone,
- the intensity of destructive processes,
- the mechanisms of destructive processes, and
- the material characteristics.

In large-scale structures, finding and determining the "destruction characterization" of all hot spots using the active NDT methods is practically infeasible. In steel structures, the hot spot volume will be on the order of cubic centimetres, whereas the whole structure's dimensions can reach dozens of meters. In addition, the identification of destructive processes requires knowledge of instantaneous operating conditions. It is not rare that failure is defined by a combination of many adverse factors leading to an unexpected disaster. The literature shows numerous failures of structures, either held stationary or under limited loading, which when tested earlier, withstood the loads exceeding the design loads.

In our opinion, the solution to the problem of diagnosing engineering structures is the use of continuous, long-term monitoring and passive NDT testing methods. One of them is the acoustic emission (AE) method.

The paper proposes the use of acoustic emission for diagnosing steel structures.

2 Acoustic emission in steel structures testing

2.1 Acoustic emission [2-5]

Every process in a material that leads to a decrease in internal energy generates AE signals.

In the case of steel structures, the sources of acoustic waves are various types of damage, such as:

- corrosion processes of steel,
- crack initiation,
- fatigue crack evolution,
- steel yielding,
- friction between crack surfaces,
- friction at the interface of component surfaces,
- extraneous noise.

The AE method allows a full-scale analysis of the structure, which means that damage is detected and located within the structure or its element, regardless of whether the faults are visible and regardless of their location in relation to the sensors installed. Simultaneously with revealing the damage, the intensity of emerging emission signals shows the level of risk the defect poses to the safety of the structure [10, 11].

The choice of acoustic emission as the research method was mainly determined by its advantages in relation to other non-destructive methods. These are:

- locating the faults that are not detectable with conventional methods,
- recording only active damage, i.e., the defect growth as it occurs,
- continuous monitoring of structures while in service or during load tests, with continuous data recording,
- AE detects all types of damage, whereas most other methods focus on particular defects,
- AE characterizes well the intensity of damage development during the in-service operation of the structure,
- AE enables the characterization of the AE signal sources.

AE test systems are designed to detect, record, filter and analyse the signals generated by AE sources. Most often, the basic AE measurement system consists of sensors, preamplifiers, the recording processor and analysis software.

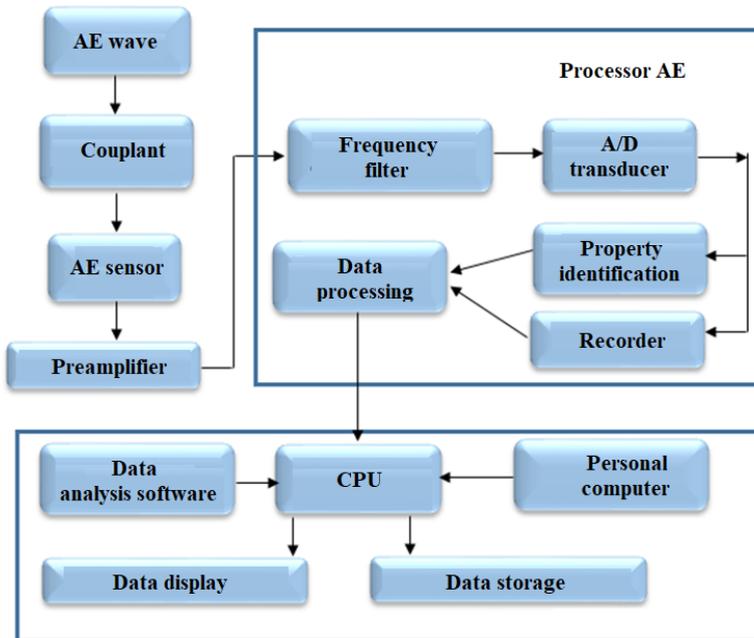


Fig. 1. Schematic diagram of an AE measurement system [12].

As shown in Fig.1, the damage-generated waves are recorded with AE sensors – transducers converting the elastic wave into an electrical signal.

2.2 Acoustic emission [5-8]

An important element in AE measurements is the location of acoustic emission sources originating from destructive processes and other processes that accompany them.

In damage location, it is essential to apply the optimised spacing of sensors. Depending on the material, the propagation of AE waves decreases due to the structure of the material or damage and this process is known as attenuation. Attenuation can be calculated with an exponential relation described by the following equation (1):

$$A_f = A_0 \times e^{-ad} \quad (1)$$

where: A_f is the amplitude at the sensor position, A_0 is the initial amplitude at the AE source, a is the damping factor, and d is the distance travelled by the wave [12].

