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Author(s):
Gollob, Stephan; Vogel, Thomas

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LOCALIZATION OF ACOUSTIC EMISSION IN REINFORCED CONCRETE USING A HETEROGENEOUS VELOCITY MODEL AND MULTILINEAR WAVE PROPAGATION PATHS

Stephan Gollob*, Thomas Vogel*

*Institute of Structural Engineering IBK, ETH Zurich, Zurich, 8093, Switzerland

Abstract

Acoustic emission analysis is a well-established non-destructive testing and monitoring method for homogeneous materials and structures. Therefore, the algorithms used to locate the source of an acoustic emission rely on homogeneous velocity models and straight wave propagation paths. Acoustic emission analysis has also become a promising method to monitor the change of conditions of concrete and reinforced concrete structures. Concrete and especially reinforced concrete, however, is a heterogeneous material. The velocity models used for determining the source location have to consider the heterogeneity of the structure. Reinforcements and cracks have a major influence on the wave propagation velocity and the wave propagation path. The most common localization methods, e.g. the Geiger Location Theorem, rely on straight wave propagation paths (Maochen 2003). For the case of cracked reinforced concrete, however, the assumption of a straight wave propagation path is far from reality. A new, non-iterative localization method is proposed taking a heterogeneous velocity model and multilinear wave propagation paths into account.

Keywords: Acoustic Emission Analysis, Monitoring, Non-destructive testing, Numerical Simulations, Reinforced concrete

1 Introduction

Acoustic emission analysis is a non-destructive monitoring and testing method. The data recorded by sensors can be used to evaluate the condition and monitor the change of condition of the specimen. One of the major targets of acoustic emission analysis is to locate sources of acoustic emissions. The publication of Kaiser’s dissertation in 1950 is often quoted as the start of the history of acoustic emission analysis (Grosse & Ohtsu 2008). Kaiser and his successors focused on homogeneous materials. Therefore, the common algorithms used to determine the source location of an acoustic emission rely on homogeneous velocity models and straight wave propagation paths. The area of application of acoustic emission analysis has been extended and includes now also heterogeneous materials and structures like concrete and reinforced concrete. The heterogeneity of concrete and in particular the reinforcements in reinforced concrete have a significant influence on the wave propagation. Hence, heterogeneous velocity models have to be used.

The tensile strength of concrete is low in comparison to its compressive strength. Most design standards ignore the tensile stress contribution. Reinforcements are added to concrete structures to carry the tensile forces. The reinforcements are activated after cracks occur in the tensile section of loaded concrete. The cracks do not affect the load capacity of the reinforced concrete structure, however, these cracks have a substantial influence on the wave propagation path. Cracks are normally filled with air, which inhibits the elastic wave propagation. The majority of the wave energy is reflected at the crack’s surface. Hence, only the arrival of waves traveling around the cracks can be detected. Therefore, the predicted wave propagation path used for the source localization algorithm should not cross cracks. In general, the assumption of a straight wave propagation path is far from reality in the case of both, cracked and uncracked reinforced concrete.
Fig. 1 Displacement field in x-direction within an unreinforced cracked concrete specimen 72 µs after the acoustic emission event at cross section y = 100 gp. The source location is marked with a *. 1 gp is equal to 1 mm.

The signal recorded by the sensors can be used to determine the arrival time of the first p-wave (primary wave) at the sensor. The p-wave velocity, \( c_p \), is the highest of the wave velocities and therefore the p-wave is the first wave arriving at the sensors. The picked arrival time of the wave at one sensor is one input for the source localization. In order to determine the source location based on picked arrival times the fastest wave propagation path between the sensor and the source location is of interest. In the case of heterogeneous materials and especially cracked structures, the shortest path between two points namely the straight connection, is not always the fastest. Hence, multilinear wave propagation paths should be used to determine the source location.

2 Numerical wave propagation simulations

The elastic wave propagation can be simulated numerically. The elastic wave propagation is calculated using a FORTRAN® application (Heidimod 6.4), developed by E. H. Saenger, based on a modified finite-difference grid (Saenger, Gold & Shapiro 2000). For numerical wave propagation simulations, a discretized numerical model of the specimen is used. The numerical model consists of cubical voxels with the edge length of 1 gp. The resolution of the velocity model is given by the conversion of the dimensions of the specimen into a number of voxels. Different material properties can be assigned to each voxel. The calculated displacement field caused by the elastic wave can be visualized (Fig. 1), and the displacement of the surface at defined sensor locations can be recorded.

