Chapter 2
Concrete Structures

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Abstract Implementation of Non-destructive Evaluation (NDE) procedures in concrete structures seems to be the only way towards a safe and economic infrastructure management. Since concrete structures have reasonably ceased to be regarded as maintenance-free, periodic inspection is deemed necessary. Although destructive techniques can provide information on the strength of the material, this is only based on sampling and cannot be performed in a wide basis. Therefore, NDE methodologies, especially with the capability of visualizing the interior of the structure, have been developed and applied in structures to answer a question that cannot be addressed destructively. This chapter focuses on the current trends of elastic wave and general techniques that are used and new trends with some examples of how NDE assists in the identification of damage and maintenance of concrete structures are highlighted.

Keywords NDT devices · Transducers · Radar · Thermography · AE · Data processing

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2.1   Introduction

Concrete is a material used to create the infrastructure supporting nearly all fields of human activity. Residential buildings, bridges, highways, dams and other structures are made of concrete. The long expected life span involves continuous deteriorating actions by own weight, external loads, temperature cycles, chemical degradation and earthquakes. The optimal performance of concrete structures is crucial for economic reasons but more importantly for human safety. Concrete structures should be inspected regularly in order to evaluate their vulnerabilities and apply proper repair action. Maintenance schemes of the structures should be based on the importance of the structure and its damage condition. Therefore, economic, fast and reliable on-site measurement techniques are in high demand.

2.2   Material and Structural Conditions for Measurements

Concrete is a special material. For construction purposes cementitious materials are nowadays the most widely used materials replacing traditional building materials like stone, masonry and wood for many applications. Considering that the world-wide consumption of cement was in 2012 approximately 3.7 Billion tons [51] demonstrates the importance of concrete for every national economy. The success of this material class is mainly due to the composite structure and the flexibility is given at the construction site. However, this causes also a problem due to materials heterogeneities since concrete consists usually of the cementitious matrix as well as of aggregates (of different size), pores, water and several additives. On the same structural macro or meso level, metallic materials exhibit a much more homogeneous structure than concrete. The large variety of concrete mixes used in practice is leading to very different behavior concerning the applicability of NDT. Moreover, a mixture out of the same ingredients (qualitatively and quantitatively) can perform differently due to the boundary condition during casting (temperature, segregation, compaction, etc.). Since concrete alone is unable to accept higher tensile loads, it is usually reinforced using steel bars for example. This makes a steel-reinforced concrete (SRC) structure tougher and broadens the application range but it further enhances the degree of heterogeneity of the individual structural components.

NDT techniques are affected by various material components (water, reinforcement, voids) in a different way. NDT methods based for example on electro-magnetic waves (like RADAR) are more affected by the reinforcement and by water compared to methods based on elastic waves like ultrasound. The latter interfere vice versus extensively with air pores leading to higher attenuation and scattering. The situation is even more difficult due to the geometrical boundary condition. At real constructions, the accessibility limits the types of NDT in most cases, allowing one-sided access only. The geometry of the structural parts is

complex since they consists of the slabs, beams or columns a structure, has often dimensions in the range a typical wavelength of NDT or affect the results by side reflections that can camouflage the desired signal. This is certainly also true for different types of reinforcement (bars, wires, tendons and fibers). In addition, the surface conditions (rough concrete surface due to the formwork), coatings and covers may have an influence on NDT methods or at least on the efficiency. All of these complex conditions are somehow limiting the applicability and success of modern test methods.

2.3 Requirements by the Stakeholders

NDT techniques are mainly used as tools for quality control of concrete structures—either during the building process or in form of maintenance applications (monitoring or inspection) during the lifetime of a structure. However, NDT applications in civil engineering are still in its infancy compared to other fields. While in most mechanical engineering applications the number of similar objects or its similarity, respectively, is high, this is not the case for concrete structures. It is a feature of civil engineering to create unique objects being the best suitable for the local needs in regard to the owner, climate, topography and so on. A stakeholder of today asks even more for a specialized construction including new compositions of material components, for a more robust and durable construction and finally also for the most cost-efficient way of construction. These optimization requirements lead to new high-tech materials including for example new fiber reinforcements, self-compacting, lightweight or high-strength concrete. A stakeholder expects that NDT is capable to handle all these materials reliably. Existing structures and older constructions can be even more difficult if (what happens often) no or little information about the design and its materials is available. To summarize this point one can state that considering the uniqueness of objects and compared to other industries like automotive and aeronautical traditional NDT methods are less efficient. Although a big percentage of a gross domestic production of a nation goes into buildings of the infrastructure applications of quality control techniques including NDT are limited. This is a surprise since in a modern economy maintenance of the infrastructure should have a high priority. It is certainly a big task to enhance the efficiency of NDT techniques for applications in civil engineering and to give stakeholders modern tools at hand to keep the value of their properties. This certainly requires the development of new devices and data processing techniques that will be addressed in the next section. Others topics are as important as this. Training of the experts should be further improved including even teaching of NDT basics in the civil engineering curricula at universities. The training of specialists should be standardized similar to the level certifications required in other industries. Standardization should be enhanced regarding test equipment and data processing techniques as well. All of these could lead to a modern quality management that is not yet existing in most countries. Stakeholders finally require a clear result of NDT

measurement. Still missing are modern NDT tools being used in the construction phase of a building in terms of quality assurance. Without the application of NDT for quality assurance in such an early phase the application of inspection and monitoring techniques later on during the service life of a structure is more difficult since a complete assessment of a building have to be done then prior to NDT applications. A certified inspection right after finishing a construction could lead to a more solid and reliable quality control since only deviation of an initial status have to be detected. Such a certificate (like a "birth certificate") could be given to the stakeholder enhancing also the value of a construction. Such a procedure is well known in other industrial branches for objects with a much lower total value and briefer lifetime.

