ACOUSTIC EMISSION WIRELESS TRANSMISSION SYSTEM FOR STRUCTURAL AND INFRASTRUCTURAL NETWORKS

A. CARPINTERI[1], G. LACIDOGNA[1], A. MANUELLO[1], G. NICCOLINI[2]

[1]Politecnico di Torino
Department of Structural, Geotechnical and Building Engineering
Corso Duca degli Abruzzi 24, 10129 Torino, Italy
[2]National Research Institute of Metrology – INRIM,
Strada delle Cacce 91, Torino, 10135, Italy
e-mail: alberto.carpinteri@polito.it, giuseppe.lacidogna@polito.it, amedeo.manuellobertetto@polito.it, g.niccolini@inrim.it

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Abstract:

The damage assessment of buildings is currently made visually. The few non-visual methodologies make use of wired devices, which are expensive, vulnerable, and time consuming to install. Systems based on wireless transmission should be cost efficient, easy to install, and adaptive to different types of structures and infrastructures. The Acoustic Emission (AE) technique is an innovative monitoring method useful to investigate the damage in large structures. It has the potential to detect damage, as well as to evaluate the evolution and the position of cracks. This paper shows the capability of a new data processing system based on a wireless AE equipment, very useful to long term monitoring of concrete and masonry structures. To this purpose, computer-based procedures, including an improved AE source location based on the Akaike algorithm, are implemented. These procedures are performed by automatic AE data processing and are used to evaluate the AE results in notched concrete beams subjected to three point bending loading conditions up to the final failure. In this case, the final output of the code returns a complete description of damage pattern and evolution of the monitored structure. In the most critical cases, or in some cases requiring long in situ observation periods, the AE monitoring method is fine tuned for a telematic procedure of processing AE data clouds to increase the safety of structures and infrastructural networks. Finally, the proposed AE monitoring system could be used to determine the seismic risk of civil constructions and monuments subjected to earthquakes.

1 INTRODUCTION

Continuous structural health monitoring should provide data in order to better understand structural performances and to predict durability and remaining life-time.

In the last few years, the Acoustic Emission (AE) technique has been used in several applications due to its capability to detect crack growth, damage accumulation and AE source localizations in historical monuments, concrete structures, and infrastructures [1-7].

In Europe, the sudden collapse of a training hall in Bad Reichenhall (Germany) in early January 2006 and the collapse of a new trade building in Katowice (Poland) some weeks later, confirm dramatically the necessity of structural control in civil structures [8]. In U.S.A., the tragedy (August, 2007) of the highway bridge collapse in Minneapolis, Minnesota, raises the question of whether U.S.A bridges are safe. In particular, recent events such as the reconstruction of the Noto Cathedral in 2007, after the collapse and the effects of the L'Aquila earthquake in April 2009, brought the problem of structural safety as a priority in the maintenance of Italian civil structures and monuments. These recent events lead to the conclusion that a large number of structures need monitoring and inspection procedures, reliable, inexpensive, and easy to implement.

During the last few years the AE technique has been used during long-term monitoring in order to analyze the time evolution of microcracking phenomena [9-19]. According to this technique, it is possible to detect the onset and the evolution of stress-induced cracks. Crack opening, in fact, is accompanied by the emission of elastic waves which propagate within the bulk of the material. These waves can be detected and recorded by transducers applied to the surface of the structural elements. AE monitoring is performed by means of piezoelectric sensors that give out signals when subjected to a mechanical stress [1-3]. In this way, the AE technique makes it possible to estimate the amount of energy released during the fracture process, to obtain information on the criticality of the process underway and to localize the damage source locations [7, 8-16].

In the present paper a new AE equipment based on a wireless data acquisition system is presented. Due to the attenuation of acoustic waves and geometrical spreading in concrete structures, numerous sensors have to be applied to cover all critical parts. These circumstances make the traditional way to apply AE techniques too expensive [8,9]. Monitoring systems for large structures should be based on a new kind of AE equipment using wireless transmission systems. In the new monitoring system, AE signals are detected by the sensor array, recorded in situ by a synchronisation and storage unit, and, subsequently, they are sent via the GPRS/UMTS system to the central server for the elaboration phases. In this way, it is possible to use a centralised station to control continuously and simultaneously, in real time, individual structures situated in different sites.

