

Chapter 5

Assessment of bonding, delamination and interfaces

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1 Introduction to debonding and delamination

Concrete can be viewed as a continuous, homogeneous and isotropic material when the investigation does not consider the microstructure scale (this level will not be considered in this report). “Interface”, as generally defined, is a physical limit between two materials. Such a limit can be viewed as an alteration of the mechanical continuity of concrete, and then, as a possible alteration of its mechanical and physical properties.

Engineers are interested in the knowledge of this flaw due to its signification: either an indicator of damage (for instance, as a consequence of rebar corrosion), or a parameter conditioning the damages (due to its influence on the concrete transfer properties for example), or an internal geometrical characteristic. Generally such flaw must be considered at the local scale, at the material level, but its influence, when evolving, can finally disturb the whole structure.

The knowledge of the initial cause of the interface is important for an appropriate characterization. However, in most cases, additional information is required. The aims of an investigation can be: the detection, the identification, the location, the extension, the depth, the intensity, and the activity (possible evolution) of an interface.

So practically, the consideration of “interface” in the frame of the TC is motivated by the fact that their detection and in situ characterization is a way to assess the condition of the structure at a moment of the structure life (which is the characteristic at the date of investigation). It also allows assessing the possible

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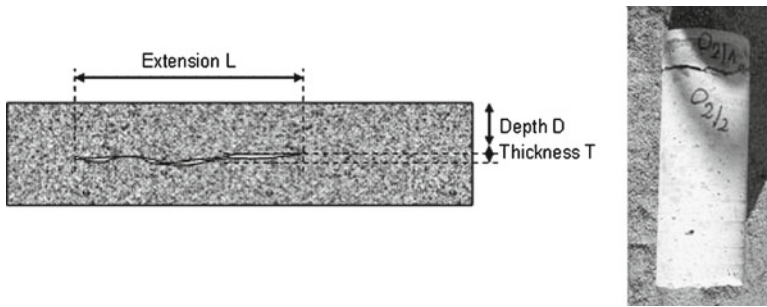


Fig. 5.1 Example of Delamination. Core (at the right) shows a typical delamination

duration for the structure (what is the impact of the damage on the structure, and how could evolve the interface with time?).

2 Description /definition of the problem treated

2.1 *What is being looked for? At what scale? For what purpose?*

Concrete debonding can be defined as an open interface where there had been a close interface yet, such as a construction joint. We speak about debonding when this interface causes a mechanical discontinuity, a weakness. In extreme cases, the debonding can be observed as a layer filled with air or water. The presence of concrete debonding can be due to a defect during construction. A common debonding is the contact defect between a precast slab and the concrete cast over it. Another classical case of debonding in concrete bridge decks is at the separation level of the asphalt concrete overlay material from the concrete deck. In a debonded area, one would expect to find a hole, a tear, or other form of deterioration in the petromat membrane, which would allow water to accumulate between the membrane and the bridge deck.

Delamination is defined as cracks parallel to the surface. It is generally consecutive to a damage of concrete or to the structure: Fire, freeze/thaw, or rebar corrosion are classical causes of this kind of damage (Fig. 5.1). Unlike debonding, delamination is not located where there had been an interface yet. An example of common observed delamination is a splitting of the concrete at the rebar level. It stems from the expansion stress generated on the concrete by the corrosion products when the reinforcing steel is corroding. A hollow plane is then created in the concrete slab (Fig. 5.1).

Whole structures or a part of them can be investigated with regards to debonding or delamination. Multilayered debonding or delamination usually disturbs surfaces about some square decimeters to square meters. Interfaces can sit very close to the surface when they are associated with physico-chemical alterations coming from the surface (i.e. frost, fire ...). Other phenomena can generate interfaces deeper in concrete: limits between precast concrete and concrete cast on site, debonding around rebar or around internal heat pipe – Fig. 5.2 & Fig. 5.3).

Fig. 5.2 Interface at heat pipe level in a concrete slab (P. Toussaint in Breysse et al. 2005)

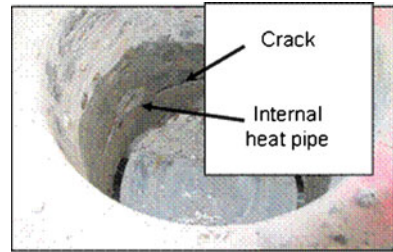


Fig. 5.3 Interface at the reinforcement level due to rebar corrosion (Naar, 2006)



Interface investigation can be motivated by checking whether some elements of buildings complying with standards (to search for possible explanations when a problem occurs,); or, in case of damage appearance, by detecting any alteration of concrete (due to ageing, for instance). Investigations can be planned at the end of the construction (to check the conformity), during the life of structure (to diagnose an alteration), or to control the efficiency of repair works (injection for example).

The type of interface disturbs the homogeneousness of the structure and can condition its structural behavior. This interface can correspond to a preferential path for fluids to flow. Geometries and properties of these defects can vary (considering the filling, the cause, the evolution...). Interfaces can also evolve to spalling concrete. Owners can see them as source of hazard (considering the possible fall of concrete pieces from wall facing), or as an aesthetic issue (with regards to facing degradation or moss deposits).

2.2 What level of interpretation? Required accuracy?

2.2.1 Detection / localization

The first aim of an investigation involving to debonding or delamination issues is the detection of the flaw and its location. The question of detection is generally asked in term of speed of investigation with regards to the probability of detection (or non detection). The skill of the specialist consists to select the technique that

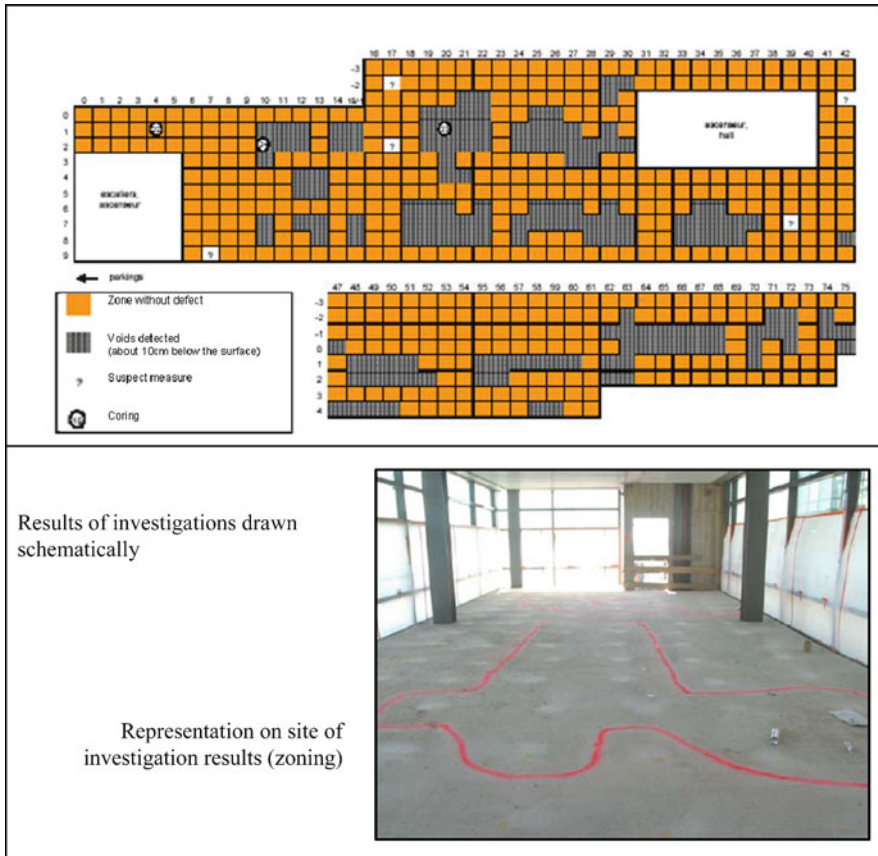


Fig. 5.4 Region of delamination in a concrete slab determined by impact echo investigation (P. Toussaint in Breyse et al. 2005)

would allow the right adjustment of two above parameters. Techniques allowing the optimal measurement cadences are usually those that are less performing in terms of information accuracy. For instance, infrared thermography is a fast technique commonly used for investigating large surfaces but quantitative interpretation of data cannot be done. On the other hand, impact echo, a slow technique, allows characterizing interfaces sharply.

The determination of lateral extension of an interface below the surface gives information that is very useful for a better work planning. An example of a case study involving impact echo method is presented below (Fig. 5.4). The objective was to assess and localize the damaged surface. Impact echo has lead to a mapping of the damaged area in proportion relatively to the investigated surface.

Techniques based on a punctual measurement, such as impact echo or electrical resistivity, allow determining interfaces with an accuracy that depends on the measurement grid spacing. In some cases, this procedure is suitable for the problem: when the need is focused on the description of spread damages, only a global approach

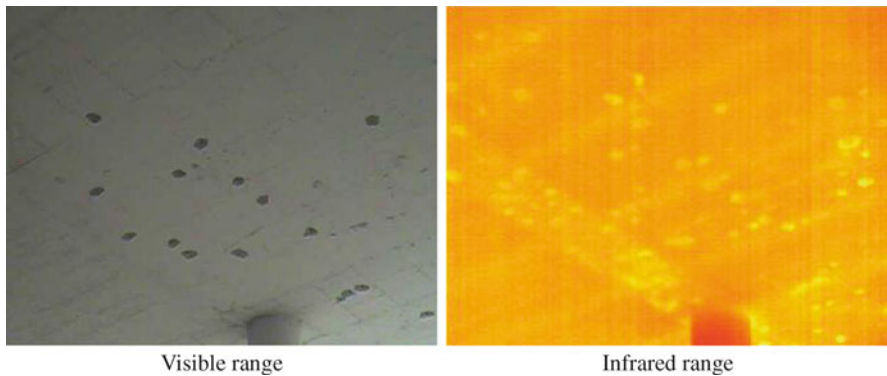


Fig. 5.5 Image of underface of an aqueduct (Gilles et al., 2007). Spalls pits are indicated by light shaded spots on the infrared image

is possible. Figure. 5.5 shows the detection and localization of spallings (few square centimeters) associated with the bad quality of spacers. These disorders are spread out spatially and the issue was only to locate altered zones within a 59m x 290m surface.

