Evaluation of the Accuracy of Time of Arrival Source Location Algorithm of Acoustic Emission in Concrete-Mortar Structure

Hisham A. Elfergani, Ayad A. Abdalla, Ahmed R. Ballil

***Abstract*—**Acoustic Emission (AE) is one of the most effective non-destructive tests that can be used to detect the defect process as it is occurring. AE techniques can be used to monitor a wide range of structures and materials such as metals, non-metals and combinations of these when load is applied. The current work investigates the effectiveness and accuracy of TOA method in AE tests involving reinforced composite concrete-mortar structures. A series of experimental tests were performed using the Hsu-Neilson (H-N) source to study 2-D location accuracy using this method on concrete-mortar (400×400 mm) specimens. Four AE sensors (R3I – resonant frequency 30 kHz) were mounted to the mortar surface and six sources were performed at each point of preselected locations on the upper surface of the mortar. Results show that the TOA method can be used effectively to locate signals on composite concrete/mortar specimen and has high accuracy.

***Keywords*—**Acoustic emission, time of arrival, composite materials, reinforced concrete.

I. Introduction

AE testing is advantageous over other non-destructive testing methods because of its ability to reliably detect and locate the defect process as it is occurring. AE is defined as the elastic energy liberated from materials undergoing deformation [1]. Also it can be defined as "the transient elastic waves generated by the rapid release of energy from localized sources within a material" [2]. The phenomenon is also sometimes called stress wave emission, stress waves, micro-seismic activity, microseism, and rock noise.

The release of elastic energy, which is the AE event, causes rapid propagation of waves through the structure to arrive at the structure surface. Piezoelectric transducers are mounted to the surface to detect the displacement of the surface at different locations and to convert the mechanical wave into electrical AE signal [3].

The severity and location of the AE source can be assessed by converting the AE signal into an electronic data set, then displaying the recorded data into diagrams for evaluation and interpretation [3]. Figs. 1 and 2 show a summary of the AE detection process.

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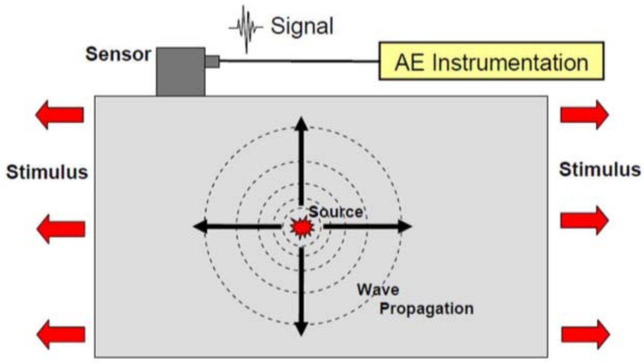


Fig. 1 AE method [4]

AE testing is often considered the most sensitive method of non-destructive testing because it is the only technique that can detect the defect process as it is occurring. AE techniques can be used to monitor a wide range of structures and materials such as metals, non-metals and combinations of them. There are two main differences between AE testing and other non-destructive techniques which are:

a) The energy which is detected is generated from the test object itself in AE testing.
b) The dynamic processes associated with the degradation of structures can be detected by only AE testing [1], [6].

The advantages of AE testing compared with other non-destructive methods include [2], [7]:

a) AE testing is a dynamic test technique.
b) The significance of discontinuities in the entire structure during a single test can be detected and evaluated by AE testing (real-time evaluation).
c) It can be applied to vessels and other pressure systems during service which requires no downtime.
d) Catastrophic failure of systems with unknown discontinuities can be prevented by AE monitoring.
e) It requires only limited access to detect discontinuities.
f) It can be used in all stages of testing such as pre-service testing, in-service testing, leak detection and location, in-process weld monitoring and mechanical property testing.

The limitations of AE testing include [2], [7]:

a) Repeatability: AE is stress unique and each loading is different.
b) Attenuation: The AE wave in the component will be attenuated during testing.
c) History: Testing is highly effective when the loading history of a component is known.

d) Noise: Extraneous noise may affect AE testing.

Test object and application of load produce mechanical tensions
Source mechanisms release elastic energy
Wave propagation from source to sensor
Sensors converting a mechanical wave into electrical AE signal
Acquisition of measurement Data converting an AE signal into an electronic data set
Display of measurement data Plotting the recorded data into diagrams
Evaluation of the display from diagrams to safety-relevant interpretation

Fig. 2 The AE chain [5]

There are several mechanisms which give rise to AE in materials. In metals, source mechanisms include moving dislocations, slip, crack growth, grain boundary sliding, twinning and fracture and de-cohesion of inclusions. In composite materials, matrix cracking, the deboning and fracture of fibers are AE sources.

