Chapter 30
Wireless Acoustic Emission Monitoring of Structural Behavior

A. Manuello, G. Lacidogna, G. Niccolini, and A. Carpinteri

Abstract The few non-visual methodologies make use of wired devices. Systems based on wireless transmission should be cost efficient and adaptive to different structures. The Acoustic Emission (AE) technique is an innovative monitoring method useful to detect damage, as well as to evaluate the evolution and the location 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 steel, 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 steel structures monitored during fatigue loading condition. 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.

Keywords AE monitoring • Telematic procedure • Damage evolution • Akaike algorithm • Seismic risk

30.1 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 of 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 unsafe. 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 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 (PZT) sensors, using crystals 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

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fracture process, to obtain information on the criticality of the process underway and to localize the damage source locations [7–16]. The different analysis were used to evaluate the damage of a steel double girder bridge crane subjected to service loads.

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, 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.

30.2 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, 17–20]. The final output of the AE data processing code returns a complete description of damage characterization and evolution [7, 17–20]. 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 structure 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. 30.1a, 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).

In Fig. 30.2a, 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. 30.3. Each channel consists of an Analog to Digital Converter module (ADC) with the capacity to acquire 10 (mega-sample/s) Ms/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. 30.3). Each channel, connected with the central processor, has a devoted memory of 64 Mb and is able to perform the data synchronization.

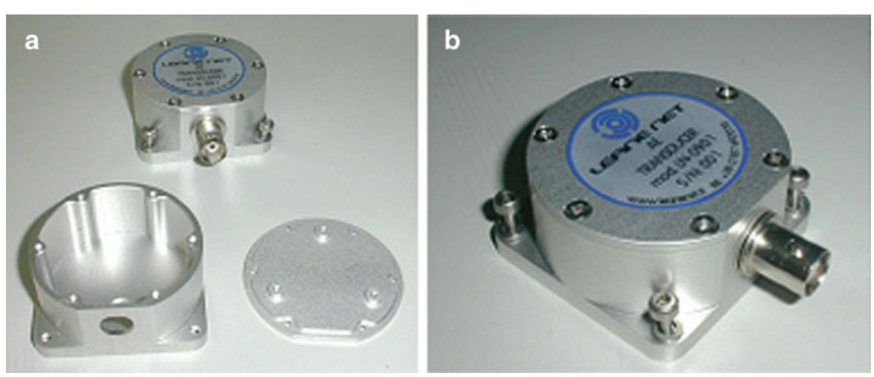

Fig. 30.1 (**a**) New PZT AE sensors. (**b**) The new AE sensors, working in a frequency range between 50 and 800 kHz, are designed to optimize weight, size, and applicability to different structural supports

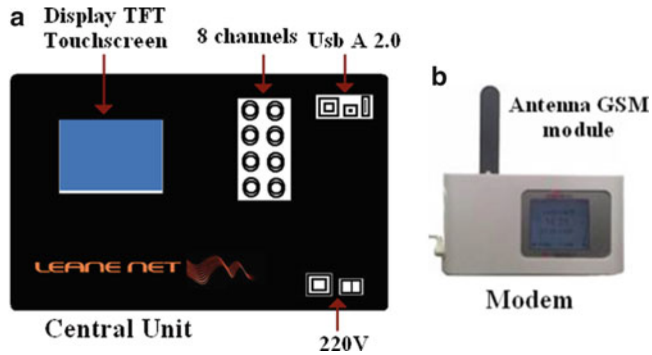

Fig. 30.2 Central Unit interface (**a**) Modem for AE wireless data transmission (**b**)