Attenuation is important in that the source is located by defining the difference in arrival times between the sensors when the velocity of the wave in the material is known. The location of the AE source can be determined along a straight line (linear location), on a surface (planar location) or in space (spatial). This method has been successfully used in steel structures. A system consisting of different techniques of location should be incorporated in the structural design procedures. For example, linear and planar location techniques should be applied in the beam-type elements examination, and planar location in the joints, with guard sensors for eliminating extraneous noise.

Figure 2 illustrates two-dimensional location used in damage quantification for steel column joints.

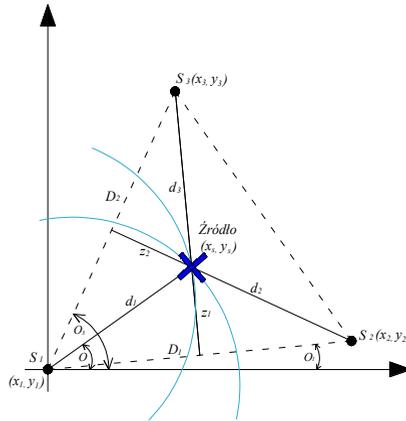


Fig. 2. Two-dimensional location scheme.

Three sensors, S_1 , S_2 and S_3 , are placed on the surface of the structure at sites having coordinates (x_1, y_1) , (x_2, y_2) and (x_3, y_3) . The source location is defined by the (x_s, y_s) coordinates. The spaces between the sensors are indicated as D_1 , D_2 and D_3 and are known. The distances between the source and sensors d_1 , d_2 and d_3 are to be determined. T_1 , T_2 and T_3 are the signal arrival times at sensors S_1 , S_2 and S_3 .

Using the relationships in [13], distance d_1 can be determined from (2) and (3):

$$d_1 = \frac{D_1^2 - \Delta t_1^2 \times c^2}{2(\Delta t_1 \times c + D_1 \cos(\theta - \theta_1))} \tag{2}$$

$$d_1 = \frac{D_2^2 - \Delta t_2^2 \times c^2}{2(\Delta t_2 \times c + D_2 \cos(\theta_3 - \theta))} \tag{3}$$

where: θ , θ_1 and θ_3 are the values of angles defined in accordance with Fig. 2 and formulas (4) and (5):

$$d_2 - d_1 = c(t_2 - t_1) = \Delta t_1 \times c \tag{4}$$

$$d_3 - d_1 = c(t_3 - t_1) = \Delta t_2 \times c \tag{5}$$

where: ΔT_1 and ΔT_2 are the arrival time differences $(t_2 - t_1)$ and $(t_3 - t_1)$, and c is the wave velocity.

Source location is given by relationships (6) and (7):

$$x_s = x_1 + d_1 \cos \theta \tag{6}$$

$$y_s = y_1 + d_1 \sin \theta \tag{7}$$

By using the appropriate iteration system that takes into account different values of angle θ , we minimize the error between the two calculated locations of the AE signal source and find the location of the defect.

2.3 AE signals database [5-8]

Each destructive process is an acoustic emission source characterized by the parameters of the recorded signal. These quantities make it possible to classify signals and thus destructive processes by attributing specific destructive processes to the defects (using similarity of signals approach), thus creating a database of reference signals.

The image recognition-based grouping and the classification of the AE signals make use of:

1. database of the signals registered during the quasi-static tests of specimens subjected to tension, bending and bending with notch. The tests were performed on three grades of steel: St3S, 18G2A and bridge steel, using the MTS 322 testing machine, a set of extensometers and a cryogenic chamber. Tensile tests were carried out on round and flat specimens, while bending on flat and notched specimens. The experiment was also carried out at temperatures $T(20) = +20^{\circ}\text{C}$, $T(0) = \pm 0^{\circ}\text{C}$, $T(-20) = -20^{\circ}\text{C}$, and $T(-60) = -60^{\circ}\text{C}$,
2. database of the signals registered during cyclic loading of steel beams with riveted and notch welded joints, made of steel St3S, 18G2A and bridge steel,
3. database of the signals recorded during cyclic and quasi-static loading of welded and bolted joints.

