Accuracy of Acoustic Emission Localization for Masonry Structures Monitoring

Jie Xu[1*], Qinghua Han[1], Giuseppe Lacidogna[2], Alberto Carpinteri[2]

[1] School of Civil Engineering, Tianjin University, Tianjin, 300072, China
[2] Department of Structural, Geotechnical and Building Construction, Politecnico di Torino, Turin, 10129, Italy
* Corresponding author: jie.xu@polito.it

Abstract Acoustic Emission (AE) is a promising non-destructive monitoring technique to investigate the damage location and to evaluate the structural health conditions. Based on the tests performed on a masonry bridge, three ingredients −sensor distribution, onset time determination and degree of inhomogeneity− affecting the accuracy of AE localization are discussed. The test result shows a reasonable sensor arrangement is of great importance for the localization capability. The highest accuracy can be achieved for damage sources localized among the sensor distributions. Distances of sources far from the sensor network are less accurate. Onset time determination of an AE signal is another important factor in this technique. A widely used approach, based on the Akaike Information Criterion (AIC), is confirmed to provide more reliable onset time determination of AE signals. Moreover, the inhomogeneity of the test object may lead to errors in the ultrasonic wave travelling model. Different-scale fluctuations and structure variations in the composite structure can result in random variations of the propagation velocity and systematic errors. A new proposed parameter, the degree of inhomogeneity ξ, introduced into the classical method, can effectively decrease the crack localization unavoidable errors due to inhomogeneities in masonry material.

Keywords Acoustic emission, masonry structures, crack localization, structural health monitoring.

1. Introduction

Various masonry structures, such as towers, bridges and historical buildings are widely distributed all over the world. As a consequence of building with old techniques, long-time exposing to the environmental conditions and changing loading regimes, many of these masonry structures are placed in repair and strengthening programs [1, 2]. Prior to repair and rehabilitation, inspections of the structures to estimate the current state in service are essentially required. As one of the non-destructive evaluation and diagnostic techniques, Acoustic Emission (AE) technique is gradually employed in the masonry monitoring [2-5].

Within civil engineering practice, the AE technique is a widely applied non-destructive technique for the detection of damage onset and growth [6, 7]. AE is the class of phenomena whereby transient elastic waves are generated by the rapid release of strain energy when damage occurs within a material. By investigating onset times and other characteristics of acoustic signals, AE techniques provide an insight into the deterioration processes of a tested object [8]. As the onset times of AE signals at different sensors are linked to the propagation speed inside the material, algorithm can be used to locate the emitting sources and to predict their subsequent development [1, 9]. AE is widely used for monitoring metallic [10], rock [11, 12] and concrete structures [13, 14], because AE is well suited for homogeneous or qusai-homogeneous materials with good acoustic transmission. However, its application in heterogeneous materials such as masonry is much problematic [15].

This paper presented the recent research about the accuracy of the crack localization of AE technique in masonry structure, which is one of the most important and challenged topics in AE applications. The application of AE monitoring in masonry structure is highly complicated, as attenuation and wave propagation are dependent on the heterogeneity of the material. Besides, the presence of voids, cracks and cavities does also influence the AE detection itself. The AE waves, generated at the other side of a large crack to which the sensors are placed, will generally not be detected by AE sensors. This, for example, would be the case between the disconnected layers of a multiple-leaf wall, which is often encountered in historical masonry structures. All these ingredients make the source localization in masonry structure rather difficult [9].

In order to address these issues regarding damage region assessment in masonry, a series of tests were designed and carried out on a masonry model bridge. The results for the tests are discussed in this paper.

2. Source location of AE events and classical localization method

Localization of AE sources is important to assess the regions of active damage in the monitoring technique. Location problems are usually solved by various triangulation techniques based on mathematical analysis of acoustic wave trajectories [16]. This analysis cannot be simply performed if the structure of tested specimen is geometrically complicated. Generally, these techniques depend on the mode of propagation, the elasticity modulus, and signal attenuation due to the heterogeneity and anisotropy of material. In this Section, a general overview on the classical localization method and the corresponding knowledge is depicted.

