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ASSESSMENT OF THE TECHNICAL STATE OF LARGE SIZE STEEL STRUCTURES UNDER CYCLIC LOAD WITH THE ACOUSTIC EMISSION METHOD – IADP

Barbara Goszczyńska, Grzegorz Świt, Wiesław Trąmpczyński
Kielce University of Technology, Kielce, Poland; e-mail:bgoszczynska@tu.kielce.pl

In this paper, a global monitoring system based on the measurement of acoustic emission (AE) due to active deterioration processes within steel structures is presented. This allows one to locate and identify deterioration processes (initiation and development of cracks) under cyclic load for large size structures as bridges, gantries, etc. The resulting data can be used to locate damage zones that are dangerous for construction, to assess the general condition of the structure and to serve for structural health monitoring.

Keywords: acoustic emission, cyclic load, crack initiation, large size steel structures

1. Introduction

The material fatigue, fatigue cracking and damage caused by corrosion are the main reasons for failures of steel structures. Yet, the knowledge of the fatigue life of large steel structures is rather limited. Additionally, computational methods or criteria for assessing the life of such objects operating under variable loads are not available.

Analyses of fatigue life within the range of high-cycle fatigue (at the stage of crack initiation) are based on the Wöhler diagram, which is constructed using the results of fatigue tests carried out for sinusoidal load cycles at a constant amplitude. The diagrams are also used when making calculations for elements of structures under load cycles at random amplitudes in accordance with the Palmgren-Miner rule (Palmgren, 1924). The fatigue crack propagation is usually described by the Paris law (Paris and Erdogan, 1960). For the sake of the assessment of the service life of engineering structures, a number of simplifications is introduced into the procedures mentioned above. Although those make calculations easier, on a number of occasions even make them possible, the results obtained for the fatigue life or the crack propagation velocity may differ several times from the real values.

Recently developed methods for calculating the strength of structure members containing defects, such as R6 curve method, FITNET or methods based on failure advanced models (e.g. that of Gurson-Twergaard-Needelman) still have very limited practical applications (Neimitz *et al.*, 2008).

Hence, when the calculation methods provide only limited information on the fatigue life, the solution can be experimental investigations to assess the technical state of structures in service. Recently, non-destructive testing (NDT) methods, which allows one to detect and locate various damages and defects has been developing dynamically (Hoła and Schabowicz, 2010).

Practical applications of majority of non-destructive testing methods are limited only to a relatively small measurement area which results from features of a given method. That does not constitute a major limitation if the structure, or its elements, is relatively small-sized. By repeating the measurements, it is possible to cover the whole object with the measurement area rather quickly. For large size structures, e.g. bridges, gantries, wheel excavators in surface mining, that becomes a serious drawback.

Such limitations do not have the acoustic emission method AE (Ono, 2011; Ranachowski *et al.*; 2009, Yu *et al.*, 2011; Ziehl, 2008), which makes it possible to detect and locate destructive processes, and also to determine how intensive they are. The AE method shows the occurrence of destructive processes and their location, yet it does not describe the mechanisms generating such processes, which is a very important aspect of the structure diagnostics.

Therefore, in works by Gołaski *et al.* (2012), Goszczyńska (2014), Goszczyńska *et al.* (2012, 2013), the acoustic emission method called Identification of Active Damage Processes (IADP) was proposed. It does not only record the occurrence and location of destructive processes, but also makes it possible to identify them. The method has been applied to the analysis of destructive processes in pre-stressed concrete members and it has been successfully used to diagnose over seventy real engineering structures, mainly bridges.

The present paper presents the application of the IADP method to the analysis of steel structures under cyclic load.

2. Acoustic emission method – The IADP method – basics

The acoustic emission (AE) involves generation of transient elastic waves due to local dynamic change in the structure of the material. A signal of the acoustic emission is generated as a result of sudden release of energy accumulated in the material by propagating micro-damages. The attenuation of waves results from absorption, a transformation from elastic energy into thermal one. Thus, the generation of AE signals provides information on degradation of properties of the material when compared with its properties at an instant preceding the emission. The fact the processes generating AE signals accompany only the active damage, i.e. that brought about or developed under conditions prevailing during the measurement.

Figure 1 presents a diagram of wave generation by destructive processes caused by beam loading. The waves are recorded by sensors, usually piezoelectric ones, with the frequency operating range of 0.1-2.0 MHz, mounted on the structure surface.

