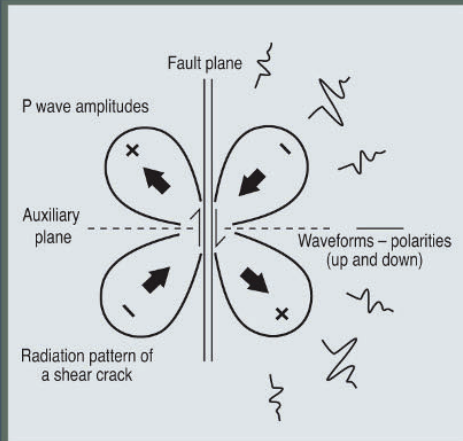




Non-destructive evaluation of reinforced concrete structures

Volume 2: Non-destructive testing methods

Edited by Christiane Maierhofer,
Hans-Wolf Reinhardt and Gerd Dobmann



WP

Non-destructive evaluation of reinforced concrete structures

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Contents

<i>Contributor contact details</i>	<i>xv</i>
<i>Preface</i>	<i>xxi</i>
Part I Planning and implementing non-destructive testing of reinforced concrete structures	1
1 Planning a non-destructive test programme for reinforced concrete structures	3
C. MAIERHOFER, BAM Federal Institute for Materials Research and Testing, Germany	
1.1 Introduction	3
1.2 Strategies for the application of non-destructive testing (NDT) methods	4
1.3 Overview of non-destructive testing (NDT) methods	6
1.4 Qualification/validation of methods	8
1.5 Sources of further information and advice	10
1.6 References	12
2 Non-destructive testing methods for building diagnosis – state of the art and future trends	14
C. FLOHRER, HOCHTIEF Construction AG, Germany	
2.1 Introduction	14
2.2 Tasks for building diagnosis	14
2.3 Efficient testing methods	15
2.4 Examples of the application of the testing methods	18
2.5 Future trends	28
2.6 References	29
	v

3	Development of automated non-destructive evaluation (NDE) systems for reinforced concrete structures and other applications	30
	G. DOBMANN and J. H. KURZ, Fraunhofer-IZFP, Germany; A. TAFTE, BAM Federal Institute for Materials Research and Testing, Germany; D. STREICHER, Joint Lab of Fraunhofer & BAM, Germany	
3.1	Introduction	30
3.2	The innovation cycles	31
3.3	Data acquisition, control and evaluation in automated multisensor systems	34
3.4	Case studies of successful innovations to automated systems in non-destructive testing (NDT) engineering	36
3.5	Non-destructive testing for structural engineering	46
3.6	Multiple-sensor data acquisition by the OSSCAR (On-Site SCAnner) scanner	54
3.7	Conclusions	60
3.8	Acknowledgements	60
3.9	References	60
4	Structural health monitoring systems for reinforced concrete structures	63
	W. R. HABEL, BAM Federal Institute for Materials Research and Testing, Germany	
4.1	Introduction	63
4.2	Demands on monitoring systems: monitoring capabilities	64
4.3	Innovative monitoring methods	67
4.4	Selected examples of effective and innovative monitoring technologies	74
4.5	Reliability of structural health monitoring (SHM) systems and standardization	87
4.6	Future trends	90
4.7	References	91
5	Combining the results of various non-destructive evaluation techniques for reinforced concrete: data fusion	95
	C. MAIERHOFER, C. KOHL and J. WÖSTMANN, BAM Federal Institute for Materials Research and Testing, Germany	
5.1	Introduction	95
5.2	Combination of non-destructive testing (NDT) and minor destructive testing (MDT) methods	96
5.3	Data fusion	98

5.4	Fusion of radar data	100
5.5	Fusion of radar and ultrasonic data recorded along a beam of a box girder bridge	101
5.6	Fusion of radar and ultrasonic data at a cross beam inside a box girder bridge	103
5.7	Sources of further information and advice	105
5.8	Conclusions and future trends	105
5.9	Acknowledgements	106
5.10	References	106
Part II	Individual non-destructive testing techniques	109
6	Wireless monitoring of reinforced concrete structures M. KRÜGER, University of Stuttgart, Germany	111
6.1	Introduction	111
6.2	Basic principles of wireless monitoring	112
6.3	Definition of the monitoring task	114
6.4	Monitoring system design and assembly	116
6.5	Wireless monitoring systems in operation	119
6.6	Application of intelligent wireless monitoring	119
6.7	Conclusions and future trends	122
6.8	References	122
7	Non-destructive testing of concrete with electromagnetic and acoustic-elastic waves: data analysis K.-J. SANDMEIER, Sandmeier Scientific Software, Germany	125
7.1	Introduction	125
7.2	Similarities and differences between seismic, ultrasonic and electromagnetic wave propagation and their implications on data processing	125
7.3	Standard data processing	127
7.4	Sophisticated data processing	136
7.5	Conclusions and future trends	142
7.6	References	142
8	Non-destructive testing of concrete with electromagnetic, acoustic and elastic waves: modelling and imaging K. J. LANGENBERG, K. MAYER and R. MARKLEIN, University of Kassel, Germany	144
8.1	Introduction	144
8.2	Electromagnetic, acoustic and elastic waves	145

viii	Contents	
8.3	Numerical wave field modelling for acoustic, electromagnetic and elastic waves	151
8.4	Wave field inversion and imaging: acoustic waves	154
8.5	Wave field inversion: electromagnetic and elastic waves	158
8.6	Conclusions	159
8.7	References	161
9	Laser-induced breakdown spectroscopy (LIBS) for evaluation of reinforced concrete structures	163
	G. WILSCH, BAM Federal Institute for Materials Research and Testing; A. MOLKENTHIN, Specht, Kalleja + Partner GmbH, Germany	
9.1	Introduction	163
9.2	Laser-induced breakdown spectroscopy (LIBS): fundamentals and measurement	164
9.3	Characterization of cement, mortar and concrete	167
9.4	Detection of specific elements: specific testing problems	173
9.5	Mobile set-up: on-site applications	180
9.6	Limitations and reliability	183
9.7	References	184
10	Acoustic emission (AE) evaluation of reinforced concrete structures	185
	C. U. GROSSE, Technical University of Munich, Germany	
10.1	Introduction	185
10.2	Basics: parametric and signal-based acoustic emission (AE) analysis	187
10.3	Sensors and instruments	191
10.4	Source localization	193
10.5	Source mechanisms and moment tensor analysis	197
10.6	Applications	199
10.7	Limitations and accuracy	206
10.8	References	210
11	Magnetic flux leakage (MFL) for the non-destructive evaluation of pre-stressed concrete structures	215
	G. SAWADE, University of Stuttgart, Germany; H.-J. KRAUSE, Forschungszentrum Jülich, Germany	
11.1	Magnetic method for inspection of reinforced concrete structures	215
11.2	Description of equipment required	233

11.3	Examples of applications of the magnetic method on site	235
11.4	Perspective: recent developments of the magnetic method for inspection of reinforced concrete	239
11.5	Recommendations for the application of the magnetic flux leakage (MFL) method	240
11.6	References	241
12	Electrical resistivity for the evaluation of reinforced concrete structures	243
	J.-F. LATASTE, University of Bordeaux 1, France	
12.1	Introduction	243
12.2	Physical principles and theory	244
12.3	Use of electrical resistivity	255
12.4	Other developments	264
12.5	Impedance spectroscopy	268
12.6	References	270
13	Capacimetry for the evaluation of reinforced concrete structures	276
	X. DÉROBERT, LCPC, France	
13.1	Physical principle and theory	276
13.2	Equipment	279
13.3	Calibration	280
13.4	Data acquisition and interpretation	280
13.5	Applications	281
13.6	Limitations and reliability	282
13.7	References	283
14	Techniques for measuring the corrosion rate (polarization resistance) and the corrosion potential of reinforced concrete structures	284
	C. ANDRADE and I. MARTÍNEZ, Instituto de Ciencias de la Construcción Eduardo Torroja (CSIC), Spain	
14.1	Introduction	284
14.2	Principles	285
14.3	Measurement methods	293
14.4	How to interpret the measurements	303
14.5	Practical application	306
14.6	Monitoring systems	310
14.7	Future trends: new techniques	311
14.8	Conclusions	312
14.9	References	313

15	Ground penetrating radar for the evaluation of reinforced concrete structures	317
	J. HUGENSCHMIDT, EMPA, Switzerland	
15.1	Introduction to ground penetrating radar (GPR)	317
15.2	Physical principles and theory	318
15.3	Display formats for ground penetrating radar (GPR) data	322
15.4	Data processing and interpretation	323
15.5	Equipment	325
15.6	Limitations and reliability of ground penetrating radar (GPR)	326
15.7	Current and future trends	327
15.8	Symbols and constants	331
15.9	References	332
16	Radar tomography for evaluation of reinforced concrete structures	334
	L. ZANZI, Politecnico di Milano, Italy	
16.1	Introduction	334
16.2	Physical principles	335
16.3	Fundamental equations	337
16.4	Resolution	338
16.5	Equipment	339
16.6	Acquisition procedures	341
16.7	Data pre-processing	344
16.8	Data inversion	346
16.9	Artefacts	349
16.10	Interpretation of results	350
16.11	Examples	354
16.12	Hints on advanced algorithms	363
16.13	Conclusions	365
16.14	References	365
17	Active thermography for evaluation of reinforced concrete structures	370
	C. MAIERHOFER, M. RÖLLIG and J. SCHLICHTING, BAM Federal Institute for Materials Research and Testing, Germany	
17.1	Introduction	370
17.2	Physical principle and theoretical background	372
17.3	State of the art	375
17.4	Experimental equipment and calibration	376
17.5	Data processing	380
17.6	Areas of applications	386