2.2.2 Characterization with depth

The sharp characterization of discrete interfaces in concrete is related to the determination of (1) the depth of interface, (2) the thickness of interface.

Depth of interface

After having detected the lateral location of alteration, the next step is characterization of its position with depth. This description is based on the material properties and must be considered as an inverse problem to be solved. A first approach consists in comparing the results with regards to their location. With impact echo, for instance, the calibration is usually made on a reference zone (known to be sound), then, further results obtained elsewhere are compared with the reference signal (Fig. 5.6).

The estimation of the interface depth from the measures values can also be performed by an inverse analysis. This approach has not been very successful up to now. One main reason is that field concrete presents variable properties that cannot be considered in models used to inverse measurements. Therefore, results analysis does not yield accurate evaluation of some characteristics of alterations. That is one of the main concerns regarding the assessment of the interface depth from the surface. The concrete is generally variable with depth (from the surface to its heart), due to the skin effect, but also to carbonation and other climatic/environmental processes or water content. These variations enhance the complexity of assessing parameters with depth due to the creation of bias. The technique effectiveness with regards to variation of concrete properties is a first consideration in the limitation of the accuracy/reliability of the diagnosis.

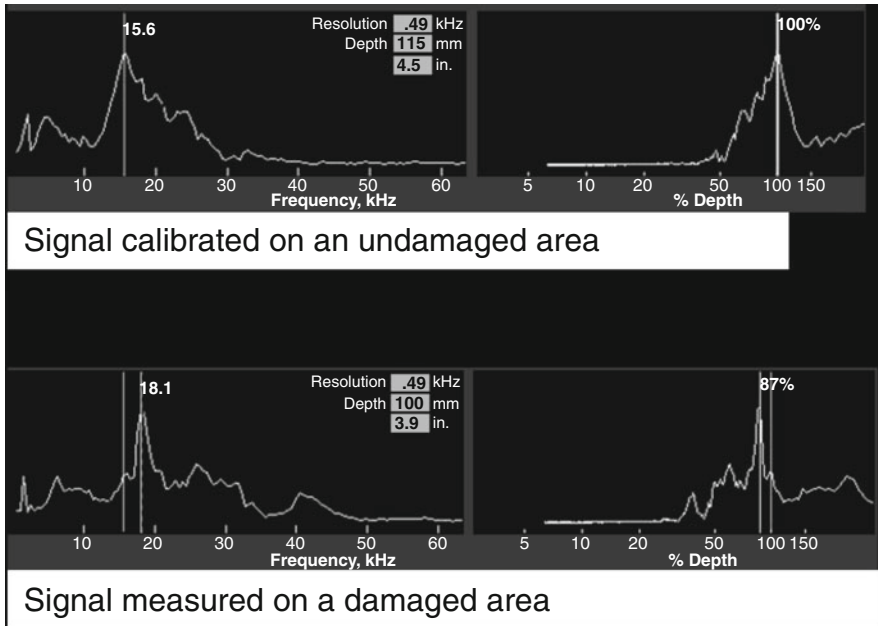


Fig. 5.6 Amplitude vs. frequency of signal for the impact echo technique. (This result allows detection of delamination within a concrete slab)

Another limit of inverse analysis can be the need, to know the exact measurement “input”. With infrared thermography, for example, the natural heating or cooling of the environment (exciting thermal behavior of the concrete structure) is not mastered by operators during assessment. The work conducted with impulse infrared thermography aims at improving the interpretation: In this approach, operator controls the energy impulse. Then, the measurement of the response can be interpreted in terms of damage characteristics, such as the depth.

Thickness of interface

A flaw is detected because its physical properties differ from the surrounded concrete. The contrast is influenced by the physical properties of the flaw, relatively to surrounding material; but also by the volume of the flaw. For instance, considering two delaminations with the same physical properties, the thicker flaw is more easily detected than the thinner.

In favorable cases, the thickness even if it is not directly detected, can be approached: the parameter influences the final response by increasing the contrast.

For example, crack detection with electrical resistivity is possible due to the sharp electrical contrast between the crack and the concrete. The width of flaw can be “viewed” (from electrical criteria) as a variation of the material filling the crack; however both elements cannot be distinguished. Also, combination of filling material

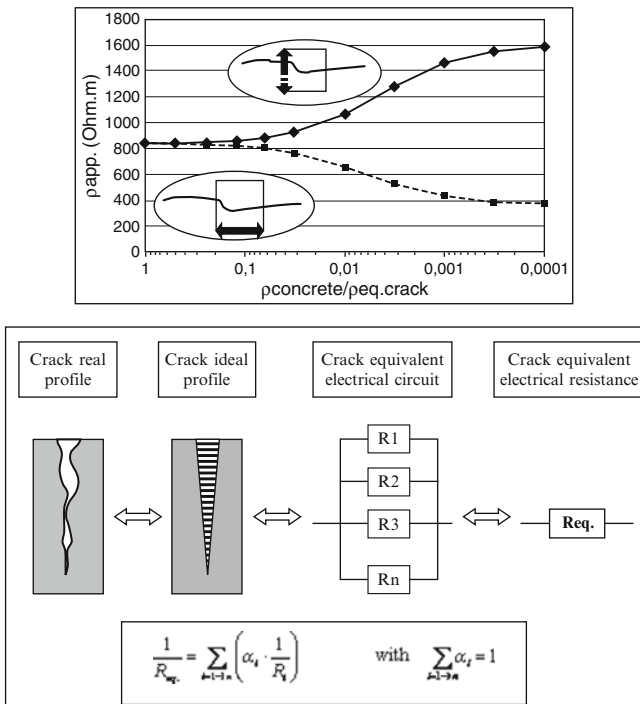


Fig. 5.7 Apparent resistivity depending on resistivity of the crack. Numerical results on resistive crack, and analogical model corresponding (Lataste et al. 2003(2))

an crack geometry can be expressed in term of electrical resistivity, stated as the “equivalent resistivity of the crack” (Fig. 5.7).

2.3 Why it is difficult?

The first reason may appear obvious: internal interfaces in concrete structure are not visible from the surface. For engineer and managers, the first problem to be deal with () is the detection of the damage, then its location and characterization. Techniques that have been currently proposed allow either a quick detection of alterations, or a sharp description of the damage (the second being slower than the first). It does not seem possible actually to obtain both results with a single technique.

Of course, the issue of debonding detection is based on the contrast of the physical property measured by the ND technique: In other words, a delamination can only be detected if the contrast of the physical property that are measured is above the technique or equipment resolution.

The effectiveness to detect and characterize flaws with NDT, depends on the capacity to identify the “signature” of the defect on measurement. This can be done

if 1) the signal is stronger than the measurement noise (this consideration is explained above, and will not be more developed here) or 2) the data processing allows highlighting it. The direct model (analytical or numerical) is reliable enough to reach to the measurement response, for given hypothesis. Inverse analysis consists of the calculation of direct problem with hypothesis on input values. Then, by iterative steps, and improvement of the inputs, one tries to converge to a solution where the lowest gap between the measured and calculated values. This is done according to inversion methods, and in the range of uncertainties. The final result is a combination, derived from the hypothesis used for calculations, of probable characteristics of the material (physical, geometrical...) that can explain what was measured. One of the main difficulties is the knowledge, or at least, the calibration of the direct models: How to be sure (or even to control) of the reliability of the hypothesis used for direct model? How to identify the bias effect from the data that are looked for? How can the model take into account the interaction between the influencing parameters? Another issue is the mathematical technique used to find the better mathematical solution, or more practically: how to converge quickly towards the optimal solution?

The technique resolution and the ability for engineer to represent the final results can also be improved. Some developments for sharp data imaging may improve the capacity for engineer to identify flaws. The visualization of structures or geometries associated with classical damage patterns can influence the interpretation of measurements. It is common with radar investigation to represent the layer thicknesses in pavement in 2D, with commercial softwares used for data processing.. Another example is tomography, which yields a 2D colored picture where one seems to ‘view through material’, helping engineers to understand the results. Representation of the results in term of complex parameters only understood by specialists limits the interest of the techniques: for owners who want to understand the conclusion of evaluation, and also for engineers who want to use the results even if they are not NDT specialists. Some developments are in progress in this field of results representation for easy understanding, as proposed by Mayer *et al.* (2003) who have been working on SAFT for radar signals, or Gucunski *et al.* (2009¹) with regards to impact echo.

Visualization and imaging of results are in great demand for practitioners and engineers in charge of inspection. Recently the civil engineering community has identified this need in a general manner. This supports the new TC RILEM “On-site measurement of concrete and masonry structures by visualized NDT” (led by Prof. Masayasu OHTSU; see <http://www.rilem.net>).

3 Description of Techniques

3.1 Common techniques

Most techniques presented in this document can be used to detect delaminations. Many have been tested on real cases (on site) and have proven their sensitivity to delamination. According to experts, the principal development that is needed

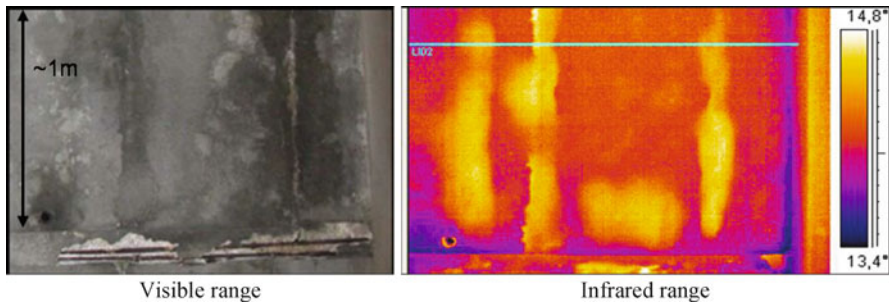


Fig. 5.8 Investigation of under face of a concrete slab of bridge using passive infrared thermography (Naar, 2005). Lighter shaded zones in the infrared image (right) (up to 14,4°C), correspond to spalled regions

remains progress toward the inverse problem, either for assessing the depth of delamination (ground penetrating radar, or infrared thermography), or thickness. The issue of the exact geometrical limit of delamination can be raised for the infrared thermography, which appears to be the fastest method for the detection and location of damage in concrete.