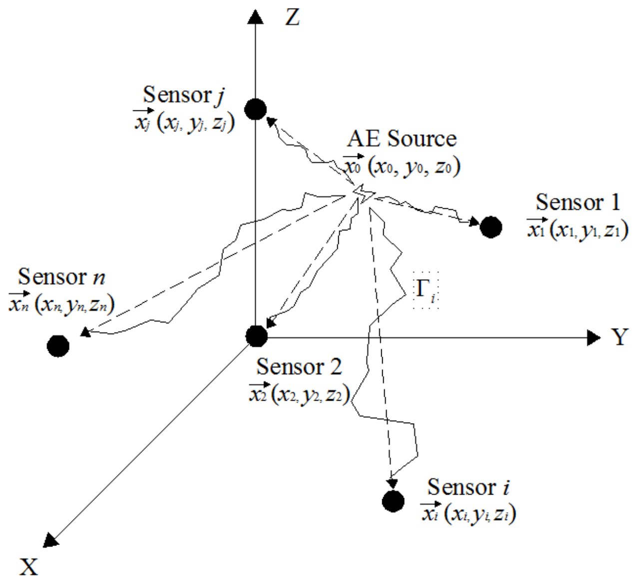

Figure 1. Localization of point AE source involving a generic array of *n* sensors.

As shown in Fig. 1, in a theoretical model with wave propagation velocity v_{Pi}, the onset time t_i^* at sensor $\vec{x}_i$, unknown crack coordinates $\vec{x}_0$ and origin time t_0 can be estimated by an integral along the actual ray path Γ_i:

$$t_i^* = t_0 + \underbrace{\int_{\Gamma_i} (d\Gamma_i / v_{Pi}(\mathrm{r}))}_{\mathrm{I}}, \tag{1}$$

where $v_{Pi}(\mathrm{r})$ is the wave velocity field in the specimen or structure. If the material is homogeneous, Eq. (1) can be simplified as:

$$t_i^* = t_0 + \frac{|\vec{x}_0 - \vec{x}_i|}{v_p} = t_0 + \frac{\vec{x}_{i0}}{v_p}. \tag{2}$$

For each sensor *i* there will be residual r_i between the detected onset time t_i and the calculated onset time t_i^*:

$$r_i = t_i - t_i^*. \tag{3}$$

If t_j is the onset time at another sensor $\vec{x}_j$, the measured onset time difference between sensors *i* and *j* is used. Usually we have:

$$r_{ij}^* = \Delta t_{ij} - \frac{(\vec{x}_{i0} - \vec{x}_{j0})}{v_p}, \qquad (i \neq j). \tag{4}$$

If there are more than four onset times available for one event, the problem is overdetermined. These residuals are minimized using the least square method, in which the total error for (*n*-1) equations is simply the sum of all squared time-residuals:

$$\chi^2 = \sum_{i=2}^{n} (r_i^*)^2. \tag{5}$$

Residuals are reduced by applying corrections $\Delta\vec{x}$ and Δv_p to the source parameters, which can be written as:

$$A^T A\vec{r} = -\mathrm{A}(\Delta\vec{x},\ \Delta v_p)^T. \tag{6}$$

Thereby, $\vec{r}$ is the data vector with the residuals for *n* observations of one event. **A**, which is a $(n-1)\times 4$-matrix, contains the partial derivatives of the calculated travel times with respect to the source coordinates, calculated at $\vec{x}_0$:

$$A = \begin{pmatrix} \frac{\partial r_2^*}{\partial x} & \frac{\partial r_2^*}{\partial y} & \frac{\partial r_2^*}{\partial z} & \frac{\partial r_2^*}{\partial v_p} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{\partial r_n^*}{\partial x} & \frac{\partial r_n^*}{\partial y} & \frac{\partial r_n^*}{\partial z} & \frac{\partial r_n^*}{\partial v_p} \end{pmatrix}_{\vec{x}_0}. \tag{7}$$

Due to the linearization of Eq. (6) the problem is solved iteratively until convergence, starting with an initial guess for the crack source location.

3. Experimental setup and operation

According to the aforementioned crack source localization problem in masonry structure, several tests based on a two-arch masonry model bridge are operated in this research.