17.7	Future trends	396
17.8	Guidelines and sources of further information and advice	397
17.9	References	399
18	Nuclear magnetic resonance (NMR) imaging for evaluation of reinforced concrete structures	403
	B. WOLTER, Fraunhofer IZFP, Germany	
18.1	Introduction	403
18.2	Physical background	404
18.3	Nuclear magnetic resonance (NMR) hardware	407
18.4	Application possibilities	409
18.5	Reliability and limitations	413
18.6	Conclusions and future trends	414
18.7	References	415
19	Stress wave propagation for evaluation of reinforced concrete structures	417
	S. TESFAMARIAM, The University of British Columbia, Canada; B. MARTÍN-PÉREZ, University of Ottawa, Canada	
19.1	Introduction	417
19.2	Stress wave propagation methods	419
19.3	Applications	424
19.4	Discussion and future trends	435
19.5	Conclusions	436
19.6	References	436
20	Surface wave techniques for evaluation of concrete structures	441
	J. S. POPOVICS, University of Illinois, USA; O. ABRAHAM, LCPC, France	
20.1	Introduction	441
20.2	Basic principles of surface wave propagation	443
20.3	Signal processing and data presentation	449
20.4	Equipment	457
20.5	Field application of surface wave methods	459
20.6	References	460
21	Impact–echo techniques for evaluation of concrete structures	466
	O. ABRAHAM, LCPC, France; J. S. POPOVICS, University of Illinois, USA	
21.1	History of the development of the method	466
21.2	Basic principles of the impact–echo method	467

xii	Contents	
21.3	Data interpretation	469
21.4	Numerical simulations	474
21.5	Signal processing, data presentation and imaging	475
21.6	Equipment	480
21.7	Impact–echo method applications	481
21.8	Future trends	484
21.9	References	485
22	Ultrasonic techniques for evaluation of reinforced concrete structures	490
	M. SCHICKERT, Institute of Materials Research and Testing (MFGPA Weimar), Germany; M. KRAUSE, BAM Federal Institute for Materials Research and Testing, Germany	
22.1	Introduction	490
22.2	Ultrasonic wave propagation in concrete	491
22.3	Applications and requirements of ultrasonic non-destructive testing	499
22.4	Transmission methods	500
22.5	Imaging of concrete elements	503
22.6	Future trends	521
22.7	Sources of further information and advice	525
22.8	References	526
Part III	Case studies	531
23	Inspection of concrete retaining walls using ground penetrating radar (GPR): a case study	533
	J. HUGENSCHMIDT, EMPA, Switzerland	
23.1	Problem description	533
23.2	Data acquisition	534
23.3	Data processing	536
23.4	Results	538
23.5	Conclusions	542
23.6	Reference	542
24	Acoustic emission and impact–echo techniques for evaluation of reinforced concrete structures: a case study	543
	M. OHTSU, Kumamoto University, Japan	
24.1	Introduction	543

24.2	Applications of acoustic emission (AE) and impact–echo (IE) for concrete structures	544
24.3	Case studies	551
24.4	Conclusions and future trends for on-site application	571
24.5	References	572
 25	 Using ground-penetrating radar (GPR) to assess an eight-span post-tensioned viaduct: a case study X. DÉROBERT, LCPC, France; B. BERENGER, LRPC Angers, France	 574
25.1	Introduction	574
25.2	Localization of post-tensioned ducts	575
25.3	Gammagraphic imaging	577
25.4	Windowing	577
25.5	Evaluation of the structure and reinforcement proposal	579
25.6	Localization of post-tensioned ducts and coring	579
25.7	Discussion of the applied methodology	580
25.8	Acknowledgements	583
25.9	References	584
	 <i>Index</i>	 585

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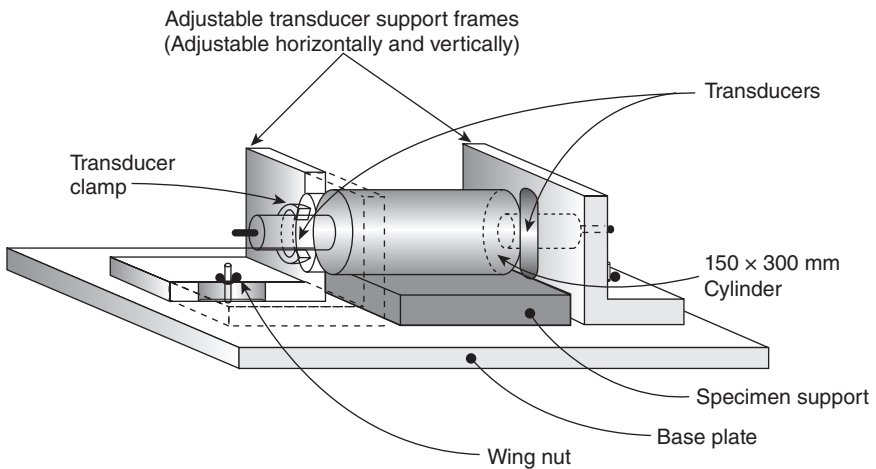
The P wave velocity C_p is the fastest, and it is often used to quantify damage and strength. For an infinite, homogeneous, isotropic and uniform material, the P wave velocity is related to the dynamic modulus of elasticity E_d ($\text{kg m}^{-2} \text{s}^{-1}$), mass density ρ (kg m^{-3}) and Poisson's ratio ν of the material and is computed by the following equation (Krautkramer and Krautkramer, 1990):

$$C_p = \sqrt{\frac{E_d(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad [19.1]$$

Although concrete is a heterogeneous and anisotropic medium and the rigorous application of equation [19.1] may not be valid, the P wave velocity is still considered to be strongly influenced by the material stiffness. The S wave velocity C_s is related to the shear modulus of elasticity G ($\text{kg m}^{-2} \text{s}^{-1}$) and ρ :

$$C_s = \sqrt{\frac{G}{\rho}} \quad [19.2]$$

When the stress wave is generated through ultrasonic pulse, the method is referred to as ultrasonic through-transmission (UTT), also known as ultrasonic pulse velocity (ACI Committee 228, 1998). The UTT works with two transducers: a generator and a receiver (Fig. 19.2). The use of UTT in concrete structures dates back to the 1940s at the Road Research Laboratory in the UK for thickness measurement of pavement layers (Jones, 1953) and



19.2 Ultrasonic through-transmission set-up (Tefamariam, 2000).

at Ontario Hydro Canada for finding crack depths (Leslie and Cheesman, 1949). This method is standardized in ASTM (ASTM Standard C597, 2002).

When the stress wave is generated through an impact, the method is referred to as impact echo or IE (ACI Committee 228, 1998). In the IE technique, the stress is generated through an impact, and the signal is collected using an adjacent transducer. The development of IE in concrete applications dates back to the mid-80s (Sansalone and Streett, 1997). Various applications of UTT and IE in civil infrastructure systems have been reported, and a review is provided in section 19.3.

Once the stress-wave signal generated through UTT or IE is collected, the interpretation of the signal can be undertaken in the time domain using velocity and attenuation coefficient, or in the frequency domain using quality factor (Q-factor). Since concrete is a heterogeneous material, its strength is affected by the elastic (aggregate, sand, and cement) and inelastic (air voids and flaws) constituents. The velocity is used to measure the elastic component. The inelastic component can be quantified through attenuation measures.

19.2.1 Velocity

For the UTT, the P velocity is measured from the time of first arrival to the receiver. Calculation of the P wave velocity C_p from the time of first arrival is given by:

$$C_p = \frac{X}{t} \quad [19.3]$$

where X is the distance that the P wave is propagated between source and receiver, and t is the travel time. For the impact–echo method, the P wave velocity is measured using the P wave resonance frequency f_p as:

$$C_p = 2Xf_p \quad [19.4]$$

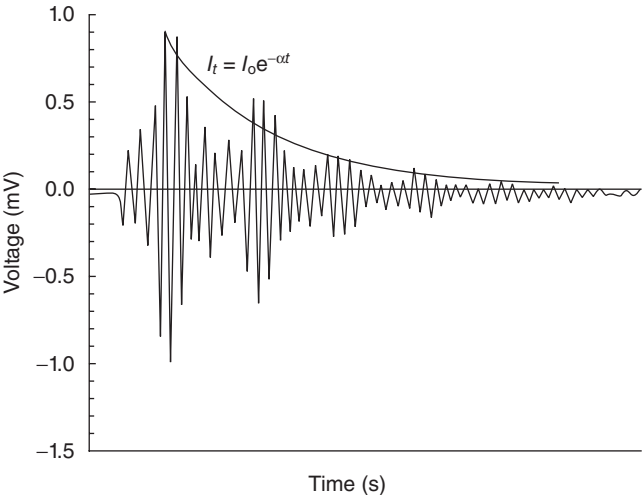
where X is the distance between the top and bottom of a two-layer solid system. The velocity measurement can readily be related to the condition of the concrete (e.g. Table 19.2).

19.2.2 Attenuation coefficient

As the stress wave propagates through concrete, the energy of the propagating wave decreases with increasing path length. The decrease in wave energy is the result of attenuation and divergence, caused by the absorption and scattering of the wave energy. Absorption and scattering losses can give information about the structural and physical properties of the medium (Blitz and Simpson, 1996). Absorption is the result of converting the stress

Table 19.2 Correlation of pulse velocity and condition of the structure (Whitehurst, 1951a)

Pulse velocity	Condition
>4570	Excellent
3600–4570	Generally good
3050–3660	Questionable
2130–3050	Generally poor
<2130	Very poor



19.3 Attenuation coefficient α in the time domain.

wave energy into heat, caused by friction as a result of particle movement. Scattering in concrete structures is a result of wave reflection, refraction, diffraction, and mode conversion owing to dissimilar materials, microcracks and air voids. The stress wave intensity I_d over a distance d can be described by an exponential function (Krautkramer and Krautkramer, 1990):

$$I_d = I_0 e^{-\alpha_d d} \tag{19.5}$$

where I_0 is the intensity at a distance 0 and α_d is known as the attenuation coefficient (m^{-1}). For a given distance, an exponential best-fit curve can be fitted through the time domain signal as depicted in Fig. 19.3, and the corresponding attenuation coefficient α (s^{-1}) can be calculated as:

$$I_t = I_0 e^{-\alpha t} \tag{19.6}$$

where I_t is the intensity at time t .

Table 19.3 Correlation of attenuation coefficient and damage (Kesner *et al.*, 2004)

Decay constant	Crack density	Damage level
<3100	<0.5%	Little or none
3100–4000	0.5–1%	Minimal
4000–5000	1–2%	Moderate
>5000	≥2%	Severe

The attenuation coefficients (decay constants) have been correlated with damage level as shown in Table 19.3. The results of Table 19.3 were generated by Kesner *et al.* (2004) using the IE technique for detecting distributed cracks in concrete. After each IE test, the crack densities were obtained from neutron radiographs. Furthermore, the crack densities were used to define the damage level that is further related to the attenuation coefficient (Table 19.3).

Research of these methods was first published in the mid sixties. Galan (1967; 1990) used ultrasonic pulse velocity (UPV) and the attenuation coefficient α to estimate elastic and inelastic components of concrete. This method has been utilized by other researchers (Ismail *et al.*, 1996; Tesfamariam *et al.*, 2006; Tharmaratnam and Tan, 1990).

