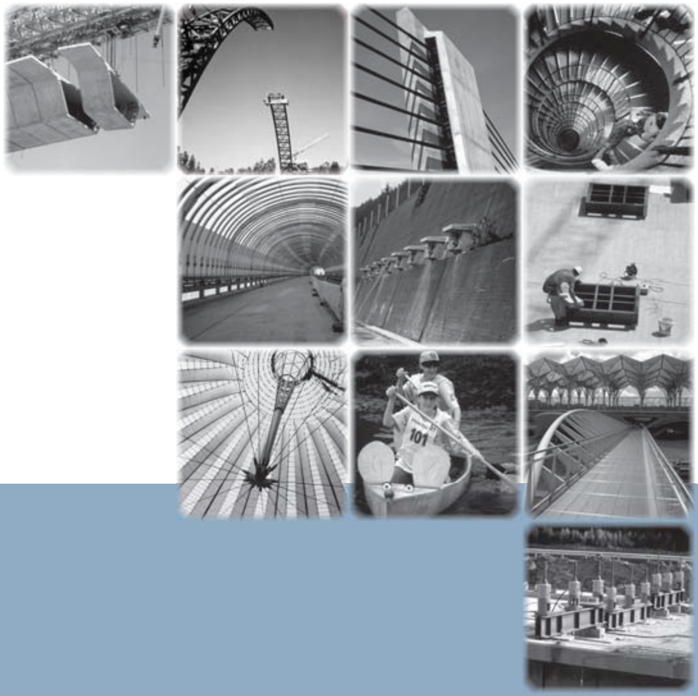
Localisation of Acoustic Emission in Reinforced Concrete using Heterogeneous and Orthotropic Velocity Models

Conference Paper

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

Publication date:
2014

Permanent link:
https://doi.org/10.3929/ethz-a-010265293



Author(s):
Stephan Gollob and Thomas Vogel

Title:

Localisation of Acoustic Emission in Reinforced Concrete using Heterogeneous and Orthotropic Velocity Models

Publisher:
Université Laval

Publication Place:
Québec (Québec), Canada

Publication Date:	Start Page:	End Page:	Language:
2014	375	380	English

Editor(s)
Josée Bastien, Nicolas Rouleau, Mathieu Fiset, Mathieu Thomassin

Book Title:
The 10th fib International PhD Symposium in Civil Engineering

Event Name:
The 10th fib International PhD Symposium in Civil Engineering

Event Location:
Université Laval, Québec (Québec), Canada

Event Date:
July 21 -23, 2014

Assigned Organisational Unit(s):
03353

Localisation of Acoustic Emission in Reinforced Concrete using Heterogeneous and Orthotropic Velocity Models

Stephan Gollob and Thomas Vogel

Institute of Structural Engineering,
ETH Zurich,
Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland

Abstract

Acoustic emission analysis (AEA) has become a promising method to monitor the change in the condition of concrete structures. The research project aims at establishing localisation algorithms using heterogeneous velocity models. Taking the heterogeneity of concrete and the influence of reinforcement into account will improve the source localisation accuracy. Until now it is common to use homogeneous velocity models to localize the AE source. A new numerical reinforced concrete model (NRCM) as well as a MATLAB script for three dimensional acoustic tomography are developed. These two approaches are used to generate models where the wave propagation velocity is a function of the coordinates. Subsequently, a localization method is modified for processing these heterogeneous velocity models. The combination of three dimensional acoustic tomography with AE analysis is a novel and promising approach.

1 Problem statement

Acoustic emissions (AE) are caused by strain energy release and occur with all building materials. AEA has become a promising method to evaluate the condition and to monitor the change of condition of concrete and reinforced concrete structures. Quantitative procedures try to identify all characteristics of an AE source and therefore have to consider the wave propagation between source and sensors [2]. Profiting from the methods of geophysics, considerable results have been achieved with respect to determination of arrival times (picking), source localization and moment tensor analysis. Further progress depends on the handling of cracking and cracked concrete as the medium for elastic wave propagation, considering also other elements of structural concrete like reinforcement, post-tensioning tendons and inserts.

The research project aims at investigating the influence of reinforcement and cracks on wave propagation. Afterwards a localisation algorithm using heterogeneous velocity models will be established to take the investigated phenomena into account.