II. Fundamental of AE

The principal idea of AE is that, elastic waves or AE is released from solid materials or components due to deformation or fracture which occurs due to applied mechanical or thermal stress.

The purpose of the AE test is to detect and locate sources of emission and to gain sufficient information about them. The detected waveform contains qualitative and quantitative information for characterization of a source. The main factors which influence the AE signals are the source's characteristics, the path between the source and transducer, transducer's characteristics and the measuring system.

The main parameters of waveform are AE hit, AE count, AE hit energy, signal amplitude, signal duration and signal rise time. Fig. 3 shows the definitions for a simple wave form [2].

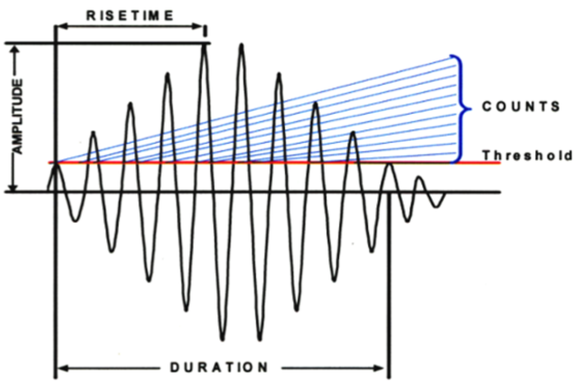


Fig. 3 Characteristics of a burst type of AE signal [8]

A. Emission Hits and Count

Separate signal bursts, which are generated by local material changes, are called AE hits. However, the number of times a signal crosses a preset threshold is called hit count, which depends on the transducer frequency, the transducer damping characteristics, the damping characteristics of structure and the threshold level [1].

B. AE Event Energy

The AE event energy is the rapid release of energy in the material which can be expressed by the true energy which is proportional to the area under the AE waveform [2]. The electrical energy, U, present in a transient hit can be defined as:

$$U = \frac{1}{R}\int_0^\infty V^2(t)dt \quad (1)$$

where R is the electrical resistance of measuring circuit (ohm), V is the output potential (volt) and t is time (second). Direct energy analysis can be achieved by digitizing and integrating the waveform signal or by special devices performing the integration electronically [1].

C. AE Signal Amplitude

AE signal amplitude is the peak voltage of the signal waveform which depends on the intensity of the AE source in the material. Peak amplitude measurements are generally achieved using a log amplifier (logarithmic scale) to cope with a wide range of signal amplitudes (large and small signals) [1].

A usual unit for measuring the amplitude of an acoustic signal is the decibel (dB). The decibel is not a fixed measurement unit but rather expresses a logarithmic ratio between two conditions of the same dimension. In AE, the reference level 0 dB AE is defined as a signal of 1 μV at the transducer before any amplification.

The fundamental decibel is:

$$N_{dB} = 10\log_{10}\frac{P}{P_o} \quad (2)$$

where P is the measured power and P_o is the reference power in watts.

In a sense, the power is a square function of voltage:

$$N_{dB} = 10\log_{10}\left(\frac{V}{V_o}\right)^2 \quad (3)$$

or

$$N_{dB} = 20\log_{10}\frac{V}{V_o} \quad (4)$$

where V is the measured potential and V_o is the reference potential in volts.

Wave propagation in a solid material is complex. In an infinite medium, waves propagate as bulk waves in two fundamental modes; longitudinal waves (P-wave) and transverse waves (S-wave). Each has a special characteristic velocity depending on material properties such as the density and elastic constant. The characteristic of transverse waves is the particle movement perpendicular to the wave propagation direction, whereas the motion of the particle in longitudinal waves is parallel to the wave's propagation direction. By introducing the surface boundary, the longitudinal and transverse waves combine in the region close to the surface, so that the overall particle motion is neither purely longitudinal nor transverse, this is called a Rayleigh wave or surface wave. Another kind of surface wave is known as a Lamb or plate wave. The Lamb wave is formed in a medium bounded by two surfaces (plates) [9]-[12]. Wave attenuation is another important AE characteristic. It can be described as the way in which the wave amplitude/energy decreases with distance. There are four main cases of attenuation which are geometric spreading, internal friction, dissipation of the wave into adjacent media and velocity dispersion [13].