19.2.3 Quality factor

It has been shown that attenuation in concrete can be estimated by the quality factor (Q-factor). The Q-factor is the measure of the spectral width of the peak frequency of the stress wave. The particular frequency can be identified after converting the time domain signal (Fig. 19.3) into the frequency domain signal (Fig. 19.4), using the fast Fourier transform (FFT). The equation for the calculation of the Q-factor is shown as (Krautkramer and Krautkramer, 1990):

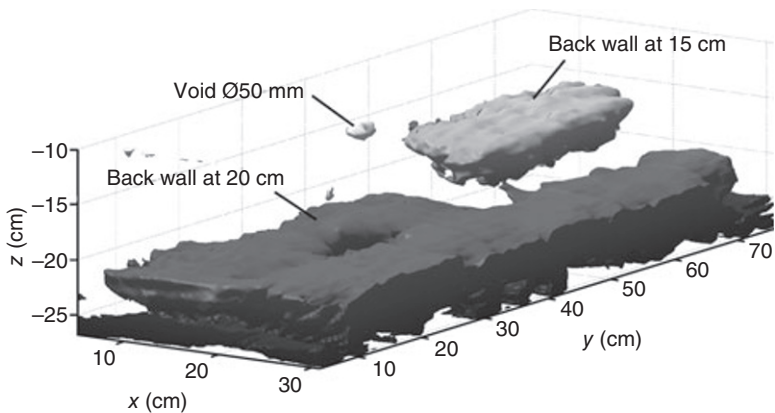
$$Q = \frac{f_r}{f_2 - f_1} \quad [19.7]$$

where f_r is the peak frequency, and f_2 and f_1 are the frequencies at 70.7% of the spectral peak amplitude. It should be highlighted that dispersion is a frequency-dependent phenomenon that also affects the Q-factor measurement. The propagations of stress waves having higher frequency (lower wave length) are more affected by the anomalies in the concrete than low frequency waves.

The Q-factor, as a measure of the attenuation index, has been used to monitor deterioration of concrete owing to the alkali-silica reaction



22.20 Ultrasonic array with 48 transducers in 16 groups.



22.21 Iso-surface view of the three-dimensional SAFT reconstruction of a sample containing a void and a back wall displacement.

to be combined to apertures of different size for optimized range-resolution ratios.

The ultrasonic array and the multiplexer are used with the scanning and measurement system shown in Fig. 22.11. Together they form an integrated scanning multi-channel measurement and imaging system for the application at concrete elements. With the aid of the electronically switched linear array, the acquisition time is reduced by a factor of 10 to about 12 min m^{-2} (for roughly 2600 measurements). During measurements, a two-dimensional SAFT image of each electronic array scan is displayed, and the resulting three-dimensional SAFT image is shown directly after completion of the acquisition process (Schickert and Hillger, 2010).

Because the system is new, its merits and drawbacks are still under investigation. Figure 22.21 shows an example measurement at a sample containing a back wall displacement from 20 to 15 cm and a hard foam ball of

50 mm diameter with a cover of 11 cm. The original image is coloured and can be rotated for better position determination.

22.6.2 Air-coupled imaging

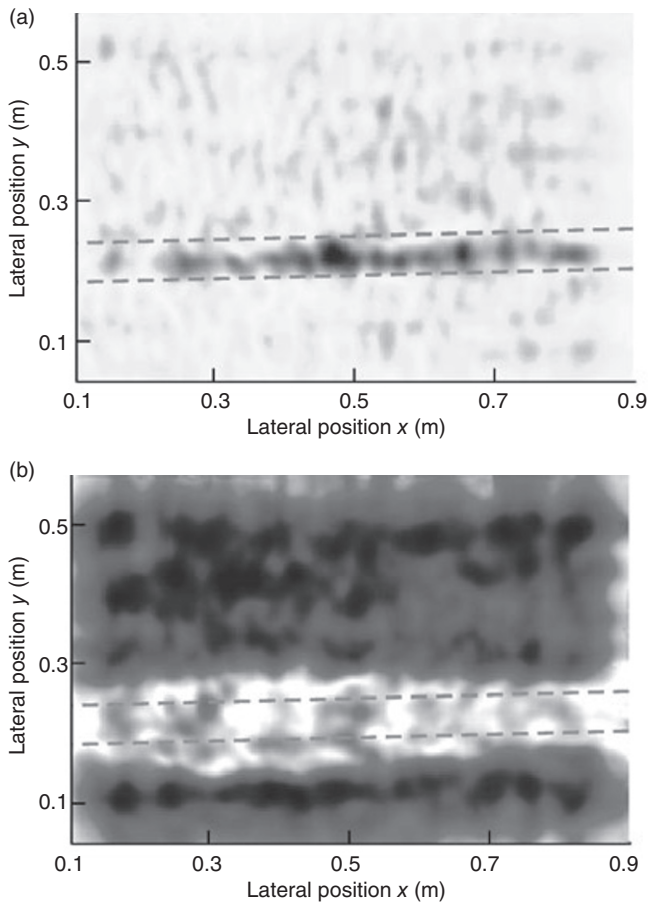
In order to accelerate ultrasonic scanning measurements, air-coupled ultrasonic transducers can be used. The absence of a mechanical contact to the concrete surface allows for faster scanning, thus reducing the measuring time considerably. Whereas air-coupled transducers already exist, two problems remain to be solved for one-sided experiments: firstly, the enormous acoustic impedance mismatch between concrete and air poses a barrier to waves passing this boundary in either direction. On its path into the concrete and then back into the air, most of the emitted energy will be reflected and only a very small fraction of it remains to be measured. Secondly, the same impedance mismatch leads to a high sensitivity of the incidence angle on the propagation angle in the concrete, requiring high accuracy in setting up the incidence angle.

The following example was conducted at a 20 cm thick concrete sample with a slightly inclined side-drilled hole of 58 mm diameter (Krause *et al.*, 2008b). The sample was investigated using a pair of air-coupled transducers with a centre frequency of 85 kHz in the pitch-catch technique. The transducers were mounted for a V-shaped propagation path and acoustically shielded against each other using plates. The concrete surface was scanned on a planar grid, and the measurements were processed by three-dimensional SAFT reconstruction (Gräfe, 2009). Figure 22.22 shows two depth sections obtained from the volume data. In Fig. 22.22a, a direct indication of the side-drilled hole is visible (mean of depths from $z = 9.1$ to 9.9 cm), whereas Fig. 22.22b shows an indirect indication of the hole through back wall shadowing (mean of depths from $z = 18.8$ to 20.1 cm). This gives the perspective to develop an air-coupled ultrasonic method as a fast tool of tendon duct testing.

22.6.3 Tomographic imaging

The imaging methods presented so far use one-sided pulse-echo measurements. This approach faces problems if heavy reinforcement is encountered, leading to strong reflections that can mask objects and shadows regions behind. This is the case in the detection of honeycombing (unconsolidated concrete) in columns.

To overcome this problem, ultrasonic measurements can be conducted in transmission, where the pulse velocity is measured at different paths through the cross-section of the columns. If many such measurements are processed by a computed tomography algorithm, an image of the cross-



22.22 Air-coupled scanning measurement of a specimen containing a side-drilled hole: (a) depth cuts through the three-dimensional SAFT reconstruction in depths of the side-drilled hole, and (b) the back wall.

section of the column can be calculated that also yields an improved resolution.

The feasibility of this method is demonstrated in Fig. 22.23. The sample simulates a column with 38 cm outer diameter containing a cylindrical cavity with a circular cross-section and 7.6 cm diameter. A total of 440 measurements were carried out using a pair of pressure wave transducers at 250 kHz (Schickert, 2005). From the pulse velocities, a tomographic reconstruction was computed employing the Filtered Backprojection algorithm. A comparison with the outline of the sample shows that the cavity is correctly imaged. Additional research is necessary to include reinforcement and to investigate the resolution of this method.

- A1040, 509
- A1220, 508
- A1220 Monolith, 51
- A scan processing, 127
- A scans, 7, 477
- Acoustic Control Systems, 508, 509
- acoustic–elastic waves
 - non-destructive testing of concrete, 125–42
 - future trends, 142
 - sophisticated data processing, 136–42
 - standard data processing, 127–35
 - wave propagation and implications on data processing, 125–7
- acoustic emission analysis, 121
- acoustic emission array processing, 202
- acoustic emission sensors, 191–2
- acoustic emission technique
 - AE waveform
 - and AIC values, 548
 - and two parameters, 546
 - parameters, 544
 - and impact–echo techniques for reinforced concrete structures
 - evaluation, 543–72
- applications, 199–206
 - beamforming localisation, 205
 - bridge deck signals, 206
 - Concerto Bridge, 204
 - field applications, 201–6
 - history of occurrence, 202
 - laboratory applications, 200–1
 - splitting test set-up, 200
- applications for concrete structures, 544–50
 - parameter analysis, 544–5
 - SiGMA analysis with AIC picker, 546–8
- corrosion detection, 551–69
 - accelerated corrosion test results and corrosion loss mode, 555
 - AE activities and half-cell potentials, 553
 - AE parameter analysis results in cyclic wet–dry test, 556
 - ferrous ions distributions on rebar surface, 558
 - rebars visual observation, 557
 - reinforced concrete specimen, 552
- crack models in SiGMA analysis, 547
- cracks classification, 545
- future trends for on-site application, 571–2
- limitations and accuracy, 206–10
 - accuracy picking signal onset times, 209–10
 - activity measured with sensors, 208–9
 - Kaiser effect, 207
 - localisation accuracy, 209
 - standard errors for localisation, 210
- parametric and signal-based analysis, 187–91
 - comparison, 190
 - parameter-based techniques, 188–9

- signal-based techniques, 189–91
 - typical parameters, 188
- reinforced concrete structures
 - evaluation, 185–210
 - burst signals compared with continuous acoustic waves emission, 187
- sensors and instruments, 191–3
 - recording devices, 192–3
 - sensors, 191–2
- shear failure mechanisms in reinforced concrete by AE-SiGMA, 559–61
- AE events analysed by SiGMA, 560
- observed AE generation behaviours, 560
- reinforced concrete beam sketch and AE sensor array, 559
- SiGMA analysis results by auto-picker, 561
- source localisation, 193–7
 - 3D localisation, 194–7
 - 3D visualisation, 196
 - onset time extraction, 196
 - planar location principle, 194
 - seismograms recorded by triaxial sensor, 195
 - zone and planar location methods, 193–4
- source mechanisms and moment tensor analysis, 197–9
- inversion techniques principle, 198
- shear crack radiation pattern, 199
- acoustic impedance
 - pressure wave and reflection factors relative to cement matrix, 494
 - received signals, 495
- acoustic methods, 6
- acoustic wave equation, 126
- acoustic waves
 - non-destructive testing of concrete, 144–59
 - constitutive equations, 147–8
 - fundamental waves, 148–51
 - numerical wave field modelling, 151–4
 - underlying physics, 146–7
- wave field inversion and imaging, 154–8
- FT-SAFT, 156–8
- SAFT, 154–5
- wave field inversion as non-linear problem, 155–6
- ACSYS A1220, 55
- active thermography, 5, 397–9
 - applications, 386–96
 - automatic crack detection in thermograms, 394
 - CFRP on concrete, 390
 - concrete parameters for different test specimens, 387
 - crack signature increase owing to capillary water transport through the crack, 393
 - cracks characterisation, 390–1, 393
 - grey scale coded temporal crack growth, 395
 - large area with voids after heating with IR radiators, 391
 - limits and requirements, 393–6
 - material properties investigation, 386–9
 - maximum temperature contrast and time, 388
 - plaster on concrete, 389
 - temperature transient curves, 388
 - thermograms of an image sequence during cooling down, 392
 - voids location in industrial precasted concrete beams, 389
 - data processing, 380–6
 - combination with other methods, 385–6
 - histogram of thermogram recorded at a concrete test specimen, 383
 - pulse-phase thermography, 381–3
 - reconstruction, 384–5
 - segmentation, 383–4