3.1.1 Thermography

Thermal techniques (infrared thermography involving active or passive way) are common techniques used to detect delamination and debonding in concrete. A standard describes the use of passive infrared thermography to detect delamination in concrete bridge decks

ASTM D4788-03: Test method for detecting delaminations in bridge decks using infrared thermography.

The main limitation of this technique is the depth of flaws: when delaminations are too deep inside, thermography is not effective at detecting delaminations. For instance, the domain considered in the standard is concrete deck with concrete overlay as thick as 10cm:

One concern regarding this technique is that the thermal image shows only a surface view. The location of the subsurface flaw can only be localized in two dimensions, Fig. 5.8. The resolution of the measurements is related to the number of pixel per image, and depends on the distance between the camera and the investigated surface. The depth of the defect (i.e. the third dimension) requires locating the true position, which is unknown.

A second concern is the temperature contrasts: measurement conditions have to be convenient to flaw to be detected. It depends on the resolution and accuracy of scanner used and also on temperature contrasts. The structure must be warm enough to radiate heat in an enough wide band for the scanner to detect. (Alt 1996). The aim of any thermographic investigations is to detect hidden flaw (Fig. 5.8), and there is

no result obtained from inversion (depth of bond...). Generally, the required information is only relative, and no calibration is needed.

Generally the camera accuracy is about $0.08 - 0.1^{\circ}\text{C}$. Authors consider that the critical temperature difference between sound and damaged areas should be approximately $0.2 - 0.3\text{ C}$ to allow detection (Clark *et al.*, 2003). This difference between sensors and true measurements is due to the external influences. Attempting to limit these, numerous considerations have to be taken into account prior to investigations (ASTM D4788-03): range in external temperature, range for wind, specific process to avoid shade on the investigated surface (i.e. drying the zone 24h prior to test), etc.

Operators have also a significant effect: the standard also reports that tests performed with several operators on the same structures, materials, and conditions lead to a variability range of 5% (ASTM D4788-03).

Work conducted on active thermography allowed determining a threshold for flaw detection. The results can be extended to passive thermography. It is given that to be detected, a defect must be closer to the surface than twice its diameter (Maldague, 1990). This is related to the equation:

$$t \approx (z^2 / a) \text{ and } PC \approx (l / z^3)$$

where t is the observation time, z the depth of delamination, and PC the contrast loss; and with a the thermal diffusivity ($\text{m}^2 \cdot \text{s}^{-1}$) $= k/cp$, and k the thermal conductivity ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), c the specific heat ($\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$), p the density.

In conclusion, the technique is easy to use, easy to read (result is an image depicting surface temperature), allows large surface to be investigated in small periods of time, and is contactless. The main limitations are the cost of the camera, and the fact that, with passive measurements, data inversion cannot be performed to provide results with depth. Furthermore, environmental conditions have great effects on heating process and on measurements. For example, a long-term investigation may be carried out during sunny days followed by raining days. It has also been shown that wind can influence the temperatures that are recorded.

3.1.2 Mechanical wave techniques

Measurements of concrete properties by mechanical wave techniques encompass a broad range of methods. Some of them are already well-known and broadly applied for the characterization of interface and debonding: pulse echo, impact echo, impact hammer, SASW and chain drag.

Ultrasonic pulse (US)

The method called pulse velocity (UPV) method consists in measuring the time of flight of an ultrasonic wave pulse between two transducers. Most commonly, this method is set up with a direct transducer arrangement, where both sides of structural

element are accessible. The increase of time can be a reliable indication of an internal defect (e.g. debonding) along the wave path in the concrete. Several standards (listed below) exist for the assessment of concrete with pulse velocity, but the detection of internal defect detection has not been standardized yet:

EN 12504-4, Determination of ultrasonic pulse velocity, testing concrete- Part4, 14p.

ASTM C597: Test method of pulse velocity through concrete

BS1881, part 203-1986: Recommendation for the measurement of velocity of ultrasonic pulse in concrete.

When an ultrasonic signal is sent, reflected and collected from a single surface, the technique is called Ultra Pulse Echo (UPE). If one measures the reflected signal energy, then it is also possible to estimate the depth of the interface or the flaw. Another approach, coming from geophysical fields, monitors multiple wave pulses reflected from the interface: the time of flight values for different offsets are measured. The waves refracted on interfaces can be used to assess the depths of bounded interfaces when the wave velocity increases with depth. This approach has been used on fire damaged structures, for instance (Abraham and Dérobert, 2003). Soundings that were performed on several parts of a tunnel allowed distinguishing three alteration levels and assessing the thickness of concrete layers. The sound zone (SZ) was studied as the reference for further comparison. A moderately damaged zone (MZ) and a heavily deteriorated zone (HV) are presented in Fig. 5.9. Results shows that MZ is surprisingly more damaged than HZ in term of thickness of the delaminated layer (13 cm in MZ instead of 9cm in the HZ), as well as in terms of residual properties of surface concrete (wave velocity is 2260 in the sound zone, 870 in the MZ, and 1130 in the HZ).

Both resolution and investigation depth depend on the generated frequencies: in concrete, classical frequencies are 50-200 kHz in pulse echo mode, so the investigation depths are about 10-50 cm and the resolution is about few centimeters. Higher frequencies lead to higher resolution, but reduce the investigated depth due to wave diffusion on the aggregates and energy attenuation. It must be pointed out that the surface of the flaw is detected, not the whole body.

Impact echo (IE)

The method essentially is a spectral analysis of local vibration response of a structure. Fig. 5.10 presents recorded data (time domain plot) and processed results (frequency domain plot) allowing the interpretation: The technique is used either to detect delamination or debonding by comparison of measurements made on solid concrete, or to calculate the interface depth from the main frequency peak. In the second case, the accuracy of the technique is partly associated with the calibration of the compression wave velocity (the P-wave),

ASTM-C1383: Test method for measuring P-wave speed and thickness of concrete plates using the impact-echo method.

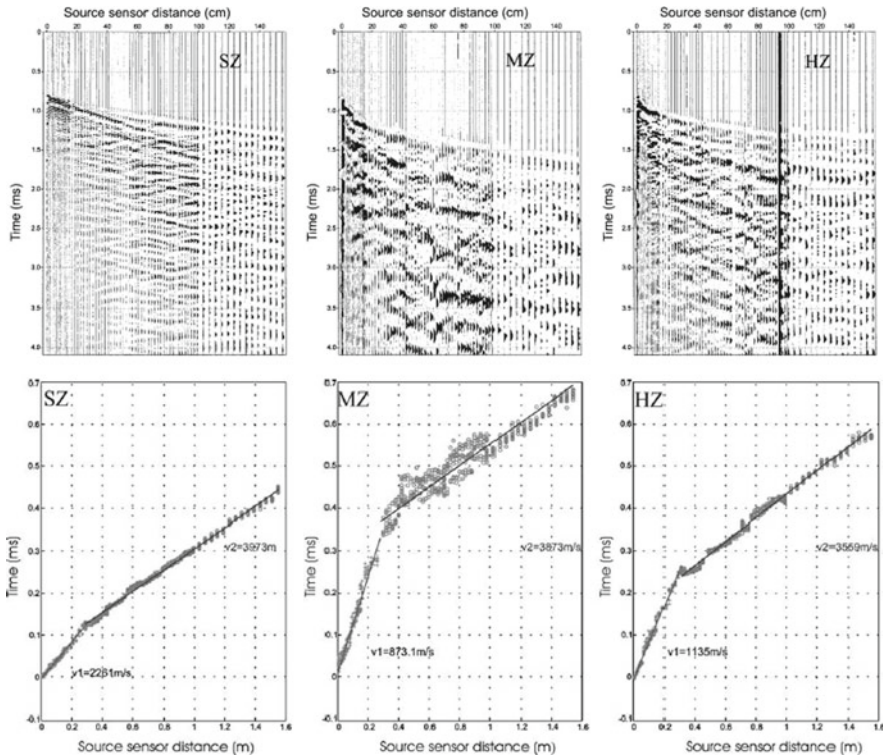


Fig. 5.9 Recorded seismograms and time versus offset plots on fired concrete tunnel wall (Abraham and Dérobert, 2003)

The depth of a defect is approximated from the impact-echo resonance frequency according to the relation $d \approx v/2f$ with d the defect depth, v the compression wave velocity (P-wave), and f the main peak of frequency spectrum. Note that this formula is appropriate only if the impact-echo thickness stretch mode of vibration is excited by the testing set-up. This formula is not appropriate if flexural modes of vibration are set up, which are normally associated with debonds close to the surface or with large areal extent.

Based on an analytical and experimental study, the size of the smallest detectable flaw can be defined by its lateral dimensions (for a planar crack or void) exceeding 1/3 of its depth (Sansalone and Street, 1997). The influence of the bond quality has also been studied, numerically and experimentally. Results are that IE can be used only to detect areas where interfaces are partially debonded or are about to debond (tensile strength to be negligible). The quality of debonding (delamination, interface with loose of particles, micro cracks...) does not significantly affect the results (Lin *et al.*, 1996). The unbonded fraction at the interface affects IE response as follows (Lin and Sansalone, 1996): the depth of interface with zero unbonded fractions cannot be determined; unbonded fraction up to 20% enables measuring a significant

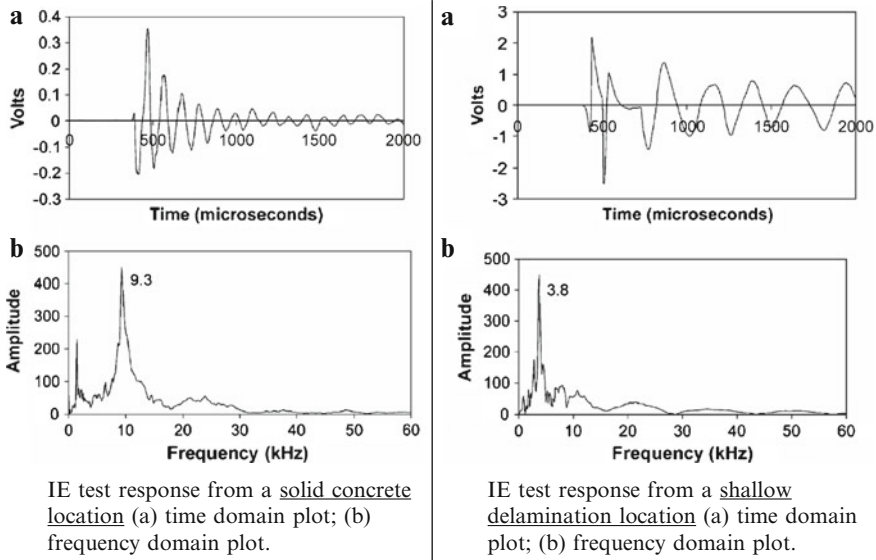


Fig. 5.10 Impact Echo response (Scott et al., 2003)

echo peak (which amplitude increases with unbonded fraction); unbonded fraction up to 80% responds similar to a crack.

