Detection of Hidden Cracks in Concrete Structures Using Reverse Time Migration of Ultrasonic Echo Data

Markus König

August 11, 2016
Detection of Hidden Cracks in Concrete Structures Using Reverse Time Migration of Ultrasonic Echo Data

MASTER OF SCIENCE THESIS

for the degree of Master of Science in Applied Geophysics at
Delft University of Technology
ETH Zürich
RWTH Aachen University

by

Markus König

August 11, 2016
IDEA LEAGUE
JOINT MASTER’S IN APPLIED GEOPHYSICS

Delft University of Technology, The Netherlands
ETH Zürich, Switzerland
RWTH Aachen, Germany

Dated: August 11, 2016

Supervisor(s):

Dr. rer. nat. Ernst Niederleithinger

Committee Members:

Dr. rer. nat. Ernst Niederleithinger
Prof. Dr. Hansruedi Maurer
Eidesstattliche Versicherung

König, Markus ___________________________ 316470
Name, Vorname Matrikelnummer (freiwillige Angabe)

Ich versichere hiermit an Eides Statt, dass ich die vorliegende Arbeit/Bachelorarbeit/Masterarbeit* mit dem Titel
Detection of Hidden Cracks in Concrete Structures using Reverse Time Migration of Ultrasonic Echo Data

selbständig und ohne unzulässige fremde Hilfe erbracht habe. Ich habe keine anderen als die angegebenen Quellen und Hilfsmittel benutzt. Für den Fall, dass die Arbeit zusätzlich auf einem Datenträger eingereicht wird, erkläre ich, dass die schriftliche und die elektronische Form vollständig übereinstimmen. Die Arbeit hat in gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen.

Berlin, 10.08.2016

Ort, Datum Unterschrift

*Nichtzutreffendes bitte streichen

Belehrung:

§ 156 StGB: Falsche Versicherung an Eides Statt
Wer vor einer zur Abnahme einer Versicherung an Eides Statt zuständigen Behörde eine solche Versicherung falsch abgibt oder unter Berufung auf eine solche Versicherung falsch aussagt, wird mit Freiheitsstrafe bis zu drei Jahren oder mit Geldstrafe bestraft.

§ 161 StGB: Fahrlässiger Falschew; fahrlässige falsche Versicherung an Eides Statt
(1) Wenn eine der in den §§ 154 bis 156 bezeichneten Handlungen aus Fahrlässigkeit begangen worden ist, so tritt Freiheitsstrafe bis zu einem Jahr oder Geldstrafe ein.
(2) Straflosigkeit tritt ein, wenn der Täter die falsche Angabe rechtzeitig berichtigt. Die Vorschriften des § 158 Abs. 2 und 3 gelten entsprechend.

Die vorstehende Belehrung habe ich zur Kenntnis genommen:

Berlin, 10.08.2016

Ort, Datum Unterschrift
Abstract

Ultrasonic echo measurements are widely used in the field of non-destructive testing (NDT). In civil engineering, concrete structures are evaluated by this technique. Currently, Synthetic Aperture Focusing Technique (SAFT), a group of migration algorithms, is state of the art in ultrasonic data processing. Reverse Time Migration (RTM), recently introduced to NDT, shows significant improvements in mapping complex structures, like vertical steps. Modelling a concrete test specimen, synthetic experiments confirm that RTM can be used to map notches and crack-like structures in concrete. With introducing heterogeneous synthetic models, the influence of the migration velocity of RTM was investigated. Furthermore experiments on real concrete structures were conducted. Thereby ultrasonic echo data is acquired on a test specimen with a known vertical notch. A commercial ultrasonic tomograph and a scanner system, developed at BAM, are used. The data from both systems is processed using SAFT and compared to results of RTM of the scanner data. Results from the SAFT migration do not reveal any information about the vertical notch, other than an indication of the lateral position. Data migrated using RTM shows the side wall of the notch and affirms its potential for such purposes. Processing the data from the commercial ultrasonic device using RTM does not show any improvements compared to the initial SAFT result. The fixed aperture of the device is not suitable for RTM. An additional measurement is performed on a second specimen using the scanner system. The specimen shows several fine cracks of which only outcrops at the sides are visible. Results of RTM indicate mapped signatures from those cracks. Their lateral positions along the specimen as well as an estimate about the crack height can be determined within the final images. This study thereby introduces the applicability of RTM for detecting cracks within concrete structures.
Acknowledgments

First of all, I would like to thank my supervisor Dr. Ernst Niederleithinger for his expertise and advises throughout my Master thesis.

Second, I appreciate the collaboration with my colleagues at Division 8.2., especially Maria Grohmann. She introduced me to the Madagascar software and the scanner system used. I am very grateful for her contributions and patience.

Furthermore the collaboration with Division 7.1. and Stephan Pirskawetz, who supported this project with one of their specimen and further data, is acknowledged.

Berlin
August 11, 2016

Markus König
# Table of Contents

Abstract vii
Acknowledgments ix
Acronyms xix

## 1 Introduction 1

## 2 Theory and Numerical Modelling 5

2-1 Reverse Time Migration (RTM) ........................................ 5

2-2 Finite Difference modelling ........................................... 9

2-2-1 Source wavelet ......................................................... 10

2-2-2 Stability and numerical dispersion .................................. 11

2-2-3 Boundary conditions .................................................... 12

2-3 Madagascar software environment ..................................... 12

2-4 Synthetic Aperture Focussing Techniques (SAFT) .................. 14

2-5 Ground Penetrating Radar (GPR) ....................................... 15

## 3 Synthetic Experiments 17

3-1 General parameters ....................................................... 17

3-1-1 Model dimensions ..................................................... 18

3-1-2 Parameters for numerical simulation ............................... 20

3-1-3 Data acquisition parameter .......................................... 23

3-2 Homogeneous models ....................................................... 26

3-2-1 True scale model ....................................................... 26

3-2-2 Modification 1 - shorter notch ..................................... 30

3-2-3 Modification 2 - notch close to boundary .......................... 32
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-2-4 Modification 3 - two notches</td>
<td>33</td>
</tr>
<tr>
<td>3-2-5 Modification 4 - random crack-like structure</td>
<td>35</td>
</tr>
<tr>
<td>3-3 Heterogeneous models</td>
<td>37</td>
</tr>
<tr>
<td>3-3-1 True scale model</td>
<td>37</td>
</tr>
<tr>
<td>3-3-2 Modification 1 - random crack-like structure</td>
<td>41</td>
</tr>
<tr>
<td>3-3-3 Modification 2 - complex crack-like structure</td>
<td>42</td>
</tr>
<tr>
<td>4 Experiments on concrete structures</td>
<td>43</td>
</tr>
<tr>
<td>4-1 Measurement devices</td>
<td>43</td>
</tr>
<tr>
<td>4-1-1 A1040 MIRA ultrasonic tomograph</td>
<td>44</td>
</tr>
<tr>
<td>4-1-2 Scanner system</td>
<td>45</td>
</tr>
<tr>
<td>4-1-3 Ground Penetrating Radar (GPR)</td>
<td>47</td>
</tr>
<tr>
<td>4-2 Test Specimen PKN</td>
<td>47</td>
</tr>
<tr>
<td>4-2-1 A1040 MIRA ultrasonic tomograph</td>
<td>47</td>
</tr>
<tr>
<td>4-2-2 Scanner system</td>
<td>49</td>
</tr>
<tr>
<td>4-2-3 Ground Penetrating Radar (GPR)</td>
<td>58</td>
</tr>
<tr>
<td>4-3 Test Specimen PKR</td>
<td>61</td>
</tr>
<tr>
<td>4-3-1 Scanner system</td>
<td>61</td>
</tr>
<tr>
<td>5 Discussion</td>
<td>67</td>
</tr>
<tr>
<td>5-1 Synthetic Experiments</td>
<td>67</td>
</tr>
<tr>
<td>5-2 Experiments on concrete structures</td>
<td>68</td>
</tr>
<tr>
<td>6 Conclusion and Outlook</td>
<td>71</td>
</tr>
<tr>
<td>Bibliography</td>
<td>73</td>
</tr>
<tr>
<td>A Synthetic Experiments</td>
<td>77</td>
</tr>
<tr>
<td>B Experiments on concrete structures</td>
<td>81</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>1-1</td>
<td>Schematic setup of ultrasonic echo measurement. Transducer (S) acting as source, emitting a signal which is reflected and recorded by a receiver (R).</td>
</tr>
<tr>
<td>1-2</td>
<td>Exemplary cross section through a concrete structure. Red arrows indicate different aggregates, yellow circle shows a steel bar.</td>
</tr>
<tr>
<td>2-1</td>
<td>Schematic explanation of the RTM algorithm.</td>
</tr>
<tr>
<td>2-2</td>
<td>Ricker wavelet used as source function. Center frequency of 50 kHz, shifted 0.02 ms to ensure minimum phase.</td>
</tr>
<tr>
<td>2-3</td>
<td>Schematic architecture of the Madagascar software package. Adapted from [Fomel et al., 2013].</td>
</tr>
<tr>
<td>3-1</td>
<td>Concrete test specimen &quot;PKN&quot;.</td>
</tr>
<tr>
<td>3-2</td>
<td>Schematic cross section through the test specimen indicating dimensions.</td>
</tr>
<tr>
<td>3-3</td>
<td>True scale velocity (upper model) and density (lower model) models of the concrete test specimen &quot;PKN&quot;. Exact values for velocity and density can be found in Table 3-1.</td>
</tr>
<tr>
<td>3-4</td>
<td>Snapshots of the simulated wave field, using the model in Figure 3-3, from shot no. 26 at location x = 540 mm. Yellow dashed line separates the concrete specimen from air boundaries. The blue rectangles indicate the notch.</td>
</tr>
<tr>
<td>3-5</td>
<td>Synthetic shot record simulated on the true scale model from Figure 3-3, emitted at position x = 640 mm. The blue arrows points towards the direct wave, indicating a fast decay in amplitude. The red arrow shows the reflection of the direct wave at the tip of the notch.</td>
</tr>
<tr>
<td>3-6</td>
<td>Stack resulting from 30 sources and a recording time of ( t = 0.20 \text{ ms} ).</td>
</tr>
<tr>
<td>3-7</td>
<td>Comparison of different RTM stacks using varying number of sources. The upper stack results of ten equally spaced shot points. The middle stack consists of 30 single shots and the lower stack is the sum of 75 single shots.</td>
</tr>
<tr>
<td>3-8</td>
<td>Homogeneous velocity and density models for simulation of source wave field ( W_S ) and the receiver wave field ( W_R ).</td>
</tr>
<tr>
<td>3-9</td>
<td>Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-3.</td>
</tr>
</tbody>
</table>
1-10 Four different shot records (A to D) from the forward simulation on the true scale model. The dashed turquoise lines mark the position of the notch along the x-axis; yellow annotations highlight influences of notch on the recorded signal.

1-11 Resulting stack of 75 migrated shots using RTM on the true scale model of the test specimen. The green dashed line indicates the outer frame of the notch.

1-12 Schematic explanation of the signals reflected at the side walls of the notch and their cross correlation, causing the migrated signal within the final image.

1-13 Homogeneous velocity model of the test specimen 'PKN' including shorter model of the notch.

1-14 Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-13.

1-15 Synthetic shot record from source located at x = 650 mm. Simulated on model seen in Figure 3-13. The yellow circle indicates the reflections caused by the shorter notch.

1-16 Homogeneous velocity model of the test specimen 'PKN' including a true-scale model of the notch shifted to position x = 1350 mm.

1-17 Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-16.

1-18 Homogeneous velocity model of the test specimen 'PKN' including two true-scale notches separated by 100 mm.

1-19 Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-18.

1-20 Homogeneous velocity model of the test specimen 'PKN' including a finer, randomly shaped crack-like structure. The area marked in the upper model is magnified and shown beneath to further illustrate the shape of the crack-like structure.

1-21 Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-20.

1-22 Heterogeneous model (velocity and density) of the test specimen PKN including the true-scale notch.

1-23 Stacks from RTM of the data acquired on the heterogeneous true scale model, Figure 3-22, using different migration velocities of 2500 \( \text{ms}^{-1} \) (A), 2620 \( \text{ms}^{-1} \) (B) and 2740 \( \text{ms}^{-1} \) (C). Density of the migration model is set to \( \rho = 2.4 \text{ gcm}^{-3} \). Red arrows marking the point used for Figure 3-24. The yellow dashed line separates the concrete model from the air boundary.

1-24 Comparison of the source wave field \( W_S \) (upper plots), time reversed receiver wave field \( W_R \) (center plots) and their correlation (lower plots) for a single point at the back wall of shot no. 26, indicated in Figure 3-23. Signals are compared for a migration velocity of 2500 \( \text{ms}^{-1} \) (A), 2620 \( \text{ms}^{-1} \) (B) and 2740 \( \text{ms}^{-1} \) (C).

1-25 Heterogeneous model (velocity and density) of the test specimen PKN including finer, randomly shaped crack-like structure.

1-26 Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-25. The red circle indicates the signal related to the tip of the crack-like structure.

1-27 Heterogeneous model (velocity and density) of the test specimen PKN including a more complex crack-like structure.

1-28 Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-27. Yellow circles indicate signals related to the tip of the crack-like structures. The red semicircle highlights the migration artifact above.
4-1 Ultrasonic transducer of type T1802. Adapted from [Grohmann, 2014].

4-2 Image of the A1040 MIRA device and the transducer arrays underneath. Adapted from [ACS, 2014].

4-3 Schematic explanation of the different source and receiver combinations of the A1040 MIRA device. Adapted from [ACS, 2014].

4-4 Picture of the used two-axial scanner device, developed at BAM. The scanner is fixed to the test specimen “PKR”, performing a line measurement (yellow dashed line).

4-5 Overview of the instruments associated with the scanner device. 1: DAQ-Pad, 2: Source signal generator, 3: Amplifier for received signal and 4: PC running LabView-program.

4-6 GPR survey conducted on test specimen PKN (Figure 3-1). A regular grid of 5 cm is projected onto the specimen along which the orange GPR antenna is moved to acquire data.

4-7 Schematic illustration of the survey conducted on specimen “PKN” using the A1040 MIRA device.

4-8 Resulting image of specimen “PKN” using SAFT on data acquired with A1040 MIRA device. The yellow dashed line indicates the back wall reflection, red arrows pointing towards reinforcement steel bars perpendicular to the shown section. Green arrows showing the vertical position of parallel oriented steel bars.

4-9 Stack of the RTM results, using the full 660 shots from the data acquired with the A1040 MIRA device. The yellow dashed line separates the model from the boundary.

4-10 Schematic illustration of the survey conducted on specimen “PKN” using the scanner system.

4-11 Recorded data from shot no. 26 ($x = 520 \text{ mm}$). Comparison of raw shot data (left) and interpolated, cut shot record (right). The yellow dashed line highlights the recorded back wall reflection.

4-12 Recorded data from shot no. 26 ($x = 520 \text{ mm}$). Comparison of interpolated, cut shot data (left) and 3D/2D corrected shot record (right).

4-13 Amplitude spectra of trace no. 13 ($x = 130 \text{ mm}$) from shot no. 26 ($x = 520 \text{ mm}$) before and after applying 3D/2D correction.