- superpositioning of
 - photogrammetric equalised digital photo, 386
- surface temperature as function of time for each pixel, 380
- thermal contrast, 380–1
- thermogram with maximum temperature contrast for heating time, 384
- thermograms, amplitude images, phase images and radar depth slices, 382
- direct heating sources applied in civil engineering, 378
- experimental equipment and calibration, 376–80
 - calibration, 379–80
 - characteristic data of various objective lens used for SC1000 IR camera, 379
 - heating sources, 377–8
 - infrared camera, 378–9
 - schematic principle of the method and typical example, 377
- future trends, 396
- guidelines and sources of further information and advice, 397–9
 - national (German) and international standards and guidelines, 398
- physical principle and theoretical background, 372–4
 - concrete, red brick and granite spectra, 374
- heat transfer theoretical background, 372–3
 - temperature measurement physical principle, 373–4
- reinforced concrete structures evaluation, 370–99
- state of the art, 375–6
- advanced infrared technology and application, 397
- ageing phenomena, 52
- AGFA type F8 film, 577
- Akaike information criterion, 543
- alkali metals, 176–8
- alkali-silica reaction, 176–8, 255
- ALOK, 44
- alternating current impedance spectroscopy, 268–9, 270
- American Society for Testing and Materials, 397, 399
- Ampère's law, 145
- amplitude, 476
- amplitude tomography, 337, 342–3, 344, 353
- AMUS-P, 44
 - 32-channel unit, 45
- anisotropy, 266
- aperture, 506
- Archie's law, 245, 252, 255
- Association of German Engineers, 399
- ASTM C403, 425
- ASTM C597, 421
- ASTM C786, 286
- ASTM C876, 554
- ASTM C1202–97, 243
- ASTM C1383–4, 467
- ASTM C 876–87 standard, 303
- ASTM C403M, 425
- ASTM E251, 90
- ASTM E610, 187
- ASTM E 976–99, 204
- AURA *see* automated ultrasonic rail
 - Aura Kaiserslautern, 39, 40
 - AURA Krefeld, 39, 40
 - AURA Paderborn, 39
- AUROMA, 36–8
 - integration into inspection rail, 38
 - train before in-motion inspection, 39
 - transducer side view with probe housing, 38
 - transducer top view, 37
- AUROMA II, 37
- automated non-destructive testing
 - case studies of successful innovations, 36–46
 - in-line pipeline-inspection gauges, 43–6
 - railway safety, 36–43

- construction engineering, 46–54
 - ageing phenomena diagnosis, 52
 - analysis procedure schematic, 53
 - BetoScan, 47–51
 - BetoScan system features, 51–2
 - driving modes, 51
 - life prediction, 53
 - project partners, 48
 - quality management, 54
 - repair planning, 54
 - service life management, 54
- data acquisition, control and evaluation
 - multisensor data acquisition and analysis, 35
- multiple-sensor data acquisition by OSSCAR scanner, 54–9
 - application for bridge testing according to German Standard DIN 1076, 56
 - development and features, 56–7
 - general remarks, 54–6
 - method combination, 58
 - scanner frame, 55
 - scanner software screen shot, 59
- reinforced concrete structures and other applications, 30–60
 - innovation cycles, 31–4
- automated ultrasonic rail, 38–41, 43
- autoregressive models, 119, 120
- B scan, 7, 477–8
- B scan processing, 127
- bandpass filtering, 127–8
- beamforming acoustic emission, 203
- Berlin Central Railway Station, 88
- Berlin Westendbrücke, 87
- BetoScan, 31
 - features, 51–2
 - data evaluation, 52
- non-destructive diagnosis of
 - reinforced concrete structures, 47–51
 - demonstrator system, 49–50
 - NDT methods, 50
 - project partners, 48
 - robotic system, 49
 - sensors, 50–1
- borehole GPR antennae, 341
- Born approximation, 364
- boundary plane, 492
- Bragg wavelength, 70–1
- bridge testing, 56
- Brillouin scattering, 69
- British Institute of Non-Destructive Testing, 397
- building diagnosis
 - NDT state of the art and future trends, 14–29
 - applications examples, 18–27
 - efficient testing methods, 15–17
 - future trends, 28–9
 - tasks, 14–15
- C scan, 7, 477–8
- calcium/oxygen ratio, 170
- Canin +, 50
- capacimetry
 - applications, 281–2
 - radar and capacitive measurements vs volumetric salted water content, 282
 - calibration, 280
 - capacitance probe prototype, 279
 - capacitive calibration, 280
 - capacitive measurements vs volumetric water content, 281
 - data acquisition and interpretation, 280–1
 - equipment, 279
 - physical principle and theory, 276–9
 - equivalent capacitive scheme of sensor and its electrodes, 277
 - relative permittivity, 278
 - reinforced concrete structures
 - evaluation, 276–83
 - limitations and reliability, 282–3
 - capacitance, 276
 - capacitance value, 277
 - capacitive calibration, 280

- capacitive measurements
 - vs volumetric salted water content
 - on homogenous concrete, 282
 - vs volumetric water content of
 - concrete mixtures, 281
- capacitive sensor, 278
- capacitive techniques, 276
- capillary sorption, 411
- carbon-fibre-reinforced plastic, 371
 - on concrete, 390
 - test specimens that have no contact
 - at hatched areas, 392
 - thermogram after infrared radiator
 - heating, 392
- carbonation, 255, 353
- cell factor, 256
- cement, 167–71, 247
- CFRP *see* carbon-fibre-reinforced plastic
- chlorine, 173–5
- Cole–Cole model, 335–6
- compressional wave, 443
- compressive strength, 499, 502
- concrete, 167–71, 247, 250
 - see also* concrete structures; reinforced concrete structures
 - non-destructive testing with
 - electromagnetic and acoustic–elastic waves, 125–42
 - future trends, 142
 - seismic, ultrasonic and
 - electromagnetic wave propagation, 125–7
 - sophisticated data processing, 136–42
 - standard data processing, 127–5
- concrete cover, 19, 53
- concrete resistance, 256
- concrete structures
 - active thermography measurements
 - for voids location inside precast concrete beams, 390
 - impact–echo techniques evaluation, 466–85
 - applications, 481–4
 - basic principles, 467–9
 - data interpretation, 469–74
 - equipment, 480–1
 - future trends, 484–5
 - method development history, 466–7
 - numerical simulations, 474–5
 - signal processing, data presentation and imaging, 475–80
- material properties characterisation, 499, 501–2
 - compressive strength, 502
 - elastic moduli, 501–2
 - other properties, 502
- surface wave techniques evaluation, 441–60
 - basic principles, 443–8
 - equipment, 457–9
 - field application, 459–60
 - signal processing and data presentation, 449–57
- conductance, 244
- conductivity, 244
- constitutive equations, 147–8
- contact resistance, 261
- continuous wavelet transform, 449, 477
- corrosion, 261–2, 264–5, 284
- corrosion evaluation
 - how to interpret measurements, 303–5
 - corrosion potential and electrical resistance, 303
 - corrosion rate, 303–5
- measurement methods, 293–302
 - commercial corrosion rate meter and sensors, 303
 - corrosion potential and polarisation resistance, 293–4
 - corrosion rate on site in concrete structures, 297–302
 - devices for on-site determinations, 302
 - obtaining polarisation resistance, 294–7

- measuring corrosion rate and
 - corrosion potential of reinforced concrete structures, 284–313
 - future trends, 311–12
- monitoring systems, 310–11
 - embedded and surface sensors, 311
 - monitoring results in concrete structure, 312
- practical application, 306–10
 - corrosion potential measurements, 306–7
 - corrosion rate measurement, 307–10
- principles, 285–92
 - corrosion potential, 285–8
 - corrosion rate, 289–92
 - resistivity, 288–9
 - values of resistivity and corrosion risk, 289
- corrosion penetration, 291–2, 304
- corrosion potential
 - how to interpret measurements, 303
 - measurement, 293–4
 - practical application, 306–7
 - principles, 285–8
 - chloride content, 287
 - concrete moisture content, 286–7
 - cover thickness, 287
 - isopotential lines generated by corroding zone, 286
 - macrocell polarisation effects, 287–8
 - oxygen content, 288
 - pH influence, 287
 - ranges of potential and corrosion risk, 287
- corrosion rate
 - how to interpret measurements, 303–5
 - log–log diagram, 305
 - measurement on site in concrete structures, 297–302
 - critical length reached by signal, 297–9
- current attenuation with distance
 - from current electrode, 301
- error factor, 299
- localised corrosion spots on
 - current lines, 300
- modulated or sensorised
 - confinement of polarising current, 300–1
- multiple electrode or potential
 - attenuation method, 301–2
- non-uniform distribution of
 - current, 298
- theoretical confinement of applied
 - current, 300
- transmission line model, 298
- practical application, 306–10
 - accurate measurement, 309
 - auxiliary probe placement, 309
 - before starting the survey, 307
 - equipment and reinforcement connection, 309
 - location of the bars, 308
 - preparation of concrete surface, 308
- principles, 289–92
 - accumulated corrosion penetration depth, 291–2
 - corrosion rate vs time, 292
 - polarisation resistance, 289–90
 - progressive accumulated corrosion depths, 293
 - Randles circuit, 291
 - ranges and relation to velocity, 291
 - ranges of values, 291
- corrosion risk, 287, 289
- corrosion sensor, 86–7
- COST 299, 89
- counter electrode, 294
- covermeter, 5, 17
- crack intensity, 267
- cracks, 267–8
- critical length, 298
- crossbow test, 579
- current density *see* corrosion rate

