Review of Non-Destructive Test Methods for Assessing Strength, Serviceability and Deterioration in Buildings

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CLIENT REPORT

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Review of Non-Destructive Test Methods for Assessing Strength, Serviceability and Deterioration in Buildings

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SUMMARY

This report reviews non-destructive test (NDT) methods which can be used in the field for the evaluation of existing buildings. The review covers tests used to assess strength, serviceability and deterioration of the building structure including the building envelope. It does not cover areas related to the comfort of building occupants such as acoustics, lighting, heating, ventilation and air quality.

The main part of this report describes over fifty non-destructive test methods. Where possible, each description includes applications, advantages, limitations, sources of more information and available test equipment. Appendix 1 contains a list of suppliers and manufacturers of NDT equipment. Appendix 2 contains a list of standards and a bibliography on NDT methods.

RÉSUMÉ

Le rapport passe en revue des méthodes d'essai non destructives qui peuvent être utilisées en service pour l'évaluation des bâtiments existants. Cet examen s'applique aux essais permettant de déterminer la résistance, la tenue en service et la détérioration de l'ossature du bâtiment et de son enveloppe. Le rapport ne traite pas des aspects relatifs au confort des occupants comme l'acoustique, l'éclairage, le chauffage, la ventilation et la qualité de l'air.

Le rapport décrit principalement plus de cinquante méthodes d'essai non destructives. Le cas échéant, la description précise les applications, les avantages, les sources contenant davantage de renseignements et le matériel d'essai existant. L'annexe 1 présente une liste des fournisseurs et des fabricants du matériel servant aux méthodes d'essai non destructives et l'annexe 2, une liste des normes ainsi qu'une bibliographie relatives à ces méthodes.

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CONTENTS

1. INTRODUCTION

1.1 BACKGROUND

There is an increasing emphasis on the evaluation of the performance of both new and existing buildings. Evaluation of new buildings is primarily needed for quality control to check conformity with design specifications. On older buildings evaluation is needed for preventive maintenance, determining causes of failures, and determining properties and structural layout when upgrading or renovating.

Existing buildings may not conform to current structural standards (eg earthquake requirements), may be put to new uses or may have a problem. An evaluation of the present condition of such buildings may therefore be required. Specific needs therefore exist for improved and reliable diagnostic procedures ranging from simple check lists to expert systems. Evaluations have to deal with many uncertainties: effect of ageing process in building materials, workmanship, effect of past damage, repairs and alterations. The building has to be surveyed, its properties determined, causes of problems identified and analysed. The tests needed for the structural assessment of such buildings cover non-destructive evaluation which includes visual inspection, non-destructive tests and proof loading tests, and tests which may be destructive such as chemical tests, mechanical tests, breaking open sections for visual inspection and loading tests to failure. This report reviews the non-destructive test methods for use in the evaluation of buildings. Such tests cause little or no damage to the existing structure. They are especially needed for heritage buildings where minimum intervention is allowed.

An increasing variety of equipment is appearing on the market including computer systems to monitor building performance. As it becomes easier to use, more compact and cheaper, such equipment will become a common part of building evaluation. Little is generally known about much of the available test equipment especially the non-destructive ones. A first step, therefore, is a review of the technical and commercial literature on non-destructive test equipment to find out what is available and assess the usefulness of the equipment.

1.2 OBJECTIVES

The objectives of this report are to

- prepare a brief review of evaluation needs in a building
- assess the usefulness of the different types of non-destructive equipment to help evaluate a building
- assemble a list of commercially available non-destructive test equipment
- give guidance on future trends and needs.

The emphasis is on field test methods. The review covers tests used to assess factors affecting the strength, serviceability and deterioration of the building structure including the building envelope. It does not cover areas related to the comfort of building occupants such as acoustics, lighting, heating, ventilation and air quality.

2 NON-DESTRUCTIVE EVALUATION

2.1 EVALUATION OF BUILDINGS

Evaluation of a building is needed for preventive maintenance, determining causes of failure, determining structural and physical properties, and determining building layout and composition. The methods of evaluation, often called building diagnostics, cover *a set of practices that are used to assess the current performance capability of a building and to predict its likely performance in the future.* [SRI 1990].