4-14 Trace no. 119 and no. 131 of shot no. 26 and their corresponding amplitude spectra.

4-15 Recorded data from shot no. 26 ($x = 520 \text{ mm}$). Comparison of processed shot record before (right) and after (left) bandpass filtering.

4-16 Amplitude spectra of trace no. 13 ($x = 130 \text{ mm}$) from shot no. 26 ($x = 520 \text{ mm}$) before and after applying the chosen bandpass filter.

4-17 Recorded data from shot no. 26 ($x = 520 \text{ mm}$). Comparison of processed shot record before (right) and after (left) applying Automatic Gain Control (AGC).

4-18 Comparison of three final RTM stacks resulting from data processed according the schemes listed in Table 4-1.

4-19 Resulting stack from RTM using a migration velocity of $2600 \text{ ms}^{-1}$. The center of the notch is indicated by the vertical yellow line. The yellow dashed line separates the model from the boundary. Red arrows indicating the different layer of steel bars.

4-20 Resulting image of specimen “PKN” using SAFT on data acquired with the scanner system. The yellow dashed line indicates the back wall reflection.

4-21 Schematic illustration of the test specimen “PKN” and the GPR sections shown in Figure 4-22.
4-22 Resulting sections of the processed GPR survey. Slice 1 to 4 correspond to sections schematically indicated in Figure 4-21. The red arrow in section 1 indicates the center steel bar, located directly underneath the profile line. ................................. 60

4-23 Picture of exemplary test specimens with identical dimensions like the used specimen “PKR”. These specimen are used for static load test within BAM. ............... 61

4-24 Schematic illustration of the two surveys conducted on specimen “PKR” using the scanner system. The measured line of the first survey (red) has a total length of 1.31 m, the second survey (blue) has a total length of 1.30 m. The red dashed mid line represents the measurement line at y = 20 cm. ................................. 62

4-25 Velocity models of test specimen “PKR”. The upper model refers to setup 1, the lower model refers to setup 2, according to Figure 4-24. The sides marked with red dashed line using an absorbing boundary condition. ................................. 62

4-26 Resulting RTM stacks of setup 1 of the scanner survey on test specimen PKR”. A migration velocity of 2650 ms is used for the upper stack. The lower stack is migrated using a velocity of 2740 ms. The yellow dashed line separates the model from the boundary. ................................. 63

4-27 Resulting RTM stacks of setup 2 of the scanner survey on test specimen PKR”. A migration velocity of 2650 ms is used for the upper stack. The lower stack is migrated using a velocity of 2740 ms. The yellow dashed line separates the model from the boundary. Within the lower stack, signatures no. 3 and 4 are marked referring to the interpretation within Figure 4-28. The vertical red lines indicated the center of the signatures. The horizontal dashed lines are estimates of the vertical extend of the signatures 3 and 4. ................................. 64

4-28 Evaluation of horizontal crack positions. The upper part shows an extract of the resulting stack of the RTM of survey 2, using a migration velocity of 2740 ms⁻¹. The lower photograph shows the bottom side of the specimen around the center. Cracks are highlighted in grey, the dashed red line resembles the projected measurement line. The yellow lines refer to the center signal of the cracks from the resulting stack and their projections to the profile line. The distance between the projected cracks and the outcrops are stated below. ................................. 65

4-29 Detailed photograph of the side of specimen “PKR”, indicating the height of the outcrops of the cracks. The cracks are highlighted in blue. Outcrops 1 to 5 thereby resemble the five marked cracks in Figure 4-28. ................................. 65

4-30 Resulting image of survey 1 and 2 conducted on specimen “PKR” using SAFT with a migration velocity of 2650 ms⁻¹. The red circle marks irregularities in the back wall signature. ................................. 66

A-1 Homogeneous velocity (upper model) and density (lower model) models of the concrete PK. .......................................................... 77

A-2 Resulting stack of 75 migrated shots on the true scale model of the test specimen. The yellow dashed line separates the model from the boundary. ................................. 78

B-1 Exemplary raw data from shot no. 5 (x = 80 mm). Different configurations are separated by yellow dashed lines. .......................................................... 82

B-2 Geometries of the test specimen used within the study of [Reinhardt, 2007], showing the six notches of different width. Adopted from [Reinhardt, 2007]. ................................. 85

B-3 Result SAFT reconstruction of the specimen shown in Figure B-2. Adopted from [Reinhardt, 2007]. ................................. 85
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td>Parameters for numerical modelling</td>
<td>20</td>
</tr>
<tr>
<td>3-2</td>
<td>Data acquisition parameter for synthetic experiments</td>
<td>25</td>
</tr>
<tr>
<td>3-3</td>
<td>Shear wave velocity and density values for heterogeneous models</td>
<td>37</td>
</tr>
<tr>
<td>4-1</td>
<td>Summary of different processing schemes tested for data acquired on specimen “PKN”</td>
<td>55</td>
</tr>
<tr>
<td>4-2</td>
<td>Data acquisition parameter for scanner surveys conducted on test specimen “PKR”</td>
<td>62</td>
</tr>
</tbody>
</table>
Acronyms

AGC  Automatic Gain Control
BAM  Federal Institute for Materials Research and Testing
CFL  Courant Friedrich Levy criterion
EM   Electromagnetic
FD   Finite Difference
GPR  Ground Penetrating Radar
NDT  Non-destructive testing
PDE  Partial Differential Equation
RTM  Reverse Time Migration
RSF  Regularly sampled file
SAFT Synthetic Aperture Focusing Technique
SH   Horizontally polarized shear wave
Ultrasonic measurements are widely used in the field of non-destructive testing (NDT), using this technique to evaluate concrete structures. Generally ultrasonic measurements can be performed using two different approaches. The ultrasonic transmission method (or sonic pulse velocity) uses a single transducer and a receiver to measure the velocity of either compressional or shear waves, travelling through concrete structures. Thereby information about the velocity along the travelpath and the attenuation of the generated waves can be gathered. This data can help to gain in-situ information on concrete quality [Garnier, 2012]. On the other hand the ultrasonic echo (or pulse echo) method measures the time of which ultrasonic signals travelling through a concrete structure being reflected or backscattered at inner-structural components or surfaces [Krause and Mielentz, 2012].

The reflection thereby depends on the contrast in acoustic impedance (Equation 1-1).

\[
R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \quad \text{with} \quad Z = \rho \cdot v
\]  

The reflection coefficient \( R \) is determined by the difference in acoustic impedance \( Z \) of two materials 1 and 2. The acoustic impedance itself is the product of a material’s sound propagation velocity \( v \) and its density \( \rho \). Figure 1-1 shows a typical measurement setup of an ultrasonic echo method using a transducer as source and a receiver to record the reflected signal.

The possibility of imaging inner structures like steel bars and tendon ducts can help civil engineers and other scientists to state the quality of those components or of the structure itself. The exact location of reinforcement bars allows inspections after construction to validate the structure.
Concrete being a highly heterogeneous material, dispersion and scattering are influencing the propagation of ultrasonic waves. Figure 1-2 shows an exemplary cross section through a concrete structure, revealing the concrete matrix, inner aggregates and added reinforcement steel.
In order to evaluate inner structures, the acquired data needs to be migrated. In seismics, migration is a technique to focus recorded energy towards the true position in the subsurface, moving dipping reflectors and collapsing diffraction hyperbolas to their apexes [Yilmaz, 2001]. Acquired data is therefore mostly processed using Synthetic Aperture Focusing Techniques (SAFT). These techniques are based on superimposing ultrasonic signals taken from different positions, thus creating an image [Schickert et al., 2003]. Being very similar to the Kirchhoff Migration and Stolt Migration, these algorithms have a limitation when it comes to steep reflectors [Müller et al., 2012].

Recent computational development allows the use of Reverse Time Migration (RTM) in the field of non-destructive testing (NDT). Since its development in the late 1970s by [Baysal et al., 1983] and [Mc Mechan, 1983], RTM was almost exclusively used in oil and gas exploration. Now, more computers can handle the extensive memory requirements, and current studies prove that this technique can be adapted to a much wider field of application. [Müller et al., 2012] showed that RTM is able to map complex structures in synthetic experiments. Furthermore [Grohmann et al., 2016] pointed out that, using RTM and real data, concrete structures with vertical steps can be imaged. In the field of structural health monitoring, [Beniwal and Ganguli, 2015] mapped damaged areas around rebars using a focused wave field and an RTM algorithm processing the full-elastic wave equation.

Using an RTM algorithm which is capable of imaging such steep dipping reflectors could be a possible application for detecting cracks in concrete structures. The information itself is very useful for civil engineers when it comes to evaluating the quality of buildings like bridges or concrete pillars.

Within this study, RTM using a two-way wave equation is used in a completely synthetic experiment. A test specimen with a well defined groove, seen in Figure 3-1, is used to test the influence of different acquisition parameters. Real data is acquired in the laboratory using a non-commercial fully automated device developed at Federal Institute for Materials Research and Testing (BAM). Furthermore data from a standard ultrasonic tomographic device is migrated with a RTM algorithm and compared to the standard processing with Synthetic Aperture Focusing Techniques (SAFT). Results of these studies are used to give an assessment of a possible application to detect real cracks.
This chapter treats theoretical aspects of the Reverse Time Migration algorithm. The second section gives an introduction to Finite Difference (FD) methods, deriving the FD scheme used in this thesis. All FD simulations are performed with the Madagascar software package, which is introduced later. The final section of this chapter deals with the Synthetic Aperture Focusing Technique (SAFT) being the most used migration technique in practical applications up to now. This technique is briefly introduced since the results of the RTM are later on compared to the SAFT images.

### 2-1 Reverse Time Migration (RTM)

In seismics, migration is a technique to focus recorded energy towards its true position in the subsurface, moving dipping reflectors and collapsing diffraction hyperbolas to their apexes [Yilmaz, 2001]. Reverse Time Migration, developed in the early 1980’s by [Baysal et al., 1983] and [Mc Mechan, 1983], is a method operating in the time domain. In comparison to other migration techniques like Kirchhoff Migration or Stolt Migration, it can be used to map complex structures and steeply dipping reflectors. Using the full 2D acoustic two-way wave equation, RTM, in contrast to one-way wave equation based migration techniques, is also able to take multiple energy into account.

\[
\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial z^2} - \frac{1}{v^2} \frac{\partial^2 p}{\partial t^2} + s(t, x_0, z_0) = 0
\]  

(2-1)

In this equation (2-1), \( p \) denotes the acoustic pressure and \( v \) the velocity of the compressional wave, \( s \) resembles a source at time \( t \) and location \( x_0, z_0 \). However when considering multiple energy, the exact location of its origin needs to be known [Farmer et al., 2006]. This requires a very detailed velocity model and thereby information about the inner structure of the concrete test specimen in this case. This information is not given in this study, hence multiple energy is partly removed in pre-processing as stated in
Within the algorithm two independent wave fields are propagated through predefined models. A velocity model as well as a density model are used, resembling the dimensions of the test specimen, both using an average velocity/density value are used. The models themselves are homogeneous, not containing any further structural information. Using a Finite Difference approximation (see section 2-2) of the wave equation (2-1) the source wave field $W_S$ and the receiver wave field $W_R$ are simulated within the models. The source wave field $W_S$ is the propagation of the ultrasonic wave field emitted by a known source, starting at time zero. The receiver wave field $W_R$ on the other hand, is the backward propagated wave field recorded beforehand by an receiver array, starting at the maximum recording time $T$. The final image is calculated using an imaging condition. The most common imaging condition is the so called zero-lag cross correlation, indicated by Equation 2-2 [Sava and Hill, 2009]. For this imaging condition the final image $I(x, z)$ is the sum of all added cross correlations over the recording time $T$ for every point in space $x, z$, stated in Equation 2-2.

$$I(x, z) = \int_{t=0}^{T} W_S(x, z, t) \cdot W_R(x, z, t)dt$$ (2-2)

The whole algorithm can be summarized in five main steps as indicated in Figure 2-1.

- Choosing a reasonable velocity/density model.
- Forward propagation of the source wave field $W_S$ from a source using finite difference approximation.
- Backward propagation of the receiver wave field $W_R$ from receiver positions using finite difference approximation.
- Applying imaging condition at every point in space $(x, z)$.
- Summing up all images for a single shot position.
Figure 2-1 illustrates the RTM algorithm using a model, snapshots and a resulting stack from the homogenous synthetic experiment described in Section 3-2. The black dashed line separates the two independent wave field extrapolations. Blue arrows indicate the forward extrapolation of the source wave field $W_S$ with a snapshot at time $t_x$. Red arrows on the other hand show the backward extrapolated receiver wave field $W_R$ with a snapshot at time $T-t_x$. Both extrapolations are simulated using the same homogeneous velocity (and density) model shown in the upper left.

The main disadvantage of this technique, besides its high computational cost, is its imaging condition. Although providing the correct kinematics, the zero-lag cross correlation often creates noise at sharp velocity contrasts within the used models [Liu et al., 2011] and [Liu et al., 2007].

**Remark on the wave equation used**

Note that in this brief introduction the given wave equation (Equation 2-1) describes a two dimensional acoustic wave propagation. The code later on used to simulate the wave fields within the set up models is also based on purely compressional wave propagation. However, acquiring data on concrete test specimens, as shown in Chapter 4, uses transducers emitting and detecting horizontal polarized (SH) shear waves. It is known, when only considering a two-dimensional case, that these SH waves do not convert into other wave modes,
when passing any contrast of impedance [Shull, 2002]. Using transducer emitting compres-
sional (p-) waves, mode conversion to shear waves would occur, which are recorded at the
surface. These additional modes are not applicable, since such signals are not considered
using a purely acoustic simulation, leading to wrong results within the RTM algorithm.
Since the kinematics of the used SH waves are identical to the one of p-waves, this as-
sumption can be made, although the overall amplitudes are not correct. Extensive stud-
ies, e.g. [Müller and Niederleithinger, 2014], [Grohmann et al., 2015] and [Grohmann, 2014],
have shown that this is a valid assumption and the usage of such transducers produces rea-
sonable results. The implementation of an RTM code using a full-elastic wave field is the
focus of ongoing research (Ph.D. thesis) of Maria Grohmann at BAM.
2-2 Finite Difference modelling

In order to simulate the two wave fields $W_S$ and $W_R$, the acoustic two-way wave equation (2-1) needs to be approximated. Therefore a finite difference code available within the Madagascar software collection, introduced in section 2-3, is used. Finite Differences (FD) is a very common method for numerical simulation of (seismic) wave propagation [Fichtner, 2011]. FD estimates the derivatives in the wave equation (2-1) by approximating them using a pre-defined grid and a number of neighboring nodes. The expression in Equation 2-3 can be defined as the central difference of the function $f(x)$ at position $x$, with $\Delta x$ being the grid size.

$$\partial_x f(x) = \lim_{\Delta x \to 0} \frac{f(x + \Delta x) - f(x - \Delta x)}{2\Delta x}$$ (2-3)

However when computing this derivative numerically the distance between two nodes $\Delta x$ needs to be finite. Therefore the derivative in Equation 2-3 can also be expressed using a Taylor Series Expansion (TSE).

$$f(x \pm \Delta x) = f(x) \pm \frac{\Delta x}{1!} \partial_x f(x) + \frac{\Delta x^2}{2!} \partial_x^2 f(x) \pm \frac{\Delta x^3}{3!} \partial_x^3 f(x) + \cdots$$ (2-4)

Using the expression from Equation 2-4 to approximate the expressions in 2-3 results in the second-order finite difference stencil shown in equation 2-5.

$$\partial_x f(x) = \frac{1}{2\Delta x} [f(x + \Delta x) - f(x - \Delta x)] + O(\Delta x)^2$$ (2-5)

According to this exemplary approximation of a first spatial derivative, the wave equation used in the numerical simulations 2-1 is approximated in a second order accurate scheme for the time $t$, using the following expression 2-6.

$$\partial_t^2 f(x, z, t) |_{x,z} = \frac{f(t + \Delta t) - 2f(t) + f(t - \Delta t)}{\Delta t^2} + O(\Delta t)^2$$ (2-6)

The second spatial derivative is approximated using an eighth order accurate 9-point stencil. This stencil uses the neighboring four nodes to approximate the derivative at point $f(x, z)$. A compact form of the stencil is adopted from [Fichtner, 2011] and can be found in the following expression (Equation 2-7). This expression refers to the derivative in x-direction, with the same holding for the corresponding derivative in z-direction.
\[ \frac{\partial^2 f}{\partial x^2} \approx \sum_{i=1}^{N} \left[ -g_n f(x + n\Delta x) - g_0 f(x) + g_n f(x - n\Delta x) \right] \frac{\Delta x^2}{\Delta x^2} \quad (2-7) \]

The corresponding FD coefficients can be found in [Fornberg, 1988] and are listed below:

\[ with \quad g_0 = \frac{205}{72}, \quad g_1 = \frac{8}{5}, \quad g_2 = \frac{1}{5}, \quad g_3 = \frac{8}{315}, \quad and \quad g_4 = \frac{1}{560}. \quad (2-8) \]

The coefficients from Equation 2-8 are furthermore used to set up a linear system of equations which can be solved using a matrix notation like

\[ Au = b \quad (2-9) \]

with the matrix \( A \) containing the respective coefficients for the different neighboring nodes for all the calculated grid cells in the system. The vector \( u \) contains the state variables of the system and the vector \( b \) includes the boundary values.