Nevertheless, NDT has values also being applied during service life. Modern test methods have the potential to deliver data for the prognosis of the residual lifetime for civil engineering structures. Semi-probabilistic or full-probabilistic techniques can enable for a reduction of safety factors and slender constructions and a much more efficient maintenance procedure what is both of immediate value for a stakeholder. However, these techniques are not yet fully developed and need more attention in future.

2.4 New Developments on Devices

In the past NDT techniques for probing CE structures have not been developed to the same high level compared to applications in the field of medical diagnoses or testing power plant components, automotive or aeronautical parts. One reason is the before mentioned variation of different materials in CE (concrete, wood, stone, masonry, steel, polymers etc.) leading to complexity. Considering concrete alone, one can see a significant improvement of NDT methods in the last decade [23]. Former drawbacks of NDT applications at concrete structures are handled and new sensors and devices have been established as a workaround. This includes the time-consuming setup of sensors and devices as well as implementing flexibility to the measuring system and more sophisticated data processing algorithms. Some of the recent developments are addressed in the following sub-sections.

2.4.1 Improvement of Devices and Sensors

The major task of sensors and NDT devices is to use waves and wave fields in a way that changes of the signal can be related to deteriorations inside opaque materials like concrete or SRC. Other tasks concerning material properties or the quality of a component are also addressed by NDT. It is the benefit of developments in micro-electronics in the last years to enable for sophisticated NDT techniques

adjusted to the needs of CE applications. Most of these techniques certainly still need more involvement but the basic concepts can already be found in the literature.

2.4.2 Calibration of Equipment and Transfer Functions of Transducers

The signal that any NDT device display as an "output" is certainly influenced by the whole recording system, where each individual part of the measuring chain (emitter, medium/structure in which the signal propagates, sensor/receiver, recording and storing unit, data processing, Fig. 2.1) can be considered as a filter altering the original signal. As a filter system we indicate something that can manipulate, change, record, or transmit signals. For example such a system can transform the displacement of a ground motion into equivalent velocity or acceleration or restrict the frequency content. In this regard the concept of transfer functions (TF) is useful.

According to Fig. 2.1 each system is represented by its individual transfer function and the resulted post-processed recording ("output") can be seen as a convolution of all these influences onto the originating signal. This process is also known as *linear filter theory*, where the output is treated as a sequence of more or less linear filters. To apply filter theory, all of the known influences are assigned by a different transfer function. In most NDT applications it is important to know or guess the weight of these functions as a precondition to eliminate their influence and to reveal one desired "filter function", i.e. the medium or the source. While the intention of non-destructive testing methods is the investigation of material parameters or material failure and not the characterization of the measuring system, one has to reduce the effects related to sensors, coupling or the recording system with care. An ideal sensing system acts as a zero filter producing only little distortions to the data transmitting the information more or less unaltered. In the worst case the data are distorted by the sensing filter so much that the original information is completely camouflaged or even erased.
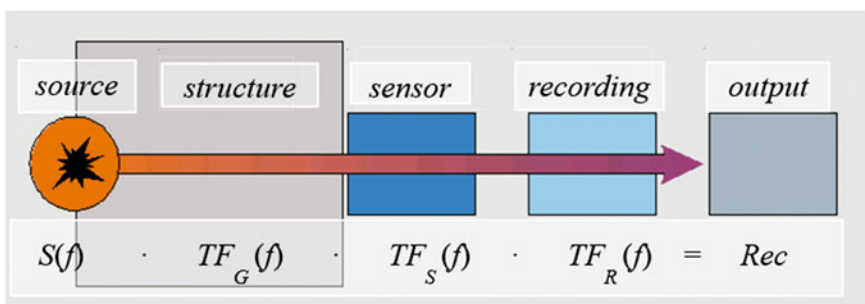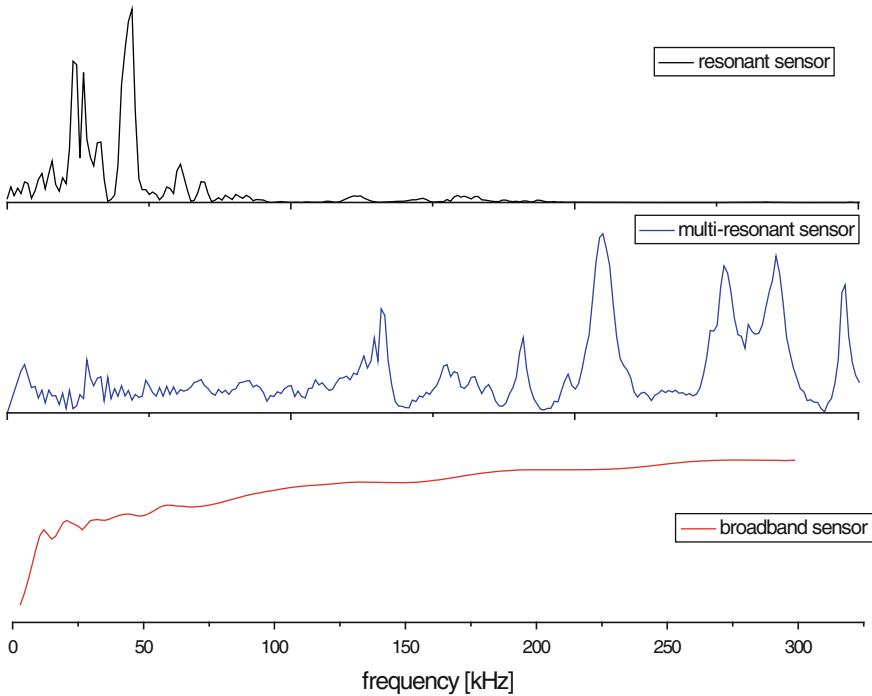

