PAPER • OPEN ACCESS

Tracking of Crack Formation in Concrete Using Acoustic Emission Method and Digital Image Correlation

View the article online for updates and enhancements.

Tracking of Crack Formation in Concrete Using Acoustic Emission Method and Digital Image Correlation

Pawel Tworzewski [1], Michal Teodorczyk [1], Justyna Tworzewska [1]

[1] Kielce University of Technology, al. Tysiaclecia Panstwa Polskiego 7,
25-314 Kielce, Poland

ptworzewski@tu.kielce.pl

Abstract. The paper presents analysis of crack formation in a reinforced concrete beam using an acoustic emission method (AE) and a digital image correlation (DIC). The examined element was loaded monotonically until reaching 50 kN force during the three-point bending test. Six acoustic emission sensors (two on the left and right surfaces of the sample and the other two on the bottom surface) combined with three-dimensional location method were used to find the destructive processes. The optical measuring system ARAMIS (DIC) was used to verify the obtained results. This device help to specify the location of crack and track its development on the basis of the strain map. The crack width was measured in 6 sections, which were located in different positions of the element height with the use of ARAMIS software. First section was applied at the centre of gravity of the longitudinal reinforcement. The following cross-sections were set every 2 cm towards the top edge of the element. In the first part of the analysis, a graphical comparison of the strain map (obtained with ARAMIS system) and the location of events (obtained with AEWin software) was made. In the second part of the analysis, the obtained crack width results were compared with number of AE events counted in zones, which were defined around the previously mentioned sections. The statistical analysis (Pearson's linear correlation) shows that the number of recorded events depends on the maximum crack width, the average crack width as well as the crack width increase registered between successive load levels. The results of the study conclude that simultaneous use of DIC and AE methods provided complete information on local strain and damage location in concrete.

1. Introduction

Modern technologies in construction are not limited only to the production of materials, construction or its elements. More and more often an integral part of the buildings are systems to monitor their condition. This contributes to the development of measurement techniques that allow for more and more accurate tracking of phenomena occurring in the structure. The paper presents the results of the location and analysis of the process of formation and development of cracks in a reinforced concrete beam using the acoustic emission method (AE) and digital image correlation (DIC). In the research, the spatial location of destructive processes based on the Simplex method was carried out using six AE sensors. Strains on the lateral surface of the element and its displacement were recorded using the optical ARAMIS measuring system (DIC). This system allowed to track the process of crack formation on the surface of the tested element and to measure the width of the cracks. The paper presents a comparison of the obtained results together with the analysis of counts and crack width depending on the load stage and location on the length of crack.

2. Application of a quantitative method to acoustic event location in concrete

Diagnosis of concrete structures is important for assessing their structural integrity and suitability for further use. Non-destructive methods play a special role among diagnostic methods. The acoustic emission method used to locate destructive processes is one of such methods, with digital image correlation based on optical measurement of strains as another example. Complex testing of structural components uses a combination of several methods. Different techniques need to be compatible, particularly in the case of measurement and interpretation procedures, so that the results obtained by different research methods can be compared.

Acoustic emission is characteristic of brittle materials. This is manifested by pulse type emission, i.e., acoustic emission events are distributed over time, for example, the formation and development of cracks in concrete. Concrete has characteristics of a brittle body in which pulse signals with identifiable beginning and end are produced [1, 2]. One of the first reports on acoustic emission measurement in concrete was published in 1969. The tests were conducted on a small pressurized concrete tank simulating a nuclear reactor. It was found that elastic wave data can be used to determine the onset and development of concrete damage processes, including the location of cracks, loss of strength properties or loss of constancy of performance of the tank. Measurement capabilities of the apparatus at that time did not allow detecting all potential destructive processes [3].