### 2-2-1 Source wavelet

To model a source, the very commonly used Ricker wavelet is chosen. The Ricker wavelet was introduced by [Ricker, 1953] and is nowadays frequently used in every field where simulation of seismic data is required [Gholamy and Kreinovich, 2014]. The wavelet describes a change in amplitude \( x(t) \) with respect to time \( t \) according to a linear combination of wavelets of the type

\[ x(t) = (1 - \frac{(t - t_0)^2}{\sigma^2}) \cdot \exp\left(-\frac{(t - t_0)^2}{2\sigma}\right) \quad (2-10) \]

Here \( t \) and \( t_0 \) represent two different points in time and \( \sigma \) states the duration of the wavelet [Gholamy and Kreinovich, 2014]. The Ricker wavelet, according to [Schneider, 2010], can be described as

\[ x(t) = (1 - 2(\pi f_c(t - t_0))^2) \cdot \exp\left(-(\pi f_c(t - t_0))^2\right) \quad (2-11) \]

with \( f_c \) being the center frequency and \( t_0 \) a time delay. Figure 2-2 shows the Ricker wavelet used throughout this study. In the field of ultrasonics this wavelet is often referred as an RC2 impulse [Zimmer, 2008]. A center frequency of 50 kHz used, matching the frequency of the transducer used for the data acquisition on the test specimen. Mathematically the wavelet amplitude peaks at \( t = 0 \). Therefore the zero phase wavelet has to be shifted depending on the center frequency to obtain a physically meaningful minimum phase wavelet. For a center frequency of 50 kHz the shift accounts 0.02 ms, as seen in Figure 2-2.
2-2 Finite Difference modelling

Approximating a hyperbolic Partial Differential Equation (PDE), the influence of numerical instabilities and errors has to be considered. These uncertainties can be evaluated using von Neumann Analysis [Crank and Nicolson, 1947][Charney et al., 1950] and [Fichtner, 2011]. In order to ensure a stable propagation of the modelled wave field there are restrictions to the discretization that have to be met. When assuming a certain grid size $\Delta x$ as well as a certain time step $\Delta t$, both have to match the used velocity and frequency information. If the velocity of the pressure, for example, is higher than the velocity of the discretised model space ($\frac{\Delta x}{\Delta t}$) the pressure will not be sampled regularly. Using the Nyquist criterion

$$\Delta x \leq \frac{v_{\text{min}}}{2f_{\text{max}}} \quad (2-12)$$

it can be seen that a stable sampling theoretically needs two grid points per minimum wave length. Setting an even finer grid with 10 grid points per minimum wave length, like proposed by e.g. [Fichtner, 2011], guarantees a stable propagation. Equation 2-13 thereby can be rewritten as

$$\Delta x \leq \frac{v_{\text{min}}}{10f_{\text{max}}} \quad (2-13)$$
to obtain the maximum grid size $\Delta x$. Once the grid size is set, the so called Courant-Friedrich-Levy criterion (CFL) is used to determine an accurate time step $\Delta t$. According to Equation 2-14 the following condition has to be met

$$\frac{v_{\text{max}} \Delta t}{\Delta x} < \frac{1}{\sqrt{D}}$$

(2-14)

$D$ thereby states the dimension of the discretised model space and $\Delta t$ being the largest realizable time step.

### 2-2-3 Boundary conditions

When defining a numerical model there are requirements to implement at the borders of the chosen domain. So called boundary conditions have to be implemented, handling the very last nodes in each direction. There are very common boundary conditions like the Dirichlet boundary or the Neumann boundary. These conditions are used to set the simulated quantities and their derivatives respectively to a fixed value. Combinations of these conditions are realized in the so called Robin boundary condition [Hahn and Ozisik, 2012].

The wave field extrapolation code contained in Madagascar offers different implementations of boundary conditions. In order to prevent reflections from the model boundary a so called absorbing boundary condition is used. This condition is realized using two approaches implemented in an additional boundary region around the previously built model. The first approach within the `awedf2d` code is the change of the two way wave equation into a one way wave equation within the respective boundary area. This only allows propagation away from the model, suppressing reflected energy [Clayton and Engquist, 1977]. This approach however shows difficulties for very small angles of incidence, hence a second approach multiplies a damping factor to all amplitudes within the boundary region [Cerjan et al., 1985] to ensure no energy is reflected back into the model space. At the top surface of the model an option for a free surface is used, which ensures a total reflection of the energy by setting the velocity to zero.

### 2-3 Madagascar software environment

Reproducibility of scientific publications by attaching the software code used and data onto the publication itself. That is the basic idea behind the Madagascar software project, which was launched in 2010 [Fomel et al., 2013]. Madagascar offers an environment in which single stand alone programs, like for example `awefd` for acoustic wave field-extrapolation, are available and callable by the software construction tool SCons, [MediaWiki, 2016]. Data is handled in a universal, so called RSF (regularly sampled file) format, which directs to a second binary file, containing the raw data stored in arrays [Fomel et al., 2013]. This makes data storing very efficient.

Figure 2-3 shows the schematic architecture of the Madagascar collection. The specific modules are mostly written in C and are specific to a certain task only. These specific programs
Figure 2-3: Schematic architecture of the Madagascar software package. Adapted from [Fomel et al., 2013].

are called by a Python based make utility, called SConstruct. The scripts are based on four main operations Fetch, Flow, Plot and Result (see Figure 2-3), being responsible for executing single programs or creating plots of different results, respectively [Fomel et al., 2013]. The main programs used within all SConstruct scripts within this study are the 2D acoustic wave field extrapolation (awefd2d) and the 2D acoustic reverse time migration implementation (artm), both available within the fdmod package. The basic SConstruct scripts for the experiments performed for this thesis can be found in Appendix A and B.
2-4 Synthetic Aperture Focussing Techniques (SAFT)

Measurements obtained by the ultrasonic tomograph A1040 MIRA, an industrial standard measurement device for tomographic images of concrete structures 4-1-1, are migrated using Synthetic Aperture Focusing Techniques (SAFT). In order to compare these results to the results of the RTM algorithm a brief overview of the SAFT algorithm is given. Originally adapted from optical holography and synthetic aperture techniques in radar, first computer based implementations for concrete testing were developed in the early 1990s [Schickert et al., 2003]. [Krause et al., 1992], for example, developed a 1D SAFT application for thickness measurement of concrete structures and [Schickert, 1995] combined 2D SAFT to pulse echo data. Synthetic apertures use multiple transducer measurements across a certain area in order to approximate a large transducer. Transducers with large diameters show a smaller divergence angle of the emitted ultrasonic wave field, hence the wave field is more focused. Yet the coupling onto concrete surfaces of these large diameter transducers is rather difficult. These measurements can either be performed by transducer array, like the A1040 MIRA device used in this project, measuring simultaneously or combining point measurements [Schickert et al., 2003]. The underlying SAFT algorithm uses the principle of superposition to focus received signals to any point of the image. For a 3D case in time domain, it can be stated by the following expression ([Schickert et al., 2003])

\[
g(x_i, y_j, z_k) = \frac{1}{MN} \sum_m \sum_n f(x'_m, y'_n, t_{mn}) \quad (2-15)
\]

with

\[
t_{mn} = t_0 + \frac{2}{c} \sqrt{ (x'_m - x_i)^2 + (y'_n - y_j)^2 + z_k^2 } \quad (2-16)
\]

where \( g(x_i, y_j, z_k) \) is the resulting 3D image from the planar measurements \( f(x'_m, y'_n, t_{mn}) \). The planar aperture is divided into a grid of \( M \times N \) cells in directions \( x' \) and \( y' \). The two way travel time \( t_{mn} \) is calculated for each cell and the corresponding measurement \( f \) is attached. This procedure is repeated per shot or per measurement and the resulting images are stacked, resulting in a final image. Thereby the size of the planar aperture resembles the size of a large virtual transducer. For the 2D application, also used in this study, the expressions in 2-15 and 2-16 can be rewritten as

\[
g(x_i, z_k) = \frac{1}{M} \sum_m f(x'_m, t_m) \quad (2-17)
\]

with

\[
t_m = t_0 + \frac{2}{c} \sqrt{ (x'_m - x_i)^2 + z_k^2 } \quad (2-18)
\]
This technique is very similar to the Kirchhoff Migration used in seismics. Both are based on diffraction stack, hence they also share the same disadvantages, like not being able to handle steep or vertical reflectors [Müller et al., 2012].

2-5 Ground Penetrating Radar (GPR)

In order to evaluate results from ultrasonic echo data referring to the occurrence of reinforcement steel bars within concrete structures, used in Chapter 3, an additional GPR survey was conducted.

Ground penetrating radar is a high resolution geophysical method, based on electromagnetic (EM) wave fields. Such EM waves are reflected and transmitted at an interface with a contrast in dielectric properties. The velocity of EM in air is (almost) the speed of light $c = 0.3m/ns$. Within the subsurface, the velocity is reduced due to the influence of the relative dielectric permittivity $\epsilon_r$, the relative magnetic permeability $\mu$ and the electrical conductivity $\sigma$. In low loss materials like sand or concrete the expression for velocity of EM waves reduces to

$$v = \frac{c}{\sqrt{\epsilon_r}} \quad (2-19)$$

where $c$ is the speed of light. Contrasts in dielectric permittivity $\epsilon_r$ cause reflections of the signal, which can be recorded at the surface. Emission and detection are done by antennas with a fixed frequency and geometry. The peak frequency of the used antenna thereby determines the depth of investigation since higher frequency signals are attenuated faster within the subsurface. Similar to seismic data, the data acquired with GPR is processed and migrated in order to get a true depth section of the investigated structure. Migration is most commonly done using SAFT or Kirchhoff migration, depending on the program used. A detailed list of processing can be found in Section 4-2-3. A broad range of available antennas and its straightforward application makes GPR a widely used tool in Geophysics and NDT [Jol, 2008].

Related survey details and the processing schemes used are listed in Chapter 4. For more detailed insights to the field and applications of GPR, see [Jol, 2008].
Chapter 3

Synthetic Experiments

In order to evaluate the applicability of RTM to detect cracks and crack-like structures within concrete, the Madagascar software package is used. Synthetic experiments are performed to test whether such structures can be imaged in general. Furthermore the influence of different acquisition parameters on the image quality is tested. Increasing complexity of the experiments allows to give an indication on what kind of image quality to expect from measurements on real concrete structures.

3-1 General parameters

The general concept is to model the geometry of a concrete test specimen, which is used later for real data experiments. Thereby results from both experiments can be compared. Figure 3-1 shows the concrete block used in this study. In case of a synthetic experiment, models for generating synthetic data are required. MATLAB programs have been written to create a true scale model referring to the dimensions of the test specimen schematically illustrated in Figure 3-2. In addition models not containing any information about the notch are used for simulation. For testing the algorithm and acquisition parameters, such as number of sources and receivers, models are created using the assumption of homogeneous concrete (Section 3-2). For a more realistic prediction of the real data, more complex and heterogeneous models are built (Section 3-3). Within both sections, the model of the notch or the crack-like structure, respectively, is modified with increasing complexity. In addition, this section treats further parameters for a stable wave simulation within the model, as well as the influence of data acquisition parameters, like number of sources and receivers or the recording time. Note that the density of air given in Table 3-1 does not correspond to the true value of $\rho = 0.00012 \text{gcm}^{-3}$. This value however causes the simulation to get highly unstable. According to a personal correspondence with Yuting Duan from Colorado School of Mines (CSM) and Maria Grohmann from BAM, these instabilities are due to the high contrast in density. The code for wave field extrapolation, awefd2d, can not handle these high contrasts. Therefore the density of air is set to 1. Yet since the velocity remains zero, there is no influence on the reflection coefficient. Small changes in the amplitude however have to be accepted.
3-1-1 Model dimensions

The dimensions of the test specimen are directly translated into a model created in MATLAB using a regular grid with grid size of $\Delta x = \Delta z = 1$ mm. The general strategy of modelling the test specimen as detailed as possible also applies for the boundaries. Therefore boundary regions at the sides and at the bottom of the model are added. These regions thereby resemble air, representing a detached test specimen, just as shown in Figure 3-1. Implementation of the free surface at the top is done within the Madagascar program, without adding additional grid cells. Detailed descriptions of the boundaries are given in Subsection 2-2-3. The resulting model of the test specimen “PKN” can be seen in Figure 3-3.
Figure 3-3: True scale velocity (upper model) and density (lower model) models of the concrete test specimen “PKN”. Exact values for velocity and density can be found in Table 3-1.
3-1-2 Parameters for numerical simulation

Table 3-1 summarizes the simulation parameters used in the remaining synthetic experiments in this thesis.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Homogeneous models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid cell size $x$ and $z$ [mm]</td>
<td>1</td>
</tr>
<tr>
<td>Grid cells in $x$ direction []</td>
<td>1600</td>
</tr>
<tr>
<td>Grid cells in $z$ direction []</td>
<td>300</td>
</tr>
<tr>
<td>Time step $\Delta t$ [s]</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Total recording time $T$ [ms]</td>
<td>0.3</td>
</tr>
<tr>
<td>Boundary width []</td>
<td>50</td>
</tr>
<tr>
<td>Concrete $v_s$ [ms$^{-1}$]</td>
<td>2740</td>
</tr>
<tr>
<td>Concrete density $\rho$ [gcm$^{-3}$]</td>
<td>2.6</td>
</tr>
<tr>
<td>Air $v_s$ [ms$^{-1}$]</td>
<td>0</td>
</tr>
<tr>
<td>Air density $\rho$ [gcm$^{-3}$]</td>
<td>1</td>
</tr>
</tbody>
</table>

The values for model discretization in space and time are found using the criteria presented in Section 2-2-2. A stable wave propagation is indicated by the snapshots in Figure 3-4.