Error in thickness is mainly linked to the error made on the wave velocity determination. Considering various measurement conditions (frequency, surface roughness...) errors are less than 4% if measurement process is adapted (Sansalone *et al.*, 1997).

Tinkey et al (2007, 2008) and Olson (2010) reported on developments in impact echo scanning for more rapid testing and imaging of internal flaws such as voids, cracking, delamination, etc.. Studies were conducted on bridge concrete walls with a hand held impact echo scanner for post-tensioned ducts and on bridge decks with a bridge deck impact echo scanner, respectively.

Impulse response test method

The impulse-response uses a low-strain impact produced by an instrumented rubber-tipped hammer in order to generate local vibration resonances through the investigated element. The impact causes the element to move (vibration in the bending mode for delamination and interface parallel to the surface). A transducer placed next to the impact point measures the amplitude of the dynamic response. Normally, the transducer is a geophone type, which provides surface velocity as an output parameter. The hammer load cell and the velocity transducer data are used together in the frequency domain. Velocity divided by the force leads to the “mobility” as a function of frequency.

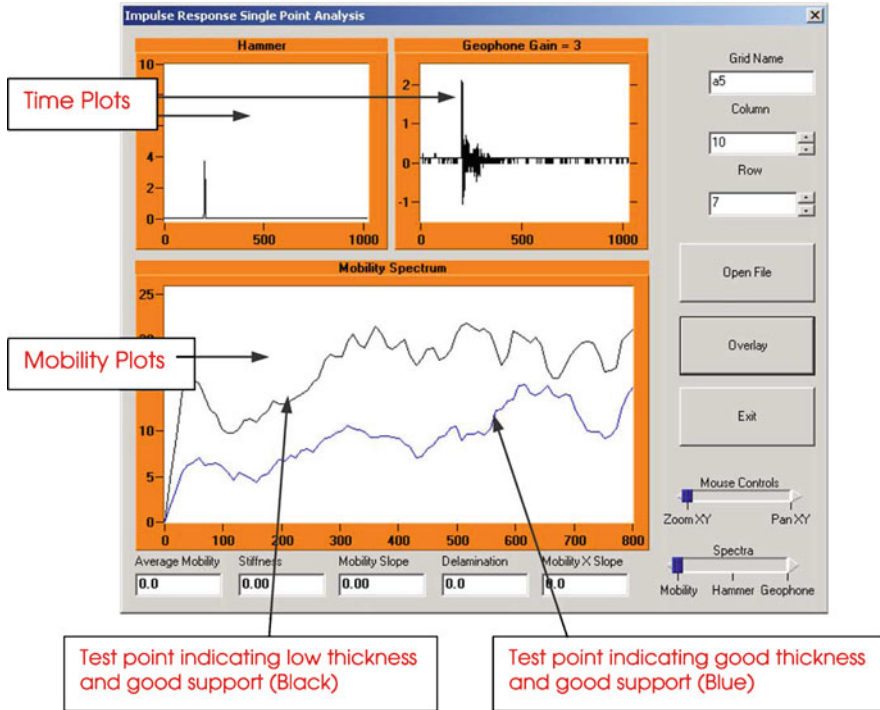


Fig. 5.11 Typical output of impulse response test. The mobility plot (in m/s/N) in function of the frequency (in Hz) allow to differentiate sound zone from altered zones (Davis et al., 2005)

The technique, which has been adapted from pile integrity testing, can be used on structures to detect voids under lining, debonding of claddings, and delaminations. The mobility versus frequency curve is drawn, yielding the dynamic stiffness and the mobility range, for the tested element (Fig. 5.11). Parameters extracted are:

- the dynamic stiffness (the curve slope for low frequency),
- the frequency interval between the peaks, mainly function of the thickness of the tested element;
- the first peak mobility (for low frequency) / average mobility ratio, also called void ratio, which is the parameter used to detect delaminations.

Davis et al. (2005) (Fig. 5.11), presented two case studies where impact response has been used to detect and localise void behind a concrete lining. Mobility study allows characterising the loss of support beneath the lining: the ratio of the amplitude of the low frequency peak (below 100Hz) to the average mobility of the slab (assessed for frequency in the range 100 to 800Hz), increase in case of void. The examination of the stiffness is also used to detect delamination: increase of dynamic stiffness traducing delamination.

A similar approach, based on the analysis of acceleration of the tested surface excited by a soft tipped hammer, was reported by Sangiorgi et al. (2003). The

authors studied the response of impact hammer tests on full-scale field trials. The tests were performed for various qualities of bonds between concrete layers. The objective was to evaluate the bond between asphalt layers in a road pavement with a fractal analysis of the signal. It can be seen from the response of the bonded system that the acceleration is heavily damped. Conversely, the response of the debonded system shows high frequency vibrations in the measured acceleration response and the damping is lower than on bounded system. This is due to vibrations induced in the surfacing layer because it is not bonded to the layer below.

Surface waves

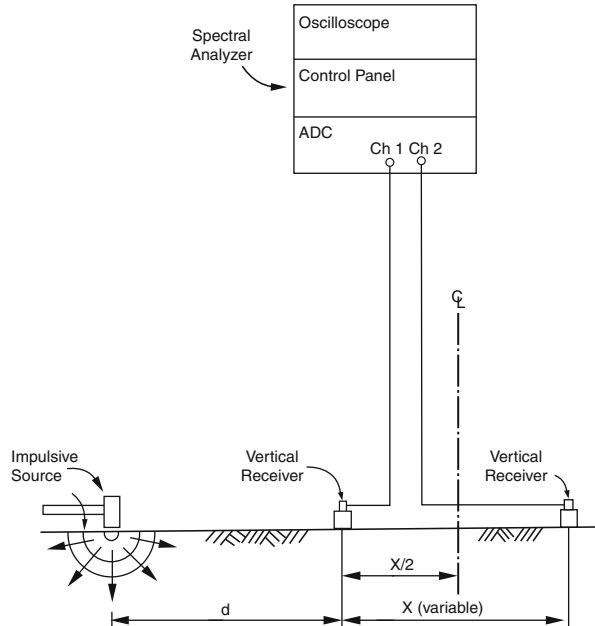
Nazarian (1984) has adapted the surface wave technique from the field of geology to the field of concrete structures. The technique called Spectral Analysis of Surface Waves (SASW), allows studying the surface waves velocity as function of wavelength. The principle is to create an impact on the surface with a hammer and monitor, in time domain, the surface wave velocities with two receivers (Fig. 5.12). Surface wave velocity varies with frequency in a layered system if the velocity in each layer is different. This frequency dependence of velocity is termed *dispersion*. The plot of surface wave velocity versus wavelength is called a dispersion curve. The material property variations with depth can be estimated from an inverse analysis of the dispersion curves. In fact, SASW is not a suitable tool for studying delaminated concrete. In case of delamination wave amplitudes are higher than those measured on sound concrete, and the spectral analysis is not needed for results interpretation. SASW is adequate for studying speed variations across successive layers in terms of depths. SASW then could be used for debonding case with partial contact. This approach has been used to assess bond quality where concrete layers can be found (Sack and Olson, 1995).

This technique is suitable for shallow investigation. The obtained results depend on the spacing of the sensors, the size and the mass of the hammer used to create the impact (which governs the energy content and the impact duration; so it partially monitors the depth of investigation).

SASW method can predict layering (by stiffness variation) within 10 % but the boundary between different layers with similar stiffness cannot be distinguished by SASW (Nazarian, 1984). Studies can be found on the use of SASW for delamination detection in concrete structures. One of them reports the case of a dam exposed to freeze-thaw, and presenting shallow delaminations (Sack and Olson, 1995). The results show the distinction between two layers. The first is the thin layer of shotcrete, characterised by a high waves speed. This surface layer on the outside is over the second layer, deeper, constituted by damaged concrete. This deeper material is characterised by slower waves speed. The condition predicted by the SASW method agreed with the repair history and coring data.

The calculated dispersion curves may show significant fluctuations due to different surface waves modes participating in the signal (Aki *et al.*, 1980)(Tokimatsu *et al.*, 1992)(Karray and Lefebvre, 2000). It breaks the basic assumption of single

Fig. 5.12 Spectral Analysis of Surface Waves testing configuration (Nazarian, 1984)



mode propagation often implemented in the SASW method, which causes additional complication with this method. The additional modes may cause misleading conclusions. In that case wave-field transforms, as proposed by more advanced methods, such as the FK method (F: frequency, K: wave-number) (Al-Wardany *et al.*, 2009) and MASW (Ryden *et al.* 2004), have been applied to improve these problems associated with SASW. It allows a proper recovering of the dispersion curve required to assess the concrete condition.

Chain Drag and hammer sounding

This basic technique may be considered as an acoustic sounding. However, it should be considered as a practice rather than a technology. A standard drives the investigation:

ASTM D4580, Standard practice for measuring delaminations in concrete bridge decks by sounding.

This procedure basically consists in dragging a chain or tapping a metal rod or hammer over the bridge deck surface. The detection of delaminations is accomplished by the operator noting dull or hollow sounds. This technique is widely used in North America, mainly for corrosion induced delamination on concrete bridge decks. This is a very low cost technique, allowing extensive application. The depth of the defect cannot be determined unless a core sample is removed. Chain drag is

a tool highly adapted to detect progressed delamination but its ability seems rather limited in detection of initial delaminations (Gucunski *et al.*, 2009²).

Inversion of the results cannot be done with this technique. Delaminated areas are marked off investigated surface. An approximate percentage of the total area delamination is then determined (Alt and Megger, 1996).

