Materials and Structures (2006) 39:161–167
DOI 10.1617/s11527-005-9043-2

Damage monitoring of an historical masonry building by the acoustic emission technique

A. Carpinteri · G. Lacidogna

Received: 15 December 2004 / Accepted: 07 February 2005

Abstract Acoustic Emission (AE) of the materials that are subject to stress and strain states is a methodology for non-destructive investigation, originally applied to industrial steel structures. Here it is proposed by the authors for identifying the damage in masonry buildings.

This experimental method was used to monitor the masonry structure of an historical building, "Casa Capello", located in the centre of the Rivoli Municipality (near Turin, Italy). This house, built on pre-existing 14th century foundations, was thoroughly restructured at the end of the 18th century and has recently undergone restoration and enlargement works.

Non-destructive AE tests were carried out on a few masonry portions of the building in order to evaluate and define the development of the cracking phenomena which had been observed in a number of structural parts after the collapse of a breast wall on the down hill side of the building. With the measurement system adopted, entailing no loading or invasive procedures, it proved possible to predict the arrest of crack growth and the concomitant onset of a new stability condition.

Résumé *L' Emission Acoustique (EA) des matériaux qui sont sujets à pression et à déformation est une méthodologie de recherche non-destructive appliquée originairement aux structures industrielles d'acier. Les auteurs proposent dans leur travail la technique de l' EA pour l'identification des dommages des constructions en maçonnerie.*

En employant cette méthodologie a été possible le monitorage de la structure en maçonnerie de "Casa Capello", une construction historique située au centre de la petite ville de Rivoli (près de Turin, Italie). La maison, qui s'élève sur la préexistante fondation du XIVième siècle, a conservé son actuelle physionomie à partir de la fin du XVIIIième siècle et récemment a été restaurée avec des travaux d'extension fonctionnelle.

Avec le procédé non-destructif de l'EA on a examiné des éléments en maçonnerie de la construction pour évaluer et établir le développement des fractures relevées sur ceux éléments structuraux après le tassement d'un mur de soutènement. Grâce à l'utilisation de cette méthodologie du monitorage EA, en évitant des procédés envahissants ou destructifs, a été possible une prévision de l'arrêt du développement des dommages structuraux et par conséquence l'établissement d'une nouvelle stabilité statique.

Dr. Giuseppe Lacidogna
Department of Structural Engineering and Geotechnics,
Politecnico di Torino,
corso duca degli abruzzi, 24
10129-torino(italy)
e-mail: giuseppe.lacidogna@polito.it
tel. +390115644871

1. Introduction

Nowadays, non-destructive and instrumental investigation methods are widely used to measure and monitor the evolution of adverse structural phenomena, such as damaging and cracking, and to predict their subsequent developments [1]. Originally developed for use in industrial steel structures, a non destructive testing method which uses the acoustic emission technique for defect and damage identification has now been extended to masonry structures. In particular, it is used to monitor the conditions of components subject to tension and distortion states [2, 3]. The onset of damage in a structure is in fact preceded, and accompanied, by an emission of elastic waves that spread in the material and can be received and recorded by sensors applied to the external surface.

Using this experimental method it proved possible to monitor the masonry structure of a building rising in the historical centre of the Rivoli Municipality (near Turin, Italy), and to evaluate the damage level and the evolution of the cracking process.

2. The building investigated

2.1. General

The historical building known as “Casa Capello” is presently a hospice for elderly people, Fig. 1. Interventions were carried out for its restoration and functional extension in the years 1996–1999, based on a design project by Professor Andrea Bruno. The building rises in an area situated in the historical centre of Rivoli, delimited by Via alla Parrocchia and Via Stella Maris, approximately half way between the Rivoli Castle hill and the valley floor.

Fig. 1 “Casa Capello” in Rivoli (Turin); in the background the bell tower of the Collegiata, in the foreground the breast wall that collapsed during the restoration works.