These snapshots are showing a wave field emitting from a source located at position $x = 540$ mm. The wave field is simulated using the true-scale model of the test specimen, shown in Figure 3-3. In general the wave field reveals a stable propagation with time, not showing any instabilities or dispersion effects. The implementation of the air boundaries works as intended, reflecting all energy and causing a reversal in phase. This can be observed in the first two subplots where the incoming direct wave gets reflected at the back wall, flipping its polarity. Thereby no energy is transmitting into the air boundaries.

Note that the fast decay in amplitude of the direct wave, marked by the blue arrow in Figure 3-5 was not expected beforehand. The amplitudes are expected to show a significant contribution to the whole record. The fast decay is, most likely, related to the implementation of the free surface as Madagascar and is further discussed in Section 5-1.
Figure 3-4: Snapshots of the simulated wave field, using the model in Figure 3-3, from shot no. 26 at location $x = 540$ mm. Yellow dashed line separates the concrete specimen from air boundaries. The blue rectangles indicate the notch.
Figure 3-5: Synthetic shot record simulated on the true scale model from Figure 3-3, emitted at position $x = 640$ mm. The blue arrows point towards the direct wave, indicating a fast decay in amplitude. The red arrow shows the reflection of the direct wave at the tip of the notch.
3-1-3 Data acquisition parameter

When simulating a wave field in a certain model the question of total period of time $T$ arises. Taking the geometry of the used test specimen into account, (Figure 3-2) reveals that the specimen is relatively narrow compared to its total length. This results in a fast occurrence of multiples of the back wall reflection. Since in this study the influence of multiples in general should be avoided (Section 2-1) the total recording time is kept as small as possible without losing a reasonable amount of information. Using a shear wave velocity in concrete of $v_s = 2740 \text{ ms}^{-1}$, the minimum recording time to obtain a signal from the back wall reflection must be larger than $0.1825 \text{ ms}$, assuming a zero offset measurement. Multiples consequently would occur at approx. $0.365 \text{ ms}$. Figure 3-6 shows the image resulting from RTM using a relatively short recording time of $t = 0.20 \text{ ms}$. It can be seen that the back wall is nicely mapped, however of the notch only the tip is visible. Taking a look at Figure 3-5 showing a shot record, modelled on the true-scale model of the test specimen, shown in Figure 3-3. A further increased recording time of $t = 0.30 \text{ ms}$, indicates that crucial information about the notch is gained by the refracted back wall reflection, indicated by yellow arrows. This refraction is arriving shortly after the back wall-reflection, highlighted by a yellow dashed line, hence it is missing in the previous example. The reflection of the direct wave at the tip of the notch is marked by a red arrow. The total recording time $t = 0.30 \text{ ms}$ resembles a trade-off between a minimum recording time and avoiding multiple energy, hence it is used for this project. The stack in Figure 3-9 in the following section shows the result of the chosen record time.

![Figure 3-6: Stack resulting from 30 sources and a recording time of $t = 0.20 \text{ ms}$](image)

To illuminate the test specimen as good as possible, different acquisition setups are tested. Different numbers of sources thereby show a significant influence on the overall image quality. In order to later on compare the results from synthetic data to real data, chosen setups have to be realizable by the measurement devices.

The number of receivers has no noticeable impact on the overall computation time, therefore the distance of receivers is set to $0.01 \text{ m}$, comparable to [Grohmann, 2014]. This leads to a total number of 151 receivers, which can be realized by the measurement device used in Section 4-1-2 in a reasonable amount of time. On the contrary, the number of sources used, linearly increases computational time, since RTM requires separate wave field simulations for each shot. Figure 3-7 shows three resulting stacks with different numbers of migrated shots stacked. All these simulations are based on the true scale model of the test specimen, shown in Figure 3-3. The first stack results from 10 shots equally spread along the surface. Various migration artifacts can be observed, like the cone-shaped shadows underneath the sources.
The most striking artifacts are the diagonal reflectors, marked by red arrows, resulting from reflections of the model corners. Additionally the fact that the right sidewall of the notch is not as well imaged as the left side indicates that the number of sources and thereby the amount of overall illuminations emitted might not be enough to image the notch. Compared to the second stack, consisting of 30 shots, several improvements can be seen. First, the reduction of the cone-shaped artifacts underneath the different source positions. Decreasing the distance between shot points leads to destructive interference of these artifacts when stacking. This results in the cones to get canceled out. The remaining artifacts right underneath the surface of the model however are still remaining. Furthermore the migration effects at the model corners continuously weaken with increasing number of shots. The additional energy due to the increased number of sources results is a better mapping of the notch. Within Figure 3-7, the last stack consists of 75 shots and shows a further reduction of the described artifacts. The small distance between the source points results in a continuous artifact along the surface, however the overall image quality results in this setup being the default setup for the remaining synthetic experiments. Table 3-2 summaries the final data acquisition parameters.

Figure 3-7: Comparison of different RTM stacks using varying number of sources. The upper stack results of ten equally spaced shot points. The middle stack consists of 30 single shots and the lower stack is the sum of 75 single shots.
Table 3-2: Data acquisition parameter for synthetic experiments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of receiver [ ]</td>
<td>151</td>
</tr>
<tr>
<td>Receiver spacing [cm]</td>
<td>1</td>
</tr>
<tr>
<td>Number of sources [ ]</td>
<td>75</td>
</tr>
<tr>
<td>Source spacing [cm]</td>
<td>2</td>
</tr>
</tbody>
</table>
3-2 Homogeneous models

The following section introduces the experiments performed on the assumption of a homogeneous test specimen. Different variations of the true scale notch are used in order to evaluate effects on wave field extrapolation and migration results. Thereby the position along the x-axis, height, width and the number of notches are changed. Figure 3-8 shows the model used for simulations of the source wave field $W_S$ and the receiver wave field $W_R$ within the RTM algorithm (Section 2-1). Using the same shear wave velocity $v_s = 2740 \text{ ms}^{-1}$ for concrete, this model does not contain any information about the notch.

![Velocity model in [m/s] including air boundary](image)

**Figure 3-8:** Homogeneous velocity and density models for simulation of source wave field $W_S$ and the receiver wave field $W_R$.

3-2-1 True scale model

Using the homogeneous true-scale model of the test specimen (Figure 3-3) and the derived parameters for the numerical simulation and data acquisition, Figure 3-9 shows the complete RTM stack of all 75 migrated shots of the initial synthetic experiment.

Within Figure 3-9 it can be seen that a very dense distribution of sources decreases migration artifacts to a minimum. Influences from the bottom corners, for example, are hardly visible anymore. In addition, the cone-shaped effects around the source positions are reduced to a continuous high amplitude noise directly beneath the surface. The position of the notch as well as its geometry are nicely mapped. Its vertical side walls are present down to the back wall.

In order to further understand the result, Figure 3-10 shows recorded shot data for different source positions along the x-axis. Recalling the exact position of the notch between $x = 888 \text{ mm}$ and $x = 900 \text{ mm}$, the first subplot (A) indicates recorded data from a source located left of the notch, at position $x = 250 \text{ mm}$. Besides the direct wave and the prominent back wall reflection, which can be observed in all of the four subplots, the second shot data includes
signals related to the notch. The source position of the second subplot (B) is located closely enough to the notch in order to detect the resulting signals within the fixed recording time of $T = 0.3\, ms$. The yellow arrow points to the apex of the hyperbola created by the reflection of the direct wave at the tip of the notch. This signal is the first reflected signal arriving after the direct wave has been recorded. The reflection of the back wall is partly reflected by the notch towards the source (indicated by the yellow circle) resulting in a second, phase reversed, apex besides the back wall reflection. The same signature can be found in subplot D, resulting from a source located right of the notch. The third plot (C) is located almost exactly above the notch. This results in almost no illumination of the sides of the notch. With the source position slightly left of the notch, a very weak reflected signal lies shortly underneath the initial back wall reflection, indicated by the two yellow dashed lines.

Taking a look at the geometry of the mapped notch, Figure 3-11 shows the resulting stack using a slightly different range of amplitudes with a green dashed line, indicating the outer frame of the notch. Other than the outer boundaries between concrete and air (yellow dashed line), this information is not available within the velocity model (Figure 3-8) used for RTM. The frame shows, that the image created by the notch does not match the exact geometry. This can be explained by the resolution of the ultrasonic wave. The resolution is related to the wavelength of the ultrasonic signal which is related to the velocity and the peak frequency of the source. Using the velocity of $v_s = 2740\, m/s$ and the peak frequency of $50\, kHz$ the related wavelength is approx. $\lambda = 5.5\, cm$. The width of the notch is $1.3\, cm$ and thereby approximately a quarter of the wavelength $\lambda$. To fully understand the mapped signal of the notch the polarity of the used source signal, shown in Figure 2-2, is recalled. The notation used by the plots in this study assigns a white color to positive amplitudes and a black colour to negative amplitudes. The notation of the source therefore is black-white-black. Whenever this signal is reflected by any air boundary within the model, the polarities are flipped due to a 180 phase shift resulting from the contrast in impedance between concrete and air. This can be observed along the back wall reflection as well as at the tip of the notch. The flipped polarity resembles a white-black-white notation. However, recalling that the sidewalls of the notch are mainly mapped by the refraction of the back wall reflection, as shown in Figure 3-10, this signal is flipped twice and therefore shown as the same polarity as the source wavelet. The notch thereby creates two signals shifted by approx. a quarter wavelength, which are correlated, creating one wider signal with the same polarity. This is furthermore indicated by Figure 3-12 and can explain the blurred signal, not exactly matching the original width of the notch.
**Figure 3-10:** Four different shot records (A to D) from the forward simulation on the true scale model. The dashed turquoise lines mark the position of the notch along the x-axis, yellow annotations highlight influences of notch on the recorded signal.

**Figure 3-11:** Resulting stack of 75 migrated shots using RTM on the true scale model of the test specimen. The green dashed line indicates the outer frame of the notch.
Figure 3-12: Schematic explanation of the signals reflected at the side walls of the notch and their cross correlation, causing the migrated signal within the final image.
3-2-2 Modification 1 - shorter notch

Note that for the upcoming modifications of the homogeneous models only the corresponding velocity model is shown. Values for the density models can be found in Table 3-1-2.

In this first modification the influence of the length of the notch and its effect in the resulting image are tested. The model in Figure 3-13 reveals a shorter notch of only 50 \textit{mm} length. Its position along the x-axis as well as its width are identical as in the true scale model. Figure 3-14 shows the resulting stack of all 75 shots. The results shows that despite shorter length, the notch is nicely mapped. A shorter notch results in a shorter reflection of the back wall reflection as seen in Figure 3-15, showing a shot record at position \( x = 650 \text{ mm} \). It can be seen that the original apex of the back wall reflection is maintained for the most part and the second reflection is weaker, compared to the shot records in Figure 3-10. This shorter signal however is sufficient to map the notch down to the back wall.

\begin{figure}[ht]
\centering
\includegraphics[width=\textwidth]{fig3-13.png}
\caption{Homogeneous velocity model of the test specimen ‘PKN” including shorter model of the notch.}
\end{figure}

\begin{figure}[ht]
\centering
\includegraphics[width=\textwidth]{fig3-14.png}
\caption{Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-13.}
\end{figure}
Figure 3-15: Synthetic shot record from source located at $x = 650$ mm. Simulated on model seen in Figure 3-13. The yellow circle indicates the reflections caused by the shorter notch.
3-2-3 Modification 2 - notch close to boundary

Moving the notch closer to the model boundary has been done to evaluate whether the lower amount of energy treating the side close to the boundary, still is sufficient to map the side of the notch. Generally the regions close to the boundary are affected by additional migration artifacts as described in the previous section.

**Figure 3-16:** Homogeneous velocity model of the test specimen “PKN” including a true-scale model of the notch shifted to position $x = 1350$ mm.

Figure 3-17 shows the resulting stack with the default acquisition setup. The notch, despite being located close to the boundary is mapped completely. Compared to the result of the true scale experiment, as seen in Figure 3-9, there is no visible influence on the quality of the reconstructed signal. Thereby the total reflection caused by the right boundary keeps the energy in place. With the notch now placed at location $x = 1350$ mm there are still 9 source positions right of its center. The energy emitted by these sources along with the reflection at the boundary can be considered to be enough to sufficiently map the right side of the notch.

**Figure 3-17:** Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-16.
3-2-4 Modification 3 - two notches

The next modification contains an additional notch, both being identical to the true scale model. The left notch is located at the original position, as seen in Figure 3-1, the right one is placed in a distance of $100\text{ mm}$. Cracks and crack-like structures in real concrete structures are generally not expected to appear separately. Most of the times damaged areas contain multiple cracks close to each other.

This model setup can be compared to the previous modification, yet there are crucial differences, leading to the result shown in Figure 3-19.

Figure 3-18: Homogeneous velocity model of the test specimen “PKN” including two true-scale notches separated by $100\text{ mm}$.

It can be seen that within this experiment the inner side of each notch is not mapped. However, the top surface as well as the outer sides are mapped as in the previous experiments. The two notches themselves acting as a restriction of the aperture to the energy emitted from the sources. Recalling the fact that side walls of notches are mapped by the back wall signal, reflected along the side of the notch. The five source points located directly above the area between the two notches are emitting a wave front with mostly horizontal and near-horizontal incidence angle with respect to the back wall. Thus reflections along the inner sides are limited. The same holds for sources positions left or right of the notches. Therefore not only the amount of energy between the notches is limited but also the reflections along the inner sides. This results in less correlation of relevant signals.

A further experiment is performed using an even smaller distance between the two notches. The results, which support the interpretation given here, can be found in Appendix A. These effects are of concern if the structure or the specimen tested contains a lot of damages close to each other. With an even higher number cracks or crack like structures, chances of being able to map inner side walls further decreases.
Figure 3-19: Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-18.
3-2 Homogeneous models

3-2-5 Modification 4 - random crack-like structure

The final modification of the homogeneous models introduces a different structure. Instead of a well-defined notch, a finer crack-like structure is modelled. This structure has a core with a width of one grid cell, or 1 mm respectively. Randomly grid cell are added to each side, resulting in a variable crack width of 1 mm to 3 mm in total.

![Velocity model in [m/s] including air boundary](image)

**Figure 3-20:** Homogeneous velocity model of the test specimen “PKN” including a finer, randomly shaped crack-like structure. The area marked in the upper model is magnified and shown beneath to further illustrate the shape of the crack-like structure.