A study by Scott *et al.* (2003) highlighted the high variability associated with this technique: the delamination percentage estimate in surface varied between 2 to 69% (The variability is strongly related to operator experience and skills. The authors recommend improving the training of inspectors and suggest to inspectors to accurately document their results.

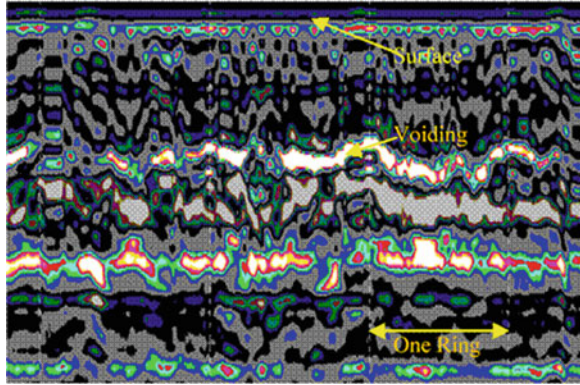
Some developments have been tested with approach similar to Chain Drag. Several investigators report hammer tapping investigations performed with a hammering trolley (Felicetti, 2008, Popovics *et al.*, 2009). A wheeled system pilots the impacts, blows are recorded by microphone connected to a lap top via an audio-card. The data processing, which is very similar to the impact echo approach, allows detecting the frequency peaks (i.e. the sounds) corresponding to altered and non altered slabs. Interpretation of data is linked to thresholds in the frequency domain. Recording and automatic data treatment decrease the importance of operators, evoked for classical chain drag.

3.1.3 Ground Penetrating Radar (GPR)

The sensitiveness of radar for detecting delamination or debond strongly depends on the antenna frequency. When a beam of microwave energy is directed at a reinforced concrete slab, a portion of the energy is reflected at the surface of the concrete, and the remaining energy is refracted across the interface. The polarity of the reflected signal differs whether the delamination is empty or filled with water (due the permittivity contrast relatively to concrete value). When the concrete slab is delaminated, usually at the level of the top mat of reinforcement, there is an additional reflection from the deteriorated section. This additional reflection is as an indicator of the presence of a delamination in the concrete slab interface.

Radar is more adapted to detect large voids than delaminations (Fig. 5.13). Scott *et al.* (2003) tested radar on site (antenna of 1.5 and 2.4 GHz) and did not obtain consistent response to delamination. According to them, this technology may mature to allow delaminations to be detected. With a 1.5 GHz antenna adapted to concrete, the wavelength is about 6 cm, so the resolution is 3cm (about half the wavelength). Therefore, with this frequency, radar could detect delamination of few millimeters thick for strong electromagnetic properties contrast between concrete and the flaw. Radar could also detect delaminations and interfaces by their indirect effects on local properties when it is associated with a local moisture increase for instance. The concrete properties can be different close to the flaw, than further, modifying the electromagnetic wave propagation (in terms of attenuation or speed). The flaw can then be indirectly detected. An example has been given by Barnes *et al* (2008) where authors used reflected amplitude provided by radar to map moistened part of a bridge, in relation with corrosion induced delamination.

Fig. 5.13 Results of GPR investigation to characterize voids behind precast elements after grout injection (Davis *et al.*, 2005)



As many techniques based on wave propagations the main limit of GPR is the relation between the size of flaw and its depth; in other words, the measured resolution vs the depth of investigation. It has been shown that, in case of delaminated repaired areas at a prestressed concrete bridge, a clear reflection could be detected. Figure 5.14 displays three radargrams recorded along the same trace with a length of about 2.5 m on top of a prestressed concrete bridge. These radargrams were recorded with the 900 MHz antenna (top) and in two polarisations of the 1.5 GHz antenna (middle and bottom). The backside reflection, the position of the reinforcing bars as well as four tendon ducts can be easily detected. In the bottom radargram, where the polarisation of the electric field of the antenna was oriented perpendicular to the rebars, instead of the rebars only a continuous reflection band is visible. This reflection band could be related to a delamination, which was confirmed after opening of the area in a destructive way.

Like acoustical techniques, GPR is based on wave propagation and its power can be limited on strong interfaces: In general, it can only detect one defect at any given location. As the electromagnetic pulse travels through the concrete element and strikes an anomaly, most of the pulse energy is reflected back to the receiver. Only a small amount of electromagnetic energy is transmitted through the defect. For instance, if a pulse struck a de-bonded area, the amount of energy passing through the de-bonded area would be so small that a delamination directly under the de-bonded area would not be likely to be found. The energy reflected from the second defect, the delamination, would probably be too small to be detected or positively identified as coming from a delamination, as presented by Alt and Megger (1996). Finally, it is possible to detect the interface, but the technique does not allow sharp characterization (Colla *et al.*, 2002).

The response of radar in relation to several kinds of interface on a masonry wall is shown in the table of Fig. 5.15 – (Maierhofer *et al.*, 2001).

Clemena (2004) reported two studies conducted on radar accuracy to detect delamination in bridge decks ((Cantor *et al.*, 1982) and (Clemena, 1983)). In the first study, 90% of the area that was predicted by radar to be distressed was confirmed as such by coring. 91% of the area that was predicted to be sound concrete was also confirmed. The second study involved a comparison of radar surveys performed on several bridge

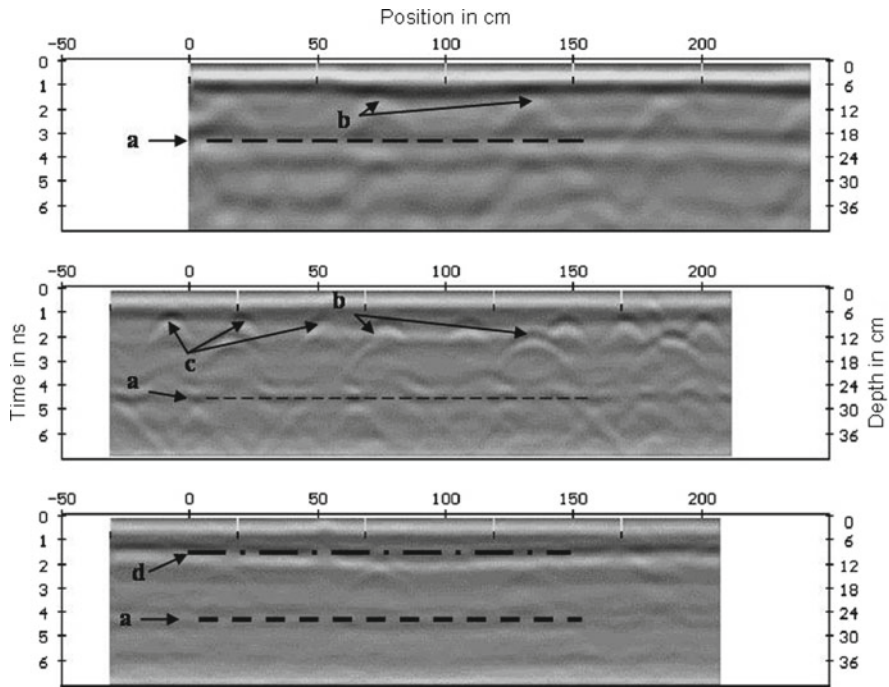


Fig. 5.14 Radargrams of a trace recorded with different antennas: **Top: 900 MHz antenna**, polarisation perpendicular to the rebars. The backside reflection (**a**) as well as the tendon ducts (**b**) are displayed; **Middle: 1.5 GHz antenna**, polarisation parallel to the rebars. The backside reflection (**a**), the tendon ducts (**b**) and rebars (**c**) are visible. **Bottom: 1.5 GHz antenna**, polarisation perpendicular to the rebars. Only the reflection from the delamination is visible (**d**)

Results of the investigations of the different physical models

Problem	Use of radar	Accuracy and limits
Determination of moisture content	Measurement of travel time of the backside reflection and determination of permittivity, comparison to calibration curves	Between 1 and 5 vol% depending on the absolute value
Determination of moisture distribution	Measurement of travel time	No absolute values
Detection of joints in masonry made of full bricks	Possible with the 1.5 GHz antenna, unfilled joints can be detected as small hyperbolas	Low moisture and salt content is required
Detection of joints in masonry made of hollow bricks	Polarisation of the electric field of the antenna must be parallel to the joints	Low moisture and salt content is required
Control of grouting of unfilled joints	Grouting can be investigated by comparing the radargrams of empty and grouted joints	It is not possible to obtain quantitative data
Detection of layers of different materials	From the travel time, intensity and phase of reflected signals information can be gained about the permittivity of the different layers	It is not possible to distinguish between air, dry and wet mineral wool (permittivity of dry and wet mineral wool is too low)
Detection of large air voids	Large air voids in masonry can be detected easily from time slices	The minimum air voids, which was detected, had a size of 800 cm ³ . No smaller voids were investigated

Fig. 5.15 Evaluation of radar capabilities relative to several interfaces (Maierhofer *et al.* 2001)

decks prior to the removal of overlays. It was found that, on an average, radar detected only 80% of the existing concrete delamination, while falsely identifying 8% of the area tested as delaminated. In these studies, radar failed to locate some of the delaminated areas, especially those that were only 1 ft (0.3 m) wide or less; partly because the strong reflections from the rebars tended to mask reflections from delaminations, which would be relatively weak in dry concrete. Barnes et al (2008) report further improvements in the identification of delamination and corrosion with GPR on decks by considering the depth of reinforcement and signal attenuation thresholds.

3.2 *Special techniques*

3.2.1 **Electrical resistivity (ER)**

The sensitivity of ER to interface is linked to the disturbance of the investigated volume. In the case of interface (between two materials with different resistivities) or void, the electrical current circulates differently than for a homogeneous material. Figure 5.16 shows an example of the electrical response on a damaged slab on site: one can see that in this case, cracks and delamination can be detected since the resistivity increases over the delamination. The final interpretation and the identification of delamination and cracks are based on the analysis of electrical anisotropy (Lataste *et al.*, 2003(2)).

Alt (1996) reported another case involving the detection of delamination below asphalt layer on a bridge. The measurement was performed according to ASTM D3633, allowing the characterization of the imperviousness of the membrane to water. It was not possible with this method to diagnose concrete, but the conclusion on the data interpretation was interesting: the evaluation is quite subjective, some criteria (based on resistivity values) are proposed but the suggested solution seemed to be oriented on a monitoring of resistivity according to the variations of environmental conditions.