2 AE EQUIPMENT AND WIRELESS TRANSMISSION SYSTEM

In the last few years a computer-based procedure including AE source location, AE event counting, and statistical analysis applied to AE time series has been developed by the authors [7,17-19]. The final output of the AE data processing code returns a complete description of damage characterization and evolution [7,17-19]. Today, the most critical cases, or those demanding long in-situ observation periods (infrastructural or monumental buildings), require AE monitoring based on telematic working procedure. Huge structures, such as large concrete structures and infrastructures, should be monitored by means of new type sensors, using efficient algorithms for processing large quantities of data.

To this purpose, the authors are working on a new type of AE equipment able to execute the AE data acquisition in real time by wireless technology. By means of this new equipment, AE signals detected by the sensor array are recorded in situ by a synchronization storage device, and successively sent via GPRS/UMTS system to the central server for the elaboration phase.

In this way, it will be possible to use a centralised station to control continuously and simultaneously individual structural elements or entire structures, possibly situated in different places. Moreover, because a correlation exists between the regional seismic activity and the AE signals collected during structural monitoring [7], AE wireless equipment can be also used for the preservation of concrete structural and infrastructural networks from the seismic risk [8]. The new AE instrumentations and the prototype are the result of a technical collaboration between the AE research unit of the Politecnico di Torino and LEANE net. srl, an Italian company leader in the design and implementation of structural monitoring systems. The new AE sensors, calibrated at the National Research Institute of Metrology (INRIM), are designed to optimize weight, size, and applicability to different structural supports (Fig.1a and b). The connection between the sensors and the acquisition module is realized by coaxial cables optimized to reduce the effects of electromagnetic noise. The modules for the signal storage are integrated within the central acquisition unit. The AE data coming from each channel are synchronized and analyzed by a mini-processor. During this phase, the main characteristics of AE signals are recognized (AE amplitude, signal arrival time, duration, signal frequency).

(a)

(b)

Figure 1: (a) New PZT AE sensors. (b) The new AE sensors, working in a frequency range between 50 and 800 kHz, are designed to optimize weight, size, and applicability to different structural supports.

In Fig. 2a and b the central unit interface and the modem for the AE wireless transmission system are reported. The scheme of acquisition, pre-processing, and data transmission adopted in the prototype is reported in Fig. 3. Each channel consists of an Analog to Digital Converter module (ADC) with the capacity to acquire 10 (mega-sample/second) Msa/s in order to cover the wide band of AE signals frequency range (50–800 kHz). The data exchange is run using a Field Programmable Gate Array (FPGA) connected with a parallel bus and integrated into the central unit (Fig. 3). Each channel, connected with the central processor, has a devoted memory of 64 Mb and is able to perform the data synchronization.

(a)

(b)

Figure 2: Central Unit interface (a). Modem for AE wireless data transmission (b).

The central unit is also equipped by a thin film transistor (TFT) touch screen for human interface and first signal processing executable in situ (Fig. 2a). The stored data are collected into a Compact Flash memory card (CF 64 Gb) and then sent in real time to the AE laboratory, by GSM/GPRS antenna (Fig. 3), for AE signal analysis. The AE sensors adopted for the new monitoring system are of two types: resonant and broadband piezoeletric transducers. These two kind of sensors were used according to different conditions and considering the different structures to be monitored. The sensitivity of the broadband sensor is lower but these sensors are able to acquire data clouds in a wide frequency band and can be used in structures and component of reduced dimensions. In other condition, and specially when the localization of the damage must be particularly accurate the resonant sensors will be used according to their greater sensitivity. These kind of sensors will be used for very large structures or in the case in which the monitored elements are characterized by heterogeneous materials.