Figure 3-21 reveals the resulting stack using synthetic data generated on the model, described above. Within the stack, the geometry of the imaged crack-like structure is comparable to the one in Figure 3-9 (true-scale model). The structure shows a similar signal at the tip of the structure. However, the correlated signals at the side are not as sharp as in Figure 3-9. Despite the crack-like structure being finer than the previous notches, the resulting signal shows the same width. Recalling the results and explanation of the imaged signal from Section 3-2-1, the resolution of the current experimental setup is not able to determine the width of the cracks or notches. Assuming a crack width of 1 mm, which is the smallest width realizable within this setup, resulting signals from both sides of the crack occur at (nearly) the same location. The result of such a cross correlation is identical to the one showed in Figure 3-12.
Figure 3-21: Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-20.
3-3 Heterogeneous models

To further increase the complexity of the models used for producing synthetic data and therefore make them more comparable to data acquired on real concrete structures, models of heterogeneous concrete are introduced. Figure 3-22 modifies the original true-scale model (Figure 3-3) by replacing the homogeneous concrete by a concrete matrix and aggregates. The aggregates have different diameters, from 1 mm to 32 mm and are randomly distributed within the concrete matrix up to a content of 50 %. The values for shear wave velocity $v_s$ and density $\rho$ of the different components are shown in Table 3-3. Between the upcoming modifications of the heterogeneous model, the aggregate distribution is not identical, however velocity and the corresponding density model within a certain experiment showing the exact same distribution.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Heterogeneous models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete matrix density $\rho$ [gcm$^{-3}$]</td>
<td>2.3</td>
</tr>
<tr>
<td>Aggregate density $\rho$ [gcm$^{-3}$]</td>
<td>2.6</td>
</tr>
<tr>
<td>Concrete matrix velocity $v_s$ [ms$^{-1}$]</td>
<td>2500</td>
</tr>
<tr>
<td>Aggregate velocity $v_s$ [ms$^{-1}$]</td>
<td>2740</td>
</tr>
</tbody>
</table>

In general the heterogeneous modifications are only used for producing synthetic data. The models used for RTM remain homogeneous. Hence the question of picking the right migration velocity arises. The assumption of a homogeneous model for RTM bares a certain velocity error since it only resembles an average velocity. Using the data from the heterogeneous true scale model, Figure 3-22, the results of RTM each using a different migration velocity, is investigated. The density of the model used for migration is set to $\rho = 2.4$ gcm$^{-3}$

3-3-1 True scale model

Figure 3-23 shows three stacks resulting from RTM using three different migration velocities. A good guess for the true velocity of the model can be assumed by taking the average of the aggregate and matrix velocity, as stated in Table 3-3. Since matrix and aggregates are distributed equally the resulting velocity of 2620 ms$^{-1}$ is considered as a good approximation of the true velocity. Furthermore two additional migration velocities of 2500 ms$^{-1}$ and 2740 ms$^{-1}$ are tested. The first stack within Figure 3-23 shows the resulting stack of all 75 shots using a migration velocity of 2500 ms$^{-1}$. This resembles the velocity of the concrete matrix, which due to the presence of aggregates, must generally be lower than the true velocity. Compared to the other two stacks the image shows a flip in polarity, which can be observed at the signals from the back wall and the notch.

The stack of the RTM using the approximation of the true velocity of 2620 ms$^{-1}$ is shown in the middle stack. The overall image is dominated by negative amplitudes (darker image) and appears sharper than the other stacks. The signal of the notch is more defined compared to the other stacks indicating a good fit of the velocity used. The overall polarities thereby
matching the results of the homogeneous analogue presented in Section 3-2-1. Since the true velocity and the migration velocity within the homogeneous experiments are identical, the strong similarity to the results of this stack further indicate a good approximation of the true velocity of the heterogeneous model.

In general the results of all tested migration velocities reveal information about the notch, indicating all velocities tested are rather suitable. The lateral position of the notch, marked by the dashed blue lines within the stacks of Figure 3-23, show no significant lateral shifts. To illustrate the changes in polarity of the stacks shown in Figure 3-23, a single point of the image directly at the back wall is investigated further. Hereby the the functionality of the imaging condition and the influence of the velocity is shown. This is done exemplary for wave field simulation results from shot no. 26 at position $x = 560 \text{ mm}$. The point of interest lies underneath the source point, directly in front of the boundary, indicated by red arrows in Figure 3-23. Within the plots of Figure 3-24 the forward simulated source wave field $W_S$ is shown (A). The second plot (B) shows the corresponding time-reversed receiver wave field $W_R$. Within the last plot (C), the resulting correlation of those two signals is shown. According to the imaging condition, presented in Equation 2-2, the integral over the total recording time $T$ is the resulting contribution to the migration result in the mentioned point. It can be seen that for the tested velocities the resulting correlations are changing. The correlation of the two wave fields at the mentioned point using a migration velocity of $2500 \text{ ms}^{-1}$ (A, lower plot) is dominated by positive amplitudes, leading to a positive (white) value after integration. Whereas the same plot for a migration velocity of $2620 \text{ ms}^{-1}$ (B, lower plot) is dominated by negative amplitudes, leading to a negative (black) contribution to the migration result. The corresponding correlations are mainly affected by the time-reversed receiver wave fields.

**Figure 3-22**: Heterogeneous model (velocity and density) of the test specimen PKN$^+$ including the true-scale notch.
**Figure 3-23:** Stacks from RTM of the data acquired on the heterogeneous true scale model, Figure 3-22, using different migration velocities of $2500 \text{ ms}^{-1}$ (A), $2620 \text{ ms}^{-1}$ (B) and $2740 \text{ ms}^{-1}$ (C). Density of the migration model is set to $\rho = 2.4 \text{ gcm}^{-3}$. Red arrows marking the point used for Figure 3-24. The yellow dashed line separates the concrete model from the air boundary.

$W_R$ which is projected to a wrong recording time by assuming an inappropriate migration velocity. This is also the reason why the back wall in every of the presented stacks in Figure 3-23 does not show a consistent amplitude. The added aggregates result in a complex velocity distribution causing (nearly) every part of the wave field to propagate with a different overall velocity. Whereas the source wave field $W_S$ propagates with a constant velocity, the shifts caused by the simulation of the receiver wave field $W_R$ causing different correlations. In order to determine the most suitable velocity to migrate the width of the correlated signal can relate to how exact two signals are matched.

The overall image quality of the resulting stack of the RTM using a migration velocity of $2620 \text{ ms}^{-1}$ is the best. With a very sharp signals from the back wall and the notch, this supports the assumption of this average velocity to be close to the true (effective) velocity of the model. Due to the results of this comparison, the remaining modifications of the heterogeneous models are migrated using a velocity of $2620 \text{ ms}^{-1}$ and a density of $\rho = 2.4 \text{ gcm}^{-3}$. 
Figure 3-24: Comparison of the source wave field $W_S$ (upper plots), time reversed receiver wave field $W_R$ (center plots) and their correlation (lower plots) for a single point at the back wall of shot no. 26, indicated in Figure 3-23. Signals are compared for a migration velocity of $2500\, ms^{-1}$ (A), $2620\, ms^{-1}$ (B) and $2740\, ms^{-1}$ (C).
3-3 Heterogeneous models

3-3-2 Modification 1 - random crack-like structure

Note that for the upcoming modifications of the homogeneous models only the corresponding velocity model is shown. Values for the density models can be found in Table 3-3. According to the experiments performed with homogeneous models in Section 3-2-5, the same crack-like structure is added to a heterogeneous model, shown in Figure 3-25. With this experimental setup it is tested whether the scattering of the wave field, caused by the added structural complexity, lead to loss in image quality and the ability of detecting such finer structures. The resulting stack can be found in Figure 3-26.

![Velocity model in [m/s] including air boundary](image)

**Figure 3-25:** Heterogeneous model (velocity and density) of the test specimen PKN’ including finer, randomly shaped crack-like structure.

A look at the final image of this experiment does reveal that scattering of the wave field does not mask the crack-like structure. However, the signal of the crack is not as well defined as in the resulting stack of the homogeneous analogue (Figure 3-21). The tip of the crack-like structure, marked by the red circle, is mapped rather weakly. The side walls are visible, however, the upper part close to the tip is missing. In addition the right side wall is mapped weaker compared to the left side.

![RTM result: heterogeneous model (modification 1)](image)

**Figure 3-26:** Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-25. The red circle indicates the signal related to the tip of the crack-like structure.
3-3-3 Modification 2 - complex crack-like structure

Up to now, the models of the crack-like structures resemble a purely vertically oriented damage. However, cracks in concrete structures, are oriented more randomly. Outcrops at the side of a structure may appear as a single (near-) vertical crack, its shape within the concrete structure might be different. Therefore a third type of crack-like structure is introduced. Figure 3-27 shows a vertical crack, splitting into two dipping ones, the left side thereby being longer than the right one. Both show a dip of approximately 70 degree. The motivation for this modification is to test whether RTM is able to reconstruct different parts of the modeled structure, such as the two dipping cracks, or the point at which the vertical crack splits up.

![Figure 3-27: Heterogeneous model (velocity and density) of the test specimen PKN including a more complex crack-like structure.](image)

The resulting stack can be found in Figure 3-28. Compared to the result of the previous modification (Figure 3-26), the tips of the dipping features are very well mapped. The mapped height (z-axis) thereby resembles the true height within the corresponding model. The two dipping parts of the crack-like structure are slightly visible. Thereby the outer sides are mapped more clearly. However the point where the lower part of the structure splits into the two dipping features can not be reconstructed. An additional artifact is visible right above the red dashed line. This mapped semicircle indicates that due to a highly complex wave field in this area of the modeled structure, RTM creates migration artifacts. The lower, vertical part of the structure is shown clearly, indicating the expected polarity character, seen in the previous experiments.

![Figure 3-28: Resulting stack of 75 shots migrated using RTM based on the models shown in Figure 3-27. Yellow circles indicate signals related to the tip of the crack-like structures. The red semicircle highlights the migration artifact above.](image)
Chapter 4

Experiments on concrete structures

This chapter covers all experiments performed on real concrete structures. In addition to the specimen introduced in Chapter 3, “PKN”, an additional test specimen was investigated. This second concrete block, “PKR”, was used for static load tests by division 7.1 Building Materials at BAM. This specimen contains a number of real cracks. Outcrops at the side of the block are visible (Figure 4-29). The first section gives an introduction to the measurement devices used and describes the experimental setups. Sections 4-2 and 4-3 summarize the experiments conducted on the two test specimen, including pre-processing and the final results.

4-1 Measurement devices

In the following section, the measurement devices are introduced. The A1040 MIRA ultrasonic tomograph as well as the scanner system are using arrays of four ultrasonic transducers. The piezoelectric transducer both emit and receive horizontal polarized shear waves. Figure 4-1 shows the transducer of type T1802, developed by Acoustic Control Systems, Ltd. and BAM.

Figure 4-1: Ultrasonic transducer of type T1802. Adapted from [Grohmann, 2014].
4-1-1 A1040 MIRA ultrasonic tomograph

The MIRA A1040 is a commercial ultrasonic tomographic device developed by Acoustic Control Systems, Ltd. It can be used for inspecting concrete structures, thickness measurements and locating rebars, cavities or damaged zones. It operates in the low-frequency ultrasonic range of 25-85 kHz [ACS, 2014]. Figure 4-2 shows the device and the transducer arrays underneath. A total number of 48 shear wave transducer are arranged in 12 blocks with four transducer each. Thereby a block of four transducers is connected in parallel acting as source or receiver. Figure 4-3 illustrates the specific combination of source and receiver arrays within a single shot. Performing a measurement, the device uses all available combinations of the different arrays. The first configuration, shown in the left part of Figure 4-3, uses the first array as a source, the eleven remaining lines as receiver. The second configuration uses the second line as a source and the ten remaining as receiver. This is repeated ending up with a total of eleven different configurations with a total of 66 source-receiver combinations, shown in the right image of Figure 4-3.

Within a single block of four, transducer are separated by 2 cm. The twelve blocks are separated by 3 cm, leading to a total aperture of 30 cm for each position of the device. The acquired data is sorted according to the predefined acquisition setup and stored on the device. After each shot, a SAFT algorithm is applied and the corresponding cross-section (B-Scan) is displayed. Thereby a quick assessment of the acquired data is possible [ACS, 2014]. In this study, data is acquired on the test specimen “PKN” (Section 4-2), in order to compare the results of current industrial devices to the results of experimental RTM. The data is migrated using a SAFT algorithm using the software package “Intersaft”, provided by the University of Kassel, Germany. Furthermore, the RTM algorithm within the Madagascar software package was adapted to the geometry of the A1040 MIRA device, to furthermore investigate the applicability of RTM on the data acquired with this device.

![Figure 4-2: Image of the A1040 MIRA device and the transducer arrays underneath. Adapted from [ACS, 2014].](image)
4-1 Measurement devices

4-1-2 Scanner system

The scanner system used is part of a family of fully automated devices for acquiring ultrasonic or other NDT data, developed by BAM. The version used within this study is a system using two moving axes to perform line measurements with two different transducer arrays, acting as source and receiver, respectively. Figure 4-4 shows the device, which is fixed by four vacuum cups in order to guarantee precise measurements. Both arrays are pushed onto the surface using compressed air to ensure a good coupling. The device is connected to a PC running a LabView program (Figure 4-5, 4) to implement acquisition setup, source function and data storing. Additional instruments, besides PC, are shown in Figure 4-5. A DAQ-Pad (National Instruments “DAQPad-6070e”), is controlling data acquisition and is connected to a source signal generator (2). In this case a rectangular function represents the source signal. The incoming signal from the receiver is enhanced to compensate for a loss in voltage, before digitization by A/D conversion by the DAQ-Pad (1).
Figure 4-4: Picture of the used two-axial scanner device, developed at BAM. The scanner is fixed to the test specimen “PKR”, performing a line measurement (yellow dashed line).

With the current setup of the scanner device it can realize transducer positions along the measurement line with a minimum step size of 1 mm. Detailed information about the specific acquisition setup can be found in the specific Sections 4-2 and 4-3.

Figure 4-5: Overview of the instruments associated with the scanner device. 1: DAQ-Pad, 2: Source signal generator, 3: Amplifier for received signal and 4: PC running LabView-program.
4-1-3 Ground Penetrating Radar (GPR)

An additional investigation with ground penetrating radar (GPR) was conducted in order to validate assumptions on the location of steel rebars within the first test specimen “PKN”. The system of type “SIR - 20” developed by Geophysical Survey Systems, Inc. (GSSI) is equipped with a “PALM” antenna, using a frequency of $2 \text{GHz}$. Using this frequency, the depth of investigation is around $0.4 \text{m}$, according to [GSSI, 2016]. The acquired data is processed and visualized using the RADAN Software package. A detailed description of the processing scheme used is presented in Subsection 4-2-3, along with the results.

Figure 4-6: GPR survey conducted on test specimen PKN (Figure 3-1). A regular grid of 5 cm is projected onto the specimen along which the orange GPR antenna is moved to acquire data.

4-2 Test Specimen PKN

This section treats the different surveys conducted on the test specimen “PKN”. The data acquired with the A1040 MIRA ultrasonic tomograph is migrated using SAFT. In addition the RTM code is adapted to the specific shot-receiver configurations of the device. It is tested whether RTM can provide a better image using the same raw data. The data from the scanner system is processed using RTM and SAFT to further compare the image quality of both migrations techniques. The results of the RTM are treated in detail to further assess the applicability of this technique to map the notch of the specimen.