In statistical methods available for structural identification, the optimised selection of AE parameters is critical, i.e., only the parameters that have low mutual correlation should be chosen. The collection of diagnostic variables should be capable of a full-scale characterisation of the most important aspects of the phenomenon under analysis [5].

Fuzzy k-means algorithm was used to create the reference database in the RPD method for steel. The k-means algorithm represents a non-hierarchical clustering approach. Its essence lies in the random choice of initial centroids. After calculating the membership function of particular points from the centroids, they are recomputed in the following iteration steps. Doing so means that the centroids look for their correct positions using relation (8) [5]:

$$\underline{\mu}_j = \frac{\sum_{i=1}^n P(\omega_i | \underline{x}_j)^b \underline{x}_j}{\sum_{i=1}^n P(\omega_i | \underline{x}_j)^b} \quad (8)$$

where: $P(\omega_i | \underline{x}_j)$ is the conditional probability of the membership of the j -th element in the i -th group,

b is the parameter that has to take values other than 1, \underline{x}_j is the j -th element.

The probability function is normalized according to formula (9):

$$\sum P(\omega_i | \underline{x}_j) = 1, \text{ gdzie } j = 1, \dots, n \quad (9)$$

where

The probability of the membership of the element in each of the clusters $P(\omega_i | \underline{x}_j)$ is calculated from (10):

$$P(\omega_i | \underline{x}_j) = \frac{\left(\frac{1}{d_{ij}}\right)^{\frac{1}{b-1}}}{\sum_{r=1}^c \left(\frac{1}{d_{rj}}\right)^{\frac{1}{b-1}}} \quad (10)$$

where: $d_{ij}^2 = \|\underline{x}_j - \underline{\mu}_i\|^2$ is the distance of a data point \underline{x}_j from the cluster centre $\underline{\mu}_i$.

The *k-means* algorithm consists of the following steps:

1. Randomly select initial centroids.
2. Compute the distances between the data points and the cluster centroids.
3. Compute the membership function value of all elements $P(\omega_i | \underline{x}_j)$.
4. Compute cluster centroids $\underline{\mu}_i$.
5. If:
 - there are no changes in $\underline{\mu}_i$ and $P(\omega_i | \underline{x}_j)$ - return $\underline{\mu}_1, \dots, \underline{\mu}_c$
 - otherwise go back to step 2.

When this algorithm is used, the number of clusters is pre-determined. However, the speed of computation and compensate for this inconvenience.

The supervised method (SPR) together with the database permits determination of the number of destructive processes, and their identification. The accuracy of the analysis depends primarily on the quality of the database.

The obtained reference file was used in subsequent stages of the test cycle to assess the condition of full-sized steel elements with different structures and loading modes, tested both in laboratory and "in-situ" conditions. The sample results will be presented in the further part of the work.

The created reference signals database makes it possible to identify individual signal classes in structures other than those being tested. The database can be supplemented on a continuous basis.

Table 1 shows the destructive processes with a colour and shape of the data point assigned to each AE signal to indicate the AE signal class.

Signal classes:

- | | |
|--------------------------|---------------------------------|
| No 1 – rupture, | No 5 – perforation/deformation, |
| No 2 – friction, | No 6 – pitting, |
| No 3 – crack growth, | No 7 – corrosion, |
| No 4 – crack initiation, | No 8 – elastic behaviour. |

Table 1. AE signal classes, symbols, risk codes and levels.

Colour								
Class	No 1	No 2	No 3	No 4	No 5	No 6	No 7	No 8
Risk code	0	1	1	2	2	3	4	5
Risk level	very high	high	high	higher medium	higher medium	medium	low	no risk

3 In-situ testing

The tests were carried out on 5 support towers of the cargo cableway for delivering excavated material from the mine to processing plants. The spatial lattice towers were made of S235 steel angles and channels connected with welds and bolts. Figure 1 below shows one of the towers being tested.



Fig. 3. View of the tower under test.

The condition of the towers was inspected using a 24-channel microSamos sound emission system, a set of preamplifiers and 55 kHz piezoelectric sensors. Due to the measurement conditions (strong ambient interference), the measuring threshold was set at 45 dB and guard sensors were mounted to eliminate the noise associated with the movement of the carriers. For accurate measurement results, the background noise was measured and the equipment was calibrated using the Hsu-Nilsen source prior to performing each measurement.

The condition of two towers will be the basis for the test results discussion further in the paper.