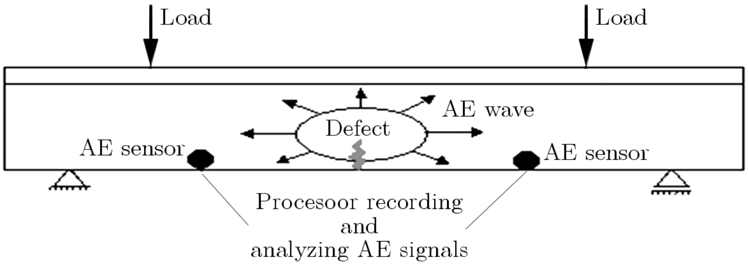

Fig. 1. A diagram of wave generation by destructive processes due to loading

The acoustic emission signal can be characterised by such parameters as: the number of counts, number of counts to peak, duration, rise time, amplitude, energy, strength, mean effective voltage, root mean square, mean frequency, reverberation frequency and initiation frequency. These parameters (twelve AE parameters called here the reference parameters) are then used (in the IADP method) to create the reference database for destructive processes using statistical analysis, based on pattern recognition.

A reliable assessment of the structure technical state depends not only on detecting the occurrence of destructive processes but also on finding the zones where those are generated. The location is accomplished on the basis of difference in time of the arrival of an AE signal generated at the area of failure to sensors spaced on the surface of the tested member at the known velocity of wave propagation. In this manner, it is possible to locate AE sources along a plane (linear location) or within a specific area (zonal location) or in space (Nair and Cai, 2010;

Goszczyńska, 2014; Goszczyńska *et al.*, 2012; Aggelis *et al.*, 2011). Using an appropriate number of AE sensors adjusted to the tested structure, it is possible to cover the whole structure or a fragment of it with the measurement areas.

The IADP method is one of acoustic emission testing techniques. It makes it possible not only to locate but also to identify active destructive processes, which is significant for the structure diagnostics (Gołaski *et al.*, 2012; Goszczyńska *et al.*, 2012; Świt, 2011). Identification of destructive processes involves a comparative analysis of acoustic emission signals measured in the tests of a structure in service against the reference signal database established beforehand for individual destructive processes. For this method, it is necessary to:

- determine and identify, in laboratory and technical tests, individual destructive processes characteristic for a given construction,
- establish a reference database for formerly determined destructive processes.

The application of the IADP method involves:

- performing measurements, in which acoustic emission signals for individual members of the structure are recorded, while the structure remains in service,
- carrying out a comparative analysis of the recorded AE signals against the reference signal database, and thus identifying the occurrence of destructive processes,
- locating places where the destructive processes occurs.

The reference signal database for those processes was compiled by means of conducting a number of tests on various types of specimens for different loading schemes. The tests were designed to obtain a single dominant destructive process among those that can occur in structures under investigation, in this case steel ones.

Experiments were conducted for three types of steel: St3s, 18G2A and steel cut out of an old bridge structure, for different kinds of specimens and types of load:

- simple loads – quasi-static tests on specimens under simple loading (tension, bending of notched specimens) conducted at the following temperatures: $T_{20} = +20°\text{C}$, $T_0 = 0°\text{C}$, $T_{-30} = -30°\text{C}$, $T_{-60} = -60°\text{C}$.
- simple load cycles – specimens with a hole and notches perpendicular to the axis of the specimen under load cycles at temperature $T_{20} = +20°\text{C}$,
- load cycles applied to riveted and welded steel beams with a notch at temperature $T_{20} = +20°\text{C}$
- quasi-static and cyclic loads applied to models of welded and bolted nodes at temperature $T_{20} = +20°\text{C}$.

In this way, four destructive processes were differentiated and the reference signal database was established. The corresponding AE signals were defined as Classes:

Class 0 – signals generated by crack initiation,

Class 1 – signals generated by steel yielding at the tip of the crack,

Class 2 – signals generated by "noise",

Class 3 – signals generated by crack growth,

Class 4 – signals resulting from the interference of waves generated by more than one destructive process.

Statistical analysis based on pattern recognition was applied to record acoustic emission signals using NOESIS software. The pattern recognition can be categorised into: arbitrary classification using *unsupervised* (USPR) learning procedure and classification that employs the training set in form of reference signals in the *supervised* (SPR) learning procedure. In order to compile a database (signal classes), arbitrary pattern analysis was used, whereas for signal class recognition, supervised analysis was applied (Goszczyńska *et al.*, 2013; Świt, 2011).