There are guides available for these tasks. Structural appraisal of buildings is covered by BRE [1991b] and ISE [1980, 1991]. Diagnosis, remedy and prevention of building failures is covered by Holland et al [1992], BRE [1991c], Addleson [1989], ASCE [1989] and PSA [1989]. Check lists for appraisal and diagnosis are helpful too. Koski [1992] gives an example of a check list for exterior masonry.

Evaluations need definite objectives and planned programs. These include:

- an historical survey including original design, plans, repairs, etc
- the present condition including support and connection details, and data on properties of materials, and analysis
- future requirements

Non-destructive tests (NDT) help achieve the second objective. Fidler [1980] says they are used to

- evaluate the total structural performance
- evaluate the building envelope
- determine the properties of individual building materials, eg. moisture content, strength, stiffness
- detect voids, cracks, discontinuities and other anomalies
- detect and analyse the chronology of construction for archaeological and historical purposes

The greatest application of NDT in industry is in the evaluation of materials and elements having uniform properties (for example steel). Such testing becomes less reliable as the material properties become less uniform (for example concrete and masonry). Non-destructive tests for the latter will in many cases only give relative not absolute values. Some non-destructive tests are expensive; the cost may exceed that of making repairs or strengthening [BRE 1991b]. The reliability of the results will often depend on the experience and judgment of the investigator. It is therefore important in most cases that tests be performed by experienced and reliable staff if worthwhile results are to be achieved [BS1881:Part201]. Digital electronics, computer hardware and computer software are making it much easier to interpret results and also increase reliability. The simpler and less expensive tests can be used to give a relative assessment over large areas of the building and indicate locations for more detailed and expensive in-situ or laboratory tests. Snell [1987] suggests that a statistical approach could be used to help decide on the number of tests and their reliability.

There is a wide range of non-destructive test equipment available to evaluate the condition of a building. Many have become standard procedures for assuring quality control on new construction, assessing deterioration damage on older structures, and monitoring the effectiveness of rehabilitation and repair works. NDT equipment can be used to get immediate results or can be used for long term monitoring.

Non-destructive techniques to assess the current condition of a building can be grouped under four main headings: visual examination, non-destructive testing, structural analysis and model testing [McLeish et al]. Only the first two are considered in this report.

2.2 NON-DESTRUCTIVE TESTING

2.2.1 Definitions

ASTM standard E1316 defines non-destructive testing (NDT) as *the development and application of technical methods to examine materials or components in ways that do not impair future usefulness and serviceability in order to detect, locate, measure and evaluate discontinuities, defects and other imperfections; to assess integrity, properties and composition; and to measure geometrical properties.* BS standard 1881:Part201 defines a non-destructive test as *a test that does not impair the intended performance of the element or member under investigation.*

Non-destructive tests are therefore a means of evaluating a building without altering or damaging it in any significant way. It includes methods which cause minor damage which can easily be repaired - for example, drilling small diameter holes for fibre-optic probes, drilling core samples and cutting slots in mortar joints for insertion of flatjacks. Some of the slightly destructive tests may be unacceptable for heritage buildings.

2.2.2 Assessing existing conditions and performance in use

Reliable NDT methods now exist to measure the depth and integrity of deep foundations, locate delamination in concrete bridge decks, find voids beneath concrete slabs, locate and measure reinforcing steel, assess risk of corrosion damage and evaluate concrete quality or deterioration in-situ [Hertlein 1992, BS1881:Part 201]. In addition a large range of properties can be assessed, including fundamental parameters such as density and elastic modulus in addition to strength.

Long term monitoring is used to help understand the behaviour of buildings and as a check on theoretical predictions [Moore 1992]. The monitoring of actual performance while a building is in service can also ensure that the assessment of safety and serviceability is not solely based on prediction. The monitoring can act as an early warning system to ensure the safety of the building users and to indicate the need for appropriate renovation and maintenance programs, and so enable owners to keep their property in use for as long as possible.

2.2.3 Types of NDT equipment

A wide selection of instrumentation is already available based on electromagnetic, vibrational, mechanical and visual principles. The following is a brief review of the basis for some of this instrumentation.