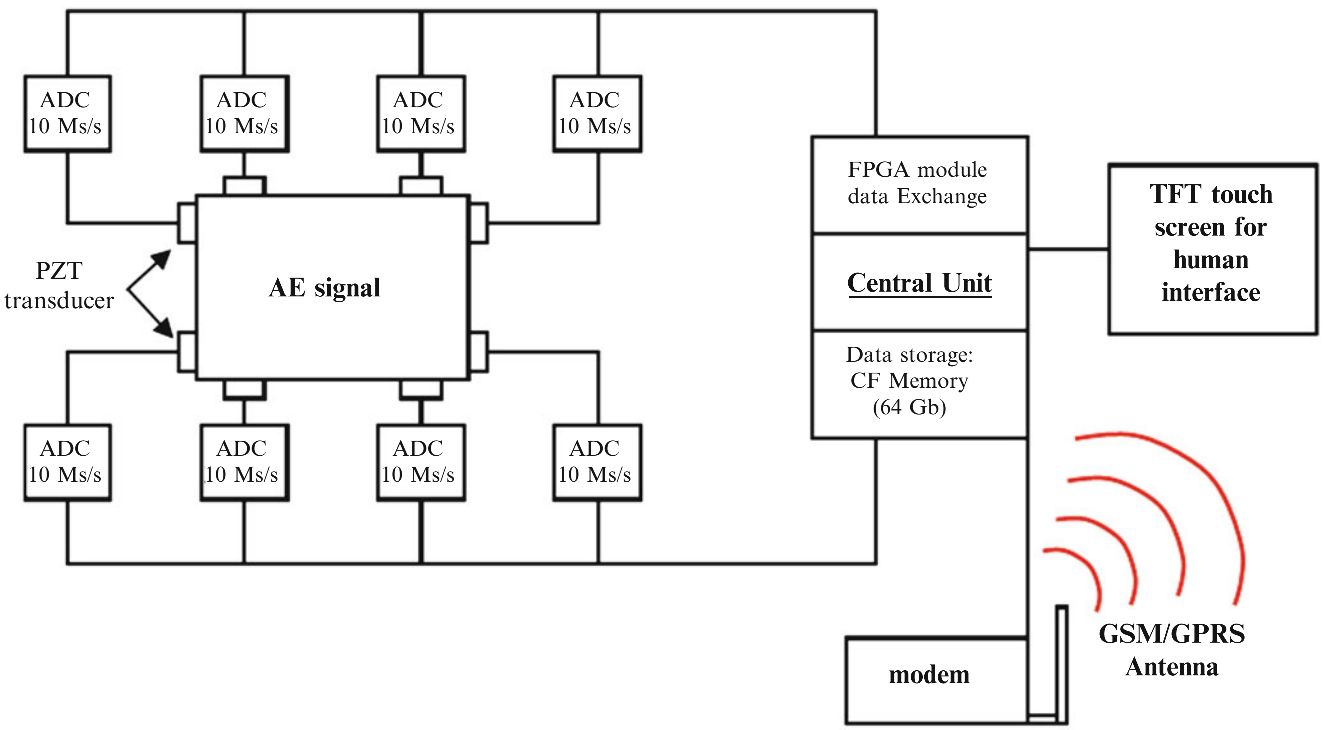

Fig. 30.3 Acquisition, pre-processing, and data transmission of AE signals for the new AE equipment

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. 30.2a). 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. 30.3), 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.

30.3 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]:

$$\eta = \frac{E}{E_d} = \frac{N}{N_d} = \left(\frac{t}{t_d}\right)^{\beta_t} \tag{30.1}$$

In Equation (30.1), the values of E_d and N_d do not necessarily correspond to critical conditions ($E_d \le E_{max}$; $N_d \le N_{max}$) 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 $\beta_t < 1$, the damaging process slows down and the structure evolves towards stability conditions, in as much as energy dissipation tends to decrease; if $\beta_t > 1$ the process diverges and becomes unstable; if $\beta_t = 1$ 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]:

$$LogN\,(\ge M) = a - bM, \tag{30.2}$$

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.