As regards statistical methods applied to item recognition, it is important to optimally select recorded parameters of acoustic emission. Because many parameters of acoustic emission show strong mutual correlation, which makes it possible for them to carry the same information on an AE source, the degree of correlation between those parameters is defined by the so called dendrograms. Using them, one can reduce the number of parameters of AE signals in the classification process, which shortens the duration of the analysis. Twelve parameters of AE signals with a different level of adjustment were adopted for the analysis (mentioned above as reference parameters, Goszczyńska *et al.* (2013)).

3. Application of the IADP method to the evaluation of the technical state of steel structures

Using the established reference signal database for steel, the destructive processes were analysed for different types of members and structures and also modes of loading.

3.1. The IADP method applied to the analysis of failure of the standard specimen under cyclic loading

Exemplary results of tests on steel specimens (with a hole) made of steel taken from an old bridge under load cycles at 10 Hz frequency, are presented below. It is a standard specimen used to determine the coefficients of the Paris equation (Paris and Erdogan, 1960).

AE sensors, spaced on the specimen as shown in Fig. 2, recorded both the AE signals generated by the fatigue process and by the background which consisted mainly of the acoustic signals from specimen friction in the hydraulic holders and the oil movement in the machine cables.

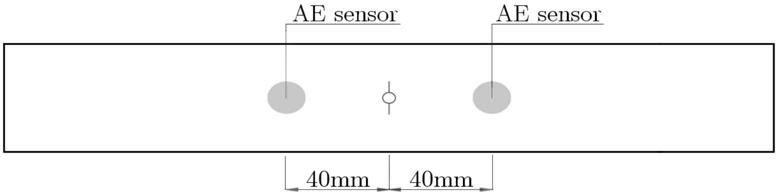

Fig. 2. Diagram of a specimen with a hole and a notch

The recorded files were subjected to multi-parameter analysis taking into account twelve (mentioned above) parameters, and the results of the analysis are shown in Fig. 3 in form of a summation graph of one of the parameters (RMS – root mean square) against time, for different signal Classes defined above.

In the first phase of the cyclic loading, a local zone of plastic deformation is created in the vicinity of partially cut notches, which precedes the crack initiation and the notch tip becomes rounded. The process is accompanied by Class 1 signals and was observed optically by using magnifying glass.

During the first 30000-70000 cycles, fatigue cracking is initiated. It is clearly formed only after approx. 25000 cycles (2500 s what was observed optically). The process, i.e. cracking initiation, corresponds roughly to the first stage of fatigue cracking and is accompanied by Class 0 signals.

The second stage, which is accompanied by Class 3 signals, involves the crack propagation in a located plastically deformed zone. The growth of the fatigue crack leads to the final stage - the specimen failure (such a process was observed optically).

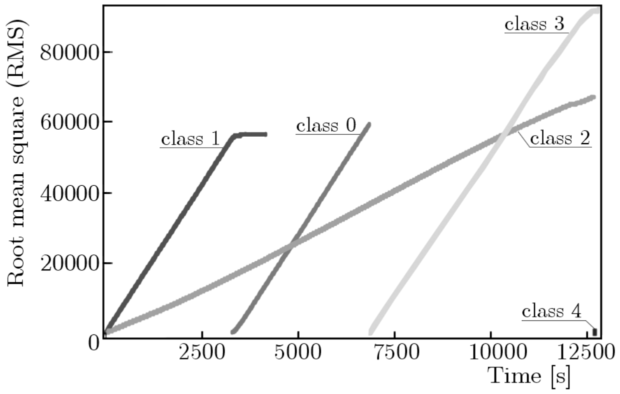

Fig. 3. Examplary graphs of changes in the RMS (root mean square) with division into classes of acoustic signals during fatigue crack propagation (steel collected from the bridge)

The end of the diagram shows Class 4 signals, which accompany the final stage of the specimen failure. It results from the interference of waves generated by more than one destructive process and the friction on the crack surface.

Class 2 signals, features signals generated by the system that loads and monitors the specimen (noise of the testing machine and specimen grips).

It can be seen that the IADP method makes it possible to trace the process of the crack propagation up to specimen failure.