3.1. Wave velocity test

A series of pencil-lead break tests are performed on the central pier of the bridge to study the attenuation and the velocity properties. The size of the central pier is of 160×50×28 cm, shown in Fig. 2, and it can be considered as a representative masonry solid structure.

Six sensors (S_0~S_5) are used to detect AE signals and the distance between two adjacent sensors increased from $S_{1\text{-}0}$ to $S_{5\text{-}4}$ with an increment of 5 units, shown in Fig. 2. The pencil is broken beneath the sensor S_0 with 5cm distance away in the same surface to study the surface velocity propagation, which is the scenario shown in Fig. 2.

Figure 2. Wave velocity test: (Left) the sketch of the pencil-lead break point and the sensor distribution; (Right) scenario of the velocity test.

The results of the measured velocities are shown in Fig. 3. The velocity named V-homogeneous, is calculated assumed the material is homogeneous [6]. The V-average is the average velocity value of all the calculated velocities in the corresponding test.

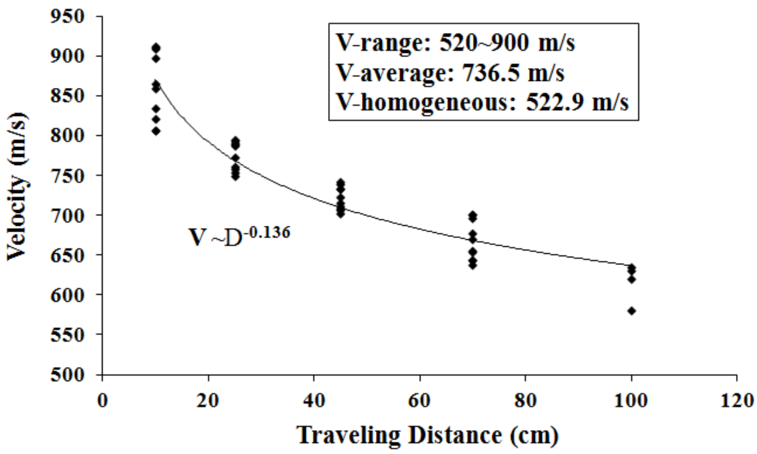

Figure 3. Wave velocity of the AE on the surface of masonry model bridge.

3.2. Sensor distribution and source localization tests

Ad hoc tests are performed to reproduce AE source using pencil-lead break on the right-side surface of the masonry abutment. Six sensors are attached to the surfaces, shown in Fig. 4. In particular, 19 different pencil-lead break points (artificial source) are drawn on this surface, and for each point the tip of a pencil is broken 8 times, so a total of 152 measurements are recorded. For this test 912 AE events from the six sensors are obtained and then sensor distribution and the source localizations of all the 19 points are analyzed in the following sections.