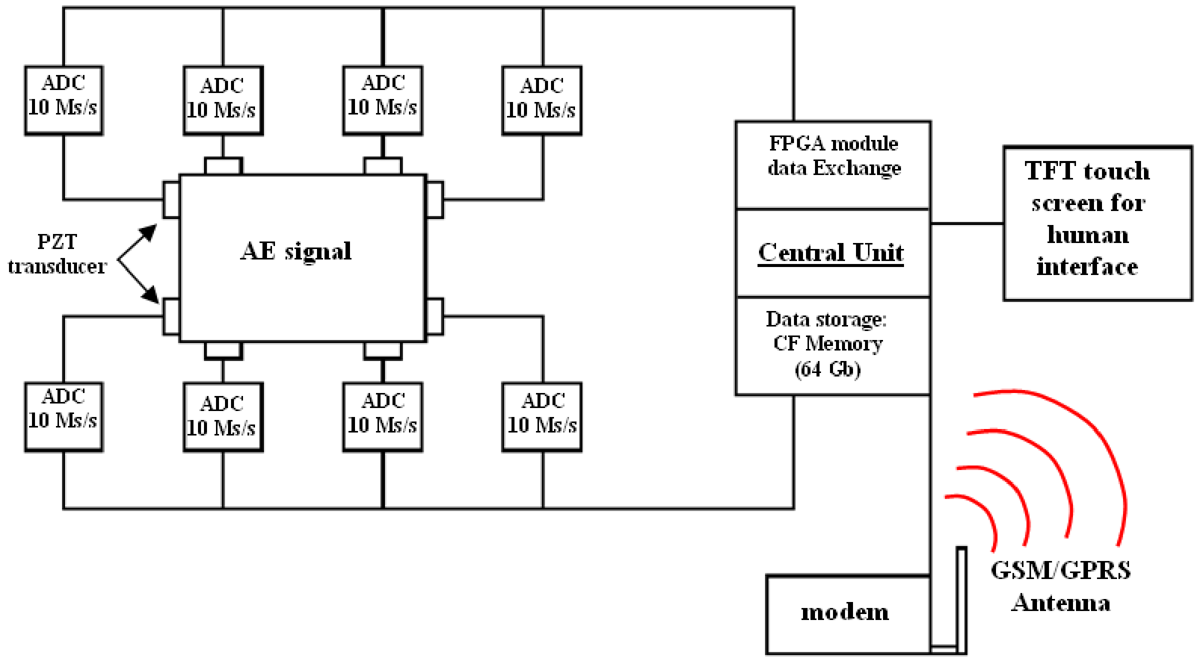

Figure 3: Scheme of the pre and post processing phase of the AE data transmission for the new AE equipment.

3 REAL TIME AE ANALYSIS: DAMAGE EVOLUTION

The new AE equipment perform automatically different kind of analysis. The first analysis are devoted to evaluate the damage evolution of the monitored structure. According to this objective different parameters are computed using the acquired data. The first indicator is represented by the cumulative number of AE signals *N,* detected during the monitoring time. In addition, the time dependence of the structural damage observed during the monitoring period, identified by parameter η, can also be correlated to the rate of propagation of the micro-cracks. If we express the ratio between the cumulative number of AE counts recorded during the monitoring process, *N*, and the number obtained at the end of the observation period, N_d , as a function of time, *t*, we get the damage time dependence on AE [1,2]:

$$\eta = \frac{E}{E_d} = \frac{N}{N_d} = \left(\frac{t}{t_d}\right)^{\beta_t} \quad (1)$$

In Equation (1), the values of E_d and N_d do not necessarily correspond to critical conditions ($E_d \leq E_{max}$; $N_d \leq N_{max}$) and the t_d parameter must be considered as the time during which the structure has been monitored. By working out the β_t exponent from the data obtained during the observation period, we can make a prediction as to the structure's stability conditions. If β_t<1, the damaging process slows down and the structure evolves towards stability conditions, in as much as energy dissipation tends to decrease; if β_t>1 the process diverges and becomes unstable; if β_t = 1 the process is metastable, that is, though it evolves linearly over time, it can reach indifferently either stability or instability conditions [6,7].

Damage assessment in the structure may be also investigated by the statistical distribution of the AE signal magnitudes fitted by the Gutenberg–Richter (GR) law [6,7]:

$$LogN\left(\geq M\right) = a - bM , \qquad (2)$$

where N is the number of AE events with magnitude greater than M, and a and b (or b-value) are fitting parameters. The b-value is an important parameter for damage assessment of structures as it decreases during damage evolution, reaching final values close to 1 when the failure is imminent [6]. The cumulative number of AE, the β_t exponent and the b-value are computed using the new AE equipment for a concrete notched beam subjected to three point bending. Eight piezoelectric transducers have been applied on the external surface of the beam. The experimental test was conducted using a servo-controlled machine (MTS) with a closed loop control. The three point bending test was realized by a linear actuator (hydraulic jack) with passing stem acting in the middle point of the upper side of the beam. For the test a concrete element measuring 1190×100×200 mm^3 was cast, a central notch of 100 mm was made starting from the middle point at the lower side and the beam was tested up to the final failure of the specimen (see Figure 4 and 5). The monitored notched beam has been conducted up to failure controlling the crack mouth opening displacement (CMOD) with an opening velocity equal to 0.002 mm/s.