Fig. 2.1 Concept of transfer functions [12]

Fig. 2.2 Typical frequency response functions of resonance (*top*), multi-resonance (*middle*) and high-fidelity broadband (*bottom*) piezo-electric transducers

The type of sensors used in Ultrasonic Testing (UT) or Acoustic Emission Technique (AET) almost exclusively are sensors that exploit the piezoelectric effect of lead zirconate titanate (PZT). While piezoelectric sensors and their design are described in numerous books and papers (e.g., [17, 19, 20], some characteristics play an influential role in measurements. These features are important in regard to sensitivity (and therefore, the detectability of signals) and the analysis of the signals with (frequency response).

To enhance the detection radius of piezoelectric sensors to AE signals [9], they are usually operated in their resonance, i.e. the signals are recorded within a small frequency range due to the frequency characteristics of the transducer as shown in Fig. 2.2. The disadvantage is that an analysis of the frequencies present in the signal is of limited range. Very well damped sensors, such as those used for vibration analysis, are operated outside of their resonant frequency allowing broadband analyses to be performed, but are usually less sensitive to acoustic emission signals. For many years a NIST (National Institute for Standards and Technology) conical transducer developed by Proctor [32, 33] was used as a reference for AE measurements.

To overcome the disadvantages of limited bandwidth transducers showing several particular resonances were developed. These sensors, which are called

multi-resonance transducers (Fig. 2.2, middle), have a higher sensitivity than sensors with a backward mass used outside of their resonance frequency. However, such sensors should not be considered as high-fidelity broadband sensors and it is essential to know their frequency response functions. Otherwise, signal characteristics from the source are not distinguishable from artifacts introduced by incorrect knowledge of the frequency response. A calibration of the sensors' frequency response, as well as understanding of the directional sensitivity, is important for many applications in non-destructive testing. It was a goal for many years to develop sensors for non-destructive testing purposed that exhibit a so-called high-fidelity behavior. The problem is similar to sound systems where in the 1960s standards were developed for music equipment (loudspeaker, microphone, amplifier, vinyl and later on tape recording) to minimize the amount of noise and distortions and providing an accurate frequency response. High-fidelity sensors for different applications (e.g., AET: [25]; Fig. 2.2, bottom) are under development to establish recording systems as a "zero-phase filter".

Essential to determine the limits of a sensor (or a measuring device) is the launch of proper calibration standards. In the AET literature (e.g., Hsu and Breckenridge [16, 26, 54]) different methods of calibrating sensors and determining their transfer functions are described. Measurements used in sensor calibration should include the frequency, as well as the phase response function and the direction sensitivity (i.e. angle of incidence of the wave). Concerning the frequency response, techniques have been proposed using a reference source (capillary) on a large steel block [16], the face-to-face technique [15] or a laser-vibrometer [53]. All these methods have drawbacks in relation to the used physical techniques (measurement of free oscillations of the sensor instead of the coupled system) or the effort needed (steel block calibration). New techniques are under development and first results are already published [24, 25, 28].

2.4.3   Coupling of Transducers

Non-destructive testing techniques in engineering can be subdivided into methods used at a laboratory scale or in situ. Challenges are—in addition to the above mentioned—related to coupling problems. Measurements at structures like buildings, facilities or bridges are in particular challenging since they are usually large compared to the aperture of NDT signals. The coupling problem is dominating some of the NDT techniques and this is the reason why so much effort was put into methods to speed up data acquisition and to overcome the coupling problem. Contact-free techniques are the first choice; among them are RADAR (Fig. 2.3, left) and Infrared-Thermography (Fig. 2.3, right). While near-field problems can be handled using for example far-field airborne RADAR [30, 55], such problems are of less importance using IR-Thermography.