III. AE Source Location

AE source location is very important to assess the areas of active damage. The most common source location technique is the TOA approach, which is an integral part of all commercially available AE software. There are other source location methods such as SSMAL, Delta T mapping method and energy based spatial location.

TOA technique is based on the source being located by several sensors in an array and measuring the time delay between pairs of sensors within the array. Several source location applications are appropriate for linear source location, i.e., where a single position along a measurement axis is adequate to define the location of a source. Most applications of AE source location are interested with locating a source in a fundamentally two-dimensional shell type component. Three-dimensional source location is required if the thickness of the object under test is significant relative to the other two dimensions or if the area of interest is internal to the specimen. For linear location, the minimum number of transducers is two; however three are required for two-dimensional location and four are required for three-dimensional location [14]. Reference [12] describes a technique that determines the location of an event in one dimension between two sensors where the propagating velocities of different wave modes of a signal and the TOA at a signal sensor is known.

A. Linear (1D) Location

Figs. 4 (a)-(d) show a situation where three sensors are placed on a linear structure such as a beam. An AE event occurring at any point in this beam will emit stress waves propagating in both directions.

The simplest technique of locating this source is zonal location which examines the order in which the event reaches the sensors in the array, i.e. the "hit" sequence. With reference to Fig. 4 (a), if the first sensor hit is sensor 2 then the region for possible location is the midpoint between sensor 1 and 2 to the midpoint between sensor 2 and 3. Further location accuracy can be gained by examining the second sensor that is 'hit' in the array. In Fig. 4 (b), sensor 1 is the second sensor to receive the hit and therefore the source can be located between the midpoint between sensors 1 and 2.

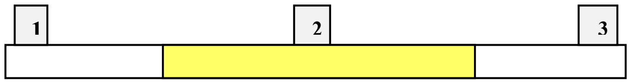
This method can be made more accurate by examining not only the hit order, but the difference in time arrival of the hit at the sensors. For instance, Fig. 4 (c) represents a hit arriving at sensor 2 first followed by sensor 1. The time difference between these hits can be calculated as:

$$\Delta t = \frac{d_2 - d_1}{C_{AE}} \tag{5}$$

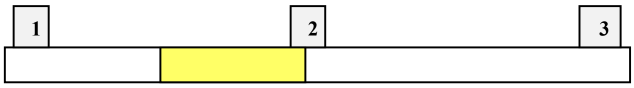
where C_{AE} is calculated wave velocity, Δt is the time difference between sensors, d_1 is the distance from source to sensor 1 and d_2 is the distance from source to sensor 2. This is however, commonly expressed in terms of d_1

$$d_1 = \frac{D - C_{AE}\Delta t}{2} \tag{6}$$

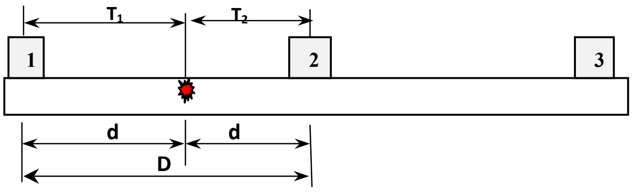
where D is the total distance between sensors. If the source originates from outside the array, Fig. 4 (d), then the time difference measurement always corresponds to the time of flight between the outer sensor pair. The source will be located at the sensor at the edge of the array; in the case of the example, at sensor 1.



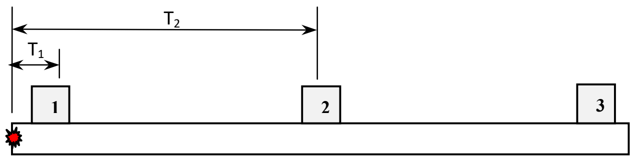
(a) Zone for first hits at sensor 2



(b) Zone for first hits at sensor 2 and second hits at sensor 1



(c) Hits sequence, time difference measurement $\Delta t = T_2 - T_1$



(d) Source outside of array $\Delta t = T_2 - T_1 =$ Constant

Fig. 4 Linear location using TOA theory [15]

B. Two Dimensions (2D) Location

The same method can be used for 2D location. Fig. 5 considers two sensors placed a distance of D apart on an infinite plane. If the stress wave from a source is assumed to propagate at a constant velocity in all directions, then it can be shown that:

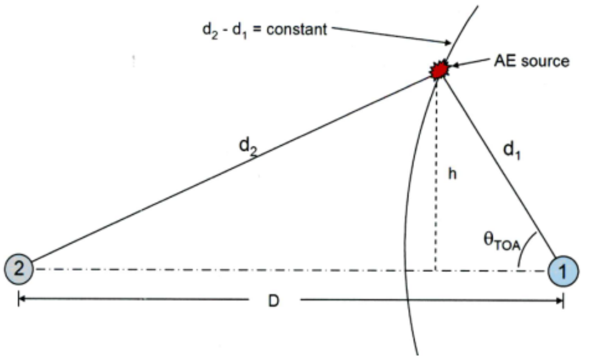


Fig. 5 D location on an infinite plate [2]

$$C_{AE}\Delta t = d_2 - d_1 \tag{7}$$

and

$$h = d_1 \sin\theta_{TOA} \tag{8}$$

$$h^2 = d_2^2 - (D - d_1\cos\theta_{TOA})^2 \tag{9}$$

Then

$$d_1^2 \sin^2\theta_{TOA} = d_2^2 - (D - d_1\cos\theta_{TOA})^2 \tag{10}$$

$$d_1^2 = d_2^2 - D^2 + 2Dd_1\cos\theta_{TOA} \tag{11}$$

Substituting $d_2 = d_1 + C_{AE}.\Delta t$ from (7) gives:

$$d_1 = \left(\frac{1}{2}\right)\frac{(D^2 - \Delta t^2 C_{AE}^2)}{(\Delta t C_{AE} + D\cos\theta_{TOA})} \tag{12}$$

This provides insufficient information to locate the source. However, by adding a third sensor to the array as shown in Fig. 6, it is possible to repeat this process for the three pairs of sensors 1-2, 2-3 and 1-3. The intersection point of three resulting hyperbola provides a more accurate 2D location. The adding of further sensors increases the number of hyperbola and consequently the accuracy and confidence of location.

The aim of the current work is to evaluate the accuracy of TOA in locating AE events in prestressed concrete structure and to check whether or not the existing of steel wire and steel plate inside the concrete will attenuate the AE waves and affect the accuracy of the technique.

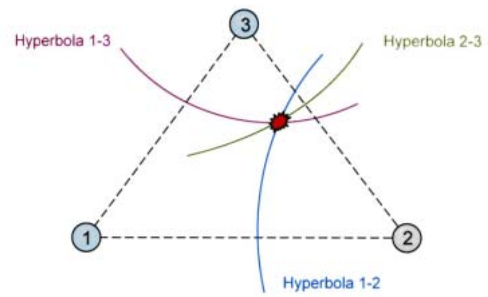


Fig. 6 2D location with three sensors [2]

IV. Experimental Procedure

A concrete specimen (400×400×230 mm) with a steel plate 1 mm thick was cast. Wires were placed on the upper surface of this specimen then the mortar 400×400 mm and 20 mm thickness was coated on the upper surface of the concrete. The mortar consists of one-part cement to three parts fine aggregate by weight [16]. The specimen was water cured for 28 days. The final construction is shown in Figs. 7 and 8.

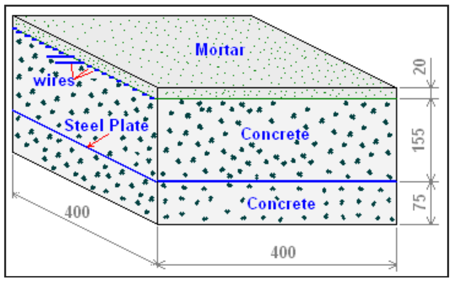


Fig. 7 Schematic diagram of the specimen

Fig. 8 Photo of the specimen

Four AE sensors (R3I – resonant frequency 30 kHz) were mounted to the mortar surface as shown in Fig. 9 by using silicon sealant.

The AE system hardware was set-up with threshold level of 40 dB and the mounted sensitivity of the sensors was checked using the H-N source. The configuration of the specimen and sensors set up is given in Fig. 9.

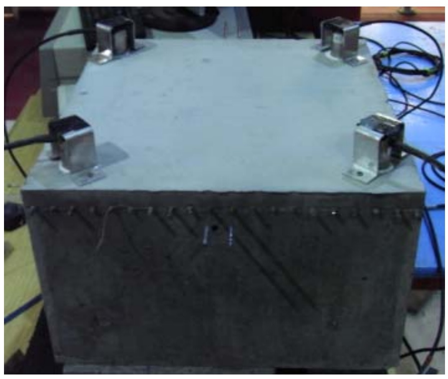


Fig. 9 Photograph of specimen with sensors setup

Several experiments were performed using the H-N source

[17] on selected points at five different locations on the upper surface of the mortar. Six sources were performed at every point. The locations of the H-N sources and sensors on upper mortar surface are shown in Fig. 10.