30.3.1 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 $\{x_1, x_2, \ldots, x_n\}$, containing the AE signal, is divided in two segments $i = 1,2$, $\{x_1, x_2, \ldots, x_k\}$ and $\{x_{k+1}, x_2, \ldots, x_n\}$, 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 $\{a^i{}_m\}$:

$$x_j = \sum_{m=1}^{M} a_m^i x_{j-m} + e_j^i \qquad i = 1, 2, \tag{30.3}$$

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 $\sigma_i{}^2$ 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. 30.3—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]:

$$\begin{gathered} L\left(\Theta_1, \Theta_2, k, M\,|x\right) = \prod_{i=1}^{2}\left(\frac{1}{\sigma_i^2 2\pi}\right)^{n_i/2} \\ \exp\left[-\frac{1}{2\sigma_i^2}\sum_{j=p_i}^{q_i}\left(x_j - \sum_{m=1}^{M} a_m^i x_{j-m}\right)^2\right] \end{gathered} \tag{30.4}$$

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. 30.4 and searching for the MLE of the model parameters we get:

$$\frac{\partial \ln L\left(\Theta_1, \Theta_2, k, M\left|x\right.\right)}{\partial \sigma_i} = 0 \qquad i = 1, 2, \tag{30.5}$$

which has the solution:

$$\sigma^2_{i,max} = \frac{1}{n_i}\sum_{j=p_i}^{q_i}\left(x_j - \sum_{m=1}^{M} a^i_m x_{j-m}\right)^2 \quad i = 1, 2. \tag{30.6}$$

Inserting Eq. 30.6 into Eq. 30.4 we get the maximized logarithmic likelihood function [29–31]:

$$\begin{aligned}&\ln L\left(\Theta_1, \Theta_2, k, M\left|x\right.\right)\\ &\quad = -\frac{k-M}{2}\ln\sigma^2_{1,max} - \frac{n-k-M}{2}\ln\sigma^2_{2,max} + C_1\end{aligned} \tag{30.7}$$

where C_1 is a constant.

The expression in Eq. 30.7 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. 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]:

$$\begin{aligned}AIC(k) &= (k-M)\ln\sigma^2_{1,max}\\ &\qquad + [n-k-M]\ln\sigma^2_{2,max} + C_2,\end{aligned} \tag{30.8}$$

where C_2 is a constant.

Alternatively, the *AIC* value can be directly calculated from the signal without dealing with the AR coefficients. As $M << n$, Eq. 30.8 can be simplified [29]:

$$\begin{aligned}AIC(k) &= k\ln\left(\mathrm{var}(\,x\,[1,k]\,)\right)\\ &\qquad + (n-k-1)\ln\left(\mathrm{var}(\,x\,[1+k,n]\,)\right),\end{aligned} \tag{30.9}$$

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:

$$\left(\sum_{k=i+1}^{10}|x_k|\right)/10 \geq 4\left(\sum_{k=1}^{i}|x_k|\right)/\,i, \tag{30.10}$$

The first value for the index *k* that makes relation (30.10) 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.

30.4 AE Monitoring of the Double Girder Bridge Crane

The monitoring results reported in the present study are devoted to the analysis of a steel structure consisted in a double girder bridge crane with a service load of 20×10^3 daN. The structure has over 30 years of service. The AE sensors were installed on one of the two beams of the bridge crane, a pair of sensors for each of the two ends, in correspondence of the supports, and the other four were positioned in correspondence of the middle part of the monitored element (see Fig. 30.4). The monitoring was carried out continuously for 120 h, from November 25 2013 to November 30 2013.

The absence of AE signals during the moving of the structure was verified considering the absence of the service loads. From the analysis of the AE time series it is possible to correlate the AE activity with the most intense activity of the crane. The β_t exponent indicated a substantial structural stability. At the same time the variability of the parameter b-value (between 3.8 and 2.8) is far from critical ($b = 1.5$) or collapse ($b = 1$) condition (see Fig. 30.5).

By means of the localization procedure reported in the previous section triangulation of the AE signals was carried out to identify the AE sources. The localization results are shown in Fig. 30.6, showing an asymmetric distribution of the AE sources, localized prevalently towards a semi-beam of the crane.