Although ultrasound is the method of choice in many applications including medical diagnosis or the inspection of welded joints, its applications concerning

Fig. 2.3 Contact-free NDT applications like Radar (*left*) and IR-Thermography (*right*) enhancing the measurement speed (*right picture* by courtesy of Dr. J. Frick)

Fig. 2.4 Ultrasound techniques like air-coupled transducers (*left*) or point-contact transducers (*right*) are developed to speed up NDT measurements

concrete structures was limited. Traditional ultrasound techniques required a coupling agent being used at the surface to avoid voids trapped between the sensor and the surface. Ultrasound is sensitive to such voids even if they are of small diameter since ultrasound waves are almost totally reflected at boundaries to air. However, the use of coupling agents is often disturbing the optical appearance of a structure and leftovers of the agents can disturb further NDT applications. More important is that measurements using such coupling agents at large structures are costly and time consuming. Some new developments like air-coupled transducers (Fig. 2.4, left) or point-contact arrays (Fig. 2.4, right) are therefore promising techniques that will certainly be further considered but need to be optimized for measurements at large concrete structures [14].

2.5 Data Processing Techniques

2.5.1 *Examples of Present Applications*

Despite the inarguable fact that wave propagation techniques are far from reaching their potential [2], results have already started to be implemented in SHM high impact applications. An example is given below in Fig. 2.5, where the elastic waves emitted by an impact hammer and recorded by low frequency accelerometers through-the-thickness of concrete helped to visualize the initial problematic areas of the dam pier. Furthermore, after the repair by grout injection it was possible to quantify the improvement [44, 46]. Since pulse velocity depends on the material's elastic properties and remaining void content, it can be used as deterministic parameter of the mechanical status in addition to the visible signs and the experience of the site engineers. Attenuation coefficients of elastic waves, Q-values being regarded as an intrinsic parameter irrespective to the frequency is also used in the latest studies [47, 48] and the Q-value has been correlated to the damage parameter Ω.

In any case, apart from the evaluation of the damage status, it is essential for an NDT technique or methodology to be capable of evaluating the condition after repair in order to confirm if the mechanical integrity has been enhanced or more action is necessary [57].

Applications based on more delicate wave features like frequency dispersion have the potential to characterize surface deterioration due to carbonation, or visualize hidden defects in concrete members. They have started to be used in
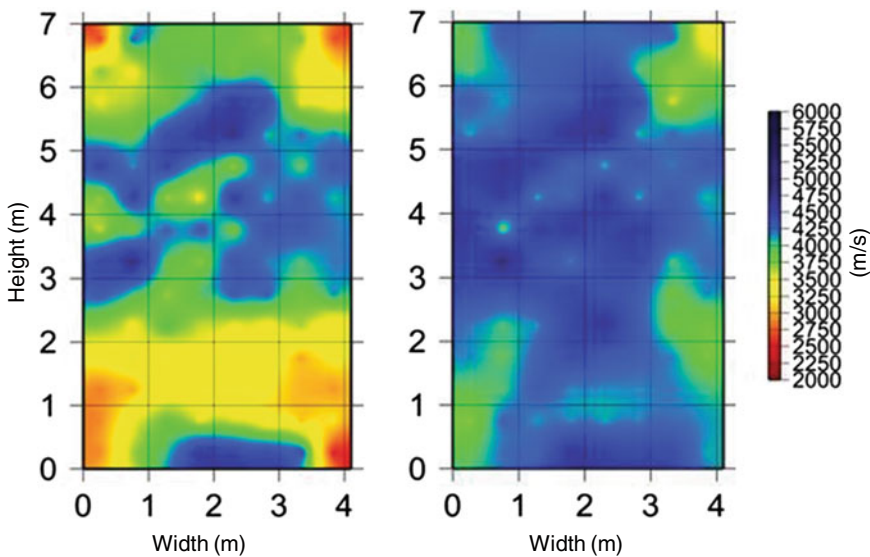
Fig. 2.5 Velocity distribution in a cross section of concrete pier: before (*left*) and after (*right*) repair by grout injection

structures but are still not widespread due to the sensitivity to experimental conditions other than the damage degree (e.g., coupling, surface roughness) [1, 31].

In the "sister" field of AE, the aforementioned difficulties again apply. Still, specific conclusions can be drawn even in large scale, mainly in the direction of quantifying the damage degree by specialized indices based on the incoming activity [44, 46] or characterizing the fracture mode [27, 45] (e.g., concrete crack, cable rupture, deboning). This supplies useful information for the remaining life of the structure. As for the other notable addresses, sensitive NDT is not always effectively in any structures. As mentioned already the structures shall be maintained according to their importance and the corresponding critical scale of defect/damage should be determined. To implement this procedure, systematic studies relating damage scale to the NDT resolution or wavelength shall be carried out more intensively.