3.2. The IADP method applied to the analysis of a beam under cyclic loading – model tests (18G2A, St3s, bridge steel)

Acoustic emission testing was conducted on beams having T-shape cross-section ($8 \times 120 \times 2000$ mm) with narrow cut-out in the centre (1.5×40 mm) of the beam span. Experiments were carried out on two types of beams:

- beam with a welded flange (Fig. 4),
- beam with a riveted flange (Świt *et al.*, 2011)

to which quasi-static monotonic loading and cyclically variable (sinusoidal) loading were applied at two points as shown in Figs. 5 and 6.

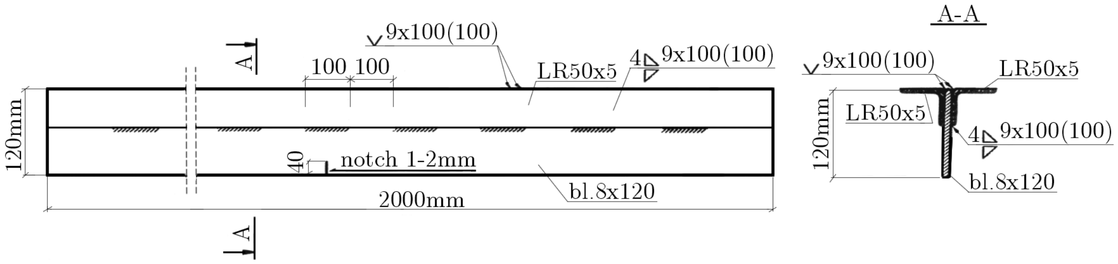

Fig. 4. Scheme drawing of welded beams 120 mm in height

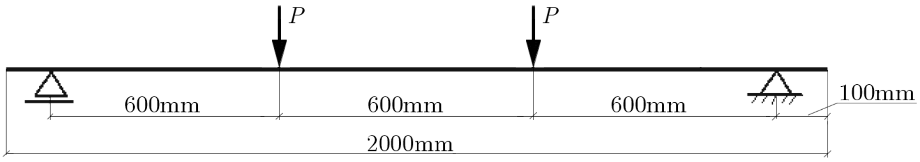

Fig. 5. Diagram showing points at which the loading force is applied and those at which the tested beam is supported

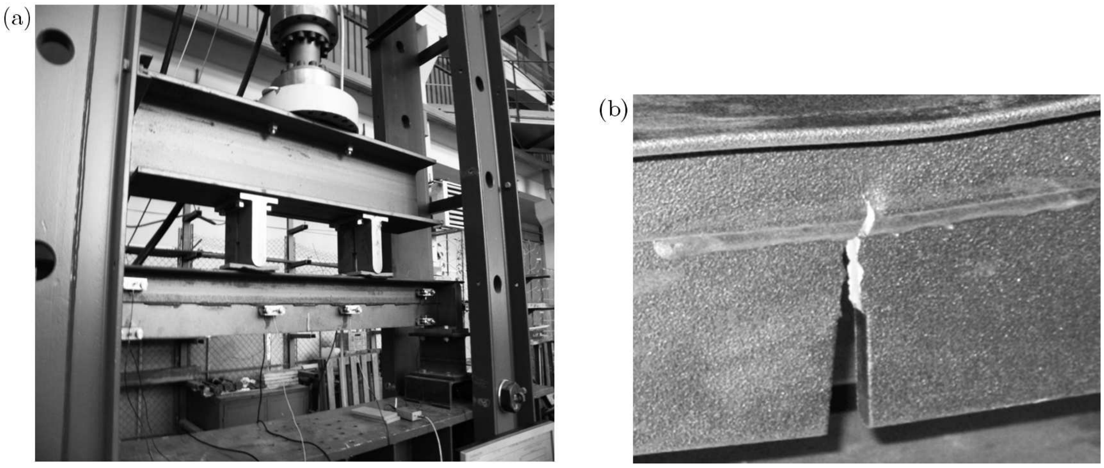

Fig. 6. The test stand with a welded beam (18G2A steel) with a narrow cut-out in the centre and acoustic sensors mounted on it (a) and cracked the beam section (b)

Figure 6 shows the welded beam positioned on the test stand, the spacing of AE sensors (sixth sensors in total, on both sides of the cut-out) and the cracked due to cyclic loading beam section.