The Load vs. Time diagram of the three point bending test is reported in Figure 5. The results of AE real time analysis are reported in Figure 6 for the monitered specimen. The cumulted number of AE computed using the new AE equipmnt shows a strong increment at the beginning of the test up to the final failure of the concrete beam.

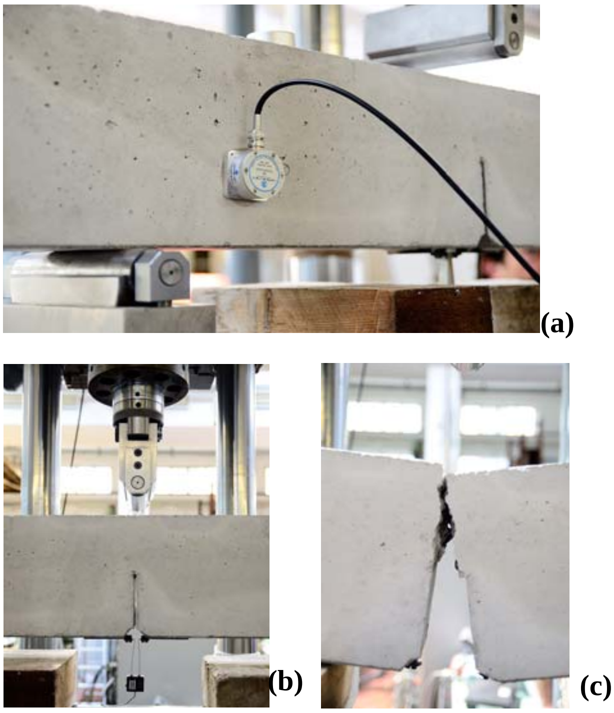

Figure 4: (a) New AE equipment applied to the monitored specimen. (b) Notched beam during the test. (c) Concrete beam after the final failure.

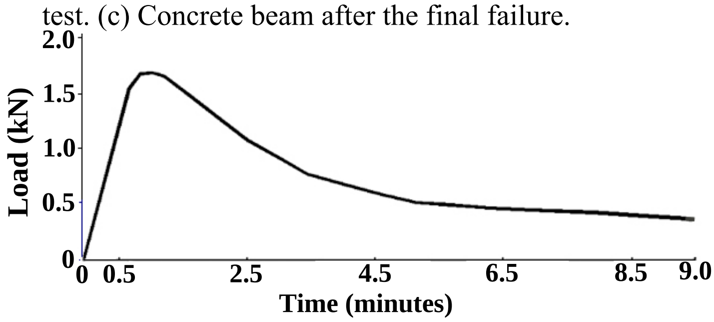

Figure 5: Load vs. Time diagram of the monitored beam.

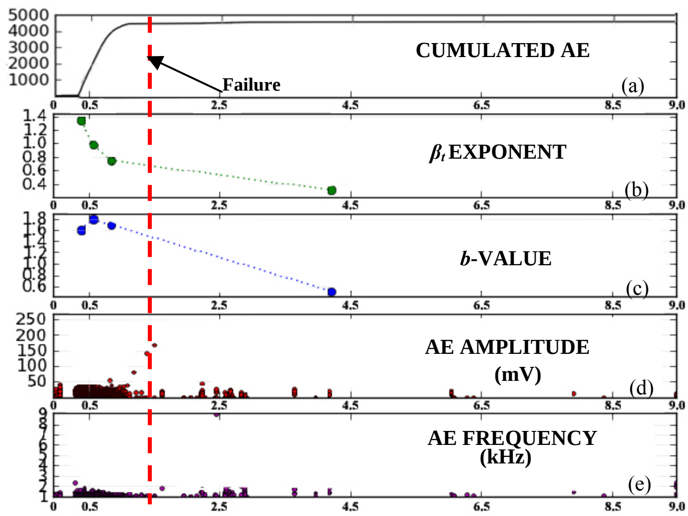

Figure 6: Real time AE analysis: cumulated AE 8a), β_t exponent (b), b-value (c), AE amplitude (d) and frequency (e) during time.