Measurement and analysis of emission signals in concrete components can be done in two manners: qualitative (classical) and quantitative, using sensors with adequate characteristics. The classical method consists in recording selected acoustic emission parameters while the shape of the elastic wave is not recorded. The elastic wave parameters that are recorded include signal rise time, number of counts, energy, amplitude, frequency, and signal duration. The acoustic emission signal described only by these wave parameters reduces the time and volume of data. Strong advantage of this method is the possibility of interpreting results in real time. Measurement of the entire concrete structure gives an overall view of destructive processes. Data are analysed using statistical methods [4]. The quantitative method consists in recording the shape of the elastic wave along with the corresponding acoustic emission parameters. As a result, the processing time and volume of data increase. Results cannot be interpreted in real time, but only after the measurement. This method is commonly used for the local assessment of concrete condition and is based on the characterization of the cause of acoustic emission source [4, 5]. Event location technique is to determine the position of the acoustic emission source to visualize cracking concrete. The emission source is located by multi-channel devices using a sensor system (minimum two sensors). This makes it possible to determine the position of the emission source on a 1D straight line, on a 2D plane and in the 3D space of the material under test [6].

In this paper, the 3D events location is demonstrated together with the crack image in concrete, using the ARAMIS optical system and acoustic emission system.

3. Three-dimensional location of AE events

Three-dimensional location is used when the component thickness is important in crack analysis and the source coordinates are determined in three directions (x, y, z). Sensors should be placed around the component, minimum on three walls, to cover the thickness of the component. This technique is similar to that used for earthquake hypocentre location, in which many seismographs record the arrival time of the wave. To determine the hypocentre of acoustic emission, wave arrival times at the sensors are used. A minimum of four wave arrival times (four sensors) are required for 3D location to determine four unknown parameters, three source coordinates and source origin time. Location is more accurate when more than four arrival times are used (more than four sensors in the system) and the iterative algorithm is employed. The coordinates of the emission source are computed in the iterative procedure by minimizing the error of unknown parameters calculation. The more sensors are placed in the system, the more reliable and accurate the source location will be. It should be stressed that the accuracy of 3D location is determined by sensor spacing; with small spacing, 3D location is more accurate [7, 8].

Longitudinal wave arrives first at the sensors and its arrival time should be recorded by at least four sensors. The 3D source location is determined based on the difference of a minimum of four arrival times at the known velocity of the wave [4, 7]. Each difference in arrival times Δt_i contains different distances from the sensor to the source, thus the formula for the three-dimensional location has the form (1), [9].

$$\Delta t_i = \frac{\sqrt{(x_i - x_s)^2 + (y_i - y_s)^2 + (z_i - z_s)^2} - \sqrt{(x_1 - x_s)^2 + (y_1 - y_s)^2 + (z_1 - z_s)^2}}{c_L} \tag{1}$$

where (x_i, y_i, z_i) are the coordinates of the sensor sites, (x_s, y_s, z_s) are the unknown coordinates of the source, c_L is the longitudinal wave velocity in the concrete. Three-dimensional location is computed by the iteration method from the arrival times (there are more than four sensors in the system), using Simplex, Geiger, or Thurber algorithms [10]. The AE source is represented as a point located in three dimensions of a concrete specimen. First, the velocity of longitudinal wave, constant throughout the test, has to be determined. The method has the opportunity do visual results in two-dimensional location.

4. Digital image correlation

The digital image correlation (DIC) method is based on the principles of stereo photogrammetry. It allows registering the mutual position of individual points on the examined object in space. Tracking of the changes in the position of the points (relative to the initial position) is possible by comparison of the pictures from subsequent stages of the measurement (at each stage a pair of photos is taken). An example of the DIC system used in the described tests is the ARAMIS optical measuring system. It uses a pair of CCD cameras (monochrome Baumer TXG 50 cameras with a resolution of 2448x2050 pixels and Schneider Kreuznach Cinegon 1.4 / 12-0906 lenses). This set allows registering up to 15 photos per second at full resolution. Optical measuring system based on ARAMIS software allow:
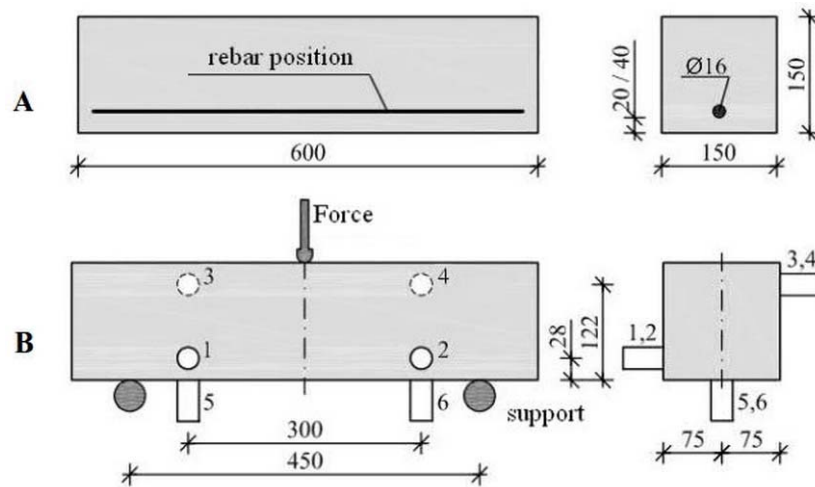
- tracking the deformation of the tested surface of the element during its loading,
- measuring displacements in 3 directions in each point that is within the registered area,
- measuring of crack width using the point-point distance function.