In the cyclic loading tests, the beam loading was set to be applied through the force P, the value of which varied sinusoidally. The value of the minimum-maximum load, both for welded and riveted connections, was set to amount up to approx. 0.1-0.46 of the maximum value obtained from the quasi-static tests. The values for welded beams, the exemplary results for which are presented in Fig. 7, were as follows: 2.6-26 kN, 18G2A steel – failure after 7500 cycles (Fig. 7a), and 2.2-22 kN, St3s steel – failure after 17377 cycles (Fig. 7b) at the frequency of 4 Hz.

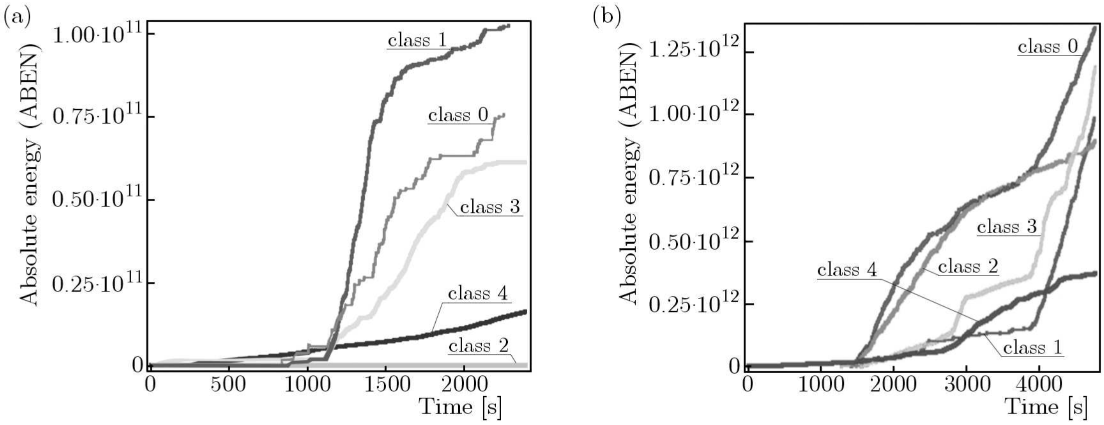

Fig. 7. Classes of AE signals recorded by two sensors as a function of the sum of the absolute energy over time; (a) – 18G2A, (b) – St3s

Figure 7 shows the sum of AE signals recorded by two sensors mounted on both sides of the cut. The signals were subjected to multi-parameter analysis employing the reference data base. The result is shown as a summation graph of one parameter (ABEN – absolute energy) as a function of time with division into signal classes.

In both cases, after approx. 5000 cycles, the processes of steel yielding (Class 1) and cracking initiation (Class 0) are recorded, which are then followed by the crack growth (Class 3).

For both types of steel (18G2A steel and St3s steel) the moments of crack initiation and its growth were clearly recognized and could be located using IADP method. The moment of crack initiation and its growth was confirmed by optical observation.

3.3. Application of the IADP method to the analysis of a node under cyclic loading – model tests

Acoustic emission tests were performed on nodes (models of the bridge nodes) fabricated in two versions:

- welded one and,
- bolted one (M8 bolts and tightening torque $M = 35\,\mathrm{N}$), which is a model of a riveted connection (Fig. 8).

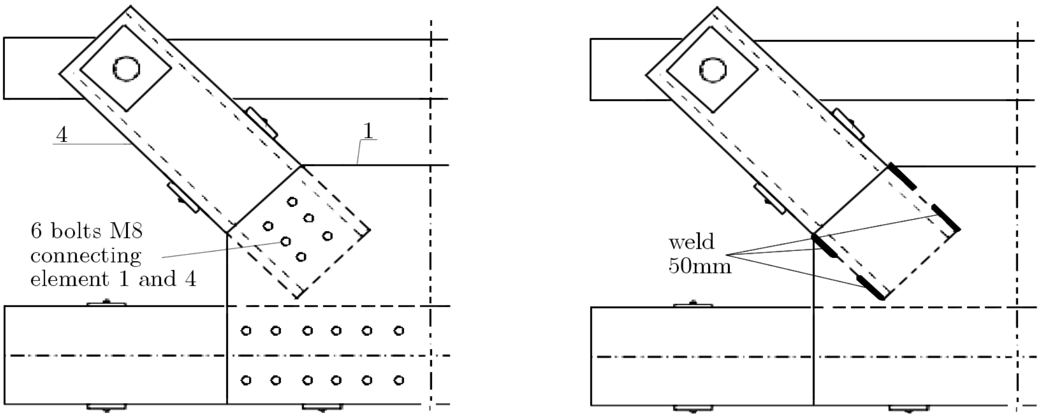

Fig. 8. Diagram of the tested node – bolted and welded

The nodes were first subjected to quasi-static monotonic loading (as in Fig. 9) up to failure due to welds or bolts cracking. Then, a cyclically variable loading whose value (the force P) varied sinusoidally at a frequency of 2 Hz, was applied. In the cyclic loading, the value of the maximum load both for welded and bolted connections was set to amount up to approx. 83% of the maximum value obtained from the quasi-static tests ($P_{min} = 2\,\mathrm{kN} - 0.83P_{max}$).