- current pulse–echo methods, 502
- cyclic wet–dry test, 556
- 3D GPR mapping, 580, 582
 - during processing with specific software module, 584
- 3D localisation, 194–7
- 3D migration, 139
- 3D SAFT, 103
- data acquisition system, 192
- data cleaning, 344
- data fusion, 28, 35, 96, 98–100
 - pixel level, 98–100
 - schematic view, 99
 - terms/definitions, 98
- data processing, 127
 - implication of seismic, ultrasonic and electronic wave propagation, 125–7
 - sophisticated, 136–42
 - deconvolution/shaping, 136–8
 - frequency-wavenumber filter, 140–1
 - migration, 138–40
 - time-depth conversion, 141–2
 - standard, 127–35
 - clutter reduction, background removal, 132–3
 - dewowing and standard bandpass filtering, 127–8
 - profile energy balancing, 134–5
 - time-base shift correction, 128–9
 - time varying gain, 131–2
 - time zero, 129–31
- decay constants, 423
- deformation, 147
- deformation rate equation, 146
- deformation sensors, 88–9
- Dempster–Shafer theory, 96
- detection spatial resolution, 69
- Deutsche Gesellschaft für
 - Zerstörungsfreie Prüfung, 14, 318
- dewowing, 127–8
- DGZfP *see* Deutsche Gesellschaft für
 - Zerstörungsfreie Prüfung
- dielectric displacement, 145
- diffraction tomography, 364–5
- dilatation, 147
- dilatation rate equation, 147
- DIN 54162, 397
- DIN 54190-1, 397
- DIN 54190-2, 397
- DIN 54190-3, 397
- DIN EN 473, 8
- DIN EN 13187, 397
- DIN EN 1330-9, 187
- DIN/ISO 17025, 8
- direct reflections, 374
- 8-channel DiSP system, 559
- displacement current, 145
- distributed computing strategy, 118
- dry point contact, 508, 513
- echelle spectrometer, 167
- EFIT *see* elastodynamic finite
 - integration technique
- EFPI *see* extrinsic fibre Fabry–Perot
 - interferometer sensors
- eight-span post-tensioned viaduct
 - applied methodology, 580–2
 - 3D-GPR mapping during processing with specific software module, 584
- evaluation of structure and reinforcement proposal, 579
- gammagraphic film showing lack of grouting, 577
- gammagraphic imaging, 577
- ground-penetrating radar
 - assessment, 574–84
- post-tensioned ducts and coring
 - localisation, 579–80
- core revealing a cut rebar, 582
- deviators after unformworking and nailing and before post-tensioning, 583
- drawing maps of reinforcement for complex cases, 581
- post-tensioned ducts localisation, 575–6

- two spans of the structure diagram, 575
- vertical GPR profile, 576
- windowing, 577–9
 - crossbow device in position on wire, 578
 - window revealing the state of grout and wires, 578
- elastic moduli, 499, 501–2
- elastic waves, 146
 - non-destructive testing of concrete, 144–59
 - fundamental waves, 148–51
 - numerical wave field modelling, 151–4
 - underlying physics, 146
 - wave field inversion, 158–9
- elastodynamic finite integration technique, 151, 154, 499
- electric field, 335
- electric flux density, 145
- electrical anisotropy
 - characterisation, 266–8
 - electrical resistivity tomography on concrete, 269
 - fibre orientation in steel-fibre reinforced concrete, 266–7
 - logarithm of variations, 268
 - study of cracks in concrete, 267–8
 - synthetic polar diagram, 267
- electrical resistance, 244, 289, 303
- electrical resistivity
 - application, 255–64
 - calibration and reliability, 263
 - equipment and measurement, 255–63
 - corrosion current-resistivity, 262
 - four-probe devices optimum locations, 261
 - four-probe resistivity measurement technique, 259–63
 - four-probes square device, 260
 - measurement cell for laboratory resistivity assessment, 256–8
 - resistivity cell device, 256
 - resistivity range related to risk of corrosion, 262
 - resistivity vs apparent resistivity, 260
 - sample surface and length, 257
 - single-probe device, 258
 - single-probe resistivity measurement technique, 258–9
 - two-probe resistance measurement technique, 259
 - impedance spectroscopy, 268–70
 - Nyquist diagram, 269
 - influencing factors, 246–55
 - aggregate, 248
 - chloride concentration, 252
 - concrete resistivity evolution, 250
 - edge on resistivity measurement, 254
 - external factors, 252–5
 - fluids, 251–2
 - intrinsic factors, 246–50
 - range of variation, 249
 - saturation rate, 251
 - variations with temperature, 253
 - water/cement ratio, 247
 - other developments, 264–8
 - electrical anisotropy characterisation, 266–8
 - electrical resistivity tomography, 268
 - monitoring for durability, 264–6
 - MRE probe, 266
 - physical principles and theory, 244–55
 - Archie's law parameters, 245
 - electrical conduction in concrete, 244–6
 - reinforced concrete structures evaluation, 243–70
 - concrete resistivity values, 244
- electrical resistivity tomography, 268, 269
- electrochemical impedance spectroscopy, 268, 297
- electrochemical noise, 296
- electromagnetic methods, 6–7

- electromagnetic waves
 - non-destructive testing of concrete, 125–42, 144–59
 - constitutive equations, 147–8
 - fundamental waves, 148–51
 - future trends, 142
 - numerical wave field modelling, 151–4
 - sophisticated data processing, 136–42
 - standard data processing, 127–35
 - underlying physics, 145–7
 - wave field inversion, 158–9
 - wave propagation and implications
 - on data processing, 125–7
- electromagnetically generated and received ultrasound, 37
- electronic scanning, 521–3
- emissivity, 374
- EN 473, 397
- EN 13791:2007, 502, 526
- extrinsic fibre Fabry-Perot
 - interferometer sensors, 72, 80
 - measured restraining effect of steel bar, 81
 - silicon mould with EFPI before casting, 78
- Faraday's law, 291
- Faraday's law of induction, 145
- fast Fourier transform, 475, 550
- FBG *see* fibre Bragg grating sensors
- ferritic steels, 217
- fibre Bragg grating sensors, 70–2, 77
 - schematic, 70
- fibre Fabry-Perot interferometer
 - sensors, 70, 72–3, 78, 80, 81, 82–3
 - microsection, 79
 - sensors fixed on reinforcement cage, 82
- fibre-optic pH sensor, 86
 - head design, 85
- fibre-optic point sensors, 73, 83–7
 - prefabricated anchors with fixed pH sensors, 86
 - water-filled topcoat, 85
- fibre-optic relative humidity sensor, 77
- fibre-optic sensors, 67–8, 91
 - long-gauge-length, 68–70
 - short-gauge-length, 70
 - types, 68
 - vs laser vibrometer results, 80
- finite difference time domain, 137, 139, 142, 365
- finite integration technique, 146, 151
- fk-filter *see* frequency-wavenumber filter
- focal plane array, 373, 375
- four-probe resistivity measurement technique, 259–63
- Fourier Slice Theorem, 339, 349
- Fourier transform, 423
- Fourier transform-SAFT, 99, 103, 156–8, 506
- FPI *see* fibre Fabry-Perot interferometer sensors
- Fraunhofer-Gesellschaft, 30
- Fraunhofer IZFP, 408
- free induction decay, 406
- French Standard NF A09–202, 577
- frequency downshift method, 363–4
- frequency-wavenumber filter, 133, 140–1
- Fresnel rays, 339
- Fresnel region, 322
- Fresnel theory, 347
- Fresnel zone, 338
- full matrix reconstruction, 509
- fundamental waves, 148–51
 - homogeneous materials, 148
 - inhomogeneous materials, 151
 - plane waves, 148–9
 - spherical waves, 150–1
- galvanostatic pulses, 295–6
- Gecor 08, 302
- Geiger method, 194
- GEOPSY, 446

- German directive RI-ZFP-TU, 526
- German Rail, 37
- German Standard DIN 1076, 56
- giant magnetoresistance sensor, 234
- global capacitance, 277
- GMA-2500, 577
- GPR *see* ground penetrating radar
- GPR ProEX system, 50
- Green's function approach, 385
- ground penetrating radar, 127
 - case study of concrete retaining walls
 - inspection, 533–42
 - data acquisition, 534–6
 - data processing, 536–7
 - problem description, 533
 - results, 537–41
 - current and future trends, 327–31
 - bridge girder, 328
 - 3D radar surveys, 328
 - inversion, 329–31
 - inversion and modelling, 330
 - inversion result from reinforced concrete, 330
 - material properties, 331
 - quotient of amplitudes and chloride/moisture content of specimens, 331
 - radargram from bridge girder, 329
 - time slice from bridge girder, 329
 - data display formats, 322–3
 - data cube acquisition and time slice display, 323
 - measurement in single position, 322
 - radargram acquisition, 323
 - data processing and interpretation, 323–5
 - processed dataset, 324
 - processed dataset with interpretation, 325
 - raw dataset, 324
 - eight-span post-tensioned viaduct
 - assessment, 574–84
 - applied methodology, 580–2
 - gamma-graphic imaging, 577
 - localisation of post-tensioned ducts and coring, 579–80
 - post-tensioned ducts localisation, 575–6
 - structure and reinforcement proposal evaluation, 579
 - windowing, 577–9
 - equipment, 325–6
 - accessories, 326
 - antennae, 325
 - central unit, 326
 - mobile GPR acquisition system, 327
 - limitations and reliability, 326–7
 - main advantages, 317
 - physical principles and theory, 318–22
 - electromagnetic wave with area, 320
 - sources and sinks in longitudinal wave, 319
 - principles, 318
 - reinforced concrete structures
 - evaluation, 317–32
 - symbols and constants, 331–2
- GSSI-SIR20 radar unit, 536
- gyromagnetic ratio, 405
- Hertzian dipole, 345
- Hooke's law, 147
- hydrogen, 178–80, 405
- ICE1, 37
- ICE III, 39
- Imote2, 120
- impact-echo techniques, 17, 23, 421
 - and acoustic emission techniques for reinforced concrete structures
 - evaluation, 543–72
 - applications, 481–4
 - applications for concrete structures, 544–50
 - SIBIE analysis, 548–50
 - basic principles, 467–9
 - impact-echo method test principle, 468

- vibrational resonances, 469
- wave propagation, 467–8
- concrete structures evaluation, 466–85
- data interpretation, 469–74
 - compression wave velocity time domain determination, 473–4
 - conventional interpretation of spectral response in plate-like structures, 469–70
 - guided-wave interpretation of spectral response in plate-like structures, 470–2
 - impact-echo shape factor as function of Poisson's ratio, 472
 - interpretation of spectral response in other structures, 472–3
 - normalised phase velocity dispersion curves, 471
- double-leaf wall thickness
 - determination, 23–5
 - view of remaining layer after demolition, 25
 - wall cross section with distortion after concreting, 23
 - wall thickness as a height profile, 24
 - wall thickness measurement, 24
- equipment, 480–1
 - automation equipment, 481
 - conventional testing systems, 481
- future trends, 484–5
- future trends for on-site application, 571–2
- imperfectly grouted sheath examples
 - 1/4 and 3/4 section grouted, 567
 - 3/4 section and full grouted, 568
- internal defect detection, 481–4
 - delamination, 481–3
 - impact-echo method for small void detection, 484
 - internal voids including post-tensioning duct voids, 483
 - other applications, 483–4
- method development history, 466–7
- numerical simulations, 474–5
- reference manuals, guidelines and standards, 467
- setting time measurement, 428
- signal processing, data presentation and imaging, 475–80
 - B scan above an empty tendon duct, 478
 - basic Fourier transform, 475–6
 - C scan measured with laser interferometer, 479
 - measurement carried out on 0.25 m thick slab, 475
 - other 2-D and 3-D image construction, 477–80
 - S1 Lamb mode extraction in noisy signal with wavelet transform, 477
 - time-frequency analysis, 476–7
- slab/wall thickness determination, 481
- strength development measurement, 430
- surface-crack depth evaluation by SIBIE, 567–9
 - conventional SIBIE images, 570
 - observed bending cracks, 569
 - scanning SIBIE images, 570
- surface response finite element modelling, 474
- ungROUTED tendon-duct identification by SIBIE, 561–7
 - frequency spectra detected, 564
 - impact test in concrete block with polyethylene and steel sheaths, 562
 - metal sheath results, 565
 - polyethylene sheath results, 566
 - sketch of imperfectly grouted sheath, 563
- impulse-echo, 157
- impulse thermography, 376
- indirect reflections, 374
- Iner City train Experimental, 37
- infrared thermography, 370
- innovation cycles, 31–4
- inside-out NMR devices, 404

