COMPARISON OF LOCALIZATION STRATEGIES OF DAMAGE IN CONCRETE BY ACOUSTIC EMISSION

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Abstract

The monitoring of concrete structures by the acoustic emission (AE) technique allows the detection and the localization of damage. The source location is determined by a triangulation algorithm based on the arrival time of AE signals recorded by sensors placed at the surface of the material, and the measured concrete wave velocity. The accuracy of AE source location depends on many assumptions. In this paper, the accuracy related to the choice of the onset detection of AE signals and to the location algorithm is studied. A statistical analysis of AE location maps based on the distribution of AE events is presented. The accuracy of AE events location is also evaluated and compared between the studied criteria.

Keywords: acoustic emission, concrete, damage, source location, accuracy.

1. Introduction

The monitoring of nuclear facilities and concrete structures is a major concern in the field of civil engineering to ensure safety and durability. A realistic description of cracking allows a better understanding of the degradation problems in concrete. In the case of a quasi-brittle material such as concrete, macro-cracks occurs after the development of a micro-cracked area also called fracture process zone (FPZ) [1-5]. The main objective of this study is to provide further insight in the description of the FPZ evolution in order to prevent the propagation of damage. This is because the accumulation of microcracks causes a local decrease of the mechanical characteristics of the material leading to crack propagation.

Micro-cracking is a phenomenon of localized damage causing the release of mechanical energy. It results from this mechanical event the propagation of an elastic wave in the material. The acoustic emission technique enables the detection of vibration by piezoelectric sensors located on the material surface. The main interest of the AE technique is that it allows the monitoring of damage continuously. It provides also, through the analysis of wave arrival time and triangulation, the localisation of microcracks.

The localization of AE events by the triangulation technique is mastered [6]. Nevertheless, the quality of the results is sensitive to different criteria [7]. An important criterion for performing a good location is the picking of arrival times from the recorded AE signals. Several onset picking techniques have been proposed in the literature: the simple manual picking technique which is very time consuming, the amplitude threshold picker, the STA/LTA picker (Short Term Average / Long Term Average) and the automatic onset detection algorithms based on the Hinckley criterion and Akaike Information Criterion (AIC) [8,9]. To determine the position of AE source, the triangulation method is performed based on the arrival times of AE signals recorded by the sensors. Several iterative algorithms, which consist in generating a sequence of testing and updating of a trial solution based on a linear least-squares algorithm, were applied to obtain the optimal source locations coordinates: grid search, simplex algorithm, Geiger’s method [10]. … However, even though the principle of location is still the same, the way in which the minimization problem is resolved affects the final result. The simplex algorithm is the most used for its timeliness. However, this algorithm only allows converging to a local minimum of the minimization problem and may lead, in some cases, to an incorrect solution.
Thus, the objective of the following work is to ensure a reliable location of micro-cracks. To achieve this, an experimental investigation is proposed. Three point bending tests were carried out on notched concrete beams and the monitoring of the damage is assessed by means of the acoustic emission technique. Two evaluation criteria for the onset time of AE signal are presented. Their influence on the overall result of the location is highlighted. Subsequently, three alternative algorithms are also applied for the resolution of the location problem. The advantages and disadvantages of those methods are discussed. The accuracy and the possibility of improving the AE technique are also studied.

2. Experimental details

2.1. Materials and Procedures

The dimensions of the tested concrete beams are $L \times h \times l = 500 \times 250 \times 120$ mm. A central notch of 4 mm width is located at the bottom part of the beams and measure 10 mm in height. The composition of the used concrete is shown in Table 1.

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Mass proportions</th>
</tr>
</thead>
<tbody>
<tr>
<td>cement CEM I 52.5 CE NF</td>
<td>320 kg.m$^{-3}$</td>
</tr>
<tr>
<td>water</td>
<td>197.5 kg.m$^{-3}$</td>
</tr>
<tr>
<td>sand 0-4 mm</td>
<td>830 kg.m$^{-3}$</td>
</tr>
<tr>
<td>aggregates 4-11 mm</td>
<td>445 kg.m$^{-3}$</td>
</tr>
<tr>
<td>coarse aggregates 8-16 mm</td>
<td>550 kg.m$^{-3}$</td>
</tr>
</tbody>
</table>

Table 1. Concrete composition.