Figure 9 shows the test stand and the spacing of AE sensors (eight sensors in total, on both sides of the node).

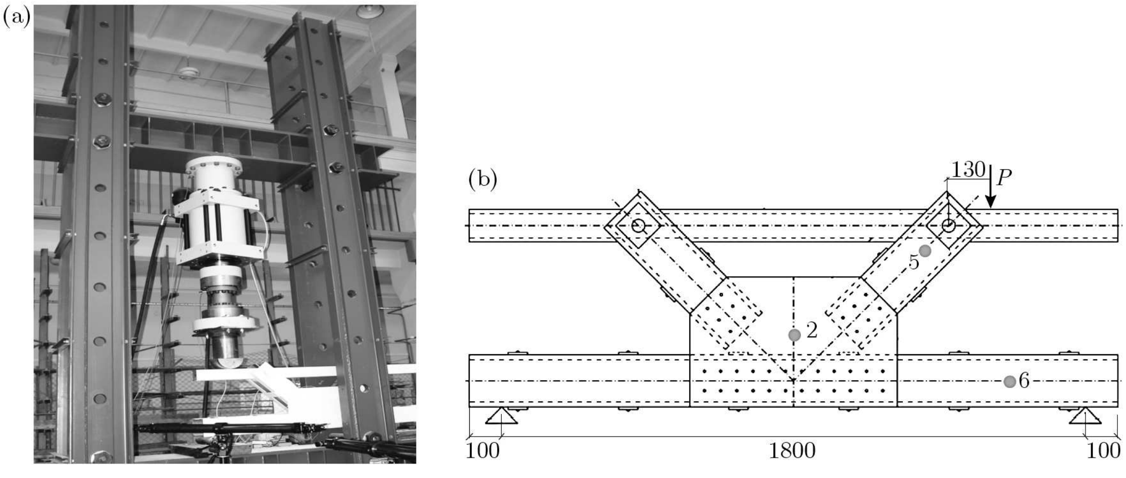

Fig. 9. The test stand (with the bolted node under loading) and spacing of AE sensors (on one side of the node)

Exemplary results of comparative analysis (employing the reference signal database) of AE signals generated while the bolted node is loaded are presented in Fig. 10. It shows the sum of AE signals recorded as a sum of the eight sensors (Fig. 10a), and signals recorded only by one sensor (sensor 5 located next to the bolts – Fig. 10b), which were subjected to the analysis using the reference data base, as a summation graph of one parameter (ABEN - absolute energy) against time with division into signal classes.

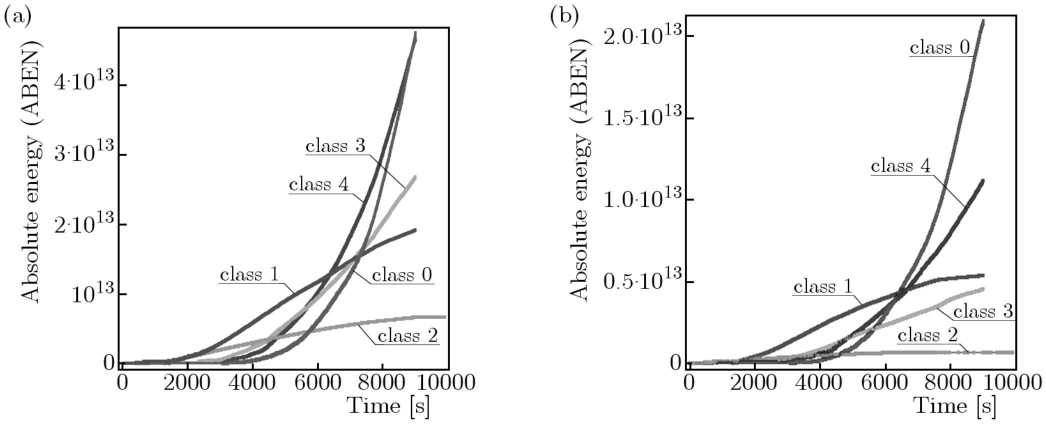

Fig. 10. Classes of AE signals recorded a sum of all sensors and by sensor 5 as a function of the sum the absolute energy over time (bolted node)