2.5.2 Automation and Combination of Techniques

The coupling problem leads to another point related to automation. It is often required in practice to investigate a large area of a structure. Moreover, the accessibility of a structure is limited either due to geometry (e.g., bridge cable) or in time due to traffic or other time constraints. Autonomous measuring units working independently from an operator can be beneficial in such cases, like robots which use magnetic flux for assessment in cable-supported bridges or in other cases apply a mechanical excitation for testing the dynamic response by accelerometers [56]. Concerning inspection techniques first devices have been developed [34] that can handle practical problems related to rough surfaces and geometrical boundary conditions in situ. The benefit of these devices is in addition the ability to use different NDT techniques simultaneously including for example RADAR, ultrasound, microwave, impact-echo, rebar detection and other methods. The combination of different techniques is advantageous for traditional non-automatized NDT applications. Every NDT technique has its own advantages and disadvantages and is more or less suited for a certain application and boundary condition [5, 52]. NDT inherent ambiguities can significantly be reduced using a combination of techniques. In many cases the combination is enhanced by "data fusion" methodologies aiming at the accurate evaluation of concrete properties including the prediction of in situ strength [4, 38], a subject that concentrates serious efforts of the engineering community [36]. Unfortunately, these advantages have to be tradeoff for a dramatic increase of data, what have to be seen in the context of the "big data" discussion and general issues related to the data-enabled techniques in engineering and the handling of many Gigabyte of data (e.g., for AET discussed in [35]). Autonomous and automated NDT inspection devices will probably be more successful in future as soon as the total price of such a system is reduced.

A combination of data from different sensing techniques is beneficial not only for a one time inspection but for a continuous monitoring of concrete structures.

Fig. 2.6 Example of a wireless sensor mote (www.smartmote.de) and measurement of acoustic emission and strain data at a concrete structure [10, 11]

Structural health monitoring (SHM) can provide data that allow a better understanding of its structural performance, and in turn allows prediction of its durability and remaining lifetime. To function properly and cost-efficient, a monitoring procedure must be reliable, inexpensive and simple to be implemented. The techniques used should be easy to adapt to different types of structures and structural elements. Given these facts, the development and application of wireless sensor pods (often referred to as Motes), incorporating micro-electromechanical systems-based microsensors (MEMS), is a powerful solution to SHM ([8, 20]; Fig. 2.6, left). Lynch [22] presents a thorough overview of wireless sensor platforms. From past work, wireless monitoring system equipped with accurate yet low cost sensors can reduce structural monitoring costs dramatically but also wired systems like fiber optical sensors have some advantages [13]. A correlation of the data obtained by different sensors (AET, GPR, vibrations, temperature, humidity, strain, etc.) will lead to a further understanding of structural behavior, as typically done in bridges [3] or other structures like the concrete transition piece in wind turbine towers [18, 50]. For example, a cross-check of AE activity (Fig. 2.6, right) with increasing strain or with a sudden or abnormal increase of the ambient or inner structure temperature can give further insight into structural state. Such sensor data correlations will also decrease the amount of data transmitted after implementing intelligent data processing and correlation algorithms. Devices for the structural health monitoring (SHM) of constructions have been numerously assembled lately and it is nearly impossible to refer to all of them here.

## 2.6 Improvement of Data Processing Techniques

A pre- or post-processing of measurement data is very often required. Referring to the concept of transfer functions earlier a data processing can be required to eliminate the influences of other systems (coupling, sensor characteristics, etc.) than the one under consideration (material properties, source function, etc.). Besides, it is

the challenge of all applications to get the maximum of information out of the limited number of observations available. In almost all cases, the number of sensors is either limited or the number of events or the time or space for further observations. To deal with these limitations scientists of all disciplines have developed methods to increase the significance of the observation for example by enhancing the signal to noise ratio. While it is impossible to describe all the different developments, concerning data processing tools one example will be given.

2.6.1 New Inversion Techniques for Ultrasound

The collection of data (e.g., using ultrasound) is very often done along lines where either several (or many) sensors are placed or where a sensor-receiver pair is moved along to perform a B-Scan. Concerning the B-Scans the data obtained will contain always some redundancy, e.g., by containing information of common reflectors in the depth. Methods to make advantage of this redundancy to enhance the signal to noise ratio and to determine the real depth of the reflectors are called migration techniques (time or depth migration) in geophysical prospecting. A simple way to perform such a migration is the use of common depth point techniques as illustrated in Fig. 2.7, left.

Techniques that are more sophisticated are the Kirchhoff migration, the Reverse Time Migration (RTM) or Gaussian Beam Migrations. Based on these geophysical developments methods called in ultrasonic applications Synthetic Aperture Focusing Techniques (SAFT) [7, 50, 41] were established a few years ago. B-Scan measurements with a single transmitter-receiver pair in pulse-echo along lines can be reconstructed with SAFT algorithms enhancing the signal quality subjected to scattering or attenuation ([40], Fig. 2.8). Phased array techniques in ultrasonic or RADAR applications can be considered the hardware equivalent to migration and SAFT techniques. Ultrasonic phased array probes consists usually of many individual crystals. One can distinguish between linear, linear curved and 2D matrix
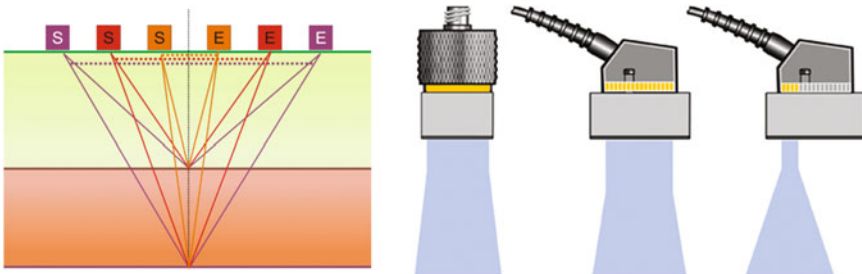
Fig. 2.7 Transmitter/receiver configuration (*left*) to perform common depth point migration in Geophysics. Comparison of the aperture of conventional and phased array transducers (*right*) with 16 elements (all or 4 are pulsing)—*Source* Olympus
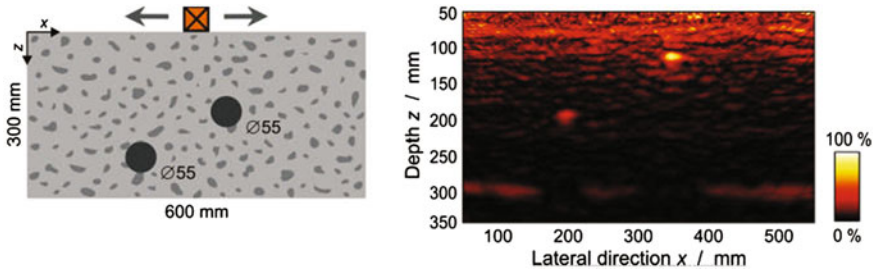
Fig. 2.8 Ultrasonic pulse-echo measurements at a concrete block with two inhomogeneities (*left*) and the SAFT reconstruction after measurement [40]