The three-point bending tests were performed using a hydraulic press MTS with a capacity of 100 kN (Figure 1 left). The load was applied with a constant crack mouth opening displacement (CMOD) control with a slow rate of 0.2 mm.min$^{-1}$. Figure 1 right shows an example of the load-CMOD curves obtained with fracture tests. The load CMOD variations are linear up to 80% of the maximal strength followed by a nonlinear variation up to the peak load and a stable failure in the postpeak region.

Figure 1. General view of the experimental fracture test setup (left). Load/CMOD curve (right).

2.2. Acoustic emission measurements

The monitoring of the damage is carried out using a network of 8 piezoelectric sensors R15 of resonance frequency equal to 150 kHz. The two main faces of the beam were instrumented with 4 sensors so as to perform a 3D localization of acoustic events.

The AE signals were amplified with a 40 dB gain differential amplifier. The signals are converted by a PCI-card 8 and filtered by a low pass filter of 400 kHz and a high pass filter of 100 kHz. The signal
3. Principals of source localization

Location of micro-cracks is based on the following hypothesis: sources are punctual, sources are temporally spaced apart from each other so that the acoustic activity resulting from the source does not interfere with the acoustic activity of the next source, wave propagation velocity is constant, material is homogeneous and isotropic. According to those hypothesis, the waves travel from a source point to sensors following a straight path with a constant velocity. Figure 2 represents the principal of the AE technique and illustrates the time of arrival approach:

![Figure 2. Principal of acoustic emission technique.](image)

As seen in previous parts, the localization process is based on measured arrival time of signals $t_{i,j}^{\text{meas}}$ where “i” denote the order of arrival and “j” the sensor indices. In practice only delays between sensors are used, $dt_{i,j}^{\text{meas}} = t_{i,j}^{\text{meas}} - t_{i,j}^{\text{meas}}$. Considering previous hypothesis, a group of delays between sensors depend on the position of event. The location of micro-cracks is determined by solving an error minimization problem between the received data by the sensors and those from an artificial event with a known position (eq. 1). This artificial event is determined by an algorithm. The retained position corresponds to that of the artificial event for which the error criterion is minimum.

$$
\zeta = \sum_{i=1}^{n} \left( dt_{i,j}^{\text{meas}} - dt_{i,j}^{\text{algo}} \right)^2,
$$

where “n” is the number of sensors associated to the event. To summarize and considering hypothesis given above, localization depends on three factors: the velocity of waves, the capability to determine precisely the beginning of AE signals and the algorithm used to solve the minimization problem. Here, the variation of wave velocity is not considered and is kept constant. In the following parts, only the influence of the two others factors is studied and discussed.

4. Influence of the onset picking technique

4.1. Fixed threshold versus AIC

The determination of the onset time of AE signals has been identified as a source of error for events location. Indeed, the overall delay measured between the sensors is influenced by the method of determining the onset time of the AE signals. The acquisition of data used in this work has been performed using a fixed threshold which is the simplest form for onset picking. This technique defines the onset time of a signal as the time at which the amplitude received by the sensor exceeds a previously established threshold (35 dB here). The disadvantage of this technique is that it is not adapted to each
signal as small amplitude signals and signal with a high noise level. Figure 3 illustrates this problem; an important delay between the beginning of the signal determined by the fixed threshold method (magenta) and the apparent onset time of the signal is observed. An intuitive way to overcome this problem could be to reduce the gap between threshold and noise. In fact, ambient noise can change during loading due to experimental environment. Thereby this gap must exist to avoid noise record.

The AIC criterion is widely used in the literature. The idea is to compare the difference between standard deviation passed and forthcoming at each point of the signal. Eq. 2 gives the exact form of this criterion.

\[ AIC_k = k \cdot \log[\text{std}(s(1: k))] - (N - k) \cdot \log[\text{std}(s(k: N))] \]

Eq. (2)

Here “k” is the considered sample and “N” the number of samples on which the computation is done. The orange curve in figure 3 shows the complete form of this function. The minimum of AIC (green) corresponds to the apparent beginning of signal. The advantage of this technique is the independence from subjective parameters like threshold. So there is no a priori about what can be the level of amplitude which correspond to the beginning of the signal. AIC gives the position where there is a modification of the signal which, in our case, corresponds to the onset time of AE signal.