4-2-1 A1040 MIRA ultrasonic tomograph

Figure 4-7 schematically illustrates the survey conducted on specimen “PKN” using the A1040 MIRA ultrasonic tomograph. The device is positioned at the very left end of the mid line on the specimen. Due a fixed aperture (max. offset) of $33 \text{cm}$. According to the measurements in the synthetic experiments (Section 3) and the survey with the scanner system (Section 4-2-2), the spacing between shot positions is $2 \text{cm}$. At every shot position, the device measures using eleven different configurations of sources and receiver, as stated in Section 4-3. A total of 60
shot positions is realized along the mid line. With a sampling rate of $1 \, MHz$ and a total of 2048 samples recorded, the total recording time $T = 2.048 \, ms$. An exemplary raw data record is shown in Figure B-1 with a total of 66 receiver from all the different configurations.

![Figure B-1: Receiver and Source Positions](image)

**Figure 4-7:** Schematic illustration of the survey conducted on specimen “PKN” using the A1040 MIRA device.

Intersaft, the program used for the Synthetic Aperture Focussing Technique (SAFT) migrations directly handles the binary files saved on the device. A bandpass filter with the same cutoff frequencies of $10 \, MHz$ and $100 \, MHz$, as in Section 4-2-2 is applied before migration. Assuming an ultrasonic shear wave velocity of $v_s = 2600 \, ms^{-1}$ and a synthetic aperture of 90 degree, the resulting image is shown in Figure 4-8.

![Image of specimen “PKN” using SAFT (A1040 MIRA)](image)

**Figure 4-8:** Resulting image of specimen “PKN” using SAFT on data acquired with A1040 MIRA device. The yellow dashed line indicates the back wall reflection, red arrows pointing towards reinforcement steel bars perpendicular to the shown section. Green arrows showing the vertical position of parallel oriented steel bars.

The assumption of the migration velocity is a result of testing different velocities within the SAFT reconstruction and approximately mapping the back wall towards its true depth of $z = 25 \, cm$. This general procedure of predicting an average velocity can be used due to the fact that SAFT, like Kirchhoff migration, is based on diffraction stack method (Section 2-4). This chosen velocity is later on also used for migrating the data using RTM. Within the image the back wall is mapped very prominently. The general lack of intensity towards the boundaries of the test specimen along the x-axis is caused by a smaller data density. Around the original position of the notch ($x = 88.8 \, cm$ to $x = 90.1 \, cm$) the back wall is interrupted and showing irregularly dipping artifacts. Besides the influences of the notch, the image shows a rather regular distribution of small circular features (marked by
red arrows). Additionally two horizontal layered reflections are visible at $z \approx 5 \text{ cm}$ and $z \approx 10 \text{ cm}$, indicated by green arrows. A further, third layer of these reflections is visible short above the back wall. These signals can be related to the occurrence of reinforcement steel bars which are generally installed in a mesh of bars perpendicular to each other. The results of the GPR survey, presented in Section 4-2-3, approves the presence of these bars. In order to evaluate a possible increase in image quality, the data gathered with the ultrasonic tomograph is adopted to the requirements of RTM. This includes splitting the binary data into single shot configurations. The data, originally acquired from one shot position, includes a total of 11 shot configurations (Figure 4-3 and Figure B-1). Splitting each shot position into eleven single shot configurations results in a total of 660 shots. These single shots thereby show an offset between 33 cm and 3 cm. Furthermore the same processing scheme including a interpolation to a finer time sampling of $10^{-7} \text{s}^{-1}$, bandpass filtering using cutoff frequencies of $10 \text{ MHz}$ and $100 \text{ MHz}$ and a 3D/2D correction is applied. This scheme is explained in detail within Section 4-2-2. Using a migration velocity of 2600 $\text{ms}^{-1}$, the resulting stack can be seen in Figure 4-9.

![Figure 4-9: Stack of the RTM results, using the full 660 shots from the data acquired with the A1040 MIRA device. The yellow dashed line separates the model from the boundary.](image)

Besides a good indication of the back wall, the RTM stack of the data acquired with the A1040 MIRA device does not reveal any information about the test specimen “PKN”. The mapped back wall shows a weak signal between approx. $x = 750 \text{ mm}$ and $x = 1000 \text{ mm}$, due to a general decay in amplitude in the whole model. Comparing the results to the image using the SAFT approach, no information about the steel bars is gained. The horizontal darker correlations between $z = 5 \text{ cm}$ and $z = 10 \text{ cm}$ most certainly relate to the previously discussed layers of steel bars. The results from Figure 4-9 are further discussed in Section 5-2.

### 4-2-2 Scanner system

Figure 4-10 schematically illustrates the survey conducted on specimen “PKN” using the scanner system. Due to a maximum offset of 1.35 m of the device, a total of 133 receiver positions separated by 1 cm is used. Furthermore a total of 66 shot positions with a spacing of 2 cm is realized. This results in a total profile length of 1.32 m. Since the two transducer are measuring inline, zero-offset measurements are not realizable. A distance of 4 cm between source and receiver has to be implemented due to the width of the transducer and a security distance between the moving parts. This results in a total of seven zero-traces in each shot, as exemplary shown in Figure 4-11.

Besides interpolating the raw data to a sampling rate that meets the stability requirements
of the FD approximation and cutting the data to a shorter recording time $T$, the data is preprocessed in order to improve the required signals. This is exclusively done using MATLAB codes adapted to the specific survey parameters. The list below introduces the different pre-processing steps, performed with the raw data acquired on test specimen “PKN”.

- Interpolation in time to match sampling rate required for RTM.
- Cutting to a suitable recording time $T$.
- 3D/2D correction to account for adoption to 2D model space.
- Bandpass filtering
- Automatic Gain Control (AGC)

In the following each of these steps is described, showing its influence on the acquired data. Afterwards results of RTM, using different combination of the listed processing steps are shown. The DAQ-Pad used along with the scanner system has a sampling rate of 1 $MHz$. The number of samples recorded for each shot is set to 2500, leading to a total recording time $T = 2.5$ ms. The stability criterion for the simulation within RTM is not met. Therefore an interpolation to finer sampling of $10^{-7}$ s, or 10 $MHz$ is done. Furthermore the data is shortened to the same recording time $T = 0.3$ ms, compared to the synthetic experiments in Chapter 3. Figure 4-11 shows an exemplary interpolated and shortened shot record.

Besides the very prominent direct wave with its high amplitudes, the reflection of the back wall can already be spotted nicely, highlighted by a yellow dashed line. The scattering visible between direct wave and reflected wave is due to the aggregates inherent to concrete and is similar to the simulations in Section 3-3. Besides the parts of the shot records already seen within the synthetic experiments, the shot record shown in Figure 4-11 offers an additional detail. Underlined with a red dashed line, several reflections of the direct wave indicate the presence of scattering elements, like steel rebars, near the surface. This issue is further treated within this section, after presenting the resulting stack.

To account for the fact, that data from a 3D environment is used in a 2D migration, a 3D/2D correction is applied. Therefore amplitudes and the phase of the recorded signal are not
matching with the 2D data simulated within the RTM code. The correction itself accounts for the amplitude mismatch by multiplying with $\sqrt{t}$. Phase mismatches are treated by a convolution with $\frac{1}{\sqrt{t}}$ [Crase et al., 1990] and [Grohmann, 2014]. Figure 4-12 shows the chosen shot record, presented in Figure 4-11 before and after applying the 3D/2D correction.

Within Figure 4-12 it can be seen that applying the 3D/2D correction results in a general amplitude enhancement, especially at later times. The back wall reflection is now more prominent, so are the near-surface reflections of the direct wave. However there are also
some unwanted signals, exemplary indicated by a yellow arrow. These signals show a general increasing trend towards greater offsets. Taking a look at the amplitude spectra of a arbitrarily chosen trace within shot record no. 26 (Figure 4-13), it can be seen that the general shape is almost unchanged after applying the 3D/2D correction. The absolute amplitudes have risen due to the multiplication with $\sqrt{t}$. A prominent change is the relatively strong increase in very low-frequent signals (red arrow). Further investigating the origin of unwanted signals, Figure 4-14 shows the raw trace and its corresponding amplitude spectrum of two trace with higher offsets, meaning the distance between source and corresponding receiver. Trace no. 119 and no. 131 thereby correspond to an offset of 0.67 m and 0.81 m, respectively. The raw traces (left-side plots) indicate a constant amount of recorded noise. Additionally each trace shows a prominent signal, right after recording starts. These signals can be related to a non-perfect shielding of the transducer and electromagnetic noise, caused within the cables connecting the transducer to the instruments. The corresponding spectra of the traces (right-side plots) indicate that this noise mostly relates to very low (up to 7kHz) and rather high (> 200kHz) frequencies. The spectra of trace no. 119 (top-right plot) additionally shows a characteristic peak (around 50kHz) due to the incoming direct wave at time $t \approx 0.25 ms$. One has to assume, that the whole shot is corrupted with this noise, however its contribution to the amplitude recorded increases with higher offsets due to the fact of source-related signals arriving at later times. This is the reason why it becomes more and more visible towards the right and left side of the shot record. Using the amplitude spectra presented in Figure 4-13 can help to design low and high-pass filter to further process the data and increase the signal-to-noise ratio.
Figure 4-14: Trace no. 119 and no. 131 of shot no. 26 and their corresponding amplitude spectra.

Figure 4-15: Recorded data from shot no. 26 ($x = 520\, mm$). Comparison of processed shot record before (right) and after (left) bandpass filtering.

The chosen bandpass filter of fourth order removed the unwanted signals, described above and further improved the overall image quality. The cut-off frequencies chosen are $10\, kHz$ for the lower cut-off frequency and $100\, kHz$ for the upper cut-off frequency. The shot record after applying the bandpass filter shows a less noisy and sharper image, in which the previously described elements appear even more defined. Figure 4-16 shows the amplitude spectra of trace no. 13 before and after applying the described bandpass filter. The low-frequency amplitudes, highlighted in Figure 4-14 are suppressed, so is the high-frequent content.
Furthermore an Automatic Gain Control (AGC) is tested on the data set. This gain function accounts for the faster loss of higher frequencies due to attenuation. An important parameter is the chosen operator length which defines the length of the AGC window used for gain computations. The window moves down the trace sample by sample and calculates a scale factor at each location. The computed gain is then applied to the sample in each sliding gate. For the data acquired on specimen “PKN”, the chosen window length contains 1800 samples. Figure 4-17 shows shot no. 26 ($x = 520 \text{ mm}$) before and after applying AGC. Within the used AGC algorithm amplitudes of the input traces are normalized.

To determine if all the processing steps introduced above improve the resulting RTM stack, three different combinations of processing steps are tested. A migration velocity of $2740 \text{ ms}^{-1}$ is used. Table 4-1 summaries the three different schemes and the processing steps included. Note, that within a certain processing step, the specific parameter are kept the same during this comparison. Figure 4-18 shows the three resulting stacks of all 66 migrated shots. Overall all three images show a good result, including signals from the notch, and further indicate the presence of reinforcement bars. A detailed discussion of the result is given later. Scheme 1, applying a bandpass filter only, shows a relatively weak back wall, emphasizing the need for the 3D/2D correction. The back wall within the results of scheme 2 and 3 is mapped more continuously, especially in close range to the notch, showing an overall stronger signal. The near-surface reinforcement steel bars are most prominent within the stack of scheme 1, with a decreasing signal strength towards scheme 3. Scheme 3, additionally applying an Automatic Gain Control does not show any significant improvements in the image of the notch, compared
to scheme 2. The influences of migration artifacts, as stated in Section 3-2, is strongest within scheme 1. Although the the signal of the notch seems less blurred in scheme 1, the signal itself seems weaker and more influenced by horizontal migration artifacts, indicated by red dashed lines. These artifacts are significantly weaker within the stacks of scheme 2 and 3, leading to an overall laterally more defined notch signal. Therefore scheme 2, namely 3D/2D correction and bandpass filtering, is chosen as the most suited scheme for the data acquired on specimen “PKN”.

Table 4-1: Summary of different processing schemes tested for data acquired on specimen “PKN”

<table>
<thead>
<tr>
<th>Processing step</th>
<th>Scheme 1</th>
<th>Scheme 2</th>
<th>Scheme 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interpolation and cutting</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>3D/2D correction</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Bandpass filter [10 kHz][100 kHz]</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Automatic Gain Control (AGC), window length = 1800</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
</tbody>
</table>

Note that the migration velocity of the stacks in Figure 4-18 is 2740 $ms^{-1}$ resulting from an earlier assumption within this study and thereby differs from the migration velocity of 2600 $ms^{-1}$ chosen later. However, no significant effect on the overall result is expected, since both migrations are based on identical raw data.

Figure 4-19 shows the resulting stack of the RTM with data acquired with the scanner system. The positions of the upper two layers of horizontally and vertically oriented steel bars are mapped very well (red arrows). The blue line indicates the center position of the notch,
The sides of the notch are not mapped slightly different. Compared to a rather sharp signal right of the marked center of the notch, the left side is rather blurry. A possible explanation might be that the left side is affected by a slightly less favorable position relative to the notch. Despite the good results for the sides of the notch, the RTM stack does not reveal any information about the tip of the notch. Similar to the results of the A1040 MIRA device using SAFT (Figure 4-8), receiving and imaging the signals from the tip was an expected result. This further strengthens the assumption of the related signal being masked by reinforcement steel bars. Results from the GPR survey, presented in the following Section further affirm this assumption. Generally the image appears to be darker, compared to the RTM using a migration velocity of $2740\, ms^{-1}$, shown in the center of Figure 4-18. Analogue to the results of the heterogeneous, synthetic experiments, this indicates that a migration velocity of $2600\, ms^{-1}$ is more suitable compared to $2740\, ms^{-1}$. However a good match of the true velocity and the migration velocity along with the accompanied darker images can also mask some significant details. A very good match results in further correlations, especially in parts where the model resembles the corresponding specimen very well. This is also observed within the study of [Grohmann, 2014] and can be further confirmed by the results of the second specimen, presented in Section 4-3-1.
Figure 4-19: Resulting stack from RTM using a migration velocity of 2600 m/s$^{-1}$. The center of the notch is indicated by the vertical yellow line. The yellow dashed line separates the model from the boundary. Red arrows indicating the different layer of steel bars.