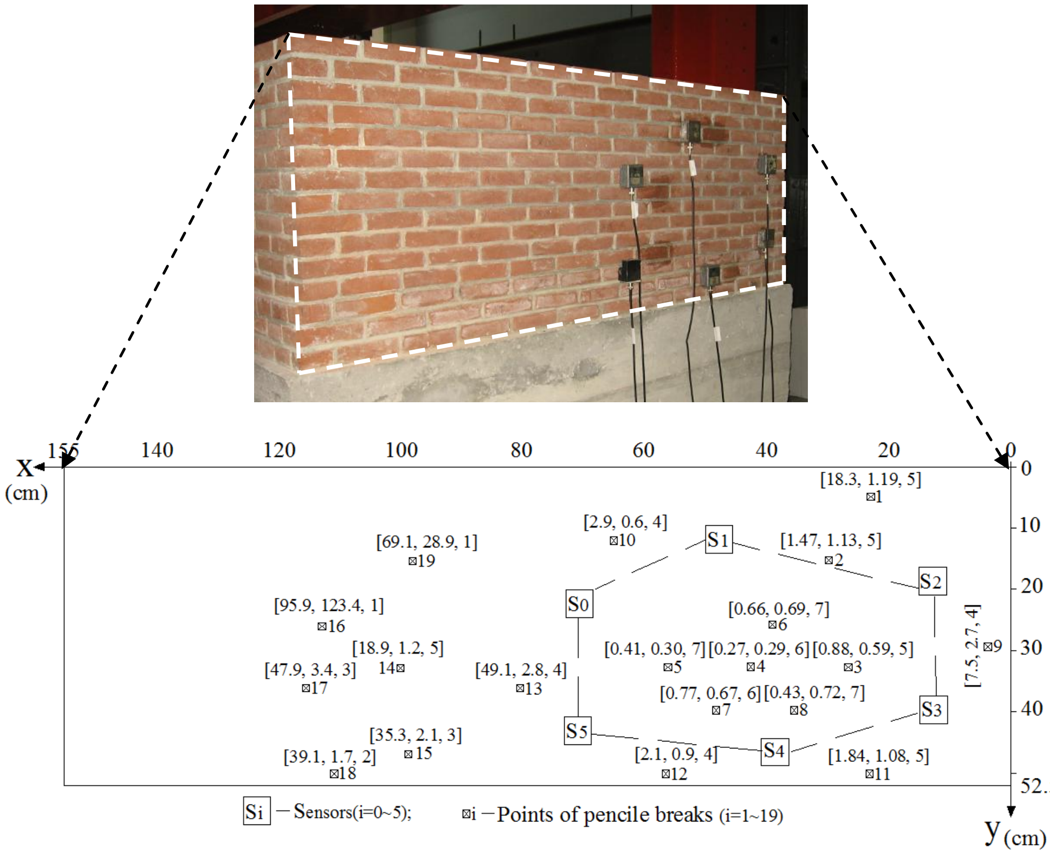

Figure 4. Results of the source localization calculated from the classical and the modified methods. In [*a*, *b*, *c*], *a* is the average error of all the available breaks from the classical method, and *b* is the average error of all the available breaks from the modified method, and *c* is the available breaks which can be used for each point.

4. Accuracy analysis of AE locations based on the test

4.1. Degree of inhomogeneity

The classical localization method can be used in the concrete structures according to the experiences [6-8]. But the localization of AE source in masonry structures is highly complicated, as attenuation and wave velocity are dependent on the heterogeneity of the material (not only the interface between bricks and mortar, but also cracks and cavities in existing structures). The theoretical analysis in Section 2 and the test result in Section 3.1 both illustrate that the classical localization method based on Eq. (2) cannot be used directly in masonry. A modified method based on the classical method is introduced in the following part.

The basic idea of the localization in masonry is the same as that in concrete. But propagation delay due to the layers in the masonry structures makes the homogeneous assumption is unavailable here. Modifications for propagation delay are implemented.

The geometry distance *ds* is still taken as the calculated path, since the detailed knowledge of the actual wave path Γ, is not possible to be known. But modification can be made for the time-delay according to the velocity property in Fig. 3 to reduce the effect of inhomogeneous property. In the modified model, the classical model result in Eq. (5) is modified into:

$$\chi^2 = \sum_{i=2}^{n} {r_{i1}}^2 = \sum_{i=2}^{n} \left[\vec{x}_{10} - \vec{x}_{i0} - (k_i t_i - t_1) v_1 \right]^2 , \tag{8}$$

where $k_i = \left(d_1 / d_i \right)^{\xi}$ is the modified factor, which is used to modify the effects of the inhomogeneity or propagation delay. The parameter ξ, denoted as degree of the inhomogeneity, in k_i reflects the inhomogeneous degree of the material. The degree of the inhomogeneity ξ is determined from the result of the pencil-lead break wave velocity test, shown in Fig. 3. It reflects the relationship between the calculated velocity and the wave propagation distance. In strictly homogeneous materials, the value ξ is 0 since the wave velocity is a constant value and does not changes with travelling distance. If the material is not homogeneous, value ξ will theoretically increases with the degree of the heterogeneity. The degree of the inhomogeneity ξ in our research is 0.14, which is taken from the relation between the velocity and travelling distance shown in Fig. 3.

4.2. Sensor distribution

The results of the locations are shown in Fig. 4 for both the modified and classical methods. It can be noted that the location accuracy varies with the position of the breaks. The break points can be approximately divided into three groups. The points 3~8 inside the central area of the sensor covered region (the dashed line in Fig. 4) have the best crack source monitoring result for both classical and the modified methods. In the second group, including points 2, 9, 10, 11, 12, points are distributed on the nearby region of the sensor covered region. The rest of the points, far from the sensor network, are in the third group.