3.1 Condition assessment by AE – Tower 1

The steel lattice tower with a height of 14.40 m (Fig. 4), made of 2.0 m high spatial segments with angular bracing of different dimensions was subjected to the tests. The members in the gusset plates were attached using welded or bolted connections. The visual inspection found lack of protective coatings on the surface, traces of surface corrosion and deformation of tower members. After performing the initial visual assessment and numerical calculations, the condition of the tower was evaluated using the acoustic emission technique.



Fig. 4. Side view of the tower under test.

Twelve piezoelectric sensors with a frequency of 55 kHz were placed on selected members of the tower. On the basis of spatial location, focal areas of surface corrosion were found. Corrosion no longer affects the load capacity of a tower and as a whole; the support structure works in the elastic range. The sites with the highest acoustic activity were located at the bolt connections and halfway up the vertical members of the tower.

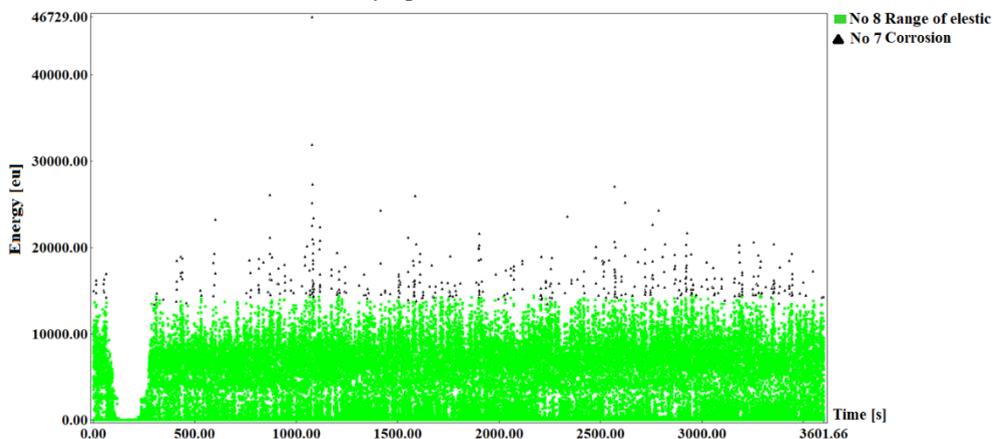


Fig. 5. Scatter plot of signal energy vs. time for sensors 1-12.

The analysis of the AE signals recorded in the tower, conducted based on the reference signal database indicated the occurrence of Class 7 and Class 8 signals (Fig. 5).

The duration (Fig. 6a) and the rise times (Fig. 6b) of these signals are long and reach 350,000 μ s and 65,000 μ s, respectively, while the energy of signals is low and does not exceed 30,000 eu. Please note that the acoustic emission signals are generated in a continuous manner and are not initiated by passing carriers weighing approximately 2,500 kg, which indicates the existence of active surface corrosion centres. The resulting signals suggest that the stress caused by the service load is in a safe range. Welded and bolted connections in the nodes can potentially be sites of bolt (plate) loosening due to significant surface corrosion and pitting. This will allow small fatigue microcracks to appear in the holes, posing no risk initially. However, as they may ultimately develop into fatigue cracks, monitoring is recommended. The acknowledgements should be typed in 9-point Times, without title.