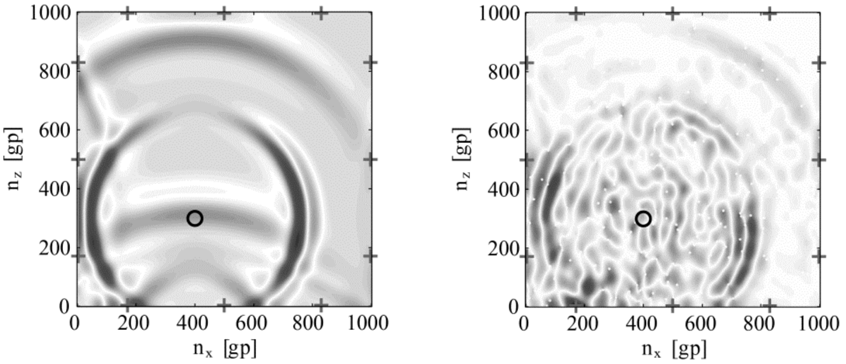


Fig. 1 Snapshot of a two dimensional displacement wave field during a wave propagation simulation. Left: Using a homogeneous velocity. Right: Using a heterogeneous velocity field generated using the NCM [3]

Proc. of the 10th *fib* International PhD Symposium in Civil Engineering
July 21 to 23, 2014, Université Laval, Québec, Canada

2 Research project

The first target of the project is to establish a numerical reinforced concrete model (NRCM) that exhibits the physical constitution and approximates the wave propagation behavior of reinforced concrete for AE localization. Until now, common localization methods (e.g. onset time based Geiger methods [1]) rely on a homogeneous velocity model. That may be correct if homogeneous materials are involved but for concrete and especially reinforced concrete structures this assumption is inappropriate (Fig. 1). The idea is to develop a NRCM, based on the NCM described in [4]. This model as like as the result of a three dimensional acoustic tomography can be used later within AE localization and elastic wave propagation simulations. The NRCM model is to be compared with velocity measurements from ultrasonic tomography and incorporated into a proved onset-time-based localization method. The NRCM and the three dimensional acoustic tomography are to be corroborated by preliminary experiments with artificial sources (pencil-lead breaks, numerical wavelets) and on destructive physical experiments (pull-out test, four-point-bending test) and evaluated in terms of how accurately AE sources can be localized.

The procedures of investigation can be subdivided in four phases:

- Development of NRCM and a three dimensional acoustic tomography algorithm
- Modification of localization method for heterogeneous and orthotropic velocity models
- Physical experiments
- Application of heterogeneous and orthotropic velocity models to evaluate physical experiments

2.1 Development of NRCM and a 3D-acoustic tomography algorithm

Two ways of creating a three dimensional velocity model are tested. The first is generating a numerical model of concrete or reinforced concrete structures. Therefore the already mentioned NCM or NRCM will be used. The second one will be a 3D-acoustic tomography of physical specimens.

2.1.1 NRCM

The goal is to extend the three phase (aggregate, cement matrix and air voids) NCM to a NRCM by implementing a fourth phase (reinforcement steel). Before that a simpler two phase NRCM is established. These two phases are homogeneous. The first phase represents concrete and the second one reinforcement. The two phase NRCM is used to investigate the effect of reinforcement on the wave propagation. Different reinforcement layouts as well as various frequencies are tested.

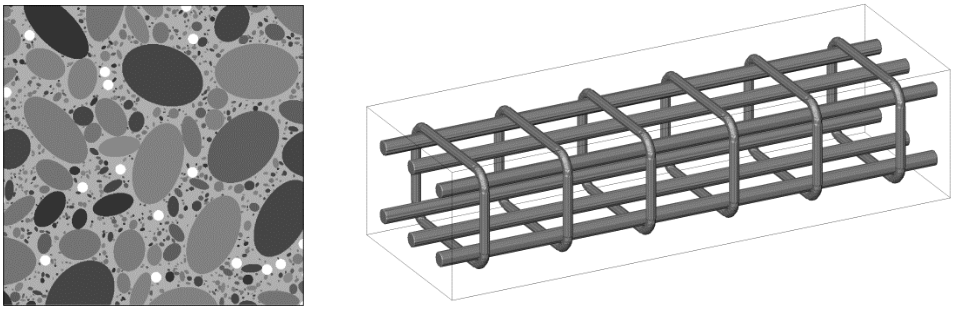


Fig. 2 Left: Two dimensional representation of the NCM with aggregates (different gray ellipsoids) and air voids (white) randomly distributed surrounded by a homogeneous cement matrix (light gray); Right: Three dimensional representation of reinforcement of a NRCM

The reinforcement models are assembled out of cylinders and quarter tori. Six longitudinal bars Ø 16 mm and six stirrups Ø 12 mm are illustrated in Fig.2 right. The NRC in Fig. 2 left as well as the reinforcement layout in Fig. 2 right is generated with FORTRAN® and visualized with AVIZO 7®.