Thanks to this, the system sets a new quality in terms of crack formation observation and analysis. This is an ideal method to verify the results obtained with the AE method. The rapid development of the DIC method is associated with its increasing use not only in laboratory conditions but also in engineering measurements, as well as in the diagnosis of building structures. Examples of application and capabilities of the ARAMIS system are presented in [11, 12, 13, 14].

5. Description of study

Reinforced concrete beam with dimensions of 150×150×600 mm was made of concrete class C40/50. As a longitudinal reinforcement, a single Ø16 bar was used in the lower part of the beam (steel S355JR). Cross reinforcement was not used. The beam was loaded monotonically until reaching the force value of 50 kN with one concentrated force (force was applied in the middle of the element span; distance between the axes of supports - 450 mm). During the load increase every 5 kN, a break of four minutes was done to perform measurements.
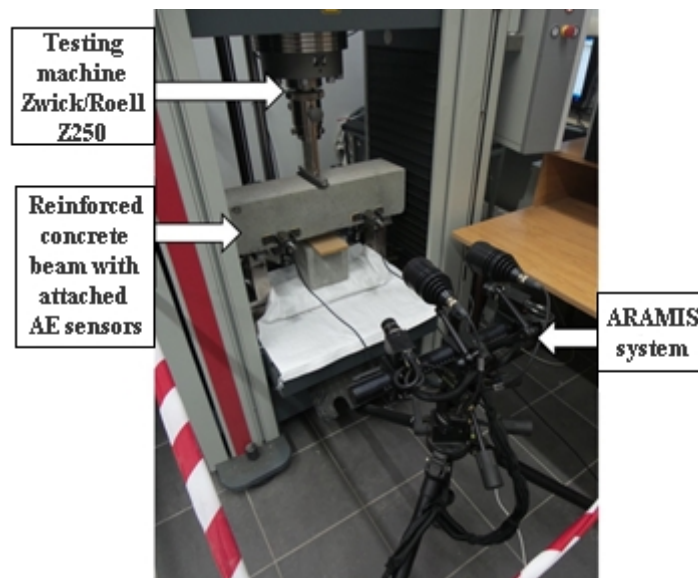
During the study, acoustic emission signals generated by destructive processes developing in concrete were measured with the microSamos device. It is a 16-channel set of acoustic emission processors. The device operates in the frequency range from 1 to 400 kHz. AEWin software has been used to register elastic wave shapes with their parameters. The beam construction and static scheme with sensors location are shown in Figure 1.

Figure 1. (A) The beam construction scheme. (B) Location of AE sensors

Six piezoelectric sensors with a flat characteristic in the resonant frequency range from 25 to 80 kHz were used for the study (Figure 1B). The sensors were placed on the element as shown in the scheme: two on the left and right surfaces of the sample and the other two on the bottom surface. Recording of acoustic emission signals occurred after exceeding the amplitude threshold value, at the level of 40 dB.