composite transducers. Instead of calculating the time delays in respect to the reflector these probes are able to steer a narrow beam focusing to a certain depth point (Fig. 2.8, right). However, the physics of migration is applicable in this case as well. Successful applications are described in the literature [37] and several applications for concrete structures have been reported.

These techniques have recently pushed forward. The main difference between seismic migration and ultrasound phased array techniques (UPAT) is the directivity pattern of the beam. In UPAT the beam is steered in a certain direction by using a time delay technique resulting in a constructive addition of signal amplitudes in a certain angle or to a certain depth point. This is causing a "blind region" underneath the surface, where objects are not detectable (near field effect). Moreover is the effort of beam steering on the hardware relatively high. As a consequence (and following seismic prospection methods of today), UPAT was developed towards transducers emitting the excited waves concentrically, what was called "sampling phased array" [6, 29]. The receiving sensing elements have a much larger aperture and no blind spots occur. More importantly are the facts that this technique is on the hardware side more easy to be implemented and probing is significantly faster. While the technique was until now mainly applied at metallic materials and those out of fiber-reinforced polymers an implementation for concrete structures is yet to be done.

2.6.2 Reliability Analysis for NDT Methods and the Effect of a Defect

It is standard nowadays to include an error analysis along with the presentation of NDT data. As all measurement data, these data are subjected to both, systematical and statistical errors. Quantification of these errors including procedures like Gauss' Propagation of Uncertainty technique and standard deviations are usually given. However, this is no proof of reliability of NDT techniques. A simple question may illustrate this. If, as a result of an application of such a NDT technique, no flaw is

detected, what does that mean? Does it mean that the object contains no flaw or is the used NDT method unable to detect it? Will the flaw be detected by a change of a certain measuring parameter or by repetitive measurements? In recent years methods determining the *Probability of Detection* (PoD) have been developed that can include also the *Receiver Operating Characteristic* (ROC). It is a surprise that these methods are not already widely applied in the NDT of concrete structures. A clear description of the capability of the applied NDT techniques should always be included in a report delivered to a customer. It can already be concluded out of several applications of PoD and ROC analyses that such techniques are probably leading back to a more original question. What type of defects and which dimensions of deterioration are acceptable for the customer; required is a guess of the *Effect of a Defect* (EoD). The NDT expert in the field can often give no answer to these questions. Prior to measurements it should be analyzed, e.g., by static analyses, what effect a certain defect has for the structure of interest.

Moreover, NDT techniques will be more and more required in future to perform a detailed failure prognosis for a structure using full-probabilistic calculations. Knowing the properties of all material and components as well as the effective load history (my means of NDT and SHM) uncertainties can be reduced and the construction can be assessed on the basis of true exposures and loads. This can lead to a reduction of safety factors (β-value). As input parameters the results of NDT techniques can be used, e.g.:

- determination of geometrical properties (e.g., thickness) to calculate the dead load
- measurement of the concrete cover
- positioning of pre-stressing elements to determine the lever arm of a force
- detection of wire breaks and missing reinforcement
- detection and localization of voids (honeycombing) in the concrete matrix.

Using NDT technique to help with the assessment of a structure in some of these problems a probability analysis using PoD and ROC techniques is required.

## 2.7 Numerical Simulation and Forward Modeling

Numerical simulations that are using for example finite elements, finite differences or boundary element methods are common today to investigate the fracture behavior of materials. A more or less accurate model of the material and the component under the test is required and the failure of such a component under a certain load can be predicted. These techniques are increasingly used to reduce the efforts of empirical destructive tests or to derive more details about the failure process.

Non-destructively derived information—that are more and more available from NDT methods—can be compared to the results of these simulations what leads to a more solid model and usually a more precise setting of the start parameters.

The interaction between destructive tests, numerical simulations and NDT methods is becoming a very efficient way to obtain information about material parameters and the behavior of structural components under different type of loads.