- inverse media, 447
- inversion, 329–31
- ionic ingress, 265–6
- ISO/IEC 17025/2000, 89
- isotropy, 266
- Japan Construction Materials Standards, 545
- joint inversion, 35
- JSM-5600, 553
- Kaiser effect, 206–7
- Kirchhoff migration, 536
- Kirchhoff's law, 374
- Lamb wave analysis, 455
- Lamb wave dispersion theory, 470
- Lamb wave ZGV frequency, 474
- Lamb waves, 447–8, 470
- Lamé constants, 148, 468
- Large Concrete Slab, 516
- Larmor frequency, 405
- laser-induced breakdown spectroscopy, 7, 167
 - cement, mortar and concrete
 - characterisation, 167–71
 - ablation crater visualisation, 169
 - calcium and sodium distribution, 172
 - hydrogen distribution in a concrete sample, 174
 - melt mineralogical structures on crater walls, 170
 - mineral aggregate and cement matrix distribution, 171
 - multi-component system concrete, 168
 - normalised intensity levels differentiation, 173
 - fundamentals and measurement, 164–7
 - plasma ignition and concrete sample with LIBS measurement, 166
 - typical result, 167
 - typical set-up, 165
 - limitations and reliability, 183–4
 - calibration function characteristics and sections, 183
 - process limits in hardened cement paste, 184
 - mobile set-up: on-site applications, 180–3
 - horizontal and vertical measuring mode, 181
 - on-site use, 182
 - schematic diagram, 181
 - reinforced concrete structures
 - evaluation, 163–84
 - specific elements detection, 173–80
 - alkali metals, 176–8
 - change in spectrum with wet building material surfaces, 179
 - chlorine, 173–5
 - chlorine distribution imaging, 176
 - chlorine gradient, 175
 - concrete prisms treated with Fe_2SO_4 , 177
 - hydrogen, 178–80
 - intensity distribution, 178
 - interaction between potassium, sodium and lithium, 179
 - sulphur, 175–6
- laser interferometers, 458
- LIBS *see* laser-induced breakdown spectroscopy
- life prediction, 53
- Light Wave 3D software, 546–7
- limit of detection, 183
- limit of quantification, 183
- linear variable differential transformers, 67
- lithium, 178
- LOCAN 320, 552
- long-gauge-length sensors, 68–70, 74–6
- longitudinal waves, 492
- magnetic field method, 17
 - detection of cracks in pre-stressed steel rods, 25–7
 - imaging of cracks of two tendons in highway slab, 27

- investigation of single transverse tendons, 26
- magnetic field scanner application, 27
- post-tensioned concrete, 26–7
- pre-stressed concrete in the direct bond, 25–6
- pre-stressed concrete roof trusses, 25
- magnetic flux density, 145
- magnetic flux leakage
 - applications, 235–9
 - equipment, 237
 - MFL signal, 237
 - pre-stressed ceiling beams, 236
 - residual field signal of damaged and intact beam, 236
 - residual field signals of sensors, 238
- non-destructive evaluation of pre-stressed concrete structures, 215–41
 - recommendations for application, 240–1
- recent developments, 239–40
 - joint bridge bearings measurement result, 240
 - system on-site, 240
- reinforced concrete structures
 - inspection, 215–33
 - amplitude of rupture signals, 224
 - analysis for measured signals
 - evaluation, 225–9
 - axial component, 220
 - damaged tendon residual field signal, 233
 - detection of pre-stressed tendons ruptures, 215–16
 - empirical parameter for rupture amplitudes estimation, 224
 - laboratory tests arrangement, 230
 - limit of detection, 229–33
 - long term test, 234
 - magnetic leakage signal, 221, 222
 - magnetisation measurement
 - scheme, 221
 - modelling, 218
 - on-site test, 232
 - physical basis, 216–25
 - pre-stressing steel magnetisation
 - curve, 218
 - principle, 217
 - residual field measurements, 223
 - rupture signals calibration, 223
 - signal analysis, 228
 - synthetic rupture and filtered
 - residual field signal, 228
 - required equipment, 233–5
 - exciting magnetic field
 - components, 235
 - probe, 234
- magnetic induction *see* magnetic flux density
- magnetic resonance imaging, 403
- magnetisation, 217
- magnitude, 476
- MALÅ ProEx, 55–6
- MASW *see* multi-channel analysis of surface waves
- Matrix techniques, 447
- Maxwell equations, 126, 145, 318, 319
- MDT *see* minor destructive testing
- measuring spatial resolution, 69
- mechanical wave *see* stress wave
- MEMS *see* microelectromechanical systems sensors
- MFL *see* magnetic flux leakage
- microbolometers, 375
- microelectromechanical systems
 - sensors, 114, 121
- Middleware, 117, 118
- migration, 138–40
- MIN-02, 562
- minimum norm stabiliser, 348
- minimum support stabiliser, 348
- minor destructive testing, 95, 96–8
- modulated confinement method, 300–1
- moisture, 265–6
- moment tensor, 197–9
- moment tensor inversion methods, 197, 198
- mortar, 167–71

- notes, 112, 113, 114
- MSP430, 120
- multi-channel analysis of surface
 - waves, 442, 453–5, 459–60, 474
- multi-channel simulation with one
 - receiver procedure, 458
- multi-resonance transducers, 192
- multihop network, 112, 113
- multiple electrode method, 301–2
- multisensor systems, 34–6
- N*-colour tomography, 348
- NAS 942, 90
- NDT Systems and Services, 43–4
- Newton-Cauchy equation, 146
- NMR-INSPECT, 404, 408, 409
- NMR logging tools, 404
- NMR-MOLE, 404
- NMR-MOUSE, 404
- noise-equivalent temperature
 - difference, 375
- non-contacting corrosion method, 313
- non-destructive evaluation
 - magnetic flux leakage for pre-stressed concrete structures, 215–41
 - application, 235–9
 - description of equipment required, 233–5
 - recent developments for reinforced concrete inspection, 239–40
 - recommendations for application, 240–1
 - reinforced concrete structures inspection, 215–33
- non-destructive testing, 418
 - acoustic waves field inversion and imaging, 154–8
 - heuristic inversion, 154–5
 - processing alternatives to SAFT, 156–8
 - wave field inversion as a non-linear problem, 155–6
 - application examples, 18–27
 - air-filled ducts and layer borders, 22
 - concrete cover measured values, 21
 - displacement bodies, 22
 - exposed pile head, 19
 - exposed pile wall area, 20
 - magnetic field method, 25–7
 - other testing problems with radar, 21–2
 - radargrams of measuring lines, 20
 - reinforcement location and concrete cover measurement with radar, 18–21
 - thickness of wall as height profile checked with impact-echo, 24
 - tunnel cross-section schematic, 18
 - vertical measuring lines per position, 19
- building diagnosis, 14–29
 - automated data recording, 28
 - efficient testing methods, 15–17
 - future trends, 28–9
 - task, 14–15
 - test tasks, 16
- combining results for reinforced concrete, 95–106
 - combination of methods for concrete structures investigation, 97
 - future trends, 105–6
 - NDT and MDT methods, 96–8
- data fusion, 98–100
 - pixel-level, 98–100
 - processing schematic, 99
 - terms/definition, 98
- electromagnetic, acoustic and elastic waves modelling and imaging, 144–59, 145–51
 - constitutive equations, 147–8
 - fundamental waves, 148–51
 - shear-vertical and shear-horizontal plane waves, 150
 - tendon duct below reinforcement, 145
 - underlying physics, 145–7

- electromagnetic and acoustic–elastic waves, 125–42
 - future trends, 142
 - seismic, ultrasonic and electromagnetic wave propagation, 125–7
- electromagnetic and elastic waves
 - field inversion, 158–9
 - elastic wave field modelling and inversion, 160
 - electromagnetic vector wave data, 159
- guidelines and recommendations, 11–12
- impact-echo
 - double-leaf wall cross section after concreting, 23
 - double-leaf wall thickness, 23–5
 - thickness of wall as height profile, 24
 - view of remaining wall layer after demolition of second layer, 25
 - wall thickness measurement, 24
- international, European and National Standards, 9–10
- methods for concrete structures, 419
- numerical wave field modelling, 151–4
 - computer model of a concrete specimen, 153
 - 2D acoustic wave scattering, 152
 - 2D elastic wave propagation, 154
 - 2D elastic wave scattering, 153
- overview, 6–7
 - acoustic methods, 6
 - electromagnetic methods, 6–7
 - optical methods, 7
- qualification/validation of methods
 - methods validation, 8
 - qualification of personnel, 8
- radar and ultrasonic data fusion
 - along a beam of a box girder bridge, 101–2
- C scans, 103
- cross beam inside a box girder bridge, 103–5
- radar data recording, 102
- radar results of vertical slice at cantilever, 104
- results with and without velocity correction, 104
- radar data fusion, 100–1
 - radar trace, 100
- recommended 3D FT-SAFT B scan along concrete floor plate, 101
- reinforced concrete structures, 3–12
 - strategies for application, 4–6
- sophisticated data processing, 136–42
 - 2D profile and fk-filter application, 141
 - deconvolution/shaping, 136–8
 - diffractors and steep reflectors, 139
 - frequency-wavenumber filter, 140–1
 - migration, 138–40
 - radargram with strong ghosts, 138
 - radargram with strong multiples, 137
 - raw and migrated data, 140
 - time-depth conversion, 141–2
 - wavelet shaping filter application, 136
- standard data processing, 127–35
 - clutter reduction, background removal, 132–3
 - continuous gain function, 131
 - 2D line before correction, 129
 - 2D raw profiles from 3D grid survey, 134
 - dewowing and standard bandpass filtering, 127–8
 - dewowing process, 128
 - errors for time zero correction, 130
 - incoherent clutter reduction methods, 133
 - noise ringing, 132
 - profile energy balancing, 134–5
 - time-base shift correction, 128–9
 - time slice for 3D grid survey, 135