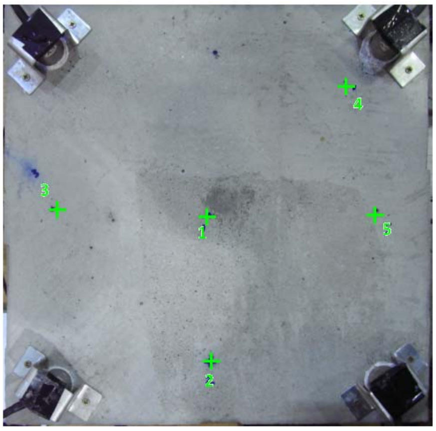
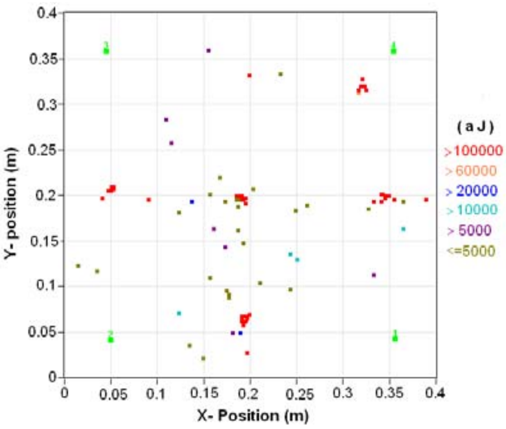
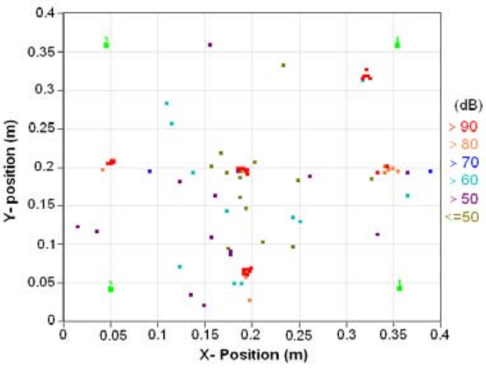


Fig. 10 Schematic photo of specimen with five artificial source locations

V. Results and Discussion



(a)



(b)

Fig. 11 Planar location of events with (a) Absolute energy (atto joules) (b) Amplitude (dB)

The location of signals above the minimum amplitude of 40 dB for six artificial source events at five different points is shown in Figs. 11 (a) and (b). Fig. 11 (a) displays planar location of the events including their absolute energy and Fig. 11 (b) displays planar location of the events including their amplitudes.

The location of events in Fig. 11 (a) can be compared with Fig. 10, which displays the planar location of sources on surface mortar in one figure as shown in Fig. 12.

Fig. 12 shows a comparison of the location of H-N source points on the mortar surface with the energy of events located, which are determined using TOA. It can be seen that highest hits concentration and highest energy in the region coincides with the artificial source location marked by a green cross. However, there are some hits with low amplitude and low absolute energy distributed across the surface. These hits could be attributed to noise such as separation of the mortar from the concrete and shrinkage in concrete or mortar as observed in other investigations.

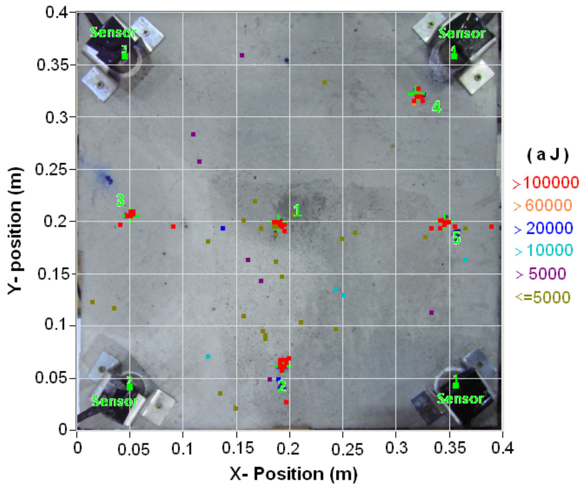


Fig. 12 Comparison of the H-N source location points with energy of events location

VI. Conclusion

In this work an experimental investigation of the accuracy of TOA method to locate AE source in composite concrete/ mortar structure is conducted successfully. Artificial events are created in the experiments at pre-set locations on the surface of the test specimen and comparisons are made to the locations found using AE. Results show that TOA method can be used effectively to locate signals on composite concrete/ mortar specimen very accurately with an average error of about 1.5%.

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