30.5 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 time 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

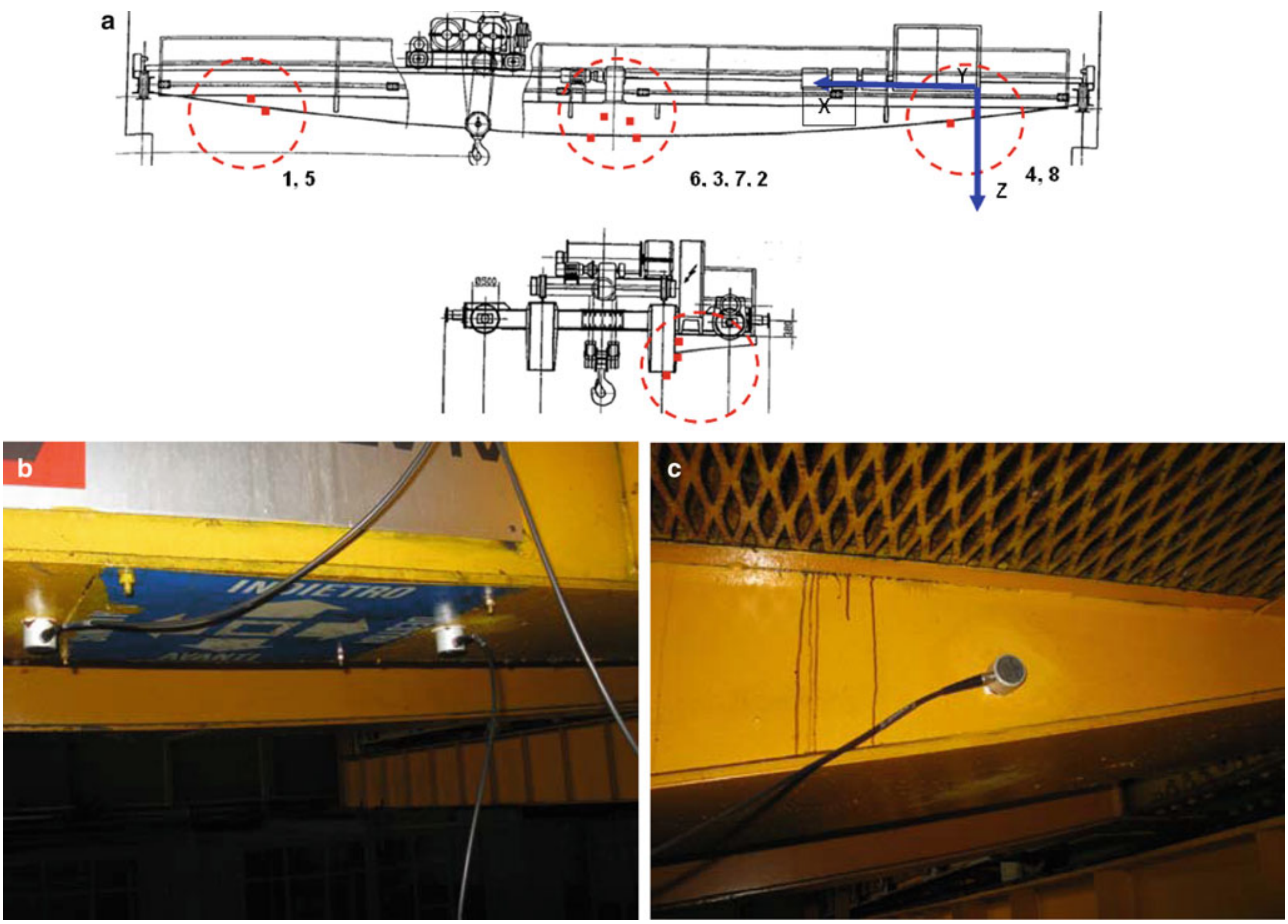

Fig. 30.4 Sensor positions on the double girder bridge crane (**a**). Application of the sensors in the middle of the beam (**b**) and in correspondence of the supports (**c**)