The building, which looks on the Medieval Church of the Collegiata, was erected on pre-existing foundations dating back to the 14th century and was drastically restructured in the 18th century, when it acquired its present appearance. The main construction is a masonry building which follows the slope of the land and has three storeys facing the streets and two storeys looking on the inner courtyard. The restoration works performed on this complex took into account its historical and architectural values and respected its sober styling by making changes and additions that blended in with the existing volumes.

2.2. Structural classification of the building

The building reflects the classical design of 18th century masonry structures. The original body, along Via Stella Maris, has partition walls which determine a box-like resisting frame specially designed to distribute the loads evenly, Fig. 2.

The thickness of the masonry walls is constant throughout, from the basement to the third floor above ground, and always at least 60 cm. The walls are made of bricks, of average size for Italian historical buildings (about 5.5 × 12.5 × 25 cm), with interposed mortar joints ca 1 cm thick. The distribution of the windows, on the front, is regular, with no discontinuity, Fig. 3. The roof structure consists of solid wooden beams.

It is interesting to note that, before the restoration and consolidation works, the attics used wooden plank-

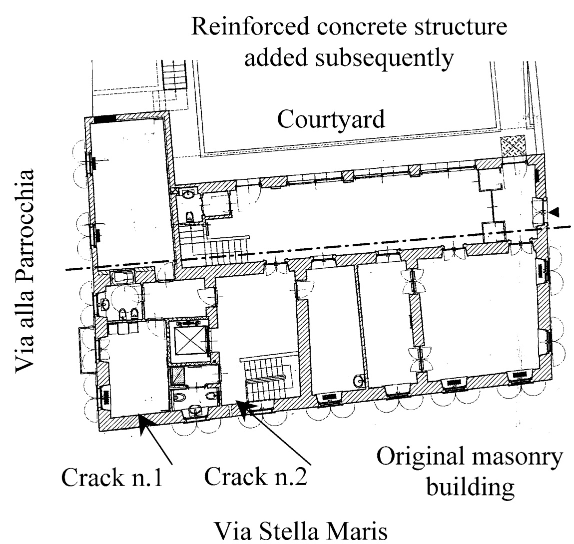

Fig. 2 Plan of the building.

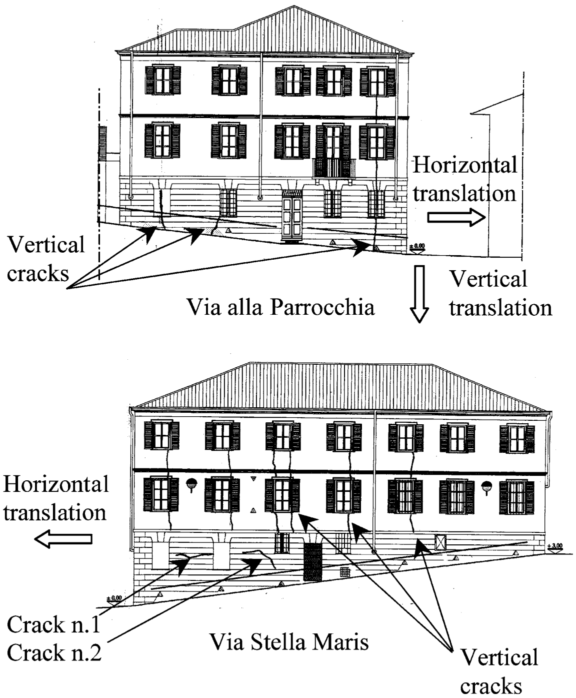

Fig. 3 Views of the building with the respective crack configurations.

ing, as was customary in many historical buildings of the City of Rivoli. Only the underground floor, which has retained its original 14th century configuration, has masonry vault.

3. Damage and cracking conditions of the building

During the restoration works of "Casa Capello", an unexpected accident caused a partial collapse of the breast wall on the down hill side of the building, which altered the equilibrium of the substructures. The damages were immediately repaired by reconstructing the breast wall and strengthening the soil under the wall. Nevertheless, following the accident, a diffused network of cracks began to form in the masonry of the original building structure, with capillary fissures propagating through the masonry front.