Visual methods

These methods include equipment based on visual techniques although many now use electronics aids. Examples are cameras, video equipment, optical probes, photogrammetry, and some levels and thermometers. Infra-red thermography could be included in this section even though it does not use a visual part of the electromagnetic spectrum.

Mechanical methods

Many of the strength tests fall into this category. Examples are penetration tests, pull-off tests, surface hardness tests, and core sampling.

Electromagnetic methods

Electromagnetic methods include methods based on magnetism and induced magnetism (eddy currents) such as coating thickness gauges, metal detectors and the magnetic field method. Instrumentation based on resistance and capacitance include moisture meters and the potential-drop technique for reinforcement integrity. Radar makes use of electromagnetic wave propagation to detect changes in composition or density within a material.

Sonic and ultrasonic methods (stress-wave propagation methods)

Various methods make use of stress wave propagation as opposed to electromagnetic wave propagation (see A2.3 in Appendix 2). This includes sonar devices to measure dimensions and movement, and five techniques collectively known as stress wave propagation methods [Sansalone & Carino 1991]: audible impacts, acoustic emission, impact-echo, pulse-echo and spectral analysis of surface waves. Elastic modulus, strength, thickness and defects such as cracks can be determined from elastic waves in a material induced by suddenly applied stresses. There are three types of wave: compression, shear and Rayleigh (wave along the surface). In a longitudinal or compression wave, the alternating zones of compression and rarefaction occur along the direction of propagation of the wave; in a transverse or shear wave, particle displacements are perpendicular to the direction of propagation. Shear waves cannot propagate in liquids or gases since they have no shear elasticity. Surface waves propagate close to the surface. Elastic waves range from sonic to ultrasonic (above audible frequency). The velocity of the wave is dependent on the material's elastic properties (E & μ), and density. The wave will reflect off the surface, subsurface layers, flaws or irregularities in an object. To determine wave velocity a pulse is introduced by means of an electromechanical transducer or mechanical impact. Another or the same electromechanical transducer picks up the resulting signals. To detect developing cracks only a receiver is needed. The smallest physical change that can be detected with certainty is governed by the wavelength of the wave.

Radiography
There are three kinds of radiation used in non-destructive test devices: X rays, gamma rays and neutron rays. X rays and gamma rays are very short electromagnetic waves with high energy enabling them to pass through materials much more easily. The primary use of radiography has been to look for defects in welded products and castings. In buildings they have been used to determine dimensions, location of reinforcement, locate cavities, determine density and moisture. Radiography is usually expensive and requires safety precautions against ionizing radiation.

2.3 APPLICATIONS
This section gives a general indication of the possible uses of the NDT test methods in the assessment of buildings. See the review of non-destructive test methods for more details on applications for a particular NDT method.

2.3.1 Geometrical properties and composition
General layout
For *initial observations and general layout*, useful items include photography, binoculars.and compass.

Dimensions
Interior and exterior dimensions can be measured using measuring tapes, levels, plumb bobs, and photogrammetry.

Member thicknesses can be detected by tape measures, radar, radiography (X ray), impact-echo, ultrasonic pulse velocity, cores, drilling, metal detectors and optical probes.

Cross-sectional composition and connections
Structural discontinuities, delamination and voids can be detected by infra-red thermography, radar, audible impact, impact echo, ultrasonic pulse velocity, drilling, cores, and optical probes. Infra-red thermography and radar are most useful where large areas have to be surveyed.

Hidden metal items such as wall ties, panel connectors, metal pipes and reinforcement can be located by metal detectors, radar, infra-red thermography and X ray. *Electric cables* can be located using electric cable sensors. *Wood studs* can be located by stress wave methods and stud sensors.

Thickness of coatings on metals can be measured using coating thickness gauges.

2.3.2 Physical properties, strength and integrity
Physical properties
Density can be determined by coring, drilling, radiography (gamma rays), ultrasonic pulse velocity and impact-echo.

An indication of *concrete porosity* is given by a permeability test.

The *dynamic modulus of elasticity and Poisson's ratio* can be estimated using ultrasonic methods. The *stress-strain behaviour and elastic modulus of masonry* can be determined using the flatjack.

The *dynamic properties* of a structural member or a complete building can be determined by the impulse-response method.