The parameter β_t is significant in correspondence to the phase before the failure of the beam (between 0 and 60 s). This exponent is very high, during the first 30 s (0.5 minutes), and, before the failure of the specimen, it showed a mean value greater than 1 corresponding to a situation in which the process diverges becoming unstable (Figure 6b). In correspondence to this phase the *b*-value decreases from higher values obtained at the beginning of the test down to values smaller than 1 (Figure 6c). This parameter shows a damage evolution from micro-cracks to macro-cracks with dimensions comparable to the beam section. The new automatic data acquisition system computes in real time also the AE amplitude and frequency (Figure 6d and e). From these data it is interesting to note that the AE amplitudes increased before the collapse (Figure 6d) with a maximum value of about 180 mV. At the same time, the AE signals trend showed a decay in the frequency domain up to the final failure of the concrete specimen.

4 POST PROCESS ANALYSIS: DAMAGE LOCALIZATION

The new AE monitoring system is also provided with a computer-based procedure, including the improved AE source location based on the Akaike algorithm [10-14]. These procedures are performed by automatic AE data processing and are used to evaluate the AE results in concrete notched beams subjected to three point bending loading conditions up to the final failure. Traditionally, picking the signal onset times was carried out by checking the signal traces based on analyst's experience. Nowadays, handling large volumes of digital and real-time data imposes less time consuming and equally objective alternatives. Here, the onset of AE signals is determined by modelling the noise and the signal in windows using the Akaike Information Criterion (*AIC*) with an automatic procedure for signal data processing able to eliminate false or doubtful onset times.

4.1 Basic principle of *AIC* criterion

Initially developed to predict the optimal order of the auto-regressive process fitting the time series in seismology [21-25], the *AIC* criterion can be used to demark the point of two adjacent time series (noise and signal) with different underlying statistics [26-31].

Suppose that a voltage time series $\{x_1, x_2,..., x_n\}$, containing the AE signal, is divided in two segments $i = 1,2$, $\{x_1, x_2,..., x_k\}$ and $\{x_{k+1}, x_2,..., x_n\}$, where k identifies the unknown signal onset time. Both segments are assumed to be two different pseudo-stationary time series, either modeled as an auto-regressive (AR) process of order M with coefficients $\{a^i_m\}$:

$$x_j = \sum_{m=1}^{M} a^i_m x_{j-m} + e^i_j \qquad i=1,2, \tag{3}$$

where $j = M+1, \ldots, k$ for interval $i = 1$ and $j = k+1, \ldots, n - M$ for $i = 2$.

The model divides either time series into a deterministic and a non-deterministic part e^i_j, the latter assumed to be a white noise. Thus, the time series $\{e^i_j\}$ is a sample of independent and identically distributed random variables, with mean zero, variance σ_i^2 and density function $f(e^i_j)=(\sigma_i 2\pi)^{-1/2}\exp[-(e^i_j/\sigma_i)^2/2]$, to which the maximum-likelihood estimation (MLE) can be applied. Then, we look at the joint density function of all variables $\{e^i_j\}$ — expressed in terms of the observations $\{x_j\}$ by means of Eq. (3) — considered as fixed parameters, whereas the model parameters $\Theta_i = \Theta_i(a^i_1,\ldots a^i_m, \sigma_i^2)$ for the *i*-th interval are allowed to vary freely. In this perspective, the joint density function is the likelihood function L [26-31]:

$$L(\Theta_1,\Theta_2,k,M|x) = \prod_{i=1}^{2}\left(\frac{1}{\sigma_i^2 2\pi}\right)^{n_i/2} \exp\left[-\frac{1}{2\sigma_i^2}\sum_{j=p_i}^{q_i}\left(x_j - \sum_{m=1}^{M} a^i_m x_{j-m}\right)^2\right] \tag{4}$$

where $p_1 = M + 1$, $p_2 = k + 1$, $q_1 = k$, $q_2 = n - M$, $n_1 = k - M$ and $n_2 = N - k - M$.