The cracks are particularly evident in the masonry walls facing Via Stella Maris and Via alla Parrocchia, Fig. 3. On the building facade looking on Via Stella Maris, the cracks reveal a predominantly vertical pattern affecting the weakest zones of the masonry at the windows. On the internal surface of the same structure,

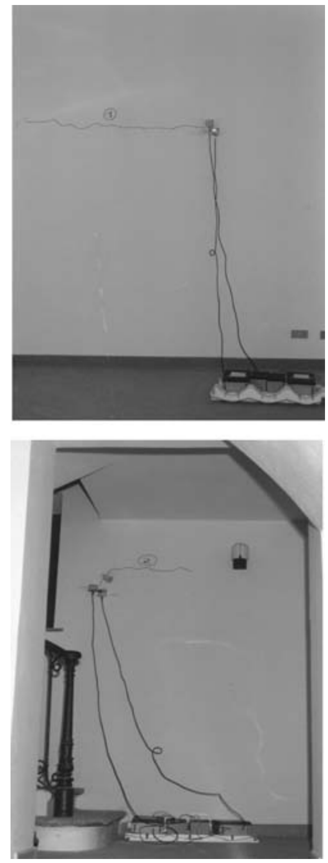

Fig. 4 Cracks n. 1 and n. 2 in the inner wall; PZT transducers placed at the tip of the cracks and AE monitoring equipment

two noticeable cracks appeared, following a horizontal pattern, about 1.8 m above the basement floor. The first (crack n. 1) opened in a room about 2 m from the corner of the building; the second (crack n. 2) in an adjacent staircase room, about 2 m from the first.

These two cracks propagated slowly, and therefore it was possible to monitor them with the acoustic emission technique, Fig. 4. The cracking pattern in the masonry facades along Via Stella Maris and Via alla Parrocchia can be accounted for by assuming a relative translation of the terminal portions of either sides of the facades, due to the subsidence of the edges of the building brought about by the collapse of the breast wall [4].

4. The acoustic emission technique

4.1. Basic information

The spontaneous generation of pressure waves by material under loading is called Acoustic Emission (AE).

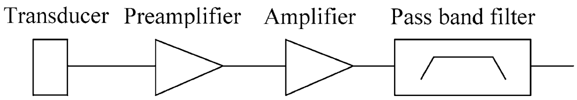

Fig. 5 Acoustic Emission measurement system.

This phenomenon, originally employed to detect cracks and plastic deformations in metals [12], is the object of studies and research in the field of rocks mechanics and can be used for diagnosing structural damage phenomena in concrete and masonry structures [3, 5, 6]. As a rule, AE monitoring is performed by means of piezoelectric (PZT) sensors, using crystals that give out signals when subject to a mechanical stress, Fig. 5. The amplitude of the elastic pressure waves, which varies from one material to another also by orders of magnitude, is usually very weak, less than a millionth (10^{-6}) of the atmospheric pressure. Accordingly, the electric signals emitted by the transducers have to be amplified greatly (10^4 or 10^5 times) before they can be processed [7, 8, 16].

4.2. Analysis of AE signals

The signal from the transducers is preamplified, converted into electric voltage and then filtered to eliminate unwanted frequencies, such as the vibrations due to the mechanical instrumentation, which are generally lower than 100 kHz, Fig. 5. Up to this point the signal can be represented as a damped oscillation, Fig. 6. The AE signals collected during the experimentation are composed of thousands of such damped oscillations. Therefore, the signals are analysed by a threshold measurer which counts the oscillations exceeding a predetermined voltage level, measured in volt (V) [13].