Measurements of spatial deformations, width of cracks were made using the ARAMIS optical measuring system (DIC). The analysis included the middle part of the beam, i.e. the area between the placement points of the AE sensors (surface dimensions: 300×400 mm). Due to the small distance of the ARAMIS system sensor from the registered surface, the obtained accuracy of measurements was in the range of 0.018 mm. Figure 2 shows the test stand.
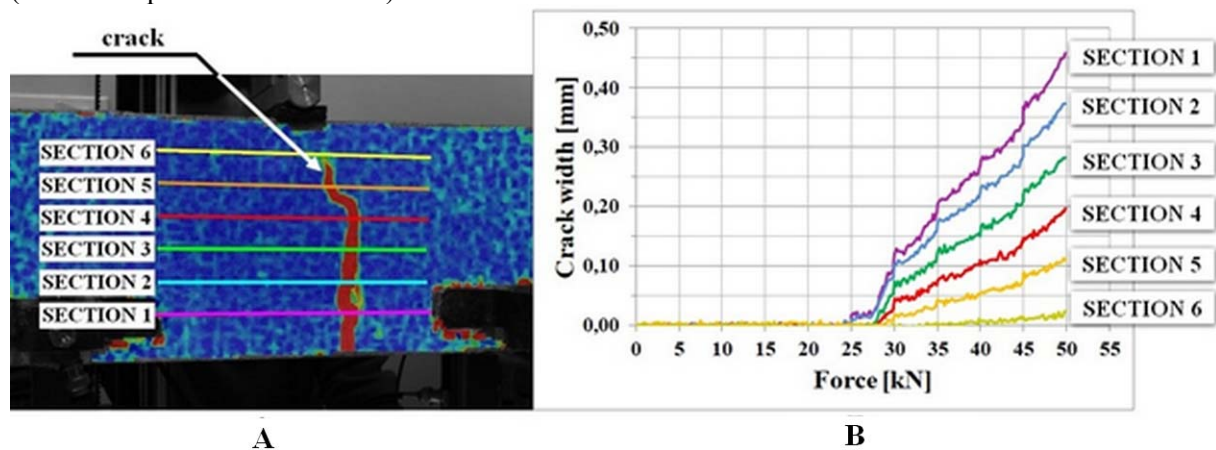

Figure 2. Test stand

6. Obtained results of measurements and analysis

Crack width measurements (ARAMIS system) and counting of the number of events (acoustic emission system) were made in 6 sections / zones on the research element - Figure 3A. Section 1 was