The p-wave velocity of reinforcement (c_P=5900 m/s) is about one and a half times the p-wave velocity of concrete (c_P=3912.15 m/s). Besides influencing the wave speed, reinforcement also reflects parts of the wave and scatters the signal. Fig.3 a) illustrates that the wave is reflected by the four longitudinal bars located nearest to the source at 75/75/75 [mm]. A damping of the signal or a delay of the propagation of the wave front behind the reinforcement bars could as mentioned in [5] not be identified.

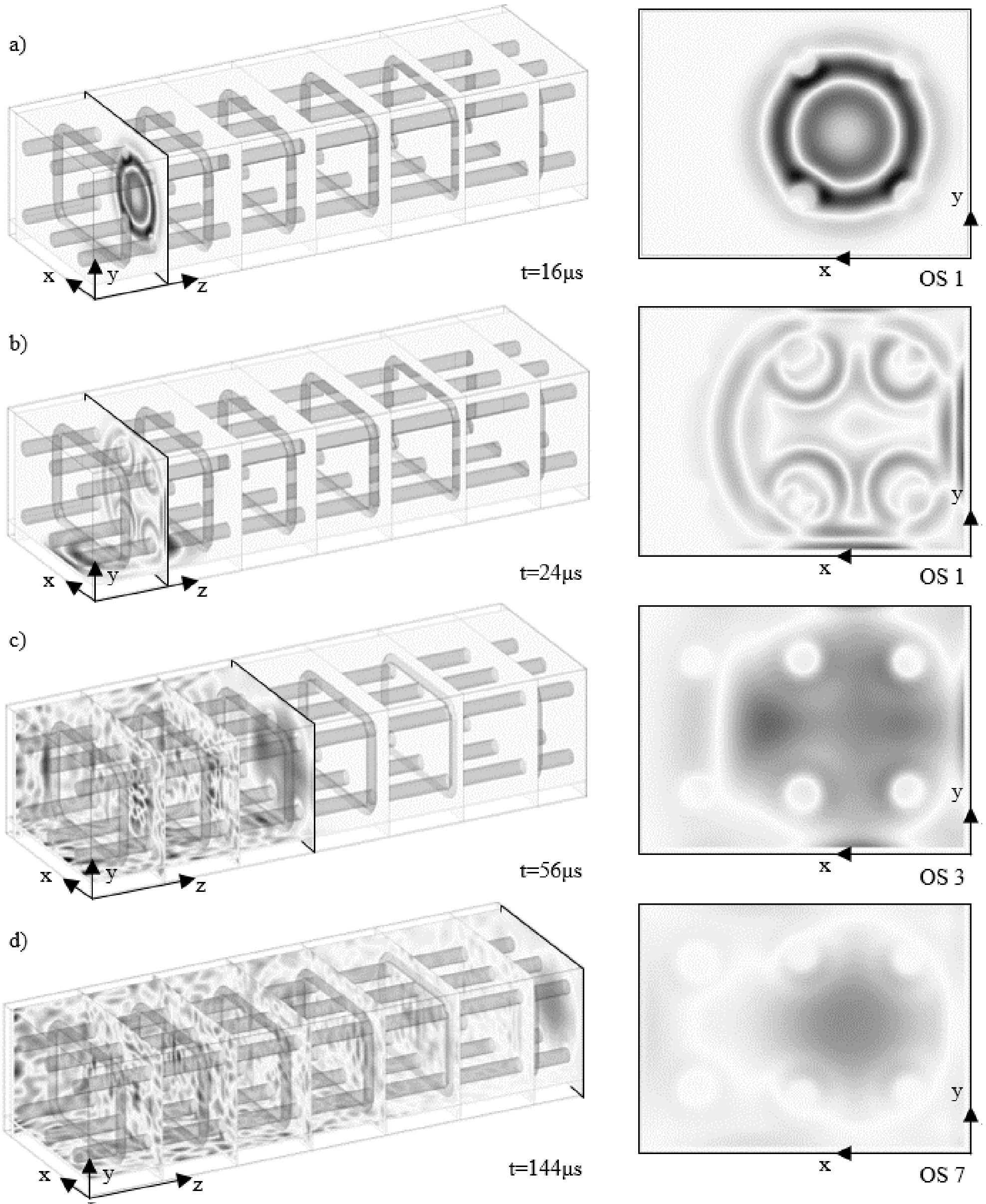


Fig. 3 Snapshots of displacement wave fields at different points in time. Left: 3D-model of the specimen with seven ortho slices (OS) xy-plane, one OS yz-plane and one OS zx-plane as well as a transparent illustration of the reinforcement. Dimensions 200/150/600 [mm] Right: Two dimensional displacement wave field of an OS.

On the contrary, in Fig. 3 a) right it seems as the wave front is shifted slightly ahead in the area of the cross sections of the bars. Fig. 3 b) illustrates that the wave front has been reflected at the surface of the reinforcement and the specimen. Fig. 3 c) right shows an already scattered wave field. In Fig. 3 d) right hardly any wave front can be spotted. If the material is homogeneous the acoustic wave would be spread spherically. Fig. 3 c) right and Fig. 3 d) right illustrate an effect of reinforcement on the wave propagation. In both cases the wave field deforms in x direction, in the direction of the last two bars.

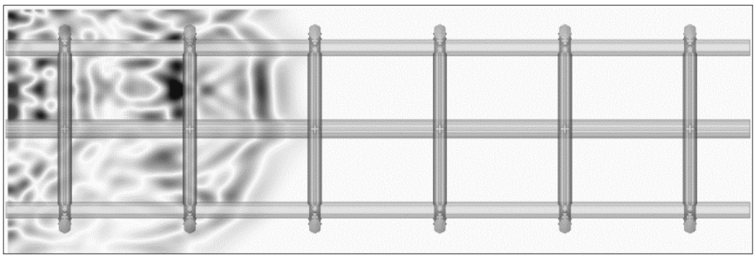


Fig. 4 Snapshots of a displacement wave t=40 μs illustrating a zx-plane ortho slice and transparent reinforcement.

The influence of the reinforcement on the wave propagation seems to be greater if the bar is aligned in the propagation direction (Fig. 4).