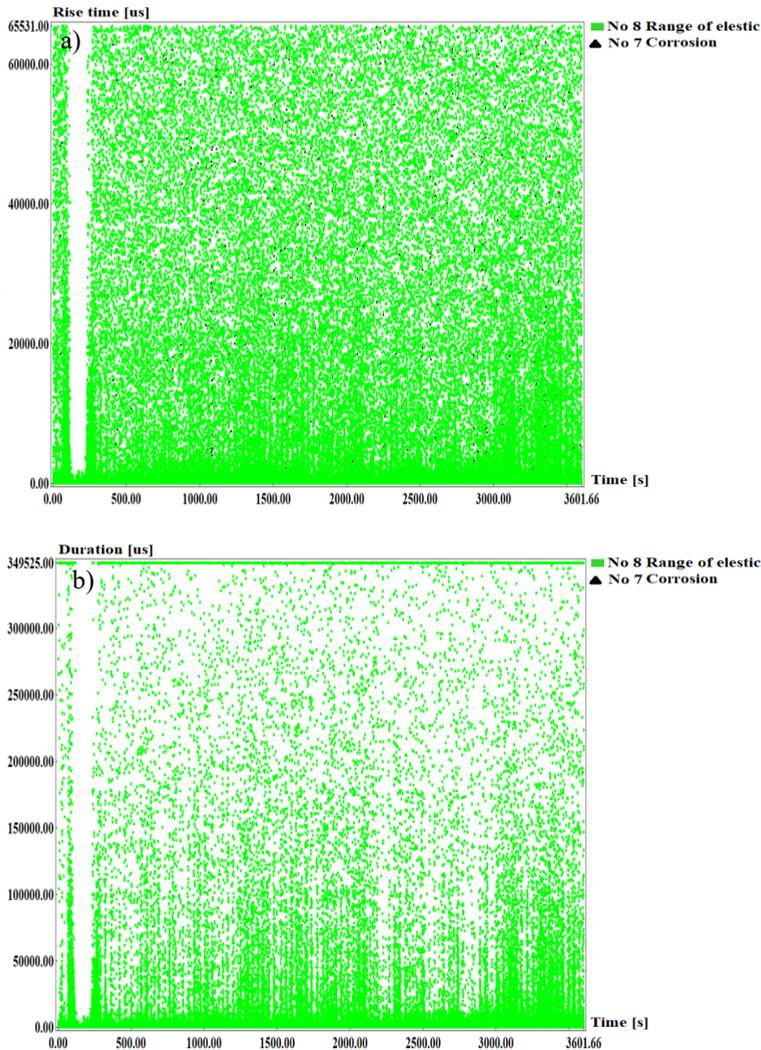


Fig. 6. Scatter plot of a) AE signal **rise time**, b) AE signal **duration** as a function of time.

3.2 Condition assessment by AE – Tower 2

Another lattice structure tower tested was 8.20 m high (Fig.7), made of spatial segments with heights varying from 1.0 to 2.0 m and an angular bracing system with members of different dimensions, connected to a flat lattice frame using a steel platform to protect the traffic from falling stones. As in the previous tower, the members in the gusset plates were connected by welding or bolting. Minor losses of protective coatings and traces of surface corrosion were found on the surface. After performing the initial visual assessment and numerical calculations of the tower, its condition was assessed with the acoustic emission technique.

On the basis of the spatial location performed with 12 sensors, the sites on the support structure where surface and pitting corrosion were active were indicated, as were the fatigue cracks within the gusset plates and connections of various structural members. Examples of fatigue cracks locations are shown in Figure 8.



Fig. 7. View of the tower with a security platform.



Fig. 8. Fatigue cracks in the tower nodes.

In the localized sites on the surface of the tower members, cracks from 5 to 18 mm were found, which indicates the possibility of further propagation and uncontrolled deterioration of the structure.

The tests were carried out at standstill as well as during normal operation. During the 5,550 s standstill no processes generating safety risk were found - only signals informing that the tested members worked in the elastic range, as marked with No. 8 and green colour in Fig. 9.

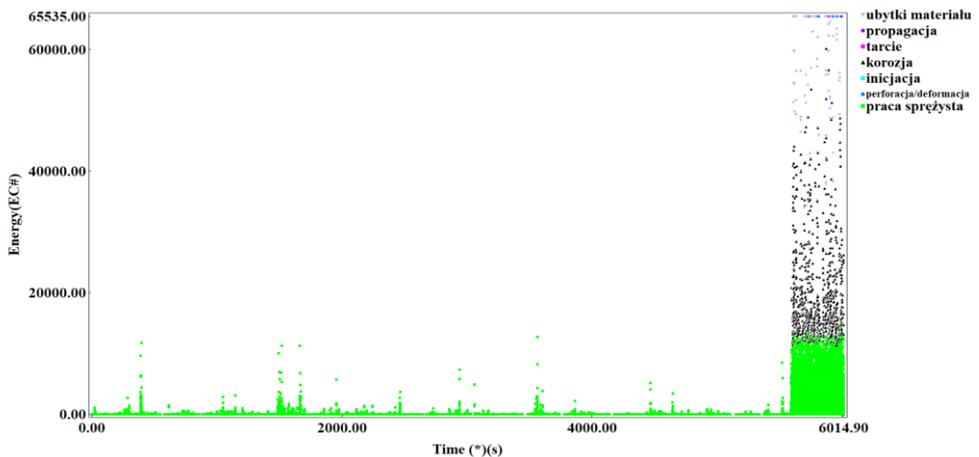


Fig. 9. Scatter plot of AE signal energy vs. time.