The interpretation of resistivity variations combined with the study of electrical anisotropy variation allows detecting and locating the delamination. According to the size of the measurement device, it is possible to modify the investigated volume, then to investigate concrete to a depth of about 5-6 cm. This increase is associated with a decrease of the resolution.

The electrical resistivity increases due to an interface can be estimated according to the methodology developed in Lataste *et al.* (2003(1)) on edges influence on resistivity measurements. Indeed, if one considers delamination as a particular edge, this approach gives an optimistic range of the resistivity ability. An ideal delamination (perfect, without contact between wall filled with air, and infinitely laterally extended); and considering a noise level about 10% on resistivity measurements (classical mean values on site), can be detected and identified if:

$$z/a < 1;$$

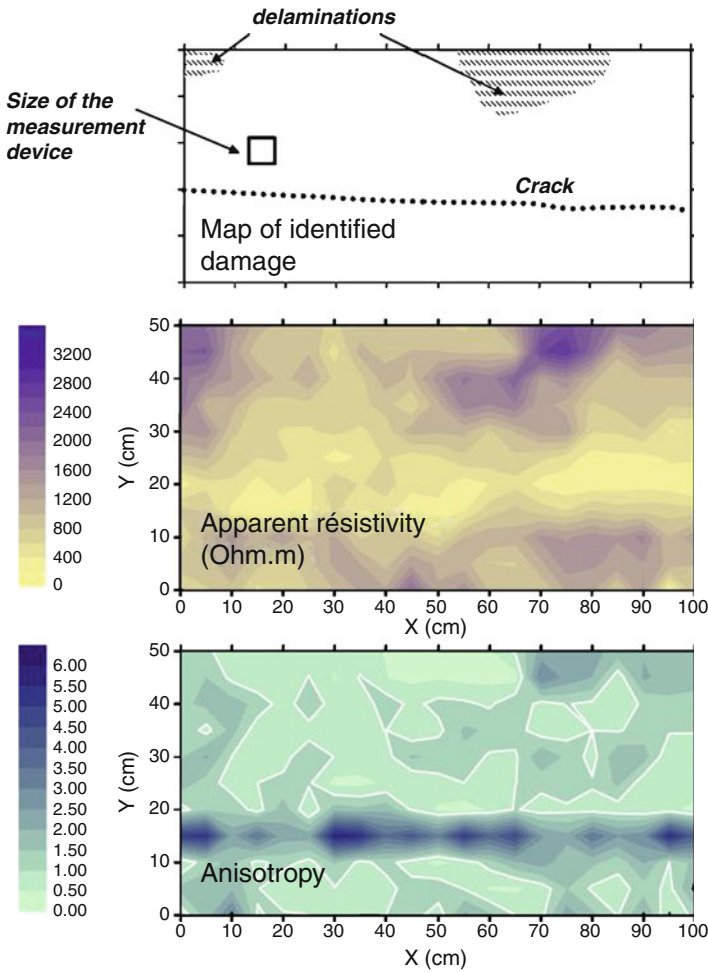


Fig. 5.16 Electrical resistivity used to detect and identify a delaminated zone in a concrete slab (Lataste *et al.* 2003(2))

with z the delamination depth from the surface, and a the size of device (i.e. the distance between electrodes for a four probes square device).

This threshold is not a function of the resistivity, but depends on the resistivity contrast between concrete and interface. It considers only a resistive interface. For conductive interfaces, the depth of investigation increases, but the effect on the measured apparent resistivity is less important. The threshold of $z/a < 1$ is a reliable order of magnitude of the lateral extension, for an interface with at least a .

3.2.2 Impulse thermography (IT)

This technique presents the same advantages and limitations than passive infrared thermography. The difference lies mainly on the thermal solicitation rather than data processing. The need to heat the investigated surface leads to practical problems regarding the homogeneity of heating and the heating apparatus (energy supply, investigations speed...). This pulse of energy can be deployed with lamps, flashes, laser beam, and air or water jets. A “warm” or a “cold” stimulation is possible since the important point is the temperature differential that is generated (Maldagues and Marinetti, 1996). The duration of the pulse is variable from μs , ms, to s depending on the thickness of material to be probed and its thermal properties. Impulse thermography allows results inversion, to go farther in flaw characterization than with passive thermography.

The investigation depth increases significantly with impulse thermography, and the inversion of results is possible. Maierhofer et al. (2002) combined experimental and numerical approaches considering voids up to 10 cm in depth. The heating time of 10 minutes allow recording temperature contrasts, which were variable during the cooling time (over 60 minutes). The value of heating time and the numerical approach enabled the determination of the depth (concrete cover) of the single defect.

4 Global strategy of approach towards diagnosis

The large range of ND techniques allows engineers coping with the issue of structural diagnosis. Whatever the flaw that is looked for, several techniques are more or less sensitive to its “signature”. Engineers have to choose the best technique with regards the context and the alteration. Then, they have to use several methods in combinative manners in order to optimize the investigation, either in terms of efficiency, or in terms of accuracy.

4.1 Complementary techniques

Taking account of the broad range of acoustic methods used for de-bonding evaluation, the complimentary aspects of the various techniques (in term of size of the object looked for) will be discussed below.

Section 3.1.2 addresses the mechanical wave techniques, covering the methods based on the analysis of the vibration induced by a mechanical impulse, whatever the source (hammer, steel ball, piezo actuator, solenoid impactor, chain, toothed wheel, etc). Five mechanical wave techniques have been cited in the present chapter, namely ultrasonic pulse echo, impact echo, impulse response, surface waves and the chain drag.

In general, three aspects can be recognized for classifying the techniques.

- the type of excitation;
- the physical principle;
- the data processing technique.

The present classification is based on the way that the data are processed for interpretation (frequency domain analysis for the impact echo, time domain analysis for the pulse echo) and also by the manner that the wave motion is excited in the structure.

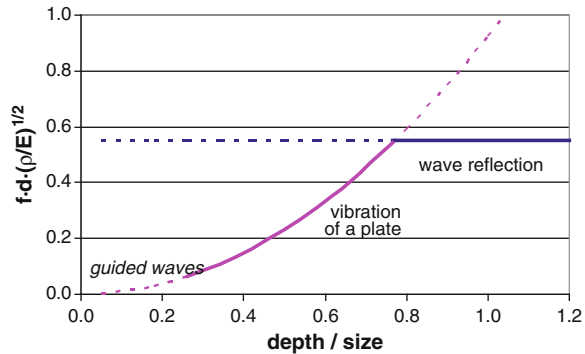
Regarding the type of excitation, these may be categorized on the basis of the frequency range and the nature of the pulses that are generated.

The classification based on the physical principle appears to be more robust: the way to implement a technique may change but the principle remains. The problem is to distinguish the principles that are being handled. Three possible schemes are proposed, depicting what happens in a structure after a mechanical pulse has been exerted.

- a) Propagation of mechanical waves through the structure: The wave (pressure or shear) is partly reflected and refracted by the interface and can be detected at the excitation point after a time delay (pulse velocity and pulse echo). Besides the interaction with the defect, the propagation of the waves is not influenced by the defect and the velocity can be assumed as a property of the investigated material.
- b) Propagation of mechanical waves within the delaminated plate: if the plate is delaminated (i.e. the surface and the top of the delamination are stress free) the dispersion curves corresponding to surface waves of the bounded media will switch to Lamb wave dispersion curves of the corresponding delaminated plate (guided wave from plates). Impact-echo and impulse response methods fall under this category, although it is possible to interpret the impact-echo vibrational response using a guided wave model (Gibson and Popovics 2005): impact echo resonance frequency corresponds to a peculiar resonance of the first symmetric Lamb wave mode where energy does not travel (zero group velocity). Specifically for the case of impact-echo, the modes of vibration that are mainly set up depend on the geometry of the debond. When the extension size of the debond is smaller than the depth, the impact-echo stretch mode is strongly excited, and the formula described in section 3.1.2 may be applied.
- c) Structural vibration of a plate: if the size of the defect is comparable or larger to its depth, the mechanical impulse activates the dynamic response of the concrete plate outlined by the delamination itself. The frequencies of the vibration modes of this plate are governed by the root of the ratio of the bending stiffness ($\sim \text{depth}^3$) on the mass per unit area ($\sim \text{depth}$). Hence, the frequencies are proportional to the delamination depth, and these frequency values will be significantly lower than the impact-echo stretch mode values (the impact echo rule where $f \sim 1/\text{depth}$). Furthermore, there are no closed-form equations to relate frequency to depth for the flexural case. In this latter case, the chain drag method does work, and ultrasonic pulse echo may be applied to estimate depth.

Providing a criterion for determining what physical principle governs the response of the investigated member would be of considerable help in determining the most promising technique to be used for a specific problem.

Fig. 5.17 Response of acoustical techniques in function of geometrical parameters of the fault



As a first tentative to separate the ranges pertaining to different principles the expected vibration frequencies of the impact echo (principle b) and of the vibrating plate (principle c) are plotted on the same graph (Fig. 5.17). To be more general, the frequency f is expressed in the dimensionless form: $f \cdot d / (E / \rho)^{1/2}$. This form is proportional to the depth of the delamination divided by a wavelength (d / λ), delaminated concrete cannot be considered as infinitely extended (relatively to wavelength). Indeed, in this case $V = (E / \rho)^{1/2}$; then $\lambda = (E/\rho)^{1/2} / f$. Where d is the depth of the interface, E is the Young modulus, ρ is the material density, f is the signal frequency, l is the wave length, and V is the wave velocity.

In this form the dimensionless frequency of the impact echo is a constant for any depths.

The shape of the defect is expressed by the ratio of the depth on the size (intended as the diameter of a delaminated disc) and the vibration frequency of the plate is a parabolic function of this ratio.

Figure 5.17 shows that, for shallow delaminations (depth < 0.75 size), the mechanism based on the plate vibration yields the lowest frequency and, probably, the strongest signal. Nonetheless, a smooth transition between both ranges is expected. This graph should also be adapted for guided waves, but no work has been done yet on this topic.