4.2. Results and discussion

Figure 4 shows the damage localization maps obtained with the fixed threshold (top) and the AIC (bottom). Each blue dot represents one of the 14621 events recorded by the acquisition system. The simplex algorithm has been used in both cases for minimisation. Figure 4 shows also the histograms of the density of events in each direction (x, y, and z). The distribution of AE events along the x axis shows that AE events are more concentrated around the cracking zone (above the notch) with the AIC which is closer to the reality.
Figure 4. AE events localization maps obtained with fixed threshold (top) and AIC (bottom) with the distribution of AE events along x, y and z axis.

Another way to compare those two techniques is to evaluate the corresponding errors (eq. 1) obtained based on the localization algorithm in each case. Comparing the errors event by event is a hard task. This is why a global analysis of errors is performed. Figure 5 shows the cumulated number of AE events in function of the error.

Figure 5. Proportion of cumulated AE events inside the beam in function of the error. Comparison between two criteria of onset time determination of AE signals: fixed threshold and AIC.

Note here that AE events with an error higher than 5 centimeters have not been represented here. Figure 5 shows that for the same error, AIC allows a greater amount of events located inside the beam. For example: 27% of events are located inside the beam with an error inferior to 2 cm with the use of AIC against 14.9% with fixed threshold.

5. Influence of the type of minimization algorithms

Analytical solutions do not exist for high order localization. In fact when the number of sensors used is higher than the unknown location parameters, the system of equations is over-estimated. Computation techniques exist to solve this problem but localization of only one event means hundreds and hundreds of calculations. This is why algorithms based on least-squares methods can be used to perform a large amount of process which lead to a solution. Three different algorithms are considered here with the main goal of finding the position (x, y, z) which leads to the minimum value of error.
5.1. Simplex

The simplex algorithm is widely used in the literature for the localization of AE sources. Simplex algorithm consist in:

i. Defining an initial position,

ii. Calculating the error criterion for this position and around. The number of positions depends essentially on the dimension of the problem,

iii. The best solution (smaller error criterion) from all the calculated solutions is stored,

iv. return to (ii) with the solution of (iii).

The main advantage of this method is its speed. However, it requires a starting position, which can greatly affect the results. There are several local minimum and only one global minimum which correspond to the sought solution. An initial position near local minimum can lead to a wrong final solution. Moreover, in its simplest form (without fixed boundary) the algorithm can converge to a solution corresponding to an event located outside the studied structure.

5.2. Adaptive meshing algorithm (AMA)

When using an AMA, the position of an event is not defined from an initial position but from a set of positions covering the damage referred area. Figure 6 shows an example in 2D of error calculation between a fictional event on the node of the mesh used and the measured data set from an event which one seeks the position. Measured delays ($dt_{\text{meas}}$) between transducers are compared to delays computed at each node of the mesh ($dt_{\text{mesh}}$). The comparison between those two set of data is made with the error criterion. The final position of AE event is the position of the node with the smallest error.

To increase the accuracy and reduce the cost of calculation time of this technique, three successive meshes are used to determine the position of a single event. Thus, the first mesh covers a large area surrounding the sensors with a coarse mesh (centimeter). A new tighter mesh is then used around the position adopted earlier. This operation is repeated until obtaining a solution in a mesh whose nodes are spaced apart by 2 millimeters. This adaptation of the mesh makes it possible to manipulate matrices of small dimensions in order to make the operation faster.

The main advantage of the adaptive meshing is to avoid local minima problems since many solutions are calculated and compared to retain the one having the lowest error. The disadvantage of this technique is the calculation time required to determine the position of an event. It is between five and ten times higher than for the simplex algorithm. It should be noted that this disadvantage is not so significant in this case since the minimization of errors for the location of the set of events (14621 in this case) is of the order of 1 hour.