The rise time (Fig. 10a) is short and does not exceed 20,000 μs , while the duration (duration) (Fig.10b) sporadically reaches the value of 150,000 μs . The energy of these signals (Fig.9) is low and reaches up to 15,000 eu. Recorded phenomena under operating load are generated by displacements caused by trolleys with spoil.

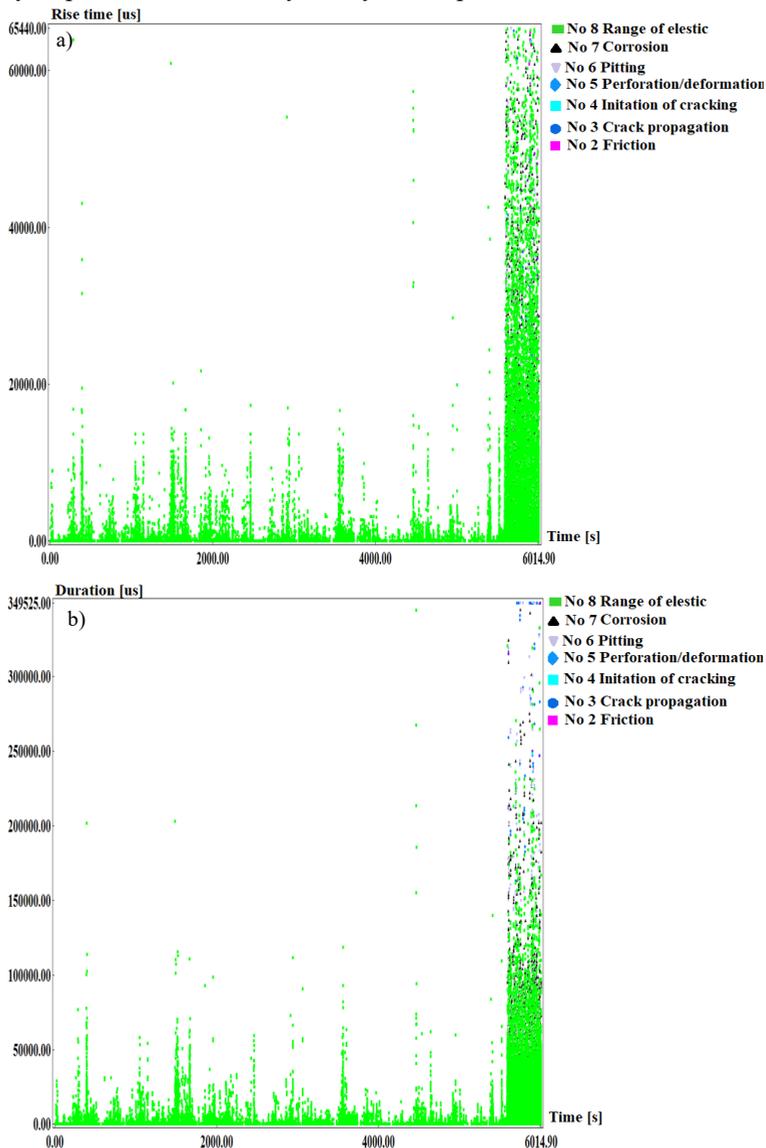


Fig. 10. Scatter plot of a) AE signal **rise time**, b) AE signal **duration** as a function of time.

Between 5,550 s and 6,020 s (operation under service load) (Fig.5), destructive processes described by additional 6 classes (yielding, crack initiation, crack growth, corrosion, deformation and friction) were revealed, which indicates the development of microcracks in the structural elements and within the connections. This shows that some elements are exposed to destructive processes caused by material fatigue. Sites of surface corrosion were also located. The most affected sites are located in the bolted connections and at mid-height of the vertical members of the tower.

4 Conclusion

Analysis of the AE test results for the cableway steel lattice tower, conducted with the aid of the reference signal database, indicates that:

1. It is possible to define the destruction mechanisms in the members of steel structures.
2. It is possible to monitor individual destructive processes in structures during their operation.
3. It is possible to locate destructive processes in spatial structures.
4. The AE method based on the analysis of destructive processes is able to quickly indicate the site that need further testing with NDT methods.
5. The monitoring system based on the AE method can be very useful in supervision of existing strategically important structures with defects.



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