This method of analysis is called Ring-Down Counting and is widely used for the identification of defects with the AE technique [9, 10, 11]. As a first approximation, the counting number (N_T) can be assumed to be directly correlated to the quantity of energy released during the loading process and it can be assumed that its increase is proportional to the crack growth [10]. Needless to say, this technique also relies on ancillary procedures, e.g., taking into account the characteristics of the transducer and, in particular, its damping action. It can be assumed that all the oscillations produced by a single AE signal belong to a single event, Fig. 7 [12].

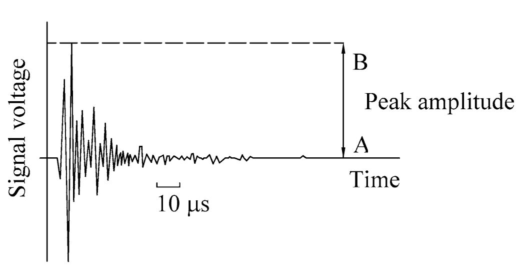

Fig. 6 AE signal identified by the transducer.

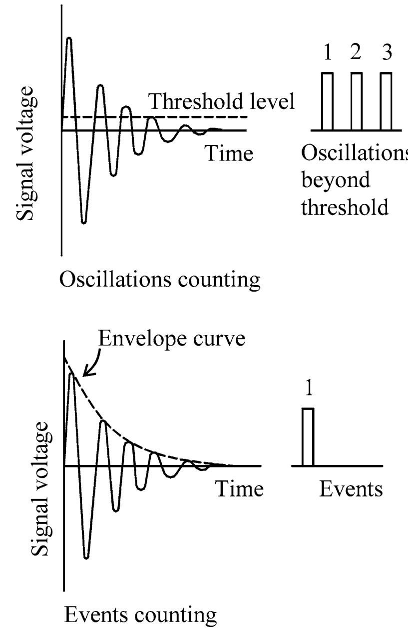

Fig. 7 Counting methods in AE technique.

5. Damage monitoring

5.1. Equipment

The measurement system used for the monitoring of the fissures (cracks 1 and 2) and counting the oscillations consists of four piezoelectric (PZT) transducers, calibrated on inclusive frequencies between 100 and 400 kHz, and four control units, fitted with a preamplifier, a signal amplifier with a pass-band filter, a measurer of the threshold level, a recorder and an oscillation counter. The system does not provide for the analysis of signal frequency.

The threshold level for the signals recorded by the equipment, fixed at 100 μV, is amplified up to 100 mV [13]. The amplification gain, given the relationship dB $= 20 \log_{10} E_u/E_i$, where E_u/E_i, is the ratio between the input voltage and the output voltage, turns out to be 60 dB. This is the signal amplification value generally adopted in monitoring AE events in concrete [12, 15]. The oscillation counting limit has been fixed at 255 oscillations every 120 seconds [2, 3]. From the literature we know that the duration of a signal emitted during the cracking of a non-metallic material, like concrete, is around 2000 μs [12] and that the maximum amplitude of a direct non-amplified signal is of the order of 100 μV [14], hence, neglecting the attenuation by reducing to a few cm the distance of the transducers from the signal generation point, it can be assumed that the system of measurement is able to detect the most meaningful AE events reflecting cracking phenomena in the masonry. Attenuation properties, in fact, depend on the frequency range: higher frequency components propagate in masonry with greater attenuation. Based on experimental results, for a measuring area at a distance of 10 m, only AE waves with frequency components lower than 100 kHz are detectable [12].

5.2. Monitoring crack n. 1

The evolution of crack n. 1 was monitored over a total of about 900 h. The date on which the equipment was first applied and the date on which it was definitely removed are specified in Fig. 8. The same figure also shows the trajectory of the crack at the time of initial application of the measuring system and the growth of the crack, expressed in cm. As can be seen, the crack displays a nearly horizontal development and retains a constant opening of about 0.2 mm during its evolution.