- time varying gain, 131–2
- time zero, 129–31
- transmitter receiver configuration, 130
- Non-destructive testing in civil engineering*, 397, 526
- normal moveout correction, 126
- nuclear magnetic resonance imaging
 - application possibilities, 409–13
 - early-age concrete hardening, 412–13
 - liquid transport coefficients
 - determination, 410–12
 - moisture depth profiles
 - determination, 409–10
- future trends, 414–15
- hardware, 407–9
 - conventional equipment with enclosing magnet and coil, 408
 - OSA–NMR equipment with open magnet and coil, 408
- physical background, 404–7
- physical principle schematic
 - description, 405
- two NMR signals schematic
 - presentation, 406
- reinforced concrete structures
 - evaluation, 403–15
- reliability and limitations, 413–14
- numerical wave field modelling, 151–4
- Ohm's law, 288
- On-Site SCANneRs, 31
 - multiple-sensor data acquisition, 54–9
 - application for bridge testing, 56
 - development and features, 56–7
 - method combination, 58
 - scanner frame, 55
 - scanner software, 59
- one-side access nuclear magnetic resonance, 404
 - calibration curve, 409
 - concrete hardening monitoring by relaxation curve measurement, 413
 - equipment with open magnet and coil, 408
 - liquid transport coefficient, 412
 - moisture profile measurement on lightweight concrete pillar, 410
- one-side access technique, 404, 414
- Ontario Hydro Canada, 421
- optical methods, 7
- optical time domain reflectometry, 74–5, 76
- OSA–NMR *see* one-side access nuclear magnetic resonance
- OSSCAR *see* On-Site SCANneRs
- p-omega transform, 454
- P-wave, 419–20
 - see also* compressional wave
- parameter-based acoustic emission techniques, 188–9
- PCUS 40, 39
- permeation, 411
- phase match filtering, 449
- phase velocity, 497
- piezo-resistive cement-based strain sensors, 74
- piezoelectric sensors, 191, 192
- pile integrity tests, 82–3
- pipeline-inspection gauges, 43–6
 - 10" -PIG backplane, 46
 - 56" PIG launching into a pipe, 45
 - crack detection PIG with 20" sensor carrier, 46
- pit factor α , 304
- pixel-level data fusion, 98–100
- planar location method, 193–4
- plane pressure waves, 149
- plane waves, 148–9
- Poisson's Ratio, 443, 470, 472, 485
- polarisation phenomena, 335
- polarisation plane, 492
- polarisation resistance, 289–90
 - measurement, 293–4
 - methods of obtaining polarisation resistance, 294–7
 - electrochemical impedance spectroscopy, 297

- electrochemical noise, 296
- galvanostatic and potentiostatic pulses, 295–6
- linear plot of polarisation curve, 295
- potentiodynamic techniques, 294–5
- response of potential to a galvanostatic pulse, 296
- portable seismic pavement analyser, 452
- potential attenuation method, 301–2
- potentiodynamic techniques, 294–5
- potentiometric titration method, 553
- potentiostatic pulses, 295–6
- pre-stressed concrete structures, 215–41
- pressure waves, 492
- profile energy balancing, 134–5
- Profometer, 55
- Profometer 5+, 50
- pulse-phase thermography, 376, 381–3
- pulse velocity, 497
- PYTHAGORE, 579
- quantitative acoustic emission technique, 188
- quantitative infrared thermography, 397
- R-wave, 419–20
- radar, 6–7, 17, 318
 - other testing problems, 21–2
 - reinforcement location and concrete cover measurement, 18–21
- radar data, 101–5
- radar data fusion, 100–1
- radar thermography, 5
- radar tomography
 - acquisition procedures, 341–3
 - amplitude calibration set-up, 343
 - time calibration, 342
 - artefacts, 349–50
 - crosshole geometry, 350
 - double crosshole geometry, 351
 - full geometry, 352
- bridge column test, 360–1
 - attenuation map from amplitude tomography on selected column, 362
 - bridge built in 1994 on eight concrete columns, 360
 - column selected for tomographic test, 361
 - full tomographic dataset recorded on selected column, 361
 - velocity map from traveltime tomography on selected column, 362
- data inversion, 346–9
 - iterative approach to tomographic inversion, 347
- data pre-processing, 344–5
 - GPR antenna real radiation patterns, 346
 - pre-processing sequence for tomographic inversion preparation, 344
 - traveltime and amplitude picking, 345
- equipment, 339–41
 - antenna frequency selection according to TX–RX distance range, 340
 - shielded antenna operating at very high frequencies, 340
- examples, 354–61
- Fresnel rays, 339
- fundamental equations, 337–8
- hints on advanced algorithms, 363–5
 - diffraction tomography, 364–5
 - frequency downshift method, 363–4
- laboratory test, 354–8
 - attenuation map from amplitude tomography on concrete sample, 358, 359
 - concrete blocks reinforcement structure, 357
 - full tomographic dataset recorded, 356
 - laboratory specimen, 354

- tomographic acquisitions, 355
 - velocity map from traveltime
 - tomography on concrete sample, 357, 359
 - physical principles, 335–7
 - reinforced concrete structures
 - evaluation, 334–65
 - resolution, 338–9
 - results interpretation, 350–4
- radargram, 328, 334
- rail wheel inspection, 42–3
 - Ilseburg, Germany, 42
 - Nishny Tagil, Russia, 43
- railway safety, 36–43
- Raman scattering, 69
- Randles circuit, 291, 294
- Randles method, 290
- rate of disturbance, 254
- ray-superposition theory, 447
- Rayleigh scattering, 69
- Rayleigh surface wave, 443
- Rayleigh wave, 36, 492
- Rayleigh wave velocity, 473
- reference electrode (RE), 294
- reference electrodes, 310
- reflection mode, 126
- reinforced concrete structures
 - acoustic emission and impact–echo
 - techniques evaluation, 543–72
 - applications for concrete
 - structures, 544–50
 - case studies, 551–69
 - future trends for on-site
 - application, 571–2
- acoustic emission evaluation,
 - 185–210
 - applications, 199–206
 - limitations and accuracy, 206–10
 - parametric and signal-based
 - analysis, 187–91
 - sensors and instruments, 191–3
 - source localisation, 193–7
 - source mechanisms and moment
 - tensor analysis, 197–9
- active thermography evaluation,
 - 370–99
 - applications, 386–96
 - data processing, 380–6
 - experimental equipment and
 - calibration, 376–80
 - future trends, 396
 - physical principle and theoretical
 - background, 372–4
 - state of the art, 375–6
- automated non-destructive
 - evaluation, 30–60
 - case studies of successful
 - innovations, 36–46
 - construction engineering, 46–54
 - data acquisition, control and
 - evaluation, 34–6
 - innovation cycles, 31–4
 - multiple-sensor data acquisition,
 - 54–9
- capacimetry, 276–83
 - applications, 281–2
 - calibration, 280
 - data acquisition and
 - interpretation, 280–1
 - equipment, 279
 - limitations and reliability, 282–3
 - physical principle and theory,
 - 276–9
- combining results of non-destructive
 - evaluation techniques, 95–106
 - data fusion, 98–100
 - future trends, 105–6
 - NDT and MDT, 96–8
 - radar data and ultrasonic data,
 - 101–5
 - radar data fusion, 100–1
- corrosion rate and corrosion
 - potential measurement, 284–313
 - future trends, 310–12
 - how to interpret measurements,
 - 303–5
 - methods, 293–302
 - monitoring systems, 310–11
 - practical application, 306–10
 - principles, 285–92
- deficiencies found in concrete
 - infrastructure, 431

- electrical resistivity, 243–70
 - application, 255–64
 - impedance spectroscopy, 268–70
 - other developments, 264–8
 - physical principles and theory, 244–55
- ground penetrating radar, 317–32
 - current and future trends, 327–31
 - data display formats, 322–3
 - data processing and interpretation, 323–5
 - equipment, 325–6
 - limitations and reliability, 326–7
 - physical principles and theory, 318–22
 - symbols and constants, 331–2
- honeycombing and voids close to reinforced concrete beam surface, 390
- laser-induced breakdown spectroscopy, 163–84
 - cement, mortar and concrete characterisation, 167–71
 - fundamentals and measurement, 164–7
 - limitations and reliability, 183–4
 - mobile set-up: on-site applications, 180–3
 - specific elements detection, 173–80
- life cycle of civil infrastructure system, 418
- NDT methods for concrete structures, 419
- non-destructive test program
 - planning, 3–12
 - overview, 6–7
 - qualification/validation of methods, 8
 - strategies for application of NDT methods, 4–6
- nuclear magnetic resonance imaging, 403–15
 - application possibilities, 409–13
 - future trends, 414–15
 - hardware, 407–9
 - physical background, 404–7
 - reliability and limitations, 413–14
- radar tomography evaluation, 334–65
 - acquisition procedures, 341–3
 - artefacts, 349–50
 - data inversion, 346–9
 - data pre-processing, 344–5
 - equipment, 339–41
 - examples, 354–61
 - fundamental equations, 337–8
 - hints on advanced algorithms, 363–5
 - physical principles, 335–7
 - resolution, 338–9
 - results interpretation, 350–4
- stress wave propagation evaluation, 417–36
 - applications, 424–34
 - future trends, 435–6
 - methods, 419–24
- structural health monitoring system, 63–91
 - effective and innovative technologies, 74–87
 - future trends, 90–1
 - innovative monitoring methods, 67–73
 - monitoring capabilities, 64–7
 - reliability and standardisation, 87–90
- ultrasonic techniques evaluation, 490–526
 - applications and requirements, 499–500
 - concrete elements imaging, 503–20
 - future trends, 521–4
 - transmission methods, 500–3
 - ultrasonic wave propagation in concrete, 491–9
- wireless monitoring, 111–22
 - application, 119–22
 - basic principles, 112–14
 - future trends, 122
 - monitoring task, 114–16
 - system design and assembly, 116–19
 - systems in operation, 119

- relative humidity, 251
- relative permittivity, 278
- relaxation time, 407
- residual field, 225
- resistivity, 243, 288–9
 - values and corrosion risk, 289
- resistivity electrodes, 310
- resolution, 350–1
- resonant transducers, 193
- retaining walls, 534
 - co-ordinate system, 536
 - ground penetrating radar inspection, 533–42
 - data acquisition, 534–6
 - data processing, 536–7
 - problem description, 533
 - processed dataset, 537
 - raw dataset, 537
 - results, 537–41
 - guiding system with antenna box, 535
 - selection of *Y* slice in data cube, 538
 - time slice, $t = 1.6$ ns, level 2, 1500 MHz antenna, 540
 - time slice, $t = 5.16$ ns, level 2, 1500 MHz antenna, 540
 - top of apparatus, 535
 - Y* slice
 - 400 MHz antenna, 540
 - 900 MHz antenna, 539
 - 1500 MHz antenna, 539
 - recorded 3.9 m off the joint, 900 MHz antenna, 542
 - recorded on joint, 900 MHz antenna, 541
 - with prominent reflector, level 1, 1500 MHz antenna, 541
- Réunion Internationale des Laboratoires et Experts des Matériaux, 399
- Reynolds numbers, 448
- RILEM *see* Réunion Internationale des Laboratoires et Experts des Matériaux
- RILEM committee TC 207, 526
- RILEM TC154EMC, 261, 263
- robots, 31, 47–51
- Runge–Kutta direct integration, 447
- rupture amplitude, 227
- rupture signals, 223, 226, 227
- Rytov approximation, 364
- S-wave, 419–20
 - see also* shear waves
- SAFT *see* synthetic aperture focusing technique
- SASW *see* spectral analysis of surface waves method
- saturation, 256–7
- saturation rate, 251
- scalar Green function, 150
- scanning SIBIE method, 550
- Scholte wave, 448
- seismic refraction, 450
- seismic wave, 125–7
- SensCore system, 87
- sensorised confinement method, 300–1
- sensors, 64, 310–11
- shear-horizontal plane waves, 149, 150
- shear modulus, 443, 468
- shear-vertical plane waves, 149, 150
- shear waves, 443, 492
- SHM *see* structural health monitoring
- short-gauge-length sensors, 70, 76–83
- SIBIE *see* stack imaging of spectral amplitudes
 - based on impact–echo
- SiGMA *see* simplified green’s functions
 - for moment tensor analysis
- signal-based acoustic emission techniques, 189–91
- signal to noise ratio, 453
- signal velocity, 321
- simplified green’s functions for moment tensor analysis, 543
 - analysis with AIC picker, 546–8
 - crack models in SiGMA analysis, 547
 - shear failure mechanisms in reinforced concrete by AE-SiGMA, 559–61