As it is known, the MLE finds the particular values of the model parameters which make the observed results the most probable or, in other words, which maximize the likelihood function L. Working equivalently with the logarithm of Eq. (4) and searching for the MLE of the model parameters we get:

$$\frac{\partial \ln L\left(\Theta_1,\Theta_2,k,M\left|x\right.\right)}{\partial\sigma_i}=0 \qquad i = 1, 2 \quad ,(5)$$

which has the solution:

$$\sigma^2_{i,max}=\frac{1}{n_i}\sum_{j=p_i}^{q_i}\left(x_j-\sum_{m=1}^{M}a^i_m x_{j-m}\right)^2 \; i=1, 2 \; .(6)$$

Inserting Eq.(6) into Eq.(4) we get the maximized logarithmic likelihood function [29-31]:

$$\ln L\left(\Theta_1,\Theta_2,k,M\left|x\right.\right)= -\frac{k-M}{2}\ln\sigma^2_{1,max}-\frac{n-k-M}{2}\ln\sigma^2_{2,max}+C_1 \qquad (7)$$

where C_1 is a constant.

The expression in Eq. (7) is the basis for the Akaike Information Criterion (*AIC*), in which the *AIC* function is defined as $AIC = 2P - 2\ln$(maximized likelihood function), where P is the number of parameters in the statistical model. Generally, a model with minimum *AIC* value is thought to be most suitable one among the competing models.

Originally this function was designed to determine the optimal order for an AR process fitting a time series. In the current application, the order M of the AR process is fixed, and therefore the *AIC* function is a measure for the model fit time. The point k where *AIC* is minimized, or L is maximized, determines the optimal separation of the two time series — the first representing noise and the second containing the signal — in the least square sense, and is interpreted as the onset time of the signal. In this sense, the *AIC* as a function of k is known as *AIC* picker [29]:

$$AIC\left(k\right)=\left(k-M\right)\ln\sigma^2_{1,max} +\left[n-k-M\right]\ln\sigma^2_{2,max}+C_2 \; , \qquad (8)$$

where C_2 is a constant.

Alternatively, the *AIC* value can be directly calculated from the signal without dealing with the AR coefficients. As $M \ll n$, Eq. (8) can be simplified [29]:

$$AIC(k)=k\ln(\mathrm{var}(x[1,k]))+ \left(n-k-1\right)\ln(\mathrm{var}(x[1+k,n])) \; , \qquad (9)$$

where k goes through all the signal trace and var is the sample variance.

As *AIC* picker finds the onset point as the global minimum, it is necessary to choose a time window that includes only the segment of interest of the signal. If the time window is chosen properly, *AIC* picker can find the first arrival of the signal (P-wave arrival for AE) accurately. In case of low S/N ratios (as for noisy EM signals) or more seismic phases (as P-wave and S-wave for AE signals) in a time window, global minimum cannot guarantee to indicate the first arrival of the signal. For this reason a pre-selection of this window is necessary to apply the procedure. Here, the onset time is firstly pre-determined using a threshold amplitude level:

$$\left(\sum_{k=i+1}^{10}\left|x_k\right|\right)/10\geq 4\left(\sum_{k=1}^{i}\left|x_k\right|\right)/i\, , \qquad (10)$$

The first value for the index k that makes relation (10) fulfilled is named k_0 and it is the first estimation for the onset time. This first estimation is always localized after the actual onset time. Thus, we apply *AIC* picker to the interval $[1,k_0]$ for a rough determination of the onset time, k_1. Then, the application of *AIC* picker to the time window with center in k_1 and width $2(k_1-k_0)$ gives the value k_{min}, which is regarded as the actual onset time of the analyzed signal.

4.2 Application of the improved *AIC*

4.2.1 Accuracy evaluation of the adopted procedure

Traditionally a minimum number of five transducers has to be employed to univocally determine the three source coordinates and the *P*-wave propagation velocity [7]. The corresponding system of nonlinear equations is solved by an iterative algorithm. Applying a least squares approach, time residuals at the different transducers are calculated and random measurement errors can be recognized [7]. The first stage in the localisation method consists in recognising the data needed to identify the AE sources, followed by the triangulation procedure. During the first stage, the groups of signals, recorded by the various sensors, that fall into time intervals compatible with the formation of micro-cracks in the volume analysed, are identified. These time intervals are obtained considering the difference between the onset times of the AE signals detected by the AE sensors. In the second stage, the triangulation technique can be applied if signals recorded by at least five sensors fall into the time intervals. The onset time determination can be obtained by the improved *AIC* shown in the previous section and can be included into the automatic localization procedure. Ad hoc tests were performed to reproduce AE using pencil breaks in small and predictable regions of a concrete specimen. A concrete cube with side length of 300 mm was cast at the Fracture Mechanics Laboratory of the Politecnico di Torino (Fig. 7). An array of seven AE sensors has been applied to the external surfaces of the concrete element (Fig. 7). In particular, a grid corresponding to 16 points (artificial sources) has been drawn on the upper face of the specimen (Fig. 7).