applied at the centre of gravity of the longitudinal reinforcement (between the points of installation of the AE sensors). The following cross-sections were set every 2 cm towards the top edge of the element as shown in the picture. The use of ARAMIS system allowed observation of the development of crack on the element side surface in the load process. Obtained results of the measurements are shown in Figure 3B and on their basis, the following values were determined: average crack width in selected load ranges; increase in crack width; maximum value of crack width in individual load intervals (results are presented in Table 1).
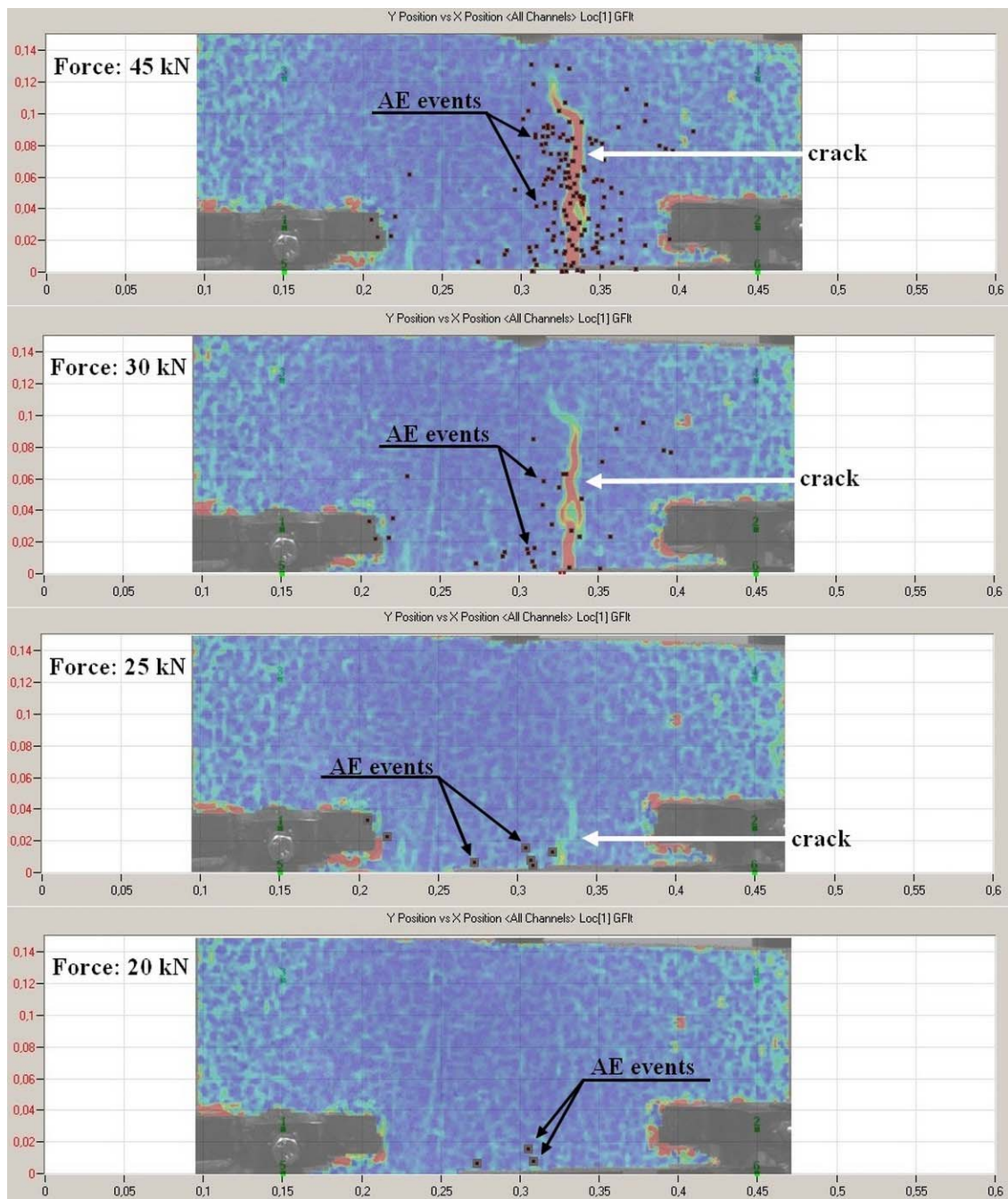

Figure 3. (A) Location of the sections determined in the ARAMIS system in which crack width measurements and acoustic emission measurements were performed. (B) The results of crack width measurements in 6 analysed sections

Table 1. Values describing the development of crack width in individual load ranges

Load level [kN]	Section I	Section II	Section III	Section IV	Section V	Section VI
Average crack width [mm]						
20-25	-0.003	0.000	-0.007	-0.007	0.001	-0.003
25-30	0.043	0.036	0.015	0.006	0.003	-0.003
30-35	0.150	0.126	0.088	0.054	0.024	-0.001
35-40	0.234	0.194	0.138	0.089	0.045	0.004
40-45	0.304	0.252	0.182	0.118	0.063	0.008
Crack width increase [mm]						
20-25	0.003	0,006	0.005	0.002	0.002	-0.007
25-30	0.089	0.077	0.060	0.036	0.014	0.006
30-35	0.068	0.056	0.042	0.022	0.023	0.004
35-40	0.063	0.048	0.027	0.033	0.009	0.004
40-45	0.062	0.053	0.044	0.039	0.021	0.008
Maximum crack width [mm]						
20-25	0.006	0.009	0.000	-0,001	0.008	0.001
25-30	0.107	0.088	0.058	0,033	0.013	0.002
30-35	0.189	0.159	0.116	0,072	0.041	0.004
35-40	0.268	0.223	0.156	0,110	0.054	0.011
40-45	0.340	0.287	0.210	0,142	0.076	0.015