4.2 Use for better efficiency

Infrared thermography, impulse thermography and ground penetrating radar (GPR) appear to be techniques that are sensitive to both void and bond in concrete, and allow a quick investigation of large surfaces. Other methods (acoustic: ultrasonic pulse, impact echo) are efficient for a sharp characterization of geometrical parameters (depth, limits...). A combination of these two different types of technique can be used to optimize the investigation time.

A classical methodology consists in combining a first technique to locate potential damages in a short period of time, and to use a second more time consuming) to validate or to define more accurately its parameters. Some references in literature present case studies with such approach:

1. Abraham *et al.* (2003) considered a fire damaged tunnel, and characterized layers and delamination of the tunnel. GPR and ultrasonic refraction measurements were performed. Damages were a multilayer structure of material. Conclusions were oriented on the first detection of damage with radar combined with sharp characterization with ultrasonic pulse (more time consuming method).
2. Scott *et al.* (2003) tested GPR and impact echo on corrosion induced delamination on a bridge. Main results were: impact echo is a time consuming method which (in this case) was not always conclusive; GPR is faster and easier, but not accurate enough for detection.
3. Meola *et al.* (2005) compared the results of infrared thermography, ultrasonic pulse and electrical resistivity on a masonry element in laboratory. Cork diskettes and plastic bags were incorporated in the masonry. They were manufactured of three different diameters, $d = 40, 60$ and 100 mm; the thickness was approximately 1 mm for cork diskettes and 2 mm for plastic bags. A plaster layer of thickness varying from 10 to 55 mm recovered the wall. The conclusion was that infrared thermography was the faster and allowed efficient detection and location of delamination, ultrasonic pulse was more time consuming but allowed the detection of deeper delaminations, and electrical resistivity was not really efficient for delamination (sensitivity to micro-cracking, porosity...). Limitations and advantages were then considered with regards to measurement cadence and investigation depth.

4.3 Use for more information

Methods sensitivity to flaws is influenced by material conditions (moisture, chloride ingress...). The quality of the interpretation can be then limited by external parameters, who can biases measurement.. So the interest of investigation may appear restricted if the information obtained from measurement is not sufficiently accurate or sharp (in terms of depth of interface for instance, or geometry, or saturation degree). Repeated investigations on a same body with various non destructive techniques can be a way to obtain various informations due to sensitivity of the different techniques. The interest would be to have shaper diagnosis. Generally, such approach (i.e. investigation with several methods on a same structure) allows to rank techniques regarding their reliability, in function of damages, and for given conditions.

For investigations the use of several techniques aims at assessment of complementary information (when the different information contributes to complete results to improve interpretation). Redundant information obtained with different techniques is generally less interesting.

Some examples showing comparison of techniques on structures or test samples regarding the interfaces or delamination question are reported in literature:

1. Gucunski *et al.* (2010) assessed bridge decks subjected to induced corrosion delamination. The use of resistivity is associated with half-cell potential for corrosion assessment. Concerning delamination, they compared results from radar and impact echo: GPR provided information about deterioration of concrete and

likelihood of delamination; impact echo enabled detection and characterization of delamination deck.

2. Drdacky *et al.* investigated plaster delamination in laboratory with ultrasound, impact echo, impulse thermography. They compare results obtained with each technique, and their sensitivity on the test element.
3. Naar *et al.* (2005¹) use on site electrical resistivity and infrared thermography to locate delaminations and cracks on a bridge. The use of both techniques allows distinguishing both damages, but no quantification could have been done.
4. Uomoto (2003) tested the sensitivity of NDT techniques (infrared thermography, ultrasonic pulse, impact echo) to detect voids in an experimental slab. The accuracy of each techniques was assessed and compared with regards to their advantages and limitations.
5. Maierhofer *et al.* (1998) worked on brickwork on site and appraised the sensitivity of GPR and ultrasonic pulse. Results were compared. No evident combination could have been outlined in this case.
6. Karastathis *et al.* (2002) used different NDT to assess the bond in a dam. Techniques were Acoustic method (ultrasonic pulse refraction), electrical resistivity and GPR and measurements were performed on a tunnel in the dam. They allowed detecting defects (as honey combing due to water flows).. GPR allowed rapid detection of questionable zones, ultrasonic pulse allowed sharp description of them, and electrical resistivity was chosen to describe moistening condition of materials. The complementarities of three techniques lead to a diagnosis of the whole structure.

The above cases indicated that measurements on test samples are generally a procedure to properly assess performance of techniques. The complete knowledge of the material and flaw characteristics (its depth, geometry, location ...) allows building evaluation criteria to compare ND methods. It is also another way to identify promising combination from less interesting ones.

4.4 Use for better reliability

Techniques response to an alteration is function of the characteristics of the flaw (e.g. detection is impossible under the investigation depth of the technique). These ability ranges for a technique, can vary with the material condition. Considering that the material conditions can change along a structure, the technique performance can change along this profile. So the risk of non-detection of an alteration or, inversely, the risk of a false alert with only one technique is high. The use of several techniques successively is a way to limit such risks. This approach aims at improving the detection by non-destructive measurement session. The use of several techniques leads to more reliable results because each technique detects something. It also allows rejecting all zones without any detected flaw and suggests further investigation, or sharper analysis, in zones where results were not concordant. To optimize this strategy, the selected technique must be sensitive to uncoupled parameters, and should avoid any redundancy in the results. In other words, from the engineer's

point a view, this approach is interesting only if it limits the risk of misinterpretation. The following studies reports on combination for better reliability:

1. Alt *et al.* (1996), tested GPR (no information concerning frequency) and infrared thermography on a bridge to find delamination and debonding on concrete bridge decks with asphalt concrete overlay and membrane. The authors concluded that both techniques were not certain in finding and identifying subsurface anomalies. Authors wrote about the problem of detection threshold, and of errors in detection. They underlined the important state of deterioration of the bridge to explain the lack of very clear results with GPR and infrared thermography.
2. Colla *et al.* (2002) studied interface between a concrete slab and a sleeper embedded in the concrete slab during construction. The aim was to characterize the bonding condition between sleeper and slab, and to detect and locate voids. They use impact echo, ultrasonic pulse and GPR and concluded that: impact echo was very efficient, ultrasonic pulse was adapted to delimit the extension of defects, GPR was sensitive to defects (GPR distinguished good bonding from weak or no bonding, but cannot made difference between weak and no bonding). Both acoustic techniques lead to similar results in localizing areas of good and bad bonding and delamination.
3. Weil (1998) published a study on a field structure (a stadium dome). The investigation combined infrared thermography for location of delamination and impact echo for validation of first detection. The use of a second technique (impact echo) improved significantly the information obtained with the faster technique (infrared thermography).
4. Barnes *et al.* (2008) combined radar and chain drag to map and estimate accurately the delaminated surface ratio on bridge decks. The study was based on the analysis of the reflection amplitude of the radar signal, compared with chain drag and half-cell potential. It lead to improved efficiency regarding the estimation of the damage on field structures.
5. Gucunski *et al.* (2009² and 2010), carried out investigations on bridge deck with radar (2.6Ghz and 1.5Ghz antennas), impact echo, chain drag, ultrasound, completed with half-cell potential, resistivity, as well as coring. They compared all techniques and underlined, that there were some similarities with impact echo and radar (wave attenuation). They concluded on the recognition of the potential benefits of evaluating decks using a complementary radar-impact echo approach.

4.5 Case study

The case study below presents an example of technique combination. This case is not representative of the common approach, due to larger number of analysis done on a bridge, but it presents several techniques adapted to interface characterization by NDT methods (Gilles 2007).

The structure is a reinforced concrete bridge exhibiting delamination related to a highly altered concrete (Fig. 5.18). The characterization of damage was first performed by coring within a selected area. Ultrasonic pulse velocity carried out on



Dark trace under bridge deck

Delamination observed on cores

Fig. 5.18 Visual detection and destructive study of interfaces on Lommersweiler bridge, Belgium (Gilles, 2004)

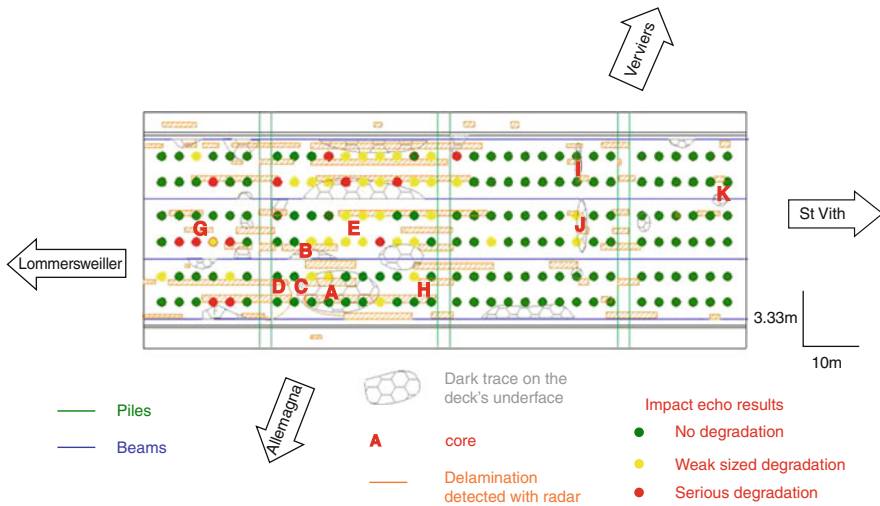


Fig. 5.19 Results of ND investigation on Lommersweiler bridge (Gilles 2004)

cores highlighted horizontal interfaces in the deck. The next step consisted in identifying the damaged zone on the whole structure.

Engineers carried out a visual inspection of external symptoms related to probable degradation, such as dark spots on the surface. They also used radar (1.5 GHz coupled antenna) to record profiles along 1400m in total length. Impact echo measurements were performed along a regular mesh of 1.3m x 3m to obtain 192 measurement points. All these results are represented on the same document as comparison (Fig. 5.19).

The final conclusion of this study indicated a very good correlation between radar and impact echo results, as confirmed by the petrographic examination conducted on cores.