After approx. 4000 cycles (2000 s), the process of steel plastic yield is recorded (Class 1), and then (following approx. 8000 cycles) signals are generated by the crack initiation and its growth (Class 0 and 3). Also signals Class 4 are found.

After approx. 12000 cycles, the shear failure of the first bolt is observed visually. For 18000 cycles, two consecutive bolts suffer shear failure. Both graphs are very similar in shape, what shows that indications of the IADP method are analogous for the sensor placed near by the zone of damage and the sensors placed within the structure.

The results for corresponding welded structures (bolts replaced with short welds) are shown in Fig. 11. As before, the sum of AE signals recorded as a sum of all the sensors (Fig. 11a) and signals recorded only by one sensor (sensor 5 located next to the bolts – Fig. 11b), were subjected to the analysis using the reference data base, as a summation graph of one parameter (ABEN - absolute energy) against time.

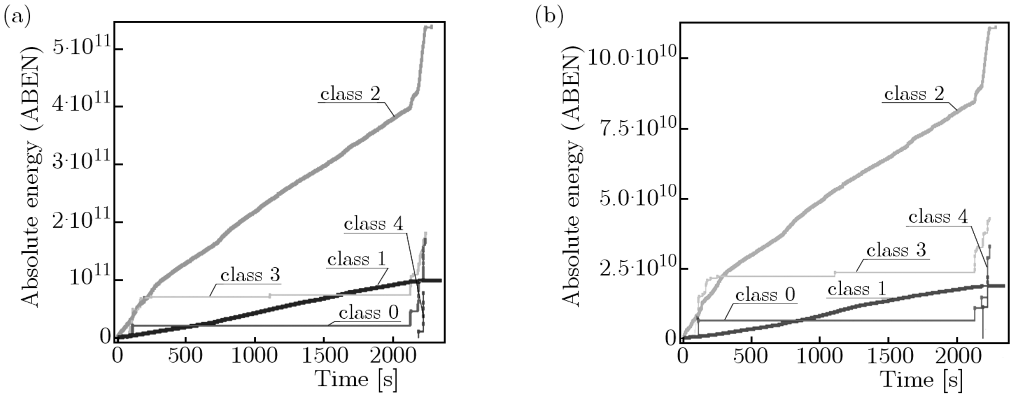

Fig. 11. Classes of AE signals recorded by all sensors and by sensor 5 as a function of the sum the absolute energy over time (welded node)

The process of plastic yielding develops in a quite uniform manner since the beginning of loading (Class 1). In the first stage (200 cycles), a crack is initiated (Class 0), which is followed by a short-term growth (Class 3). Then, the process becomes inhibited (probably due to stress redistribution), only to start again (Class 0 and 3 signals) after over 4000 cycles until failure (Class 4).

The initial crack propagation, its stop, re-development and the instant of the weld failure was recorded visually at the same time.

As before, both graphs are very similar in shape, what shows that indications of the IADP method are analogous for the sensor placed near the zone of damage and the sensors placed within the structure.

3.4. Application of the IADP method to the analysis of a structure under service load – bridge tests

The tests were conducted on the riveted steel bridge (Fig. 12a), where twenty three AE sensors were spaced along the span (1-6 sensors) and within the bridge nodes. An exemplary spacing of the sensors in the truss shoe is presented in Fig. 12b (Goszczyńska *et al.*, 2013).