For points in the first group, both methods give the ideal result, all the errors are smaller than 6 mm, and most of the crack events can be monitored. For the second group, the modified model shows better results than the classical method. The errors (*a* value in Fig. 4) in the classical method are about 15~75 mm, whereas the counterparts (*b* value in Fig. 4) can be reduced to about 6~27 mm in the modified method. In this condition, about half of the break events can be detected according to the *c* value in Fig. 4. The result from the classical method for the third group is barely acceptable for its exaggerated errors, whereas modified method is still in good conditions. Although the errors were slightly large, about three or four centimeters, the results are still acceptable considering the entire size scale of the surface. Three representative points, 4, 10 and 17 respectively, of the three groups are selected to give the detailed results in Fig. 5.

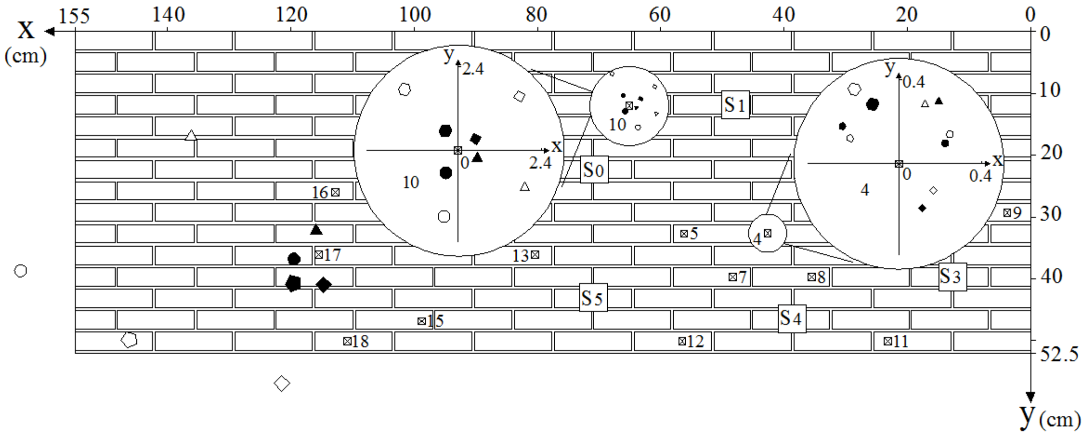

Figure 5. Detailed localization results of the point 4, point 10 and point 17. The solid points represent the results of the modified method and the empty points of the classical method.

4.3. Onset time determination

Source localization is based on the onset times or arrival times of the direct body waves. Theoretically, onset times of the direct body waves, *P*-wave and *S*-wave both can be used for source localization. However, only first wave onset times (*P*-times) are usually measurable, since multiple side reflections, structural noise and sensor response will interfere the later phases.

The true onset time of a crack AE event could be described as the moment when the first energy of a particular signal phase reaches the sensor positions [17]. In signal analysis, the onset time is usually picked as the point where the first difference between the signal and the noise takes place [18]. Determination of the onset time of AE signals is crucial for the whole localization process and is the major premise to affect the localization accuracy [6].

Manually picking is the preferred choice if there are only few events available. It is still necessary to have reliable automatic picking tools, because human analysts cannot manage the vast amount of data recorded in the monitoring. In concrete monitoring, many algorithms have been proposed for automatic detection of onset times and the detailed description can be found in [19]. Two mostly used methods, STA/LTA (STA Short Term Average, LTA Long Term Average) picker by [20] and AIC-picker [6, 21] are employed and investigated for the AE signals in masonry structures. The picking accuracy of the STA/LTA-picker and AIC-picker was quantified by a comparison with picks that were set manually.

For 1122 signals of AE events recorded at the pencil-lead break tests in Sections 3, the differences Δt between the automatic and the manual picks are examined. Fig. 6 shows the results for the STA/LTA-picker and for the AIC-picker, compared to manually picked onset times.