Strength

Concrete compressive strength can be estimated directly by testing drilled cores, or indirectly by penetration methods, pullout tests, break-off tests, surface hardness tests, and ultrasonic and impact-echo tests.

Masonry compressive strength can be assessed by testing drill cores, flatjacks, surface hardness tests and impact-echo tests. The flatjack can also determine the existing compressive stress in masonry walls. *Mortar* strength can be estimated using penetration , surface hardness and pullout tests.

The *flexural tensile strength of masonry walls* can be determined with the bond wrench test. An indication of *concrete flexural tensile* strength is given by the break-off test.

The *adhesion of added concrete* to existing concrete can be checked by a pulloff test.

The *tensile load capacity of embedded steel anchors and ties* can be checked by a pullout test.

Breaks and possible reductions in cross-section of steel reinforcement may be detected by the magnetic field method and potential drop method.

An index for the *shear resistance in earthquakes of older, unreinforced masonry* is found using the bedjoint shear test.

The design load capacity of structural members can be checked by a load test. These are carried out mainly on horizontal members such as floors and roofs.

Integrity

Dynamic behaviour of buildings or structural members such as floor slabs can be determined by the impulse-response method. This has been used to detect changes in structural behaviour with time, and to provide a basis for reducing annoying vibrations due to long span floors.

Displacements and cracks can be measured with measuring tapes, levels, plumb bobs, and crack gauges. In addition changes with time can also be monitored using tell-tales (listed under crack gauges), movement gauges, and photogrammetry.

2.3.3 Moisture and associated problems

Moisture content

The *moisture content* of many types of wood can be determined accurately using resistance moisture meters. These meters can also be used for gypsum board, masonry and concrete but only to detect relative levels of moisture. Capacitance type meters are also be used to estimate moisture content. If accurate values are needed, normally core or drill dust samples of the material need to be taken. The neutron absorption method can give accurate values too (it has been mainly used for roofing). The moisture content can also be estimated using humidity sensors located in cavities within the material.

Moisture in exterior walls can also be detected using infra-red thermography. This is mainly useful in determining distribution of moisture but not actual amount.

Humidity sensors are available to measure moisture in the air, and condensation sensors to monitor moisture derived from the air.

Wood rot

Active *dry rot* in wood can be detected by specially trained dogs. Weak areas in wood can be detected directly using impact-echo methods.

Corrosion

The likelihood and possible rate of *corrosion of steel reinforcement in concrete* can be assessed with resistance moisture meter and half-cell potential measurements. Other measurements for *likelihood of corrosion* in concrete and mortar include core test to check on depth of carbonation, the extent and level of chlorides, and the moisture levels. Radar and a neutron-gamma ray method have also been used to estimate chloride levels. Permeability tests give an indirect indication of density (porosity) which may affect long term durability.

Corrosion of reinforcement can lead to *delamination in concrete* which can be detected by infra-red thermography, radar, audible impact and impact-echo. Two methods to detect the *condition of the reinforcement* itself are the magnetic field method and the potential drop method.

Frost damage

Early cracks not yet visible within masonry caused by freeze/thaw cycling while wet can sometimes be detected by ultrasonic pulse velocity or impact-echo. Ultrasonic pulse velocity is a reliable method in the laboratory for detecting changes in bricks during freeze-thaw tests.

Water leakage

Leaks through roofs can be monitored by in-built systems in the form of moisture sensitive electronic grids. Neutron meters have been used to determine moisture levels in built up roofing. Both these methods give good results.

Water leakage through masonry walls can be assessed by permeability tests and water spray tests. These tend to give very variable results but can give experienced investigators an indication of how a wall performs. Its best use is in monitoring behaviour before and after renovation (eg after repointing of mortar joints, or applying a water repellent coating).

2.4 FUTURE TRENDS AND NEEDS

Trends

- NDT equipment will keep on improving. Future computer software for electronic test methods will filter out unwanted data and improve interpretation. Digital signal processing will make this easier to do.

- A combination of mathematical modelling in combination with the test data will improve the confidence in the results (eg with ultrasonic methods).

- Continuous monitoring of building performance will become more common. Faults and deterioration will be detected at an earlier stage. One example is the detection of roof leaks. Developments in expert systems, instrumentation and economical data acquisition will make it easier to monitor performance.