Next, a two-dimensional comparison was presented for a better visualization of the results. In Figure 4, strain maps from the ARAMIS system and the locations of acoustic emission events in the form of points were shown imposed on each other. The photos were arranged according to the load increase. The pictures show the development of cracks (red colour) and AE events (dark dots) registered around the crack. The horizontal axis is the length of the element; the vertical axis is the height of the element. Single AE events are visible at 20 kN of the load and the point cloud is at 45kN of the load.
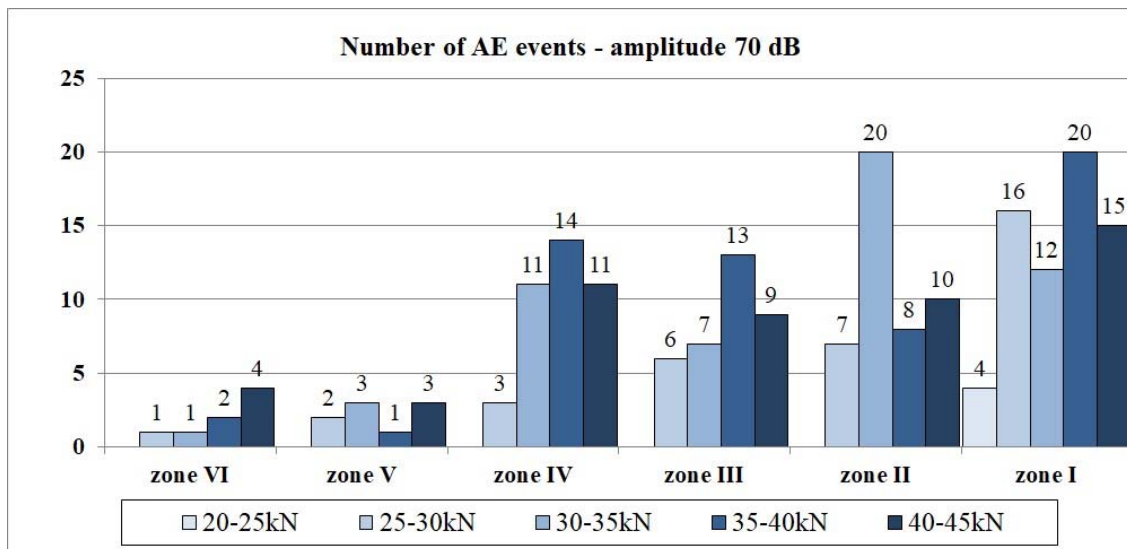

Figure 4. Comparison of results of destructive processes with the strain map obtained using the ARAMIS system and event localization above 70 dB amplitude (AE method)

Then in Table 2 the number of events in individual zones was counted (and in individual load ranges, e.g. in the load range from 20 to 25 kN). Six zones were separated, each of them covering the area consistent with the location of the sections shown in Figure 3A. The zones included a volume with the following dimensions: width of the sample × length of the sample × 2 cm (1 cm above plus 1 cm below the inserted sections). As the cracks develop with increasing load, increase in the number of events in subsequent zones can be observed. Zone I illustrates the largest number of events, because the crack starts and develops in it, and the smallest number of events in zone VI, where the crack ends. Figure 5 shows the number of AE events in the form of bars depending on the load and zone. A large number of events in zone I is visible. In comparison to other zones, it is the highest in the entire load process. This domination is clearly visible in the initial stage of the formation of cracks.

Considering the graphically presented comparison of the conducted location of events (Figure 4) and the described results, it can be stated that the acoustic emission method accurately reflects the crack development process registered with the ARAMIS system.