It is obvious that the numerical simulation of the NDT part of the experiments itself can further enhance the benefits. With the use of proper simulation tools, the interaction between a measureable NDT parameter (e.g., the potential field, elastic wave, electro-magnetic field) and the deterioration process in a component can be predicted. Using for example forward modeling tools to predict numerically the interaction of an elastic wave (ultrasound) with a crack can be important to find out, if an ultrasound device can detect a crack of a certain dimension and in a certain depth. It will enable the user to determine, if the setup, the sensors or their frequencies have to be changed. Knowing the EoD (see above) and the PoD as required by the customer, the measurement parameters could be optimized prior to do the first measurement in situ. This is clearly a much more efficient way to use NDT techniques and in particular required for complex materials (like concrete) and difficult boundary conditions (geometries, composites) as we usually have in civil engineering applications.

This can be demonstrated by an example from experiments at the Eidgenössische Technische Hochschule Zürich in Switzerland [39, 43]. One of the major problems concerning pre-stressed concrete elements (as we can found them in bridge girders) are un-grouted ducts, what can lead to corrosion and failure. For many years, it was challenging to find a setup and a NDT technique being able to detect the voids in the duct. In the mentioned study, it was investigated, if AET is able to help. The girder was loaded in 4P-bending and had a length of 4.5 and a cross-section of 0.44 × 0.44 meter as shown in Fig. 2.9.
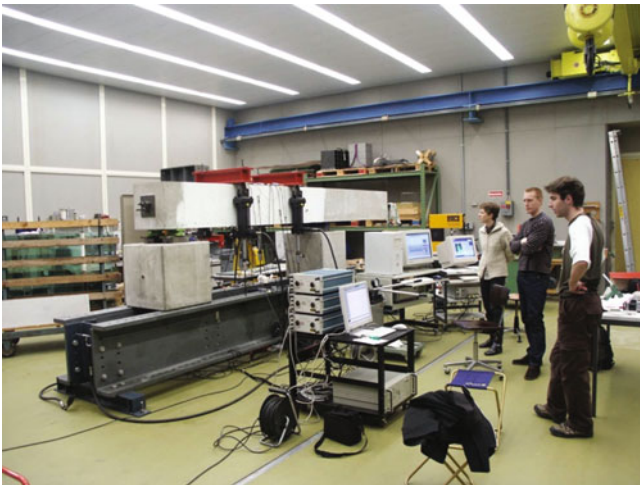
Fig. 2.9 Setup of AET during the 4-Point-Bending load of a pre-stressed concrete beam
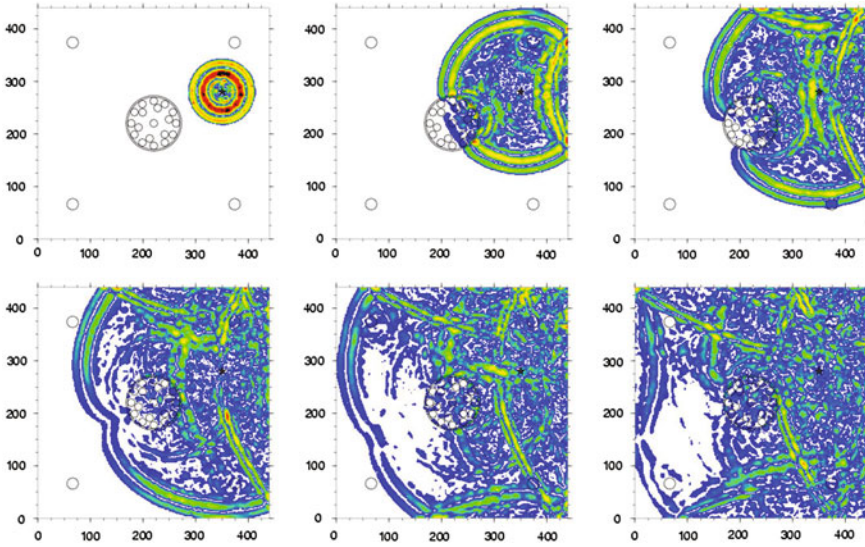
Fig. 2.10 Forward simulation of elastic wave propagation in the beam depicted in Fig. 2.8 with steel reinforcement in the corners and a PE-duct containing steel wires [39]; snap shots in time intervals of 15 μs

Figure 2.10 depicts the results of a forward modelling of AE waves travelling from a certain point inside a girder propagating through the beam to AE sensors placed at the surface. Cross-sections are shown in time steps of 15 μs computed using an elasto-dynamic finite integration technique (EFIT) code developed by Schubert [42]. EFIT enable for a correct simulation of the elastic wave propagation in highly complex composites with pores, voids, free surfaces and anisotropic changes of materials properties. Wave phenomena like mode conversion or scattering can be simulated. With unknown source or receiver functions, the simulation describes just the interaction of the waves with the material. It is noticed that the interaction of the waves (compressional and shear waves) with the heterogeneous concrete (aggregates, pores), the reinforcement bars and the duct leads to highly scattered waves. It is difficult to discriminate effects of voids in the duct from other scatterers. With given dimensions and sensor characteristics it will be difficult to detect an un-grouted part of a duct.