The wall in which this crack developed, including the external plaster, was about 60 cm thick and was made of bricks with mortar joints of about 1 cm. During the strengthening works, a concrete wall ca 5 cm thick was built adjacent to the inner face of the masonry in order to improve the compressive strength of the wall.

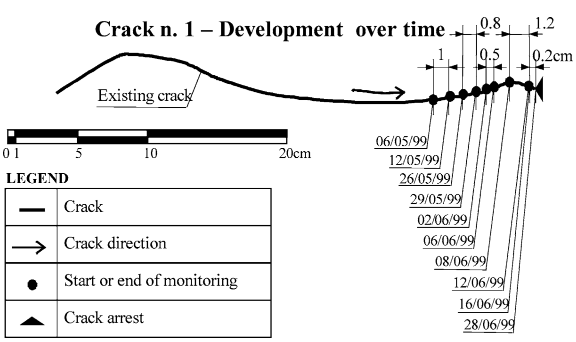

Fig. 8 Evolution of crack n. 1.

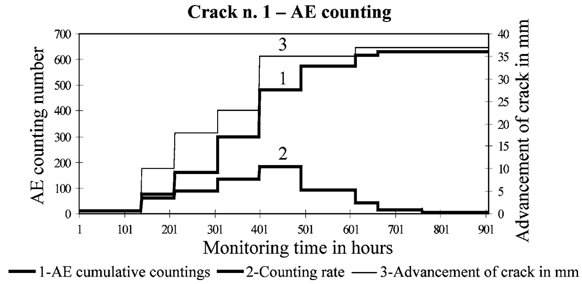

Fig. 9 Crack n. 1 monitoring results.

To collect the AE signals two transducers were applied with their centres of gravity at ca 3 cm from the crack tip (to reduce the signal attenuation due to the distance), Fig. 4. A curve illustrating the cumulative countings (N_T) of AE events measured during the monitoring period is shown in Fig. 9. This curve is juxtaposed to the curve illustrating crack growth in mm.

All the signals with an amplitude equal to or exceeding the 100 μV threshold, detected by the transducers during each monitoring stage, have been taken into account in the oscillations count. The data plotted in the diagram has been determined from the average values obtained from the pair of transducers. As can be seen from the diagram, the counting number is proportional to the growth of the crack during every phase of the monitoring process and the fading of the counting rate clearly denotes the arrest of crack propagation. The same diagram also shows that the maximum counting rate was recorded when the velocity of crack growth was highest. After this event, the number of countings and crack velocity quickly decreased to zero. Hence, it can be inferred that the peak of the AE distribution function corresponded to the most critical period of crack growth. Then the crack approached a stability condition, as it progressed towards the compressed zones of the masonry.

The effectiveness of the monitoring method is also due to the fact that the crack evolved slowly, at an average velocity of ca 0.04 m/h, and developed in an area very close to the sensors. If it had propagated rapidly and moving away from the sensors, many signals might have escaped detection due to the attenuation effect. More complex AE techniques have to be used in these circumstances, that can keep track of the tip of the crack during the propagation process by using more sensors

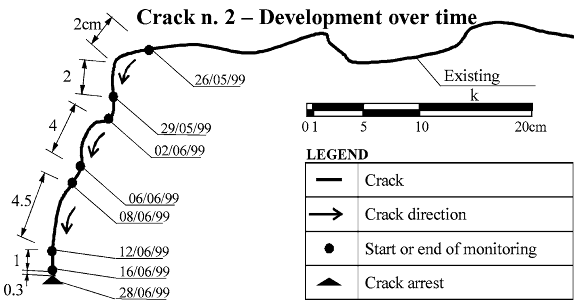

Fig. 10 Evolution of crack n. 2.