- AE events analysed by SiGMA, 560
- observed AE generation behaviours, 560
- reinforced concrete beam sketch and AE sensor array, 559
- SiGMA analysis results by auto-picker, 561
- single-probe resistivity measurement technique, 258–9
- SIR GSSI 20, 18
- slack-stack transform, 454
- smart sensors, 113
- SMARTape, 76
- Sobel filter, 391
- Sobel operator, 384
- SOFO *see* surveillance d'ouvrages par fibres optiques
- Sommerfeld integral, 345
- sound velocity, 497
- spatial resolution, 69
- spectral analysis of surface waves
 - method, 442, 450–3, 459–60
- spherical waves, 150–1
- spiking filter, 137
- spin echo signal, 406
- splitting test, 200
- SQUID sensors, 234
- SRI-CM-II, 552
- stack imaging of spectral amplitudes
 - based on impact–echo, 544, 548–50
 - conventional SIBIE and scanning procedure for zigzag crack, 551
 - cross-section divided into meshes and travel distance, 550
 - projectile and impacting system, 549
 - surface-crack depth evaluation, 567–9
 - conventional SIBIE images, 570
 - observed bending cracks, 569
 - scanning SIBIE images, 570
 - ungROUTed tendon-duct identification, 561–7
 - frequency spectra detected, 564
 - impact test in concrete block with polyethylene and steel sheaths, 562
 - SIBIE results in metal sheath, 565
 - SIBIE results in polyethylene sheath, 566
 - sketch of imperfectly grouted sheath, 563
- standard hydrogen electrode, 293
- Stefan–Boltzmann law, 373
- Stirling cooler, 375
- stress wave, 443
- stress wave propagation
 - applications, 424–34
 - ageing/deteriorating concrete infrastructure, 433
 - concrete infrastructure ageing and deterioration, 428–34
 - freshly cast concrete, 427
 - hardened concrete, 429
 - initial time of set and strength development for newly cast concrete, 424–8
 - repaired concrete infrastructure, 434, 435
 - expansion over time owing to alkali–aggregate reaction and UTT measurements, 432
- future trends, 435–6
- impact-echo
 - setting time measurement, 428
 - strength development measurement, 430
- methods, 419–24
 - attenuation coefficient, 421–3
 - attenuation coefficient and damage correlation, 423
 - attenuation coefficient in the time domain, 422
 - pulse velocity and structure condition correlation, 422
 - quality factor, 423–4
 - quality factor in the frequency domain, 424
 - velocity, 421

- reinforced concrete structures
 - evaluation, 417–36
- ultrasonic through transmission
 - set-up, 420
 - set-up for setting time
 - measurement, 426
 - setting time measurement, 427
 - strength development
 - measurement, 430
- Structural faults and repair*, 526
- structural health monitoring, 112, 113, 114, 115, 122
 - definition, 64, 65
 - effective and innovative monitoring technologies, 74–87
 - fibre-optic point sensor, 83–7
 - fibre-optic RH probe, 77
 - fibre-optic sensors and laser vibrometer results, 80
 - long-gauge-length sensors, 74–6
 - precasted sensor-equipped piles, 83
 - quasi-distributed fibre-sensor, 75
 - sensors fixed on reinforcement cage, 82
 - short-gauge-length sensors, 76–83
 - silicon mould with EFPI sensor
 - before casting, 78
- innovative monitoring methods, 67–73
 - Fibre Bragg grating sensors, 70–2
 - Fibre Fabry-Perot interferometer sensors, 72–3
 - fibre-optic point sensors, 73
 - high-performance sensors for deformation measurement, 67–70
 - types of fibre-optic sensors, 68
- reinforced concrete structures, 63–91
 - demands on monitoring systems, 64–7
 - future trends, 90–1
 - reliability and standardisation, 87–90
- Structural materials technology*, 526
- structural noise, 494
- sulphur, 175–6
- surface wave
 - see also* Rayleigh wave
 - detection using laser interferometer, 459
 - transmission coefficient and crack depth relationship, 457
- surface wave attenuation analysis, 455–7
- surface wave techniques
 - basic principles, 443–8
 - homogeneous elastic halfspace, 443–5
 - layered elastic media, 445–8
 - concrete structure evaluation, 441–60
 - equipment, 457–9
 - field application, 459–60
 - multiple time domain signals $x-t$
 - waterfall plot presentation, 450
 - one possible MASW testing
 - configuration, 453
 - real-valued phase and group velocity
 - dispersion curves for single solid layer, 446
- SASW test method testing
 - configuration, 451
- signal processing and data presentation, 449–57
 - multi-channel analysis of surface waves method, 453–5
 - spectral analysis of surface waves
 - method, 450–3
 - surface wave attenuation analysis, 455–7
 - time domain analysis for
 - homogeneous media, 449–50
- transient wave field in solid half-space, 444
- surveillance d'ouvrages par fibres optiques, 68–9
- synthetic aperture focusing technique, 28, 99, 138, 154–5, 499
 - see also* Fourier transform-SAFT
 - box girder 3D SAFT reconstruction, 515

- 2D reconstruction of sample
 - containing two side drilled holes, 507
- elastic wave scattering, 520
- foundation test slab cross-section, 513
- partly grouted tendon duct examination, 516
- pipe targets 3D reconstruction, 519
- reinforcement bars 3D reconstruction, 514
- tendon ducts in box girder, 517
- TC RILEM154EMC, 243
- TDS2014, 563
- telegraph equation, 126
- tendon ducts, 151
- tendons, 222
- theory of electromagnetism, 145
- thermal conductivity, 372
- thermal diffusivity, 372
- thermal effusivity, 372
- thermogram, 370
- ThermoSense, 397
- time-depth conversion, 141–2
- time-of-flight technique, 455, 473
- time signal clipping, 476
- time synchronisation, 118
- tomography, 334
- transmission mode, 126
- transversal wave, 492
- travelling tomography, 337
- traveltime calibration, 343
- traveltime picking, 344
- 9T15S, 579
- 10T15S, 579
- two-probe resistance measurement technique, 259
- two-way-traveltime, 321
- ultrasonic data, 101–5
- ultrasonic echo, 17
- ultrasonic pitch-catch transducer M2502, 508
- ultrasonic pulse velocity, 420, 423
- ultrasonic techniques, 185–6
 - A-scan measurement using handheld instrument, 509
- application examples, 512–18
 - 3D imaging of concrete regions, 517–18
 - detection and localisation of voids in tendon ducts, 515–17
 - reinforcement imaging, 513–14
 - tendon ducts localisation, 514–15
 - test site containing pipes, 518
 - thickness measurement, 512–13
- applications and requirements, 499–500
- automated scanning measurement systems, 510–12
 - BAM measurement equipment, 510
 - BAM scanners for post-tensioned concrete bridge ultrasonic testing, 511
 - MFPA measurement equipment, 510, 512
 - MFPA Weimer automated measurement system, 512
- common inspection tasks at concrete element, 499
- concepts and notions, 503–7
 - B-scan line measurements, 505
 - B-scan of sample containing two drilled holes, 506
 - C-scan planar measurements, 506
 - SAFT imaging, 506–7
 - single A-scan measurements, 503–5
- concrete elements imaging, 503–20
- 3D co-ordinate system used for measurements and images, 503
- future trends, 521–4
 - air-coupled imaging, 523
 - concrete column test specimen, 525
 - electronic scanning, 521–3
 - side drilled hole air-coupled scanning measurement, 524
 - tomographic imaging, 523–4

- ultrasonic array with 48
 - transducers, 522
- void and back wall displacement
 - iso-surface view, 522
- measurement equipment, 508–12
- measurement instruments and
 - transducers, 508–9
 - handheld instrument, 508–9
 - line scanner, 509
- pulse–echo experiment setting, 504
- reinforced concrete structures
 - evaluation, 490–526
- simulation, 518–20
- transmission methods, 500–3
 - concrete material properties
 - characterisation, 501–2
 - flaw detection in transmission, 502–3
 - measurement devices, 501
- ultrasonic wave propagation in
 - concrete, 491–9
 - acoustic impedance for pressure
 - wave and reflection factors, 494
 - elastic wave, 491–4
 - elastic wave propagation in
 - concrete, 494–9
 - influence of concrete properties on
 - signal shape, 498
 - received signals, 495
 - testing parameters typical ranges, 496
 - transmitted signals, 497
- ultrasonic testing, 35
- ultrasonic through transmission
 - set-up, 420
 - set-up for setting time measurement, 426
 - setting time measurement, 427
 - strength development measurement, 430
- ultrasonic wave, 125–7
- ultrasound testing, 185
- under-floor inspection unit (UFPE), 43
 - CAD drawing, 41
 - Frankfurt, 42
- UT1000, 552
- validation, 8
- variable damping factor, 348
- VDI/VDE/GESA 2635, 90
- VDI/VDE guideline 2660, 90
- water/cement ratio, 246
- wave equation, 148
- wave field inversion, 154–8, 158–9
- wave-monitor, 547
- wave-shaping filter, 136
- Weiner filter, 136
- Wenner probes, 259
- wheel set inspection, 40–1
- wireless monitoring
 - basic principles, 112–14
 - flowchart, 115
 - multihop network with sensor
 - clustering, 112
 - robust wireless sensor node, 114
 - reinforced concrete structures, 111–22
 - application, 119–22
 - future trends, 122
 - monitoring system design and assembly, 116–19
 - monitoring task, 114–16
 - systems in operation, 119
- wireless sensors, 111, 112, 113, 122
- working electrode, 294
- yoke magnet, 219
- Young's modulus, 443
- zero offsets, 127
- ZfpBau-Kompandium*, 526
- zone location method, 193–4