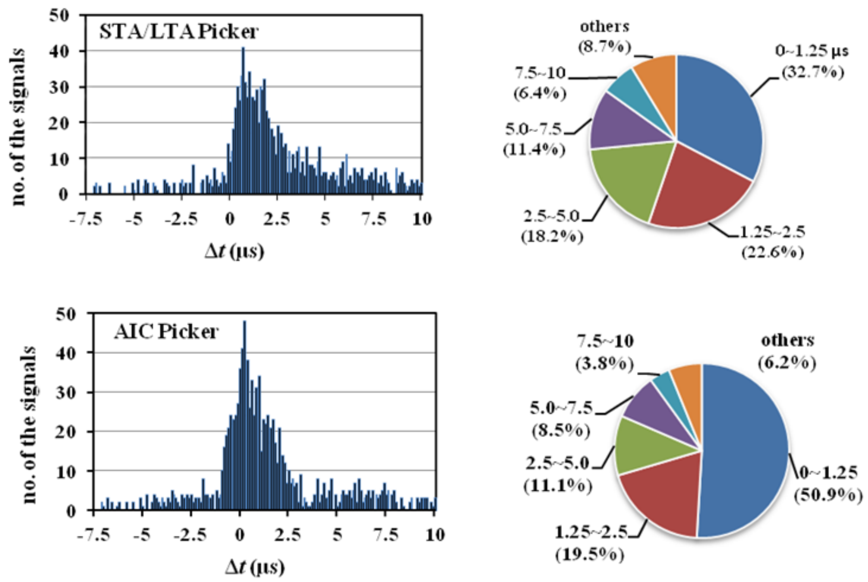

Figure 6. Differences Δt between automatically and manually picked arrival times for the STA/LTA (top) and the AIC-picker (bottom). The pie charts show the performance of both automatic pickers.

The signals have different reading precisions of their onsets, depending on the signal to noise ratio and how impulsive onsets are. The results from the two methods are both acceptable, although the STA/LTA-picker obviously shows a trade-off. With the AIC-picker almost twice as many signals than the STA/LTA-picker are picked in a very good correlation, $\Delta t \leqslant 1.25\mu s$. Also, the number of mispicks with $\Delta t \geqslant 5\mu s$ in the noise and picks too late in the signal could be reduced from 26.5% of that in STA/LTA-picker to 18.5%. Accordingly, the AIC-picker can be suggested as a reliable and accurate algorithm to determine the onset times of AE signals in masonry structures.

5. Discussion and conclusion

With wide existence of masonry structures, the monitoring techniques have received considerable attention due to the increasing demand of the structural retrofit and strengthening. As one of the non-destructive monitoring techniques, acoustic emission technique is employed for the masonry cracking analysis.

For AE applications in monitoring, localization of AE sources is important to offer the information of the active damage region. The investigation of the localization accuracy has shown that monitoring results are greatly influenced by the material of structures. Classical localization method is mostly adopted to realize the localization operation in metal and concrete structures. However, for the masonry structures, the complicated material properties make the classical localization method cannot be applied directly.

The modified localization method proposed in this paper allows giving a reasonable location results. In the modified method, a modified factor k_i related to inhomogeneous or propagation delay is introduced. The degree of the heterogeneity ξ in k_i plays a key role to eliminate the effect of the inhomogeneous of the material. Accordingly, the pencil-lead break velocity tests on the masonry structure to measure the relation between the wave velocity and travelling distance should be fulfilled before the monitoring. Based on this test result, the value ξ can be obtained and employed in the monitoring process.

The sensor arrangement is another task which should be carefully considered. The investigation of the localization accuracy has shown that the sensor distribution is essential for monitoring AE activity in the specimen. The ideal condition is to ensure that all relevant regions are covered by enough sensors before the monitoring starts. Detected events are only a fractional amount of all recorded AE signals and, again, only a limited number of all detected events can be localized with a sufficient accuracy. For a good imaging of crack progression it is necessary that enough events could be localized. Therefore the proper arrangement of the sensors can give us more available points, which is well testified by the *c* value in Fig. 4.

In conclusion, with the assistance of the reliable onset time picker (AIC-picker) and proper sensor distribution, the source localization in masonry can be realized properly by the modified model.