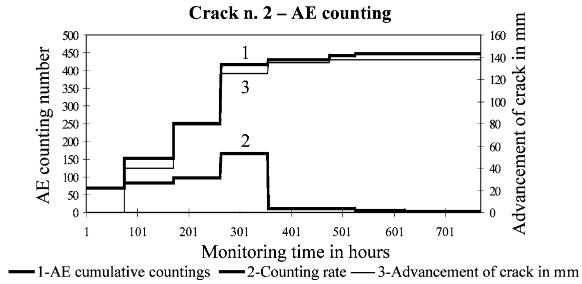

Fig. 11 Crack n. 2 monitoring results.

(at least six) distributed over a wide area of the structural element analysed [14,17].

5.3. Monitoring crack n. 2

Crack n. 2 was monitored over a total of ca 800 h. Fig. 10, illustrating the development of the crack and its growth over time, also shows the dates on which the transducers were first applied and the monitoring was discontinued.

In this case, we can see that the crack, after running horizontally over some distance, has undergone an oblique deviation, maintaining a constant width of about 0.2 mm throughout its development. The masonry where this second crack developed is 60 cm thick, is made of bricks and does not show any additional consolidation work.

For the monitoring of crack n. 2, a pair of transducers placed at 3 cm from the crack tip, Fig. 4, was also used. As in the previous case, during each monitoring stage, the oscillations count considered all the signals having an amplitude equal to or exceeding the 100 μV. Again, the crack evolved very slowly at an average velocity of 0.17 mm/h. In this case too, we observe that the cumulative counting number (N_T) is approximately proportional to the growth of the crack and that crack arrest coincides with the damping of the significant oscillations, Fig. 11.

The emission rate confirms that the maximum number of oscillations coincides with the maximum growth rate of the crack. Subsequently, a deceleration takes place and the counting rate, as well as crack velocity, quickly decrease to zero. The crack growth vs. time diagram shows a final stage denoting a stable behaviour, the same as is observed in the diagram of cumulative AE countings versus time.

5.4. Comparison between the monitoring results

In a loading process involving the propagation of a crack, even if the attenuation due to the distance of perception of the signals is overlooked, the energy measured by the AE technique through the oscillations count is proportional to the energy released during the damaging process.

Correlation diagrams (independent of time) between crack growth and the number of AE events recorded are shown in Fig. 12. In this manner, the behaviour of the two masonry structures during the cracking process can be compared at glance.

It can be seen that, over the same length, crack n. 2 released much less energy than crack n. 1, indicating that the toughness of the material where it developed was greater. For crack n. 2, the correlation values between crack growth and number of AE events are farther from the average line than the values obtained for crack n. 1. A higher scatter shows that the material crossed by crack n. 2 (bricks masonry) is more heterogeneous and therefore tougher than the material crossed by crack n. 1 (the thin concrete wall).

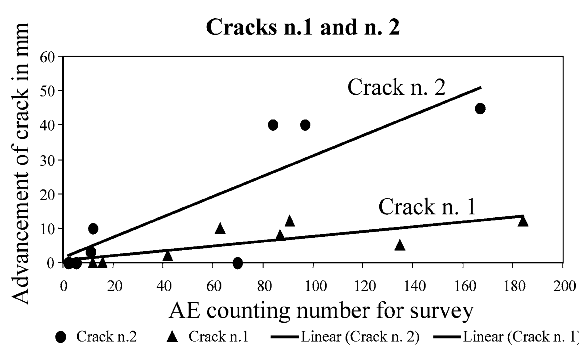

Fig. 12 Number of AE events vs. crack growth.

6. Conclusions

In view of the appreciable number of old structures still in use today, greater attention should be paid to preservation and rehabilitation issues. A sound safety assessment cannot be based solely on the visual observation of cracks and signs of damage in structural elements. The evolution and interaction of different damage phenomena should be considered instead. This is why structural monitoring is taking on ever greater importance in reliability assessment processes: in this connection, the AE technique can be highly effective.

In this work we have described how the AE technique can be used to monitor large structural elements of historical masonry buildings. In particular we have proposed an innovative methodology, based on the counting of AE events, for the determination of the quantity of energy released by the masonry, and hence its stability conditions or the risks arising from defect propagation.