The lager the percentage of reinforcement the faster the wave should propagate through the specimen. Most standards are limiting the percentage of reinforcement to four percent. Four percentages of reinforcement enlarge the speeds up to about 120% of the wave propagation velocity of unreinforced concrete. The additional velocity increase declines for higher percentages of reinforcement.

Subsequently another NRCM consisting of four phases will be established. A part of the parameter studies are going to be repeated in order to investigate the influence of reinforcement bars in combination with a heterogeneous three phase concrete model.

2.1.2 3D-acoustic tomography

Another task of this phase is to program a MATLAB® code for three dimensional acoustic tomography. The only information of disposal to calculate a three dimensional velocity model is the location of the sensors and the artificial sources as well as the period of time needed by the signal to propagate from source to sensor. This leads to a limit number of equations. In order to enable an appropriate result of the tomogram additional data processing has to be taken into consideration.

In a first step a quite simple tomography algorithm is used to investigate the possibilities and limitations of acoustic tomography. The main results of that investigation are that quite a big number of artificial sources are needed. Nevertheless the size of the investigated area as well as the resolution is limited. The voxels should not be smaller than about 1 cm^3. The investigated area cannot be bigger than the area covered by the artificial sources; usually it has to be smaller. The number of voxels, which is also the number of unknowns, is generally bigger than the number of equations. The maximum possible number of equations is equal to the number of sensors multiplied with the number of artificial sources. Thus, an iterative regression calculation might not produce an appropriate result. Reliable ways to improve the solutions have to be developed and tested.