Table 2. Number of AE events, which was registered during studies

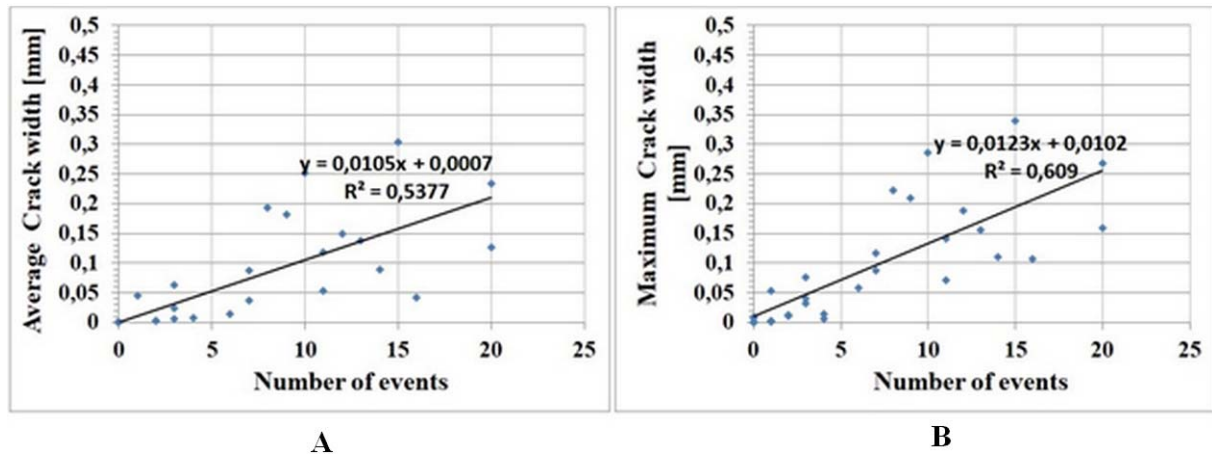| Zone	Position at the height of the element [cm]	Number of AE events - amplitude 70 dB					Σ
		Force [kN]					
		20-25	25-30	30-35	35-40	40-45	
VI	13		1	1	2	4	**8**
V	11		2	3	1	3	**9**
IV	9		3	11	14	11	**39**
III	7		6	7	13	9	**35**
II	5		7	20	8	10	**45**
I	3	4	16	12	20	15	**67**
	Σ	**4**	**35**	**54**	**58**	**52**	

Figure 5. Number of AE events in individual zones at different load levels

Next, the values of the cracks width in each load range with the registered number of events were compared. The results are presented in the graphs along with the trend lines (linear), their equations and the values of the R-squared determination coefficients successively for:
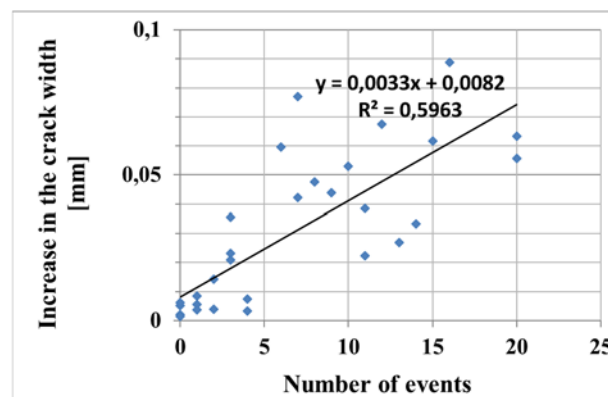- average crack width - number of AE events (figure 6A),

- maximum crack width - number of AE events (figure 6B),
- crack width increase - number of AE events (figure 7).

Figure 6. (A) Relation between the number of AE events and the average crack. (B) Dependence between the number of AE events and the maximum crack width

Figure 7. Dependence between the number of AE events and the increase of crack width

An analysis of Pearson's linear correlation for the above comparisons was also made. The results in the form of Pearson coefficient values determining the level of linear dependence between the analysed random variables are presented in the Table 3. The obtained values indicate a fairly strong relationship between the number of events and selected cracking parameters. It can be stated that as the width of crack increases, the number of recorded events increases. The highest dependence was observed between the number of AE events and the maximum crack width occurring in individual load intervals.