For comparison the data of the scanner system is additionally migrated using SAFT. Therefore the same processing scheme (2) is applied in order to further compare the results of SAFT and RTM. However SAFT does not require an interpolation on time, hence the data is only processed using the stated bandpass filter and a 3D/2D correction. Figure 4-20 shows the result for SAFT using a migration velocity of 2600 m/s$^{-1}$. Within the final result the back wall is nicely mapped. Compared to the SAFT results from the A1040 MIRA device (Figure 4-8), the upper two rows of steel bars are not as clearly mapped. However the lowest row of steel bars is more prominent and the back wall reflection appears sharper, compared the SAFT image of the A1040 MIRA device. Concerning the notch both results show a wide interruption of the back wall signal as well as some dipping artifacts. These dipping signals are most likely artifacts, caused by the downward extrapolation of the data. Besides the additional processing with a 3D/2D correction of the data acquired with scanner, the scanner system and the A1040 MIRA device differ in aperture (max. offset). The MIRA device with a maximum offset of 33 cm records a rather focused part of the emitted wave field, whereas the scanner system with an offset of 1.33 m records a wider part. This also explains the better resolution of the A1040 MIRA device within the upper half of the image. The smaller offset on the other hand causes deeper signals, like the back wall reflection to be less sharp. On the other hand, the result of SAFT using data with a larger offset, creates a much more sharper signal in the lower part of the image. Compared to the results of RTM (Figure 4-19), the results of SAFT presented in Figure 4-8 and Figure 4-20 do not show any vertical signals of the notch. Despite the presence of a variety of reinforcement steel the RTM stack reveals the side of the notch.
4-2-3 Ground Penetrating Radar (GPR)

The conducted GPR survey, introduced in Subsection 4-1-3 was performed on the top surface along a regular mesh of grid size $\Delta x = 5 \, \text{cm}$. The scheme used to process the raw data is shown in the following list.

- Bandpass filtering (High pass: 500 MHz, low pass: 4000 MHz)
- Time zero adjustment
- Kirchhoff migration using an EM wave velocity of $12.5 \, \text{cm/ns}$
- Hilbert Transformation and gain function

Besides the bandpass filter to increase the signal-to-noise ratio, the time zero adjustment sets the first arrivals to time $t = 0$. The Kirchhoff migration applied uses an average EM wave velocity of $12.5 \, \text{cm/ns}$ to migrate the data. In addition, a Hilbert transform of the migrated data, as well as a gain function emphasize the migrated signals. The results are summarized in Figure 4-21. The first two images refer to the x-y-slices ("C-Scans") indicated in Figure 4-21. The first slice shows the resulting image from a depth of $z = 4-6 \, \text{cm}$. This section gives a very clear indication of steel bars oriented in a mesh. The center bar (red arrow) along the x-axis is located directly in the center of the test specimen ($y = 30 \, \text{cm}$). This corresponds to the exact position of the measurement lines performed with the A1040 MIRA device, as well as the scanner system. The second slice corresponds to a depth of $z = 9-11 \, \text{cm}$. This cross section indicates a second mesh with a small shift compared to the upper one in the first image. This is confirmed by the x-z-slices in the last two images. Within the third slice, corresponding to the cross section along $y = 40 \, \text{cm}$, the two layers of dots (red arrows) indicate the two layers of the mesh, specifically the bars perpendicular to the cross section. The last cross section along $y = 30 \, \text{cm}$ is identical to the measurement. The image is dominated by the strong influence of the center steel bar being directly underneath the measurement line. Thereby the image quality is influenced such that the bars perpendicular to the line are not as easily distinguishable anymore. Especially in the first 50 cm of the line, the strong near-surface signal masks the steel layer underneath. The results of the GPR survey further enhance the presence of two steel meshes within the first approx. 11 cm of the test specimen. A third layer, as indicated by the results of the A1040 MIRA device (Figure
4-8), can not be confirmed, since the signals of the antenna used do not penetrate up to this depth.

Figure 4-21: Schematic illustration of the test specimen “PKN” and the GPR sections shown in Figure 4-22.
Figure 4-22: Resulting sections of the processed GPR survey. Slice 1 to 4 correspond to sections schematically indicated in Figure 4-21. The red arrow in section 1 indicates the center steel bar, located directly underneath the profile line.
4-3 Test Specimen PKR

**Figure 4-23:** Picture of exemplary test specimens with identical dimensions like the used specimen "PKR". These specimen are used for static load test within BAM.

In comparison to test specimen “PKN” (Section 4-2), the second specimen contains a number of real cracks, of which are visible at the sides of the specimen. The width of the cracks reaches approx. 0.15 mm at their widest point. Although the inner shape and the distribution within the concrete structure are not known, the cracks do not reach the top surface. A detailed sketch of all the outcrops, as well as a photograph of the cracks can be found in Figure 4-29 and Figure 4-28. Test specimen “PKR” only contains two bars oriented parallel to the x-axis and located in the lower right \((y = 5 \text{ cm})\) and lower left \((y = 35 \text{ cm})\) corner. For this reason, no direct influence of steel bars on ultrasonic data is to be expected.

4-3-1 Scanner system

Due to the geometry of the new test specimen and the maximum offset realizable with the scanner system, the measurements on specimen “PKR” are split into two parts. Figure 4-24 schematically shows the specimen and its dimensions. The fields, highlighted in red and blue, indicate the two setups along the mid line of the specimen. Table 4-2 summarizes the acquisition parameters for the two different setups. Recording time \(T\), as well as the discretization in space and time are not changed and are shown in Table 3-1. However, according to the changed geometry of the test specimen, boundaries and the relating boundary conditions have to be changed. Figure 4-25 shows the resulting velocity models for both setups. Due to a recording time of \(T = 0.3 \text{ ms}\), the right hand side of the model of setup 1 (Figure 4-25) is not expected to receive signals reflected from the right side wall of the test specimen. Therefore an absorbing boundary is implemented in Madagascar (see Section 2-2-3). Same holds for the model of setup 2, located in the center of the test specimen (Figure 4-2), in which both sides are implemented as absorbing boundaries. Top and bottom surfaces of the models are implemented as free surfaces.
Experiments on concrete structures

Figure 4-24: Schematic illustration of the two surveys conducted on specimen “PKR” using the scanner system. The measured line of the first survey (red) has a total length of 1.31 m, the second survey (blue) has a total length of 1.30 m. The red dashed mid line represents the measurement line at \( y = 20 \text{ cm} \).

Table 4-2: Data acquisition parameter for scanner surveys conducted on test specimen “PKR”

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PKR Setup 1</th>
<th>PKR Setup 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of shots ([\text{]})</td>
<td>58</td>
<td>64</td>
</tr>
<tr>
<td>Shot spacing ([\text{cm}])</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>No. of receivers ([\text{]})</td>
<td>132</td>
<td>131</td>
</tr>
<tr>
<td>Receiver spacing ([\text{cm}])</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 4-25: Velocity models of test specimen “PKR”. The upper model refers to setup 1, the lower model refers to setup 2, according to Figure 4-24. The sides marked with red dashed line using an absorbing boundary condition.
The data acquired with the two setups on test specimen is processed according to scheme 2, as introduced in Section 4-2-2. The data is migrated using a velocity of 2650 m/s, as indicated by the results of migration using SAFT (see Figure 4-30). Furthermore a slightly increased migration velocity of 2740 m/s is tested. A density of $\rho = 2.4 \text{ g/cm}^3$ is used, according to the previous simulations. The resulting RTM stack of setup 1 and 2 is shown in Figure 4-26 and Figure 4-27, respectively. The upper stack within Figure 4-26 shows a clear signal from the back wall, which is interrupted at several positions along the x-axis. These interruptions denote the presence of cracks. Vertical red lines mark the interpreted center of the signatures in Figure 4-27. The left part of the stack, not showing any relevant signals is due to the first source placed within specimen “PKR”, as stated in Figure 4-2. Compared to other results of RTM, the right end of the stack hardly shows any migration artifacts. This can be explained by the absorbing boundary used at this side of the model (Figure 4-25). Thereby no reflections lead to additional correlations during RTM. Using a slightly faster migration velocity (lower RTM stack) the described signals become sharper showing a clearer lateral position and shape. This further supports the observations that slight velocity mismatches can result in a more detailed or clearer result in the area of interest (Section 4-2 and [Grohmann, 2014]). Comparing the results of both setups, the signatures of the cracks appear more pronounced. This can be related to the static load test performed on the specimen. The force was applied to the center part of the specimen, thus leading to a stronger flexing in the center. This might have resulted in wider cracks.

![Figure 4-26: Resulting RTM stacks of setup 1 of the scanner survey on test specimen PKR.](image)

Figure 4-26: Resulting RTM stacks of setup 1 of the scanner survey on test specimen PKR. A migration velocity of 2650 m/s is used for the upper stack. The lower stack is migrated using a velocity of 2740 m/s. The yellow dashed line separates the model from the boundary.

To evaluate the lateral position of the mapped signatures of potential cracks, Figure 4-28 shows an extract of the result of setup 2 (lower stack, Figure 4-27). In addition a detailed photograph of the bottom side of the specimen is shown. Using the interpretation of the signature center as the exact position of the crack (yellow vertical line), the offset to the outcrops, crossing the projected profile line (red dashed line) can be determined. Crack no.
Figure 4-27: Resulting RTM stacks of setup 2 of the scanner survey on test specimen PKR‘. A migration velocity of 2650 ms$^{-1}$ is used for the upper stack. The lower stack is migrated using a velocity of 2740 ms$^{-1}$. The yellow dashed line separates the model from the boundary. Within the lower stack, signatures no. 3 and 4 are marked referring to the interpretation within Figure 4-28. The vertical red lines indicated the center of the signatures. The horizontal dashed lines are estimates of the vertical extend of the signatures 3 and 4.

Figure 4-29 shows the best fit between the result of RTM and the outcrop. The remaining cracks show slightly larger offsets around 5 cm. However the image quality around crack no. 2 does not allow clear interpretation. If the feature marked by a yellow dashed line refers to a (dipping) crack, the offsets are changing. It is not clear, whether this signature is caused by a crack or resembles a migration artifact, since it is located close to the boundary.

Figure 4-29 shows a photograph from the side of the specimen. Outcrops 1 to 5 thereby correspond to the cracks 1 to 5 in Figure 4-28. The outcrops of crack 1 to 4 are approx. 14 cm height. Crack no. 5 is a little shorter with a height of 12 cm. To compare these outcrops to the mapped signatures in Figure 4-27, crack no. 3 and 4 are marked within the result of RTM. Interpreting the yellow dashed as the maximum vertical extend of the crack-related signature, leads to an estimate of the height of 15 cm. This matches the outcrops in Figure 4-29 very well.

In addition the data acquired with the scanner system is further migrated using SAFT. Figure 4-30 shows the resulting images of setup 1 and 2, using a migration velocity of 2650 ms$^{-1}$. Within the results of both setups, the back wall is mapped at the true depth of $z = 0.2$ m. Compared to the SAFT results on test specimen “PKN” (Figure 4-20), the cracks do not cause a complete interruption of the mapped back wall signal. Several bulges in the mapped back wall along dipping features, exemplary marked in the lower stack by a red circle, are indications for the presence of fine reflectors. The lateral positions thereby correspond to the mapped signatures within the RTM stacks (Figure 4-26 and Figure 4-27). The dipping features can be related to migration artifacts, as seen in Figure 4-8. Besides these irregularities
4-3 Test Specimen PKR

Figure 4-28: Evaluation of horizontal crack positions. The upper part shows an extract of the resulting stack of the RTM of survey 2, using a migration velocity of \(2740 \text{ ms}^{-1}\). The lower photograph shows the bottom side of the specimen around the center. Cracks are highlighted in grey, the dashed red line resembles the projected measurement line. The yellow lines refer to the center signal of the cracks from the resulting stack and their projections to the profile line. The distance between the projected cracks and the outcrops are stated below.

Figure 4-29: Detailed photograph of the side of specimen “PKR”, indicating the height of the outcrops of the cracks. The cracks are highlighted in blue. Outcrops 1 to 5 thereby resemble the five marked cracks in Figure 4-28.

in the back wall signature, the results of SAFT do not reveal any further information about the cracks.
Figure 4-30: Resulting image of survey 1 and 2 conducted on specimen “PKR” using SAFT with a migration velocity of $2650 \text{ m.s}^{-1}$. The red circle marks irregularities in the back wall signature.
Chapter 5

Discussion

5-1 Synthetic Experiments

In general the synthetic experiments show very good results for mapping the notch and crack-like structures. The relatively fast decay in amplitude of the direct wave, as described in the beginning of Chapter 3 is most likely related to the implementation of the free surface within Madagascar. Shot records from measurements on real concrete structures, e.g. Figure 4-11, indicate the expected strong contribution of the direct wave to the whole record. The weak direct wave might lead to fewer correlations within RTM, thus producing a cleaner image. Therefore further investigations of the implementation of the boundary condition within Madagascar are needed.

Synthetic experiments do not account for any noise related to e.g. bad coupling of transducers or electromagnetic noise, as described in Section 4-2-2. The scattering of the wave field due to aggregates, which were added to the homogeneous synthetic models, approaches the synthesized data to the data recorded on real concrete structures. However, this does not account for any additional noise related to real measurements. Therefore the results of the synthetic experiments must be considered as not completely representative.

The homogeneous true scale model of test specimen “PKN” (Figure 3-3) is illuminated best for a high number of closely spaced sources. This further reduces the influence of migration artifacts near the sources. Due to further overlapping, thus destructive interference, the strong signals near the source points minimize. Same holds for artifacts created in the model corners.

Within the homogeneous models used, the perfect match of model velocity and migration velocity leads to very sharp signals as result of the correlation. The result of the initial synthetic experiment, shown in Figure 3-9, along with the schematic explanation of the signature of the notch (Figure 3-12) can explain the signal width within the RTM stack. The width of the signal thereby can not be related to the width of the notch. The resolution of the ultrasonic wave can not resolve the different side walls of the notch. A general estimate of the resolution is approx. half of wave length $\lambda$, e.g. [Reinhardt, 2007]. With the current setup, this relates
to a resolution of 2.6 cm, which is twice the width of the notch in the initial model. Therefore the signals related to notches and cracks throughout this study can only be used to give an estimate about the position within the model or structure.

Introducing a second notch to the synthetic models (Section 3-2-4) further illustrates the influence of a smaller aperture. Limiting the aperture leads to missing signals from the inner side walls. The two notches thereby focus the wave field. The wave front oriented mostly parallel to the back wall is hardly reflected at the inner side walls. These missing reflections result in no mapping of the inner sides.

When introducing heterogeneous concrete models (Section 3-3) the question of which migration velocity to use arises. The comparison of different velocities, shown in Figure 3-23, points out that a rather broad range of migration velocities is able to produce significant overlap of the signals from $W_S$ and $W_R$ in order to map the notch. One can assume, that with a better velocity match, the narrower the resulting signal of the correlation, thus the sharper the image. Given a certain difference in the mentioned velocities, this mismatch becomes more influential with larger travel times and therefore the size of the model (or structure). The signal of the notch using the average velocity of 2620 ms$^{-1}$ thereby is sharper compared to the signal of the other velocities. The changes in polarity of the RTM stack thereby depends on the recorded data and the accompanied mismatch in velocity. The influence of the velocity mismatch on the spatial position of the mapped signal has to be taken into account. Assuming a difference in velocity of 120 ms$^{-1}$ (2740 ms$^{-1}$ - 2620 ms$^{-1}$) using the total recording time $T = 0.3$ ms, the signal shift accounts for 3.6 cm. This shift in the signals still leads to significant correlation, as seen in Figure 3-23, however, this does not represent the exact location of the mapped feature.