![Figure 6. Principal of Adaptive Meshing Algorithm (AMA).](image-url)
5.3. Genetic algorithm

The different steps of the Genetic algorithms are:

i. a set of random positions is built in the damage area,

ii. delays related to those positions are computed and compared to the measured data with the error criterion (eq. 3),

iii. positions with lowest errors are stored,

iv. couples of solutions are formed from retained positions. Those couples are called “parents”,

v. new couples of solutions called “childrens” are computed from the parents. For example in 1D a couple of parents \((x_1, x_2)\) gives 2 children \((x_1', x_2')\) with \(x_1' = \frac{x_1 + x_2}{2}\) and \(x_2' = \frac{x_1 - x_2}{2}\),

vi. return to (ii) with childrens as new starting position if the precision criterion is not reached.

The number of initial solutions, the proportion of solutions retained to build parents, the way that childrens are computed from parents are parameters which can be changed but the global idea of genetic algorithm is to defined new solutions by “mutations”. This kind of algorithm is more time consuming than the two others presented above.

5.4. Results and discussion

Figure 7 shows the AE events localization maps of events related to the use of AMA algorithm (top) and genetic algorithm (bottom). In both cases and in agreement with the results obtained in the previous section (4), the AIC is used to determine the onset time of AE signals. Those maps are qualitatively identical. The maximum amount of events above the notch and the distribution of events along the main axis (x) is similar for the three algorithms (simplex from figure 4, AMA and genetic from figure 7).

Figure 7. AE events localization maps obtained with AMA algorithm (top) and genetic algorithm (bottom) with AIC as onset picking technique.
In order to compare the three algorithms, the error of localization was considered as earlier. Figure 8 shows the cumulated number of events inside the beam related to the errors for the three algorithms. For example, when the error is smaller than 8 mm, the simplex algorithm allows a greater proportion of event located than the other algorithms. In another hand, the genetic algorithm gives better results with 32% of event located with an error inferior to 2 cm against 27% for simplex and 26.3% for AMA.

The fact that simplex seems to allow a greatest number of event located with a small error may be explained by the ability of this algorithm to find the exact solution when the initial position is well defined. On the other hand, even if genetic algorithm is able to detect the global minimum of the problem, this algorithm can't determine the exact position. Final solution of genetic algorithm will always be really near the exact solution but not the real solution. In other words if the real solution is “0”, genetic algorithm will find something like “10−10” but not “0”. Finally AMA is less efficient than the 2 other algorithms for an error less than 2.3 cm. Contrariwise, AMA gives better results than simplex beyond this value. Due to the way that AMA work, the number of possible final solution is finite because it depend on a finite mesh defined by the user. So if the distance between two nodes of the last mesh is about 1mm and the real solution is between those two nods, it will not be possible to find the exact solution. However, it’s possible to make AMA final mesh finer to enhance his accuracy but at the expense of time.

![Figure 8](image)

**Figure 8.** Proportion of cumulated events inside the beam related to error. Comparison between three algorithms of resolution: simplex (blue), AMA (red) and genetic (yellow).

### 6. Conclusions

The main objective of the presented research work is to study the accuracy of the location of AE sources based on different onset picking techniques and minimisation algorithms. The influence of the onset time techniques on the location maps was analysed considering the amplitude threshold based picking technique and the AIC. The results show that the distribution of events around the real fracture is more concentrated with the AIC and consequently the size of the damage area. Furthermore a quantitative comparison between the two criteria shows that the localization errors obtained with the fixed threshold are greater. Three localization algorithms for solving the optimization problem are compared: simplex, AMA and genetic algorithms. This study shows that the choice of an algorithm depends on the desired accuracy and computation time. Each algorithm has its own advantages and disadvantages. Simplex leads to better results for smaller error while genetic algorithm gives a global better solution for error higher than 0.8 mm. Simplex is faster than AMA and event faster than genetic algorithm. To go further a mix of the 3 algorithms could lead to an optimum localization by dealing with the speed and precision of simplex and the global analysis of genetic or AMA techniques. The effect of the variation of the velocity during the damage process on the localization accuracy will be studied in the future. In addition, for a better evaluation of the accuracy of AE event location, reconstructed profiles obtained with the AE technique, based on different criteria, and real crack profile obtained with laser rugosimeter will be compared.
7. Acknowledgments

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8. Reference