References

[1] A. Carpinteri, G. Lacidogna, G. Niccolini, Acoustic emission monitoring of medieval towers considered as sensitive earthquake receptors. Natural Hazards and Earth System Sciences, 7 (2007) 251-261.

[2] C. Melbourne, AK. Tomor, Application of Acoustic Emission for Masonry Arch Bridges. Strain, 42 (2006) 165-172.

[3] A. Carpinteri, G. Lacidogna, Damage monitoring of an historical masonry building by the acoustic emission technique. Materials and Structures, 39 (2006) 161-167.

[4] J. Xu, G. Lacidogna, Modified Acoustic Emission source localization method to determine crack locations for masonry arch bridge. Applied Mechanics and Materials, 71-78 (2011) 4823–4826.

[5] E. Verstrynge, L. Schueremans, DV. Gemert, M. Wevers, Application of the acoustic emission technique to assess damage in masonry under increasing and sustained axial loading, in: NDTCE’09, Non-Destructive Testing in Civil Engineering. Nantes, France, 2009.

[6] A. Carpinteri, J. Xu, G. Lacidogna, A. Manuello, Reliable onset time determination and source location of acoustic emissions in concrete structures. Cement & Concrete Composites, 34 (2012) 529-537.

[7] CU. Grosse, M. Ohtsu, Acoustic Emission Testing: Basics for Research - Applications in Civil Engineering, Springer, 2009.

[8] B. Schechinger, T. Vogel, Acoustic emission for monitoring a reinforced concrete beam subject to four-point-bending. Construction and Building Materials, 21 (2007) 483-490.

[9] E. Verstrynge, L. Schueremans, D. Gemert, M. Wevers, Monitoring and predicting masonry's creep failure with the acoustic emission technique. NDT & E International, 42 (2009) 518-523.

[10] D. Dutta, H. Sohn, KA. Harries, P. Rizzo, A Nonlinear Acoustic Technique for Crack Detection in Metallic Structures. Structural Health Monitoring, 8 (2009) 251-262.

[11] G. Niccolini, J. Xu, A. Manuello, G. Lacidogna, A. Carpinteri, Onset time determination of acoustic and electromagnetic emission during rock fracture. Progress In Electromagnetics

Research Letters, 35 (2012) 51-62.

[12] E. Eberhardt, D. Stead, B. Stimpson, Quantifying progressive pre-peak brittle fracture damage in rock during uniaxial compression. International Journal of Rock Mechanics and Mining Sciences, 36 (1999) 361-380.

[13] SC. Lovejoy, Acoustic Emission Testing of Beams to Simulate SHM of Vintage Reinforced Concrete Deck Girder Highway Bridges. Structural Health Monitoring, 7 (2008) 329-346.

[14] A. Carpinteri, G. Lacidogna, G. Niccolini, S. Puzzi, Critical defect size distributions in concrete structures detected by the acoustic emission technique. Meccanica, 43 (2008) 349-363.

[15] A. Anzani, L. Binda, RG. Mirabella, The effect of heavy persistent actions into the behaviour of ancient masonry. Materials and Structures, 33 (2000) 251-261.

[16] T. Kosel, I. Grabec, P. Muzic, Location of acoustic emission sources generated by air flow. Ultrasonics, 38 (2000) 824-826.

[17] CU. Grosse, F. Finck, Quantitative evaluation of fracture processes in concrete using signal-based acoustic emissions techniques. Cement & Concrete Composites, 28 (2006) 330-336.

[18] J. Kurz, CU. Grosse, HW. Reinhardt, Strategies for reliable automatic onset time picking of acoustic emissions and of ultrasound signals in concrete. Ultrasonics, 43 (2005) 538-546.

[19] J. Xu, Energy emissions from critical phenmena and applications to structural health monitoring. Politecnico di Torino, Structural Engineering Department, 2012.

[20] M. Baer, U. Kradolfer, An automatic phase picker for local and teleseismic events. Bulletin of the Seismological Society of Ameria, 77 (1897) 1437-1445.

[21] J. Xu, An Effective Way to Validate Signal Arrival Time in AE Structural Monitoring. Advanced Materials Research, 163-167 (2010) 2471-2476.