- Automated equipment (robotics) remotely controlled will be developed. This equipment will be able to scan areas of buildings not easily accessible (e.g. brick cladding on high rise buildings).

Needs

- Techniques already successful in the laboratory should be adapted so that they can be used in the field (eg detection of frost damage in bricks by ultrasonic methods).

- A computer database of non-destructive test methods should be created and updated regularly. The information in this report can be used as a starting point. Regular updating is important because new NDT equipment and new applications are continually coming on the market.

- NDT test procedures should be tied in with building diagnostic procedures as they are developed.

- More practical evaluation of NDT equipment for use in buildings is needed.

- There is a need for more standard test procedures to ensure that data from different sources is interpreted correctly and that it is comparable. A RILEM committee is trying to do this for NDT methods applicable to masonry.

3. NON-DESTRUCTIVE TEST METHODS

The following list of NDT methods is not comprehensive but includes most of those in common use. The methods are listed alphabetically under one of three headings which best corresponds to their main application: (i) geometrical properties and composition, (ii) strength, physical properties and integrity, and (iii) moisture and associated problems. A description of each method is given usually including applications, advantages, limitations, examples of use, sources of more information and some of the available test equipment. The name of the manufacturer or distributor of the test equipment is included within brackets (addresses in Appendix 1). Prices where given are an approximate indication of the cost of the item.

Other reviews on NDT methods and equipment are available for application to particular materials. A review of test methods for concrete is given in the CRC Handbook on nondestructive testing of concrete [1991], in British standard BS1881:Part 201 [1986], by de Vekey [1990] and by CIRIA [1992]. A review and assessment of NDT equipment for masonry is given by Noland et al [1982, 1988, 1990], Abrams et al [1991], and de Vekey [1988]. A brief review of test methods for timber is given by Ross [1992].

3.1 GEOMETRICAL PROPERTIES AND COMPOSITION

COATING THICKNESS GAUGES

Background and principles

Based on (i) simple magnetic pull for non-magnetic coatings on magnetic metal bases (eg paint or zinc on steel), (ii) electro-magnetic induction for non-magnetic coatings on magnetic metal bases, and (iii) on eddy current principles for coatings on conductive, non-magnetic materials (eg paint on aluminum, copper or austenitic stainless steel).

Applications, advantages and limitations

- Measures thickness of coatings on metal surfaces
- Simple, easy to use handheld gauges are available
- Accuracy range from ±1% to ±10%. More difficult to determine thickness for hot-dipped galvanized coatings on steel (accuracy ±15% or better).

Equipment

- Various handheld gauges (Elcometer, Sheen)

Standards

ASTM E376

ELECTRIC CABLE SENSORS

Applications, advantages and limitations

Used to locate electric cables. One type tunes into a 50 or 60 Hz, AC current. Current must be flowing for detection to occur. Another type depends on a signal introduced into the cable which it then detects.

Equipment

- *Pacetrace.* (Protovale) Cables up to 5 m in the ground can be located; depending on the current in the cable.

Further information Le Devehat 1992

INFRA-RED THERMOGRAPHY

Background and principles

Detects relative differences in heat emission (surface temperature). A sensing device converts infra-red radiation radiated from a surface to a voltage signal. Voltages can be converted to temperatures and displayed in the form of a colour or monochrome image, the colour or shades of grey depending on the temperature. Three classes of portable infra-red devices are used for building diagnosis: imagers (shows relative temperatures within field of view), spot radiometers (spot measurements of temperature) and line scanners (scanner and cathode ray monitor producing a colour or monochrome display of calibrated temperature isothermals). Can detect temperatures from -30°C upwards (depending on the camera). Best equipment can determine temperature with an accuracy of ±1°C and has a resolution of 0.1°C. Computer analysis software needed to properly analyse the results.

Applications and advantages

- Major advantage is that it can give information over large areas not just point measurements.
- Can be used to detect moisture (eg rising dampness; areas with moisture are cooler), air leakage and heat loss, and locate structural discontinuities (eg thermal bridges), voids, metal components, insulated and uninsulated areas, heating pipes within walls, delamination in concrete decks, and delamination of tiles on a wall.