Fig. 2 Sketch of the specimen including main dimensions, location and dimension of a crack and visualization of the reinforcement bar, \( d = 30 \) mm, located at the center of the y-z plane and the sensors.

In the case of wave propagation simulations the maximum voxel size should be about 1 mm to provide a realistic prediction of the wave front and the recorded signal. A part of the elastic wave is reflected at the interface between different materials. The wave front is scattered, refracted and the signal recorded by the sensors exhibits a lot of interference. The dominant frequency of signals which
occur in reinforced concrete is usually between 50 kHz and 200 kHz. Objects smaller than 1 mm have no impact on the wave propagation (Kocur, Saenger & Vogel 2010). For the wave propagation simulations mentioned in this document the edge length of each voxel was set to 1 mm. All objects larger or equal to 1 mm can be modelled in this way.

3 Heterogeneous velocity models

The common localization algorithms use one global velocity value for the whole specimen. The wave propagation velocities are material properties. In the case of a heterogeneous specimen, this would be an unrealistic assumption. The used velocity model should also be heterogeneous. The common localization algorithm is limited to straight wave propagation paths. However, they can be adapted to handle heterogeneous velocity models.

The velocity model is a discretized numerical model of the specimen. In order to prepare an accurate velocity model, the structure of the specimen should be known. As a general rule the reinforcement layout of a structure is known or can be determined. The detection of large air voids, large aggregates with a significant different wave velocity than the surrounding cement matrix or honeycombing is more complicated. It is possible to detect such objects using e.g. ultrasonic tomography. Ultrasonic or acoustic tomography assumes straight wave propagation paths. The limitations of this assumption, especially in connection with reinforcements and cracks, are pointed out in the next section. Individual aggregates or small air voids are very hard to determine, but it is possible with X-ray technology. Since individual aggregates and small air voids are distributed randomly but evenly, they have a minor impact on the fastest wave propagation path. Hence, Kocur introduced a homogeneous concrete with the effective elastic properties (EEP) of a heterogeneous concrete (Kocur 2012). He pointed out that for uncracked and unreinforced concrete, the application of a velocity model based on a heterogeneous concrete leads to no noticeable improvement of the source location accuracy, when compared to a velocity model based on homogeneous EEP concrete.

Adopting the Geiger Location Theorem to process a heterogeneous velocity model improves the localization algorithm significantly. This can be observed even if a straight wave propagation between the source and the sensor is assumed (Gollob & Vogel 2014). Compared to the fundamental equation of the Geiger Location Theorem for homogeneous specimens, only one term in equation (1) has to be adopted for heterogeneous specimens. In the case of a heterogeneous specimen, the constant p-wave velocity $c_p$ has to be exchanged with an average wave velocity $c_{p,i}$.

$$t_i = \frac{\sqrt{(x^i - x_c)^2 + (y^i - y_c)^2 + (z^i - z_c)^2}}{c_{p,i}} + t_c$$

The variable average p-wave velocity $c_{p,i}$ has to be calculated for each straight path between the estimated source location and every sensor $i$. However, a localization error always remains due to the fact that the straight wave propagation path is not always the fastest.

4 Multilinear wave propagation paths

In order to determine the source location, only the fastest wave travel path between the source and each sensor is of interest. The fastest wave propagation path is determined with the Dijkstra algorithm. The Dijkstra algorithm was published in 1959 and is a graph search algorithm to solve the single source shortest path problem (Dijkstra 1959). The input for the Dijkstra algorithm is a certain number of nodes and the length of the path connecting these nodes. In order to determine the fastest not the shortest way, the length of the path between the nodes is less important. Instead, the travel time between the nodes is of interest. This travel time has to be calculated in a first step. The specimen is discretized into voxels. The resolution of the numerical model, used for the Dijkstra algorithm, is usually lower than that of the wave propagation simulations in order to limit the computational effort. Therefore, the numerical model used for the source localization algorithm (described in the current and following sections), for the specimen illustrated in Fig. 2, consists of voxels with an edge length of 5 mm. Hence, $5^3 = 125$ voxels with an edge length of 1 mm in the numerical velocity model used for
the wave propagation simulation (section 2) are condensed into a single voxel with an edge length of 5 mm. The wave propagation velocity of one larger voxel of dimensions 5 x 5 x 5 mm is calculated as the average wave propagation velocity of the containing 125 voxels.