An elementary limitation is that the wave velocity of any voxel cannot be higher than the wave velocity of steel. The next idea is to “push” the iterative calculation into the right direction. After a couple of iterations all voxels are assigned to concrete or steel respectively. This procedure is going to be repeated a couple of times. Later on only voxels with wave velocities in the range of the velocity of reinforcement respectively concrete are assigned to these materials. Although the improvement of the tomogram is quite satisfying it is linked with some problems and limitation. Fig. 2 right shows the result of 50.000 iteration steps without pushing the iterative calculation. It is not possible to locate the reinforcement. Fig. 2 left shows the result after 50.000 iterations. This time the calculated wave velocity of the voxel had been pushed. The result is not perfect. However it is possible to identify the mean bars and two stirrups. The next step is finding more ways to improve the results of the iterative calculation. For example predetermine and freezing the voxel at the surface (concrete cover) would make sense.

After generating a stable code, it will be validated with the data gained by simulating wave propagation in a numerical two phase specimen. The optimal mesh size covered by 16 sensors as well as the number and layout of artificial AE’s needed to calculate a satisfying tomogram are investigated.

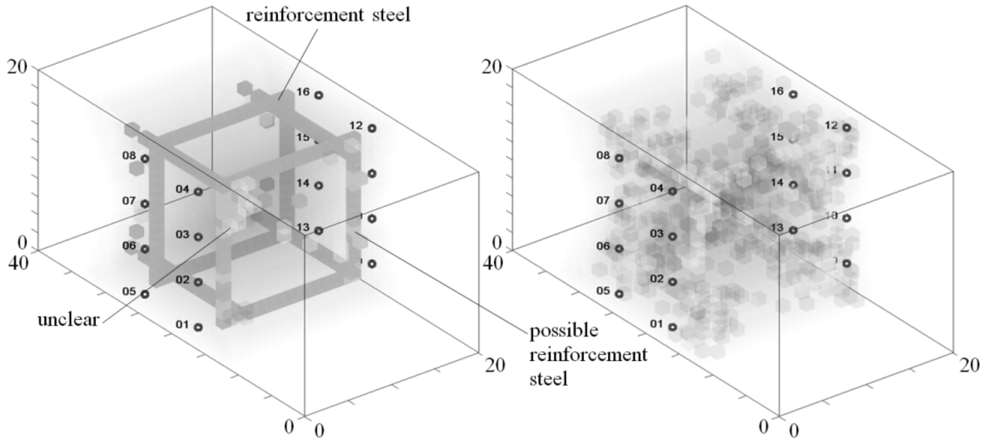


Fig. 2 Result of three dimensional acoustic tomography – 50.000 iteration steps. Dark gray voxel are symbolizing reinforcement. Transparent voxel mean there is no information about the wave velocity. Left: the result using "PUSH". Right: the result without using "PUSH".

The first milestone will be the combination of the NRCM and the three dimensional acoustic tomography. The wave propagation caused by a set of simulated artificial sources will be predicted using the NRCM. The stored data will be used for calculating a tomogram of the specimen.

2.2 Modification of existing localisation method for heterogeneous and orthotropic velocity models

The NRCM as like as the tomogram consist of maximum four phases. The wave velocity is different for each of the phases. In case of the aggregate the wave velocity is variable; within a range. Common localisation algorithms rely on homogeneous and constant velocity distribution.

The linearized localization algorithm using the AIC-picker [5] demands at least four equations and a scalar wave velocity to solve a linear system of equations and to calculate three-dimensional coordinates iteratively. The point in time the AE occur is the fourth unknown.

The idea is to define the wave velocity as a space dependent variable and to assign to each point of domain a certain wave velocity available from NRCM in a binary format within the localization procedure. Obstacles to note are the contained air voids that are assumed to transmit no energy, which can lead to instability of the algorithm. A way needs to be figured out to solve that problem. Allocation of velocities from the NCM to be used in the localization method, mentioned before, consumes computational time, but the overall result will provide a significantly improved localisation approach compared to others available at that time. The benefit of this new approach is that, once implemented, the algorithm can be applied to other three-dimensional velocity models such as an ultrasonic tomogram or other numerical models with a similar architecture.

The exact location of aggregate, cement matrix and air voids is unknown generally. Acoustic/ultrasonic tomography cannot determine their distribution. Hence, defining a certain material depending wave velocity to each point of domain is not always possible. In that case the two phase NRCM material properties can be used. The location of the reinforcement is usually allocable. The wave velocity of concrete as well as the damping and distortion of the signal can be estimated due to the almost even distribution of the aggregate, the cement matrix and the air voids.