5 Benchmark and test site

Tests body and test site are a simple mean to test technique effectiveness and accuracy with regards to controlled parameters.. Numbers of test site are then elaborated relatively to the development of a technique.. So it can be found on several sites, the same kind of “objects” (in term of geometry for instance). This is due to the similar NDT improvements needs, studied by various research teams. This is, finally, very consistent with actual engineers concerns.

Existing test site designed for the detection of interface can be broken in three large groups:

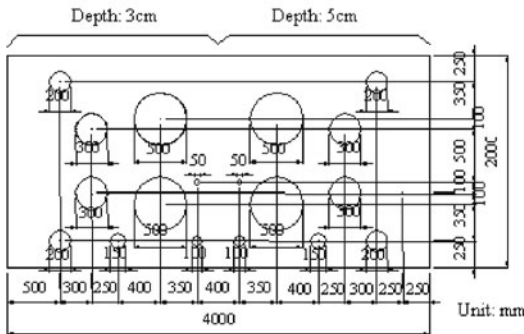
The first group considers the study of interface and delamination. Generally, the flaw is ideal, made by a plastic sheet embedded in concrete in an attempt to simulate a delamination. The irregularity of limits and the variation in its thickness are not taken into account. In this group we can list:

The University of Sherbrooke (Canada) built a concrete slab in 2008 with hidden objects, simulated flaws at various depths (Fig. 5.20). Interfaces (polystyrene sheets of 5mm thick and blocks with 50mm thick) are present, then honey combings (polystyrene bloc with holes simulating heterogeneous void), plastic pipes, and complex shapes. For all, several sizes can be found, and they are at various locations relatively to the reinforcement level.

The BAM (Berlin, Germany) proposed an experimental body, to compare techniques in relation to several disorders. The Large Concrete Slab (LCS), built to study problems in tendon ducts, thickness and geometry variations, and internal



Fig. 5.20 Test site in Sherbrooke (Canada, Quebec)



Location of defects inside the concrete specimen (Ex. defect depth: 3cm and 5cm)



Concrete slab specimen



Arrangement of defects

Fig. 5.21 Test slab done for impact acoustic method evaluation (Asano et al., 2003)

elements (gravel pockets), and the concrete elements for investigating voids at various depths and thicknesses Taffe *et al.* 2003. An area with different contact bonding conditions between two concrete layers (15 cm each) is also found. This area consists of five sections (approx. 70 x 70 cm²) with two concrete layers.

In the frame of the TC RILEM ON SITE FOR MASONRY, Drdacky *et al.* presented a trials wall to study subsurface defects (as plaster detachment for instance).

Asano et al. (2003) presented the results of impact acoustic methods, obtained on a test slab specifically made to evaluate reliability of these methods (Fig. 5.21). Thin voids (0.5cm thickness) are disposed with several depths and with various diameters, (leading to various depth/size ratios).

The second group is constituted of test sites where interfaces are not directly simulated but where flaws are quite similar to interfaces. Generally, the simulated flaws present a surface that can be compared to a very strong interface:

The BAM proposed an experimental concrete body. Voids are simulated with polystyrene blocks of few centimeters in thickness (Fig. 5.22).

Uomoto (2003) worked on a test body presenting voids in the concrete (Fig. 5.23). Several techniques, such as infrared thermography (active and passive way, for a combined interpretation), sonic method, and impact echo were tested in an attempt to compare results of each approach.

In this group we could also list the University of Sherbrooke slab that has been presented above.

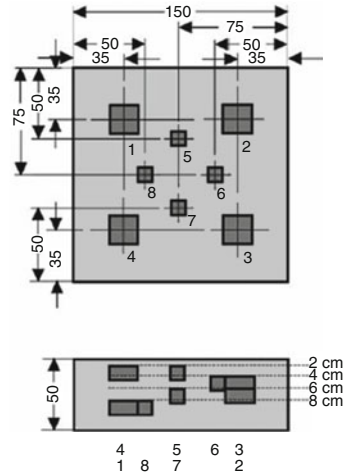
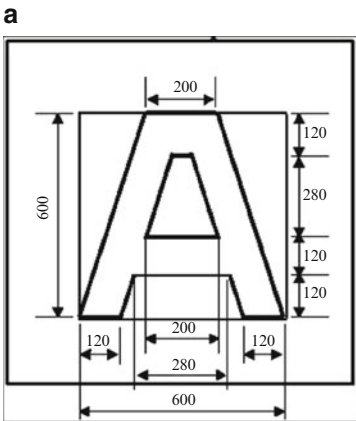


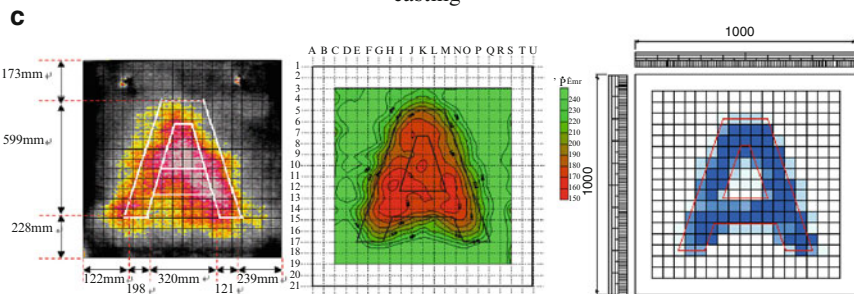
Fig. 5.22 Concrete test specimen with voids, general view (with apparatus for investigation with impulse thermography) and scheme (Maierhofer et al., 2002)



Detail of a specimen



Apperance of specimen before concrete casting



example of results respectively with thermography (combination of active and passive), ultrasonic, and impact echo

Fig. 5.23 Experimental element for NDT sensitivity study (Uomoto 2003)

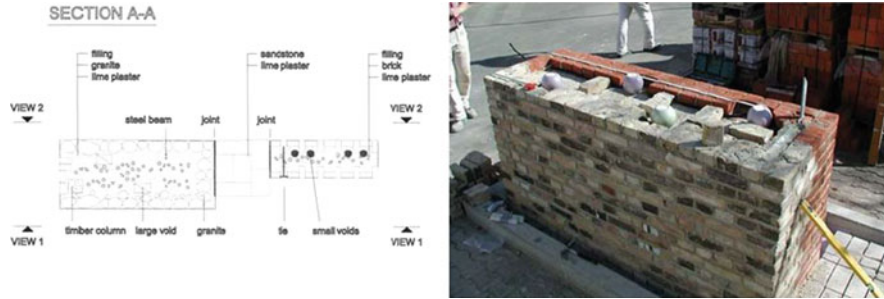


Fig. 5.24 Masonry wall at BAM for NDT sensitivity study (Maierhofer *et al.* 2003)

The third and last group is composed of test site designed for assessment of ND Techniques relatively to interfaces, but elaborated for building materials other than concrete:

LCPC Colibri test site (in Nantes, France) has been designed for development of debonding detection in road pavements. The site allowed testing techniques (impact echo) in a combined way. Results were obtained on the techniques ability in term of accuracy (Simonin *et al.*, 2006).

BAM Masonry wall (Fig. 5.24), hiding several kinds of objects and heterogeneities as voids (in the test specimen simulated by ceramic vases). The structure developed for the European research program “on site for masonry” has been used to test ultrasonic impulse-echo, and impact echo.

Beyond the possibilities of testing new developments, the main interest of tests sites that are specifically devoted to interface is relies on the opportunity of comparing and gauging different techniques. Indeed, as explain above, these sites have been built with regards to a particular issue, or to test any techniques. there are no more general test sites allowing today large and objective comparison between methods. A test site would be the mean to objectively assess the limits of techniques, and to evaluate the new development regarding a common state of the art for all methods. Such site would allow the standardization of techniques but also definition of the technique better methodology for measurements. Finally it would contribute to the training of NDT operators.

Finally, the parameters that should be taken into account on a test site specifically dedicated to interface are:

- Depth and extension of interface, from very close to the surface (few millimeters) to very depth interfaces (more than few decimeters),
- Local delamination and larger debonding (as defined in the first part of this chapter),
- Various thicknesses and partially debonded interface, with different unbonded fractions at the interface,
- Various concrete and various conditions: the aim is here to assess the influences of bias factor, such as concrete moisture, aggregate size (especially for mechanical waves techniques), interface position relatively to reinforcement layer, ...

6 Conclusion

Interfaces are particular flaws, consisting in planar discontinuity. Their detection and characterization with NDT are mainly related to the variation of physical/mechanical properties of the material filling the discontinuity or on both part of it. It must be point out that the effectiveness of any techniques also decrease with depth.

Engineers can count on several techniques, from very basic ones (chain drag for instance) to very sophisticated procedure (e.g. impulse thermography). Every ND technique can provide specific information regarding the interface. The selection of one (or more) techniques will depend on:

- the cost
- the timeframe
- the type of information to be collected
- the precision and accuracy needed

In a general manner, it can be inferred that mechanical wave methods are particularly sensitive to delamination and debonding. They can differ in their sensitivity according to the geometrical parameters of the flaw (extension, depth ...). With the appropriate technique, engineers can perform a sharp characterization of the flaw. Generally, mechanical wave methods have been advantageously completed with infrared thermography or ground penetrating radar. These techniques provide a large surface covering. They also allow a rapid detection and location of the flaws before a more detailed characterization with slower methods.

In an attempt to improve the effectiveness and reliability of the diagnosis, the TC RILEM group recommends to combine two (or more) techniques. Combination can be only the use of successively several techniques whom each technique improve the results of the previous investigation (for instance infrared thermography + impact echo). Combination could also mean the use of several techniques that would be interpreted together. This procedure allows taking into account various factors that affect techniques to reach to a sharp assessment of flaw properties. In fact, this approach is in progress (see chapter 8) and represents new development expected by engineers. This next step, associated with the development of visual representation of results, will allow automated measuring.

The TC Rilem Group considers that the standardization of NDT can also contribute to the improvement of diagnosis. The Operator experience and skills, its knowledge of the technique that is used and numbers of influencing factors strongly condition the quality of results. Therefore, the operator formation and training, as well as equipment calibration, would improve the performance of NDT. The definition and construction of benchmark test site could be a way to appraise the ability of a team to diagnose a structure with NDT. This consideration, which has been developed on interfaces in this chapter, could be generalised to the whole field of NDT. It appears to be a way to promote NDT in civil engineering.

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