Each of the voxels is a node. If the node, representing the starting point of the Dijkstra calculation, is only connected to its direct neighbor, the wave travel path limited to directions parallel to the three directions in space (x, y and z). In order to enable more wave travel path directions, the node representing the starting point of the Dijkstra calculation is connected to its 342 surrounding voxels. This means that every voxel with a distance between 0 and 3 voxels in every direction in space is connected to the starting voxel. This distance will be called radius subsequently. Increasing the radius would enable a higher number of possible wave travel path directions, but it would also increase the computational effort significantly. For example, if the radius is increased from 3 to 7, the number of voxels connected with the starting voxel increases from 342 to 3374. The computational effort increases at least tenfold, in the case of a three dimensional velocity model.

Fig. 3 Two dimensional sketch of the Dijkstra calculation setup for a radius of three voxels and two materials

Initially, the arrival time of the wave at each voxel of the specimen, starting at a sensor location, has to be calculated. Therefore, a sensor location is defined as the starting node / voxel for the Dijkstra algorithm and the arrival time of the wave at this voxel is set to zero. Calculating the distance between the starting node and any connected node is simple. The straight wave travel path between two nodes passes through a number of voxels. These voxels could represent different materials. Hence, the wave velocity assigned to these voxels could be different. Therefore, the length of the wave travel path inside each voxel has to be determined. With this information and the velocity assigned to the voxels, the wave travel time between the starting and the connected node can be determined. Adding the calculated wave travel time to the arrival time of the wave of the starting voxel leads to the arrival time of the connected voxel. The starting voxel is excluded from further calculation. The voxel with the lowest wave arrival time is used as the next starting node. Since the area inside the radius around the new staring point overlaps with the area inside the radius around the old starting point, the arrival time of the wave at the voxels inside this area is calculated again. If the calculated arrival time of the wave for a voxel is lower than the previously calculated one, the arrival time will be updated with the lower value. This process is repeated until every voxel of the specimen was used as starting node / voxel. It has to be pointed out that, if a voxel along the straight wave propagation path and within the radius, represents air, the investigated wave travel path is excluded. The result of the calculation is a matrix with the arrival times of a wave, starting from sensor i, at each voxel. Subsequently this matrix will be called Timei.

The fastest wave travel path calculated between the source and the sensors can be visualized. Fig. 4 shows the visualization of two specimens with the dimensions of 30 x 8 x 8 gp. Fig. 4 a) illustrates a homogeneous EEP concrete specimen with a crack. The fastest wave travel path is the direct connection between the source and the sensors if the straight path does not cross the crack. If the straight path crosses the crack, the fastest way passes around the crack, closely. Fig. 4 b) illustrates a homogeneous EEP concrete specimen with a single reinforcement bar. The majority of the fastest wave traveling paths passes through the reinforcement bar. The p-wave velocity of steel is about 1.5
times the p-wave velocity of concrete. Fig. 4 illustrates the significant influence of cracks and reinforcement bars on the elastic wave propagation.

![Fig. 4](image)

**Fig. 4** Visualization of the fastest wave propagation path between two sources and eight sensors. a) A concrete specimen with a crack at \( x = 10 \) [gp]. b) A concrete specimen with a single reinforcement bar.

## 5 Source localization

### 5.1 Principle of the “Fastest Way” localization

The common source localization algorithms are iterative. Error ellipsoids can be used to visualize an error estimation. However, size and especially orientation of the error ellipsoids depend strongly on the sensor arrangement. Schechinger (2006) pointed out that error ellipsoids are not able to visualize the real source location error.

The “Fastest Way” algorithm does not calculate a source location directly. Instead, based on the velocity model and the picked arrival time of the wave at the used sensors, it investigates which voxels most likely host the source. In order to identify the voxels which would be reached by waves, starting from two sensors \( i \) and \( j \), at the same moment, the *Time* matrices (see section 4) of those two sensors have to be subtracted from each other. The resulting matrix is called *LocCal*. Voxels represented by a *LocCal* value of zero are reached by the two waves at the same time. Plotting the normalized *LocCal* matrix, the figure shows a surface between the two sensors with values of nearly zero. Preliminary, subtracting the picked arrival time of the wave at the sensors \( i \) and \( j \) from the *Time* matrixes moves the determined surface. The source should now be located in one of the surface building voxels. Fig. 5 illustrates the significant influence of a crack on the shape of such a face.