Table 3. Pearson's linear correlation analysis results

	Number of AE events	Average crack width	Crack width increase	Maximum crack width
Number of AE events	1			
Average crack width	0.73	1		
Crack width increase	0.77	0.61	1	
Maximum crack width	0.78	0.99	0.72	1

7. Conclusions

Both the rapid development of acoustic emission systems and computer technology allows for more and more accurate and advanced measurements, their archiving as well as their analysis. It is associated with the growing popularity of AE systems in the diagnostics and monitoring of building structures. Comprehensive systems based on a large number of sensors used at the moment mainly in laboratory conditions allow for a detailed investigation of the destructive processes occurring in the tested elements (for example, reinforced concrete elements). The analysis presented at work can be an example of this. Based on the analysis, it was shown that:

- the 3D location of the events carried out using the AE method coincides with the crack image obtained using the ARAMIS system (digital image correlation) – pictures in Figure 4,
- practically regardless of the load level, the largest number of events was recorded in zone I (at the height of the centre of gravity of the tensile reinforcement). At the same time, this is the zone where crack occurred first,
- with the increase of crack width, an increase in the number of recorded events was observed.

The analyses showed the existence of dependence between the number of recorded events and the maximum and average width of cracks as well as the incensement in crack width recorded between successive load levels. The highest dependence was observed between the number of AE events and the maximum crack width.

References

[1]   PN-EN 1330-9, "Non-destructive testing. Terminology. Part 9: Terms used in acoustic emission testing", 2002. (Badania nieniszczące. Terminologia. Część 9: Terminy stosowane w badaniach emisją akustyczną).

[2]   J. Hoła, Z. Ranachowski, "Application of acoustic emission to fault diagnostics in civil engineering" 26/1991, Instytut Podstawowych Problemów Techniki PAN, Warszawa 1991 (Metoda emisji akustycznej w zastosowaniu do badania betonu).

[3]   A. Green, "Stress wave emission and fracture of prestressed concrete reactor vessel materials", Report 4190, Aerojet-General Corporation, Sacramento (USA) 1969.

[4]   Ch. Grosse, L. Linzer, "Signal-Based AE Analysis w: Acoustic emission testing. Basics for research - application in civil engineering", red. Ch. Grosse, M. Ohtsu, Springer, Leipzig (Germany) 2008.

[5]   T. Schumacher, "New Acoustic emission applications in civil engineering", PhD dissertation, Oregon State University", Corvallis (USA) 2009.

[6]   G. Świt, "Predicting failure processes for bridge – type structures made of prestressed concrete beams using the acoustic emission method", Wydawnictwo Politechniki Świętokrzyskiej, Kielce 2011, (Analiza procesów destrukcyjnych w obiektach mostowych z belek strunobetonowych z wykorzystaniem zjawiska emisji akustycznej).

[7]   J. Kurz, S. Koppel, L. Linzer B., Schechinger, Ch. Grosse, "Source Localization: Acoustic emission testing. Basics for research - application in civil engineering", red. Ch. Grosse, M. Ohtsu, Springer, Leipzig (Germany) 2008.

[8]   A. Behnia, H. Chai, T. Shiotani, "Advanced structural health monitoring of concrete structures with the aid of acoustic emission". *Construction and Building Materials*, vol. 24, 2014.

[9]   "PCI-2 based AE system. User's manual. Associated with AEWin", Physical Acoustics Corporation, New Jersey (USA) 2007.

[10] M. Ge, "Analysis of source location algorithms. Part II: iterative methods", *Journal of Acoustic Emission*. vol. 21, 2003.

[11] B. Goszczyńska, G. Świt, W. Trąmpczyński, A. Krampikowska, J. Tworzewska, P. Tworzewski, "Experimental validation of concrete crack initiation and location with acoustic emission method", *Archives of Civil and Mechanical Engineering*, vol. 12, pp. 23-28, 2012.

[12] J. Tyson II, "Optical 3D Deformation and Strain Measurement", *Pumps and Pipes - Proceedings of Annual Conference*, vol. V, pp. 147- 164, 2011.

[13] P. Tworzewski,   B. Goszczyńska, "An Application of an Optical Measuring System to Reinforced Concrete Beams Analysis", *2016 Prognostics & System Health Management Conference—Chengdu* (PHM-2016 Chengdu), China, 2016.

[14] B. Kuczma, M. Kuczma, "Laminated steel-concrete composite beams", *Mosty*, vol. 5, pp. 28-36, 2012, (Klejone stalowo-betonowe belki zespolone).