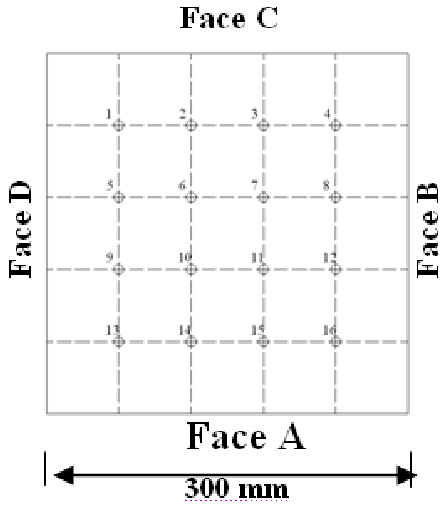

Figure 7: Concrete cube with AE sensors applied on lateral faces. A grid corresponding to 16 points (artificial sources) has been drawn on the upper face of the concrete cube measuring 300×300×300 mm^3.

The tip of a pencil has been broken for 5 times in correspondence to each of the sixteen points localized on the upper surface of the cube for a total of 80 measurements. From this experiment 560 AE events from the seven sensors were obtained for a comparative investigation. The onset times of the 560 events were picked manually as well as automatically using the *AIC* and the improved-*AIC* method shown in the previous section. The results of the localization are shown in Fig.8. It can be noted that the events localized with the *AIC* method are not all located close to the real positions of the pencil breaks (Fig. 8a). The events from the improved *AIC* method give more reliable results, although some of them are eliminated after the onset determination. Furthermore, in Table 1 the deviation of all the results obtained by the original *AIC*-picker and the improved *AIC*-picker are reported. Considering the results summarized in Table 1, it is possible to conclude that original *AIC*-picker presents a maximum deviation of 11% for y and z coordinates of the sources, the improved *AIC*-picker gives more accurate results, whose largest deviation is equal to 4%. The validity of the onset time determination using the improved *AIC* is confirmed to be effective in increasing the accuracy of the localization of AE sources in damaged concrete structures.

Table 1. Percentage deviation of localized points obtained by onset time determination using AIC and improved AIC respect to the manual determination.

Coordinates axis	*Manually*	*Original-AIC*	*Improved-AIC*
x	0.6%	9%	3%
y	0.9%	11%	3%
z	1.2%	11%	4%

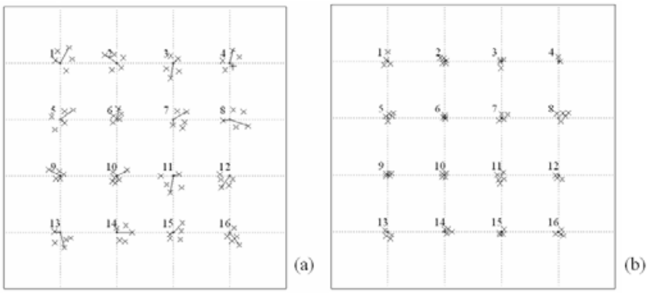

Figure 8: (a) Localization results using the original *AIC* and (b) using the improved *AIC* (maximum deviation of 4%).

4.2.2 AE automatic Localization: Results using the improved *AIC*

The improved *AIC* is also employed to determine the onset times of AE events generated during a three point bending tests of concrete beam monitored by the new AE equipment. In particular, seven AE piezoelectric transducers have been applied on the external surface of the element as shown in Figs. 9a and 9b. The onset times of the AE signals detected during the test are successively used in the localization procedure to determine the crack positions in the FRC element. The monitored notched beam has been conducted up to failure controlling the crack mouth opening displacement (CMOD) with an opening velocity equal to 0.001 mm/s. The geometrical characteristic of the beam and the testing scheme are reported in Fig. 9b,c and d. Concerning the AE monitoring, a total number of 26 AE points have been localized by means of the triangulation based on the improved *AIC*. A very good agreement is obtained between the localized points and the crack pattern configuration (see Fig. 9c and 8d).