![Fig. 5](image)

**Fig. 5** Visualization of the result of the localization of source 1, pictured in Fig. 4 a), using two sensors. Cross sections at determined source location.
To reduce the possible source location area, the data of more sensors are required. A $LocCal$ matrix is calculated for every possible combination of two sensors. The sought matrix, $LocEr$, is the normalized sum of all the $LocCal$ matrices. The values of the matrix $LocEr$ are called normalized error. A normalized error close to zero means a higher likelihood that the source is located in the voxel corresponding to this value. This voxel is shown in red in the plots. The area represented by voxels corresponding to a normalized error of less than 0.25 can be considered as the possible source location. These voxels are visualized red to yellow. The source is most likely not located in the area represented by voxels corresponding to a normalized error of 0.5 or larger. These voxels are visualized blue to white.

The determined source location is the center of the voxel corresponding to the minimum value of $LocEr$. It is mathematically possible to determine a source location with only two sensors (see Fig. 5). The reliability and accuracy of the determined source location should always be evaluated with the aid of the visualized $LocEr$ matrix (see section 5.1). The reliability and accuracy of the result depends on the sensor location and the accuracy of the determined arrival time of the wave at the sensors. The influence of cracks and reinforcements on the wave propagation path should also be considered.

5.1 Results using the “Fastest Way” localization

The numerical specimen used for the preliminary wave propagation simulation was a reinforced concrete cuboid of dimensions 600 x 200 x 150 mm EEP. The reinforcement bar was modeled with a diameter of 30 mm. A crack was introduced at the center of the specimen. The specimen and sensor layout is illustrated in Fig. 2. The signal recorded by 38 sensors can be used for the source localization. The outcome of a “Fastest Way” localization is a determined source location and the matrix $LocEr$.

![Image](image1)

**Fig. 6** Visualization of the result of a “Fastest Way” source localization using six sensors. Cross sections at determined source location.

Fig. 6 illustrates the satisfying result of a “Fastest Way” localization using the data of six sensors. The determined $x$-coordinate of the source matches perfectly the predefined source location. The deviation in $y$- and $z$-direction is only 5 mm, which is the size of one voxel. Fig. 6 shows three reddish-orange voxels. However, the voxel representing the predefined source location is colored yellow. The area colored red to yellow is quite small, which indicates an accurate and reliable outcome. The $x$-$z$-cross section illustrates the influence of the reinforcement bar on the calculated solution quite well.

For the result visualized in Fig. 7, the data recorded by 15 virtual sensors was used to calculate the $LocEr$ matrix. All the sensors are located on the opposing side of the crack with regard to the predefined source location. There are no red, orange or yellow voxels displayed in Fig. 7. Nearly the entire specimen to the left of the crack is colored green. Most of the specimen on the right side of the
crack is colored blue to white. The visualized result indicates that the determined source location is not reliable. It also indicates that the source is most probably located to the left of the crack. The determined source is located on the left side of the crack. Again the determined $x$-coordinate of the source matches perfectly with the predefined one. The deviation in $y$-direction is only 10 mm, the size of two voxels. The deviation in $z$-direction is about 50 mm. This is one third of the specimen’s dimension in this direction. The deviation in $z$-direction is clearly caused by the crack.

All the sensors are located on the site of the crack opposing the source. An accurate source location is not possible for this sensor arrangement. The visualization of the calculated $LocEr$ matrix also illustrates this effect. However, the determined source location is still surprisingly accurate.

![Fig. 7](image-url) Visualization of the result of a “Fastest Way” source localization using 15 sensors. Cross sections at determined source location.

## 6 Conclusion and outlook

The “Fastest Way” algorithm is a promising new method to determine the source localization in a heterogeneous specimen. The location and dimensions of reinforcement bars and cracks is required to provide an accurate velocity model. Small air voids and aggregates have a negligible effect on the source localization.

The determined source location, using the “Fastest Way” algorithm, is more accurate than the source location determined using a Geiger Location Theorem process within a heterogeneous velocity model. However, both methods are far more accurate than any method relying on a homogeneous velocity model.

The visualization of the $LocEr$ matrix provides a better graphical representation of the reliability and accuracy of the determined source location than an error ellipsoids.

The major disadvantage of the new method is the computational effort required to calculate the $Time$ matrices for each sensor. The resolution of the discretization of the heterogeneous velocity model used for the localization is limited to keep the computational effort within limits.

The growth of a crack is always associated with acoustic emissions. Therefore, an accurately determined acoustic emission could be used to update the velocity model. Such updated velocity models will increase the accuracy of the source localizations. However, a just-in-time update of the velocity model used for the localization is currently not possible, due to ensuing the computation time required to calculate the $Time$ matrices.
References