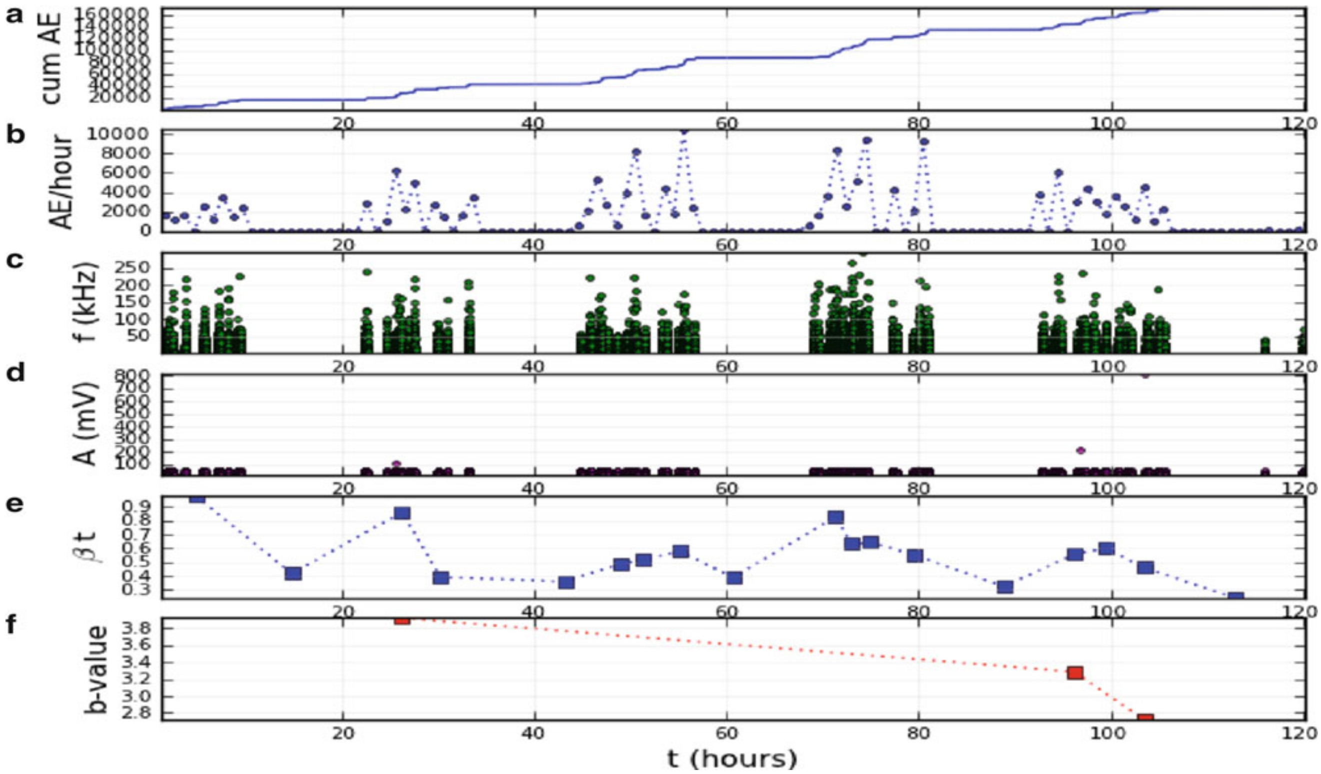

Fig. 30.5 AE cumulated number (**a**), AE number per hour (**b**), Frequency range of AE signals (**c**), Time series of AE amplitudes (**d**), β_t and *b*-value (**e, f**)

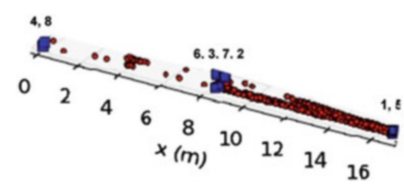

Fig. 30.6 Scheme of the sensor positions and Localization of the AE sources

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 in a double girder bridge crane subjected to service loads. These analysis 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 monitoring network on the territory, useful for reducing the seismic hazard and securing entire metropolitan areas by monitoring the seismic activity.

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