By correlating the evolution of the cracks with the cumulative counting of AE events (N_T), we ascertained that crack growth underwent a progressive deceleration as the cracks progressed towards the compressed zones of the masonry, up to total arrest. The AE monitoring method was able to predict that the building structures would reach stability conditions with crack arrest.

This monitoring method that compares the extent of structural damage with the energy released during crack propagation is easy to use and proves particularly effective in the case of slow propagation. In this case, in fact, by placing the sensors near the crack tip it becomes possible to avoid the attenuation effects due to the distance between the source and the receiver apparatus, which might entail the possible loss of AE signals. If the cracks are not visible on the outer surface of the structure, or evolve at higher speed, more complex AE techniques can be used that make it possible to locate the source of the damage.

Acknowledgements The authors wish to thank Professor Andrea Bruno for allowing the monitoring of the building "Casa Capello", and Architects Cirino Leotta, Luigi Bacco and Massimo Aprile for the support provided to the realisation of this study.

References

1. Carpinteri A, Bocca P (1991) Damage and diagnosis of materials and structures. COREP, Consorzio per la Ricerca e l'Educazione Permanente: Politecnico di Torino.
2. Carpinteri A, Lacidogna G, Pugno N (2004) Damage diagnosis and life-time assessment of concrete and masonry structures by an acoustic emission technique. In Proc. of 5th Intern. Conf. on Frac. Mech. of Concr. and Concr. Struct. (FraMCos-5), Vail, Colorado-USA (Eds. V. C. Li, C. K. Y. Leung, K. J. Willam, S. L. Billington, 2004) pp. 31–40.
3. Carpinteri A, Lacidogna G (2003) Damage diagnosis in concrete and masonry structures by acoustic emission technique. J. Facta Universitatis 3:755–764.
4. Mastrodicasa S (1993) Statical failures in building structures. Ulrico Hoepli Editore, Milano. Only available in Italian.
5. Hendry AW, Royles R (1991) Model tests on masonry arches. In Proc. Instn. Civ. Engrs., Part 2, 91, pp. 299–321.
6. Royles R (1991) Acoustic emission monitoring of masonry arch bridges. British Journal of NDT 33(7):339–343.
7. Tipler AP (1976) Physics. Worth Pubblishers, New York.
8. Holroyd T (2000) The acoustic emission & ultrasonic monitoring handbook. Coxmoor Publishing Company, Oxford.
9. Swindlehurst W (1973) Acoustic emission-1: introduction. Non-Destructive Testing 6:152–158.
10. Pollock AA (1973) Acoustic emission-2: acoustic emission amplitudes. Non-Destructive Testing 6:264–269.
11. Brindley BJ, Holt J, Palmer IG (1973) Acoustic emission-3: the use of ring-down counting. Non-Destructive Testing 6:299–306.
12. Ohtsu M (1996) The history and development of acoustic emission in concrete engineering. Magazine of Concrete Research 48(177):321–330.
13. Carpinteri A, Lacidogna G, System for the assessment of safety conditions in reinforced concrete and masonry structures. Italian Patent No. To 2002 A000924, registered on 23 October 2002.
14. Shah P, Zongjin L (1994) Localization of microcracking in concrete under uniaxial tension. ACI Materials Journal 91(4):372–381.
15. Carpinteri A, Lacidogna G, Pugno N (2004) A fractal approach for damage detection in concrete and masonry structures by the acoustic emission technique. Acoustique et Tecniques 38:31–37.
16. Associazione Italiana di Metallurgia (1984) Non Destructive Testing, Milano. Only available in Italian.
17. Carpinteri A, Lacidogna G, Paggi M, Pugno N Acoustic emission monitoring and numerical modeling of a FRP-strengthened concrete structure. Proc. of the Intern. Conf. on Concrete Repair, Rehabilitation and Retrofitting (ICCRRR 2005), Cape Town, South Africa, 2005. (In Press).