Limitations

- Suitable environments are required to perform the measurements. These include no sunshine on the building facade for at least 12 hours before the survey, and the surface should not be visibly wet. Measurements often have to be carried out at night.
- A temperature differential is required across the element being investigated. Hart [1991] suggests at least 10°C across a wall.
- Only the surface is monitored. From this the effect of interior factors have to be deduced.
- The best equipment is expensive. Operator needs experience to get good results.

Examples of use

- It has been successfully used in the laboratory to detect the condition of wall ties [Adderson 1988; Hart 1990, 1991]. They show up as hot spots on the wall; if tie cross-section has been severely reduced by corrosion or improperly attached it will not show up even though a metal detector may indicate one is there. A temperature difference of about 50°C across the wall is needed. Only likely to be successful for larger ties.

Equipment

Thermal Imaging

- *Thermovision 470* (Agema) $96,000 incl software
- *Thermovision 900* (Agema)
- *700 Series* (Inframetrics)
- *Thermal imaging systems* (Bales)
- *Probeye Model 7300* (Hughes)
- *Camera with array detector.* (Mitshubitsu) Has an array detector as opposed to a line scanning detector.

Spot radiometers

- *Microscanner D Series* (Exergen) Gives digital temperature readings.
- *Microscanner IIC* (Exergen) Gives relative temperature readings.

Standards

- ISO 6781 (detection of thermal irregularities in the insulation of building envelopes).
- ASTM D4788 (test method for detecting delamination in bridge decks).

Further information

Adderson & Hart 1988 & 1990, Burn & Schuyler 1979, Hart 1990, Hart 1991 (a good guide to use of thermography in buildings), Laurens 1983, Manning & Masliwec 1990 (application to bridge decks), McKenna & Munis 1989, Schickert 1985, Weil 1991

LEVELS

Applications, advantages and limitations

A variety of electronic levels, surveying levels and simple liquid levels are available. Some electronic levels can be set to read degrees, % slope or pitch. Liquid levels consisting of graduated vertical clear plastic or glass tubes connected by plastic tubing are useful for checking settlement.

Equipment

- *SmartLevel* (Wedge) . $120-190. Electronic level with digital readout; displays degrees, percent slope or pitch; accuracy ± 0.1°, 0.2°, 0.5°. Note that ± 0.1° is roughly equivalent to ±2 mm in a metre thus may not be suitable for some tasks.
- *Anglestar* (Sperry, Schaevitz) $900. Electronic level, range ±60°; accuracy 0.05°, resolves to 0.01°.
- *Differential water level* (Lee Valley) $30+. Measures changes in level up to 12 inches to an accuracy of 1/16 in; uses plastic tubing to connect two graduated cylinders.
- *Electronic water level* (Lee Valley $70+) (Kyowa). Same principle as the differential water level except that an electronic sensor indicates when both ends are at the same level. Kyowa level meant for monitoring (not portable).

Further information

BRE 1989b (water levels)

MEASURING TAPES

Applications, advantages and limitations

This includes simple tapes and handheld ultrasonic instruments with digital display. Electronic tapes usually use sonar transducers (eg Polaroid); accuracy better than 0.5% at distances up to 18 m. Distances up to 75 m can be measured if a target is used (electronic tape sends out an infra-red signal which activates a target which sends back an ultrasonic pulse). Many tapes include conversion from Imperial to metric, and some have functions allowing volumes and areas to be easily calculated.

Equipment

- *Electronic tapes* (Calculated Industries, Sonin)

Further information Anon 1989b

METAL DETECTORS

Background and principles

Most metal detectors are based on electro-magnetic induction for magnetic metals such as mild steel (the basis for most metal and reinforcement detectors), or on eddy current principles which can also be used to detect non-magnetic, conducting metals.