Modification 1 and 2 (Section A and Section 3-3-3) of the heterogeneous model show that thinner and less regular structures are mapped well. Especially the sides of the added features are very well observable within the resulting RTM stack. The thickness of the crack-like structures thereby has no significant influence, as long the structure itself shows a continuously air-filled shape, thus creating a very strong contrast in acoustic impedance. However the results for the mentioned models (Figure 3-26 and Figure 3-28) also reveal the problem of locating the tip of such finer structures. Assuming a vertically oriented crack-like structure, as in modification 1, the tip resembles a single point, which is very difficult to identify within such highly scattered wave fields. Modification 2, on the other hand, shows rather good signals related to the tips. The dipping features represent a wider reflector for a wave propagating downwards from the top surface.

5-2 Experiments on concrete structures

Applying SAFT to the data of the A1040 MIRA ultrasonic tomograph (Figure 4-8) results in a good image of test specimen “PKN”. The back wall is clearly mapped, so are the numerous steel bars. Concerning the information gained about the notch, besides the missing back wall in a relatively wide area around the true position of the notch, there are no further details on the overall geometry or the tip of the notch. A general study by [Reinhardt, 2007] shows that the data resolution of such transducer using SAFT is sufficient to map the top surface of different notches with a width of 1 cm to 6 cm. Results of the study are presented in
Appendix B. This information was expected to be gained for the specimen “PKN” as well. The influence of multiple layers of steel bars is most certainly responsible for the tip of the notch being masked. Especially the second steel layer, shown in Figure 4-22 is located approx. in the same height (z-axis) than the tip of the notch. This might lead to highly complex wave field in this part of the model masking the signals from the tip. The missing side walls of the notch within the SAFT reconstruction can be related to the algorithm itself, not being able to handle complex wave paths and such vertical reflectors. In addition, the smaller aperture of the device might not be favorable, since the crucial information about the side walls comes from the reflected back wall reflection, as shown in Section 3-1-3. Therefore larger apertures are generally more suitable.

This assumption is further strengthened by the results of the RTM using the data from the A1040 MIRA. With apertures (max. offsets) between 3 cm and 33 cm this data and therefore the amount of information for the backward propagated receiver wave field \( W_R \), is not suitable for RTM. Another possible, yet rather small influence to the overall image quality of the RTM stack might be the positioning of the A1040 MIRA device. Opposite to the scanner system, the device is placed by hand onto the test specimen. Using a predefined grid, marked on the surface, a certain loss of accuracy along the profile has to be assumed. Overall the data of the A1040 MIRA device is not suited for RTM. The very high amount of single shots accompanied with the small offset, hence small amount of information, makes processing with RTM highly inefficient.

The resulting RTM stack from the data acquired with the scanner system (Figure 4-19) reveals a more detailed image compared to the results of SAFT. Using a migration velocity of \( 2600 \text{ ms}^{-1} \), the dark character of the image, analogue to the results of the heterogeneous experiments (Figure 3-23), indicates a good match of the velocity. However, the results are also highly influenced by the steel bars in the specimen. Although being able to take complex travel parts into account, the RTM algorithm can not retrieve and map the signals from the tip of the notch. This further strengthens the assumption of the steel bars masking the tip. Compared to the results of SAFT, signals from the side walls indicate the advantage of RTM for mapping complex structures.

The RTM stacks of specimen “PKR” further reveal the potential of RTM for mapping fine structures, like vertically oriented cracks. Again, the first stacks (Figure 4-26 and Figure 4-27), using a migration velocity of \( 2650 \text{ ms}^{-1} \), reveal an image dominated by negative amplitudes. These darker images result of additional correlations throughout the whole model due to an accurate velocity match. Thereby relatively weak signals retrieved from the cracks are not visible clearly. These observations can be confirmed by the results of [Grohmann, 2014], also purposing slight velocity mismatches might lead to a clearer image within the area of interest. The velocity mismatch, when using a slightly faster migration model, leads to an overall smaller amount of correlations, as stated in Section 3-3. Not being dominated by the additional correlations the image gives a clearer indication of the crack related signals. However an exact location of the tips of the cracks is not possible. The overall indication of the height of the cracks gives a good estimate (Figure 4-29). Generally the width of the cracks is expected to get finer towards the tip, increasing the chances of being not completely open (air filled). This makes an exact determination of the height or the location of the tip rather difficult. Assuming the exact position of a crack at the center of the mapped signatures, the lateral position of the cracks shows a rather good fit with the positions of the outcrops (Figure 4-28). The slight offsets can be explained by the fact, that the cracks within the test
specimen resemble highly complex 3D structures. Only knowing the outcrops at the sides does not reveal any information about the inner structure. The photograph of the bottom side of the specimen also shows cracks splitting up into two branches, thus making an estimate about the lateral accuracy of the RTM result more difficult. Besides the assumption of the exact position being located at the signal center may not be correct for every signal. Furthermore the spatial offset of the mapped signals, discussed in Section 5-1 needs to be considered as well.
The synthetic experiments performed on a modelled test specimen generally confirmed the ability of RTM to map fine vertical features like notches and crack-like structures. Within the experiments the influence of different acquisition setups can be investigated. The results give an impression on the data and image quality of measurements on real concrete structures. These synthetic approaches can be used further in order to determine single parameter dependencies. A more detailed investigation of the influence of the migration velocity shows that the velocity must not be exactly known to detect the notch. Shifted correlations lead to different polarities in the stacked RTM result. Generally sharper images indicate a good velocity match. Further investigations are needed in order evaluate this issue in more detail. Fine structures, like the modelled notch or the real cracks are mapped by a broader signal due to limited resolution of ultrasonic waves. Determining the exact location of a thin reflector within a broader signature can further increase spatial accuracy. Throughout the experiments conducted on real concrete structures RTM outperforms SAFT mapping signatures from the notch and cracks. This extends the range of potential application of RTM used for ultrasonic data. To generally improve the results of RTM further efforts are needed. A study carried out at BAM has introduced the curvelet transform and further spatial filter algorithm to the results of RTM of ultrasonic data [Sieber, 2015]. These filter can be used to improve the final stack suppressing noise and improving the image quality. Extensive filter approaches might lead to better information about the notch/cracks. Furthermore the implementation of RTM using a full elastic wave equation is currently investigated within the Ph.D. of Maria Grohmann at BAM. Early results indicate that further information gained by the full wave equation can help to better map complex structures.


Appendix A

Synthetic Experiments

Modification 4 - two notches

The model presented in Figure A-1 is a further modification of modification 3 of the homogeneous true scale model, presented in Section 3-2-4. Compared to the initial modification, the notches are separated by 5 cm, half of the initial distance. The resulting stack of RTM is presented in Figure A-2.

![Velocity model in [m/s] including air boundary](image)

Figure A-1: Homogeneous velocity (upper model) and density (lower model) models of the concrete PK.

Figure A-2 shows that the signatures of the notches move closer together. The tip of the notches are mapped nicely. The small gap between the tips indicate a separation between the notches. The inner sides of the two notches are not mapped, further strengthen the assumptions made in Section 3-2-4. The even closer gap focuses the wave field, thus prevent any reflections of the back wall reflection at the inner side walls.
Figure A-2: Resulting stack of 75 migrated shots on the true scale model of the test specimen. The yellow dashed line separates the model from the boundary.

Exemplary SConstruct file for RTM of synthetic data

```python
# Exemplary SConstruct file for synthetic experiment
from rsrc import *
import fdmod, wsg

par = dict(
    nx=1600, ox=0, dx=1, lx=x', ux=xmax',
    nx=3000, ox=0, dx=1, lx=x', umax=x',
    nt=3000, at=0.0, dt=1.0, kt=1.0, ut=umax',
    jmap=50, # snapshot jump
    kt=200, # wavelet delay (samples)
    mb=0,
    frq=50 # kHz
)

# image coordinates
par['nqz'] = par['nx']
par['oqz'] = par['oz']
par['dqs'] = par['dx']

par['nqs'] = par['nx']
par['oqs'] = par['ox']
par['dqz'] = par['dz']

fdmod.boxarray(('qq',
    par['nqz'], par['oqz'], par['dqs'],
    par['nqs'], par['oqs'], par['dqz'],
    par))

Plot('qq','window j2=100 | '+fdmod.qqplot('qq',par))
Plot('wav','wav2',par['frq'],par)
Plot('wav','wav2','transp')
Result('wav','window m2=1000 | '+fdmod.waveplot('wav',par))
Plot('vbk','vbk2600','dd form=ascii')

Plot('dens','dens2600','dd form=ascii')
Plot('vbk',fdmod.cgrey('vbk',par))

# load velocity and density model for migration
Flow('vel','hetero_mod_vel','dd form=ascii')
Flow('den','hetero_mod_den','dd form=ascii')
Plot('vel',fdmod.cgrey('vel',par))

# receivers coordinates
fdmod.horizplot(('rr',0,par)
Flow('rr',tt,'window f2=50 j2=10 m2=151')
Plot('rr',fdmod.xxplot('plotfat=10',par))

ns=75 # number of shots
```
\begin{verbatim}
# shot point
os = 60  # shot point
# shot distance
diz = 60  # source-receiver offset

for js in range(ns):
    stag = "%02d" % js
    xso = os + ja * ds
    k = xso - diz
    x = ((k - 60) / 10)

    # source coordinates
    fdmod.point(["ss+stag", xso, 0, par])
    plot(["ss+stag", fdmod.asplot(plotcol='4', par)])

    Result(['vel+stag', ['vel', 'rr', 'ss+stag'], 'Overlay'])

    # FD modeling
    fdmod.aefd(['dat+stag', 'wfl+stag', 'wav', 'vel', 'den', 'ss+stag', 'rr', 'dabc=y free=y', par])

    Result(['wfl+stag', fdmod.cgrey('pcclip=99.9', par)])
    Result(['dat+stag', 'transp=' + fdmod.dgrey('pcclip=99.5', par)])

    # 2D acoustic Reverse Time Migration
    fdmod.artm(['img+stag', 'wav', 'dat+stag', 'vbk', 'dens', 'ss+stag', 'rr', 'qq', 'jdata=10 jsnap=10 dabc=y free=y memsize=100', par])

    Result(['img+stag', fdmod.cgrey('pcclip=99.5', par)])

    # plot all partial images with the same colorbar
    Flow(['imgall', ['img%02d' % js for js in range(ns)], 'cat axis=3 space=n $(SOURCES[1:4])' % ns])

    # overlay all shot locations
    Plot(['ss', ['ss%02d' % js for js in range(ns)], 'Overlay'])

    # stack all images
    Flow(['stk', 'imgall', 'stack axis=3'])

    # plot stack w/ overlay
    Plot(['stk', fdmod.cgrey('pcclip=99.9', par)])

    Result(['stk', ['stk', 'rr', 'ss'], 'Overlay'])

End()
\end{verbatim}
Appendix B

Experiments on concrete structures

Raw data from A1040 MIRA device

Figure B-1 shows an exemplary shot data of the A1040 MIRA device. The data from shot no. 5, acquired on the test specimen “PKN”, is separated into the 11 different source-receiver combinations by the yellow dashed lines. The number of receivers reduces for the different configurations, according to the descriptions in Section 4-1-1.
Figure B-1: Exemplary raw data from shot no. 5 ($x = 80 \text{ mm}$). Different configurations are separated by yellow dashed lines.
Exemplary SConstruct file for RTM of data acquired on real concrete structures

```python
# Exemplary SConstruct for RTM on test specimen P3K
#
from raf.proj import *
import fdmod, venig
par = dict(
    nx=1600, oz=0, dz=1, lx='x', uz='z',
    nz=300, ox=0, dx=1, lz='z', uzm='nx',
    nt=3000, ot=0.0, dt=0.1, lmt='t',utm='nz',
    jmap=50, # snapshot jump
    kbt=200, # wavelet delay (samples)
    nb=0,
)  

fdmod_EDIT(par)
#
# image coordinates
par['nqz'] = par['nx']
par['oqz'] = par['oz']
par['dqz'] = par['dz']
par['nqz'] = par['nx']
par['oqz'] = par['ox']
par['dqz'] = par['dz']

fdmod.boxarray(['qq', 'oqz'], ['nqz'], ['dqq'], ['oqz'], ['nqz'], ['dqz'], ['oqz'], ['dqz'])
Plot('qq', 'window y2=100 | ' + fdmod.qqplot('qq', 'par'))
#
# make the source function
fdmod_wavelet('wav', 'wav', 'par', 'frequ', 'par')
Flow('wav', 'wav', 'transp')
Result('wav', 'window m2=1000 | ' + fdmod_waveplot('wav', 'par'))
#
# importing velocity and density models created in MATLAB
Flow('vel', 'original_vel', 'dd form=ascii')
Flow('den', 'original_den', 'dd form=ascii')
Plot('vel', 'den', 'original', 'dd form=ascii', 'par')
#
# receivers coordinates
fdmod_EDIT('tt', '0', 'par')
Flow('rr', 'tt', 'window f2=60 j2=10 m2=151')
Plot('rr', 'dd form=ascii', 'par')

ns=75 # number of shots
os=60 # shot point
dz=20 # shot distance
d=60 # source-receiver offset
for js in range(ns):
    sztag = '%02d' % js
    zsn = os + js * dz
    k = zsn - dz
    sz = [(k - 60) / 10]
    
    fdmod_EDIT['sz=ijtag', 'sz=0', 'par']
    Plot('sz=ijtag', 'dmod', 'asplot', 'plotcol=4', 'par')

    fdmod_EDIT['vbk=ijtag', 'vbk=rr', 'as=ijtag', 'Overlay']
    Result('vbk', 'ijtag', 'vbk', 'rr', 'as=ijtag', 'Overlay')
#
# 2D acoustic Reverse Time Migration
fdmod_EDIT['img=ijtag', 'wav', 'dat=ijtag', 'vbk', 'dens', 'sz=ijtag', 'rr', 'qq', 'jdata=10 jsnap=10 dbac=y free=y memsize=100', 'par']
Result('img', 'ijtag', 'dmod', 'cgray', 'pclip=99.5', 'par')

# plot all partial images with the same colorbar
```
84 Experiments on concrete structures

Flows({'imgall': ['%02d' % i for i in range(ns)],
        'cat axis=3 space=n $(SOURCES[1:%d])' % ns},

# overlay all shot locations
Plot({'as': ['%02d' % i for i in range(ns)], 'Overlay'})

# stack all images
Flows({'stk': 'imgall', 'stack axis=3'})

# plot stack w/ overlay
Plot({'stk': fmod.tgrey({'pclip=99', 'par'})})
Result({'stk': ['stk', 'rr', 'as'], 'Overlay'})

# -----------------------------------------------
End()}
As stated in Section 4-2-1 and 5-2, the results of SAFT using the data acquired with the A1040 MIRA device on test specimen “PKN” were expected to map the tip of the notch. Within the study of [Reinhardt, 2007], a specimen with a total of six notches was used to determine the ability of mapping the different tips of the notches. Compared to the specimen used in this study, the specimen in Figure B-2 does not contain any steel bars. The resulting SAFT image can be seen in Figure B-3. This further strengthens the assumption of the steel layers within specimen “PKN” mask the signals from the tip of the notch.

**Figure B-2:** Geometries of the test specimen used within the study of [Reinhardt, 2007], showing the six notches of different width. Adopted from [Reinhardt, 2007].

**Figure B-3:** Result SAFT reconstruction of the specimen shown in Figure B-2. Adopted from [Reinhardt, 2007].