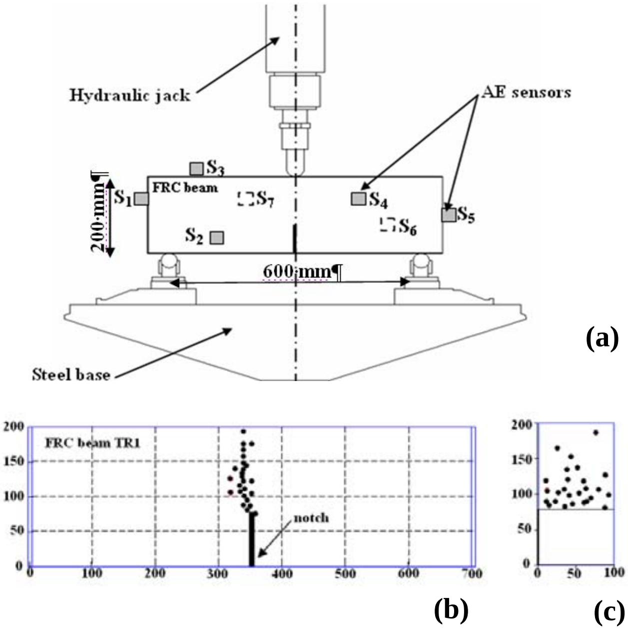

Figure 9: (a) Three point bending test and AE sensor positions. (b) Scheme of the test. (c,d) AE source localizations: During the tests, 26 AE sources have been localized by the improved *AIC* method.

The existing methods used for automatic picking of AE arrival time cannot check the accuracy of each detected AE signal. The improved *AIC*-picker here proposed allows to determine a degree of uncertainty useful to eliminate false or doubtful onset times. The results obtained during an ad-hoc experiment have shown that the deviations of the results obtained by the improved method present values ranging from 3% to 4% from the correct results. This evidence allows to consider the proposed method as the most accurate and suitable one among the onset determination methods of AE signal today available. In addition, the AE source location algorithm, based on the improved *AIC,* is included in the computer procedure of the new AE equipment described in Section 2. These method can be very useful for a telematic working approach, using the wireless transmission systems, where efficient algorithms for processing a very large amount of data are necessary.

5 CONCLUSIONS

The paper shows the capability of a new AE data processing system based on wireless AE data transmission. The new AE equipment can be employed to realize contemporary long term monitoring of different civil structures and to perform AE signal analysis in real time. This system, cost efficient, easy to install, and adaptive to different types of concrete structural and infrastructural networks, seems to be also very promising for seismic risk monitoring of civil structures and historical monuments. The AE cumulative number, the β_t exponent and the *b*-value have been computed in order to evaluate the damage evolution of concrete specimen subjected to three point bending tests. These analyses are the first parameter extrapolated from the AE data and represent damage indicators obtained in real time by the new AE equipment.

After the AE data acquisition it is possible to perform the localization of the AE sources (micro-cracks). This analysis represents the second kind of data available by the AE monitoring. The position of damage, infact, is particularly useful in damage evaluation of concrete and masonry structures. In particular, the onset of AE signals from rock fracture is determined through the joint auto-regressive modelling of the noise and the signal, and the application of the Akaike Information Criterion (*AIC*) using the onset time as parameter. This so-called *AIC* picker is able to find accurately the onset of genuine signals against the background noise. The presented study suggests the use of AE measurements to enhance monitoring, especially applied to micro-seismicity with potential applications in earthquake forecasting.

The monitoring system fine tuned could be used extending the acquisition to different kind of data in addition to AE signals. The data acquired from the sensor network will be sent electronically to a central server for real time monitoring of the condition of the buildings, by means of correlation algorithms applied to data from the different measured variables. This remote monitoring system will be maintained after the conclusion of the restoration work, allowing for detection and real time monitoring of possible structural deterioration processes of the buildings, thus constituting a useful tool for prevention of structural collapses. This monitoring system, if properly extended, may use the buildings as points of a network over the territory, useful for reducing the seismic hazard and securing entire metropolitan areas.

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