Error estimation can be performed for the results of the different methods, where the additional equations can be used to calculate error ellipsoids [5].

2.3 Planned physical experiments

The physical experiments can be subdivided in non-destructive experiments with artificial source excitations at positions known a priori, destructive preliminary (pull-out test) and the main (four-point-bending test) experiments.

The pull-out test is carried out on a concrete cube of size 200 × 200 × 200 mm with a centered steel reinforcement bar of diameter Ø14 mm. Sixteen PZT sensors are arranged on 5 available faces of the cube. The remaining face is used as the support. The load is applied displacement-controlled until failure approaches. The reinforcement of the RC beam of size 300 × 600 × 2000 − 3000 mm will be defined later. The RC beam/girder with a span of 1.7 − 2.7 m is supported on two steel plates (100 × 300 × 200 mm). A PTFE (Polytetrafluoroethylene) layer of 5 mm is placed above one of the steel plates to allow horizontal movement of the beam along the longitudinal beam axis. Below the steel plates, load cells are arranged to measure the applied load. The beam is loaded to failure using two low-height cylinders, which are resting on a stiff girder and are located below the loading cells. The load is regulated by a hand pump to minimize electromagnetic influences of electric devices. An auxiliary construction is connected to the stiff girder by tension rods to ensure correct load application at the supports. The two point loads are introduced via steel roller bearings. The loading is applied in cycles.

Before the PZT sensors are finally mounted on the beam/girder for the destructive experiment, ultrasonic tomography is performed to determine a three-dimensional velocity model. The velocity distribution is contained inside the ultrasonic tomogram, which is used as a velocity model in one AE localization method. In turn, all transmitters induce a short wavelet (e.g. Ricker) into the specimen to propagate. The set of receivers records the emitted wave field. Assuming that the travel time of the P-wave along a straight propagation path, from transmitter to receiver, is known from measurement and the distance is known as well from geometry of the specimen, then for one transmitter-receiver setup it is straightforward to calculate the corresponding P-wave velocity (c_P [m/s] = Distance/Time). The accuracy of the resulting tomogram strongly depends on the minimum mesh size. The resulting velocity distribution, once validated, can then be incorporated into the localization method.

2.4 Application of heterogeneous and orthotropic velocity models to evaluate physical experiments

Having demonstrated that the artificial source positions (pencil-lead breaks) and real AE sources (pullout test) can be localized successfully with the suggested methods, allows applying those methods on AE data from the main experiment. The goal is firstly to calculate the three-dimensional AE source coordinates including error ellipsoids and secondly to oppose the results with the results using heterogeneous and orthotropic velocity models superimposed with crack pattern from photos in order to point out the gained accurateness.

3 Conclusion

The first preliminary simulations using a two phase NRCM and only one reinforcement bar already point out that using a heterogeneous velocity model clearly increases the accuracy of the source localisation. However, it also increases the computational time significantly. Discrepancies could be kept below 4% of the specimen’s dimensions.

The 3D-tomography requires high computational power and time. Moreover, a high number of artificial sources is needed to determine a velocity model of the investigated specimen. Improving the code using additional conditions, beside the measured wave propagation data, will be the best way to enable 3D-tomography with appropriate effort.

References

[1] L. Geiger. Herdbestimmung bei Erdbeben aus der Ankunftszeit. *Nachrichten von der Königlichen Gesellschaft der Wissenschaften zu Göttingen, Math.-phys. Klasse*, 4:331–349, 1910.

[2] Christian U. Grosse and Masayasu Ohtsu, editors. *Acoustic Emission Testing, Basics for Research - Applications in Civil Engineering*. Springer-Verlag Berlin Heidelberg, 2008.

[3] Georg Karl Kocur. *Time reverse modeling of acoustic emission in structural concrete*. PhD thesis, ETH Zürich, 2012.

[4] Georg Karl Kocur, Erik H. Saenger, and Thomas Vogel. Elastic wave propagation in a segmented X-ray computed tomography model of a concrete specimen. *Construction and Building Materials*, 24:2393–2400, 2010.

[5] Babara Schechinger. *Schallemissionsanalyse zur Überwachung der Schädigung von Stahlbeton*. PhD thesis, ETH Zürich, 2006.