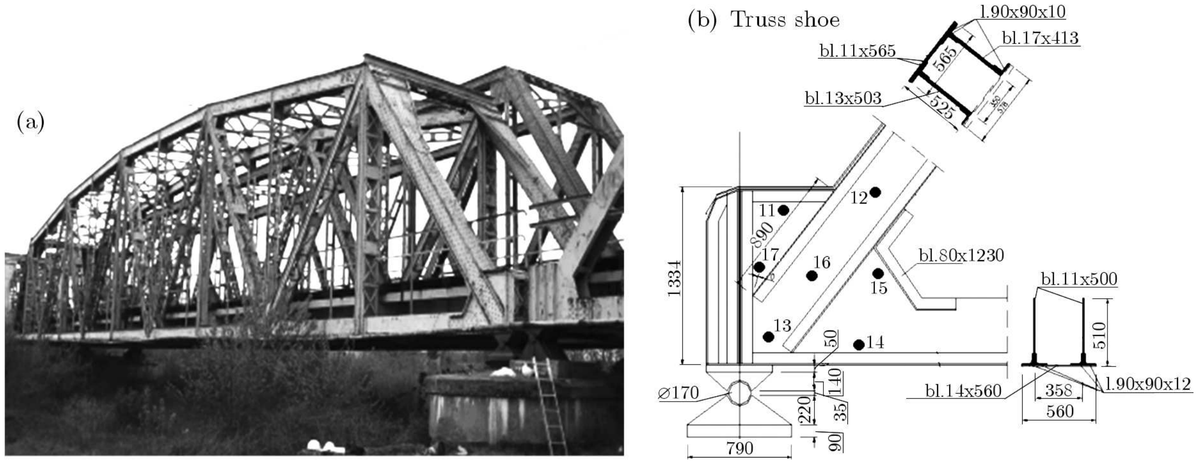

Fig. 12. Side view of the bridge middle span with an exemplary spacing of sensors in the support node

Figures 13 and 14 (Gołaski *et al.*, 2011) show the results of comparative analysis (employing the reference signal database) of AE signals generated for the unloaded bridge (Fig. 13) and with a train passing over it (Fig. 14) in form of a diagram of one reference parameter (signal strength – SSTR) as a function of channels with division into signal classes.

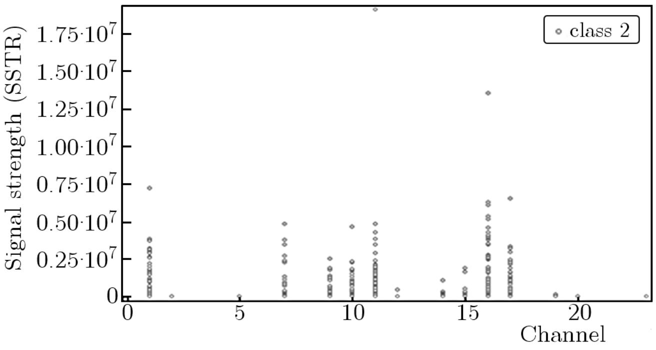

Fig. 13. Diagram of the signal strength as a function of channels (position of the sensors) for the unloaded bridge

For the unloaded bridge, all sensors record only Class 2 signals, i.e. those generated by noise. When a train passes over the bridge, additionally Class 1 signals, generated by steel yielding, are found in the measurement zone of sensors no. 10 and 16. Close visual inspection revealed in sensor zone 16 a plasticized (and loosened) rivet the damage of which was not seen under a layer of paint.

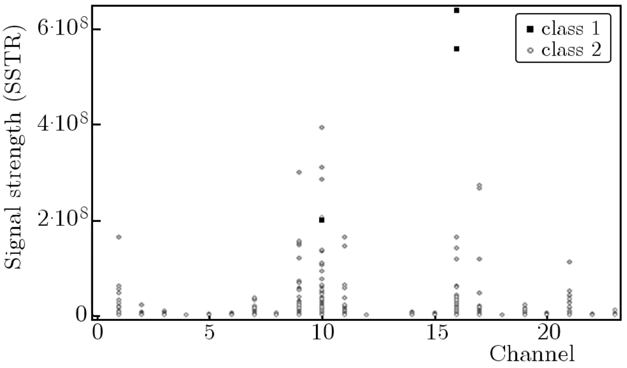

Fig. 14. Diagram of the signal strength as a function of channels with a train passing over the bridge

Hence, using the IADP method, it was possible to find a plasticized rivet within such a large size structure as a steel bridge.

4. Conclusions

The IADP method made it possible to determine the condition of steel structures under cyclic loads, i.e. to determine where, when and what kind of destructive processes appear under service loads.

The conducted analysis and results of tests indicate that the IADP method:

- allows one to detect and identify destructive processes in members of steel structures,
- allows one to detect the moment of cracks formation and track their development,
- makes it possible to locate active destructive processes in large size structures under service loads,
- consequently, the IADP method can be applied to monitor and diagnose steel structures.

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