The model used in these calculations consisted of 918 × 918 points and this 2D model alone required a significant calculation time on a standard computer. This is certainly one of the drawbacks since complex models and highly accurate forward modeling codes require some computer power. With advances in micro-computing and optimization of such codes the technique becomes more and more available for public. Codes are already available not only for elastic but also for electro-magnetic waves (RADAR) and for potential field techniques. It seems to be feasible in near future to test first, what PoD can be achieved with a certain NDT technique and

sensor setup, before any expert conduct time-consuming and costly practical measurements. This has the potential to increase significantly the efficiency of NDT applications in CE in future.

2.8 Temporal and Spatial Evaluation of PC Cable Breakage

Due to un-grouted PC ducts, corrosion-induced cables' breakage is reported frequently in post-tensioned PC structures, leading to eventual failure in the worst case. However, the specific failure mechanism as well as deterministic investigation techniques for cables' breakage have yet to be clarified. When the cable is ruptured, elastic energy is released accompanying elastic waves namely acoustic emission (AE) [49]. Identification of the breakage could be carried out by this AE activity, followed by specifying the source location. While as for the existent PC breakage, the area of breakage could be determined by examining secondary AE activity generated due to the friction between fractured grout agent and tendons, which is resulted from re-anchoring around the breakage. These AE activities are experimentally produced using a full-scale PC beam being subjected to four-point bending ([45], Fig. 2.11), where the cables' breakages are simulated by stress reduction of each of PC cables in turn and the breakage areas as well as the failure areas of grout material are quantitatively identified with AE activities. As a result of careful observation of AE activity in terms of failure types, it became obvious that the failure progress due to cables' breakage and following re-anchoring were readily identified by the AE activity (Fig. 2.12). In addition, the existent breakage with re-anchoring area could be specified by AE sources as they had peculiar frequencies than others.
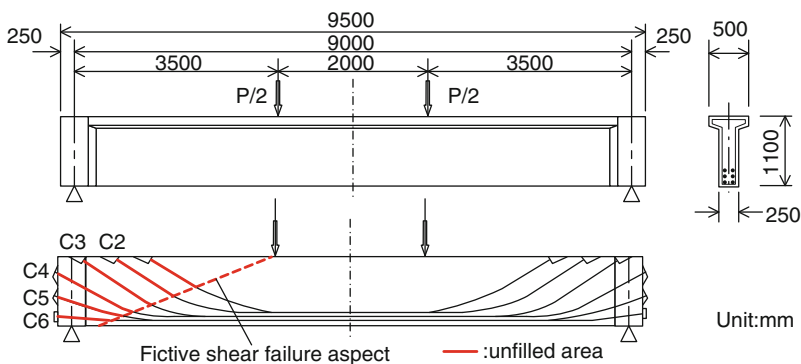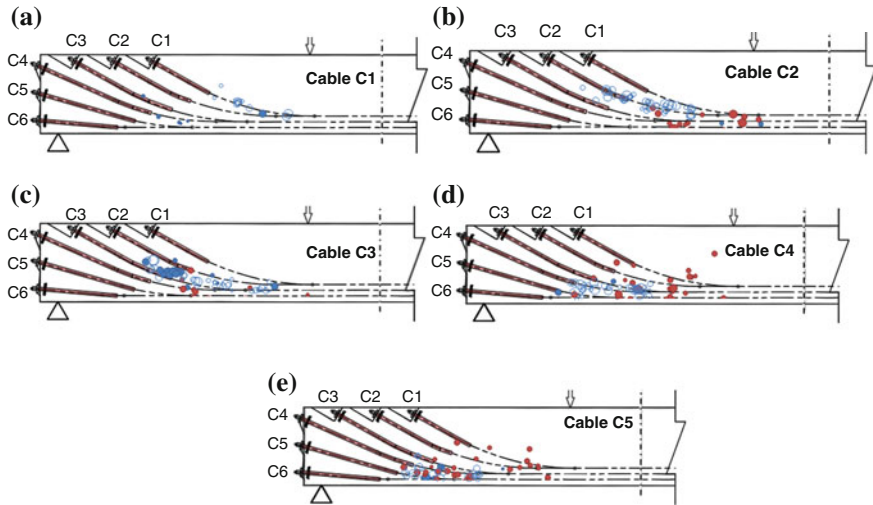

Fig. 2.11 PC beam specimen simulating step-wise cable rupture

Fig. 2.12 2D AE sources after stress release depicting open circles and ones showing solid circles during cyclic load after each stress release of cable. **a** After stress release of C1. **b** After stress release of C1–C2. **c** After stress release of C1–C3. **d** After stress release of C1–C4. **e** After stress release of C1–C5

2.9 Concluding Remarks

The present chapter intents to address issues related to the NDE monitoring of concrete structures. The importance and special characteristics of concrete make it a challenging material for the usual NDE techniques. However, due to the advancement of technology, the capabilities of testing continuously increase. Improvement of devices and new technologies like wireless sensors simplify monitoring, while tomography algorithms enable accurate visualization of the damage pattern within the structure. The developments in NDE are matching the increased needs of contemporary construction, like better control during manufacturing and operation, as well as reliable condition assessment when is judged necessary. These hopefully meet the highest quality standards, satisfy the requirements of the stakeholders and ensure a safe management of the infrastructure for the public namely infra-asset management.

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