A common use for metal detectors in buildings is the location of reinforcement in concrete. Metal detectors for detecting reinforcement in concrete are often called covermeters, pachometers or profometers. The best and most stable detectors use pulses of current in a coil to create temporary magnetic fields in the immediate vicinity of the coil (pulse-induction eddy-current method). When the current is suddenly switched off eddy currents are set up in any conductive metallic objects within the field. These currents in turn try to preserve the induced magnetic field. This in turn is detected by the instrument. The observation of a return signal thus identifies the presence of metal. The signal will be affected by any metallic conductors within the range of the magnetic path (thus both ferrous & non-ferrous). The method is not affected by moisture and magnetic (non-conducting) aggregates. Limit of detection depends on the instrument and the size and conductivity of the metal objects being detected. If the metal is magnetic, i.e. mild steel, then the detection limit is further increased.

Metal detectors also use designs based on beat frequency ocscillators (the simplest and least sensitive type of detector), induction balance (a method also used by reinforcement detectors) and VLF Phase Angle (VLF: very low frequency). These do not have the stability of the pulse induction systems. The latter is therefore used where accurate detection of cover and reinforcement size is required.

Applications and advantages

- They can be used for quality control to check depth of concrete cover and diameter of reinforcing bars, for investigations of older buildings where structural drawings are not available, for locating reinforcement before carrying out any tests where reinforcement may interfere (e.g. before taking core samples).
- Probes have been developed for concrete reinforcement and for masonry wall ties.
- Can reliably determine location and position of reinforcement, fixings and wall ties.
- The better meters for reinforcement, in addition to locating the position and direction of reinforcement bars, can detect the thickness of the concrete cover and the diameter of the bars. Cover thicknesses up to 200 mm can be detected depending on the probe and diameter of reinforcement; the greater the depth the less accuracy (up to 50 mm accuracy can approach ±1 mm). Diameter of bars can be detected up to depths of 50 mm.
- Covermeters can be used to detect thickness of smaller members by attaching a metal plate on one side of the member.
- Wall ties in masonry cladding can usually be detected to within 50 mm. Coils for ties should be designed to look near the surface. Most will detect ferromagnetic and non-ferrous metals but some will not detect austenitic stainless steel very well (less conductive) without special search coils and/or special electronics.
- Equipment generating eddy currents can be used to identify type of metal.
- The weight and shape of the reinforcement detectors are important since they will be carried up ladders and onto scaffolding. They should be light, robust, waterproof and have their own battery supply.

Limitations

- Beyond a given depth/spacing ratios of the bars, it becomes difficult to detect individual bars.
- There are limits on the depth of detection
- Little use in situations with complex dense reinforcement arrangements.
- It is difficult to detect any reinforcement beneath a welded steel mesh.

Equipment

<u>Location and detection of reinforcement</u>

- *Profometer 3* (Proceq) $3000 incl accessories.
- *CM5 Digital* (Protovale) $3000
- *Rebar Plus* (Protovale) $1500

- *IMP wall tie locator* (Protovale) $1000
- *Rebar locator C-550* (Brainard & Kilman) $350
- *Micro-covermeter* (ELE, Geneq, Soiltest)
- *Covermeter* (ELE, Soiltest)
- *HR rebar locator, DR meter* (James)
- *Reformeter Model A* (Nema) $600

Eddy current instruments

- *Smart Eddy 3.0* (FaAA)
- *Nortec eddy current inspection instruments* (Staveley)

Standards

BS 1881 Part 204 (use of covermeters to detect reinforcement in concrete).

Further information

Anon 1979, BRE 1988, Armer 1987, ISE 1989, Lauer 1991, Le Devehat 1993, Snell et al 1985 & 1987

OPTICAL PROBE

Background and principles

Also known as borescopes, endoscopes & fibrescopes. The probe consists of a rigid or flexible tube containing optical lenses, mirrors and/or glass fibres enabling an observer to look into inaccessible cavities. A light source is provided usually through optical fibres. The end of some optical probes can be articulated so that several directions can be observed. Alternatively some probes have interchangeable heads so different lenses can be attached including side viewing ones. Tube diameters for use in buildings normally range from 8 to 15 mm. A camera or video camera can be attached to the eye piece of the probe. A newer probe uses an electronic chip at the end of the probe which acts as a camera. It gives better colour, resolution and lighting but needs a video monitor and is much more expensive.

Applications and advantages

- For viewing cavities and details behind cladding.
- Can give an indication of the condition of metal components in the cavities behind the wall (eg steel ties).
- Gives a good image although the larger the diameter the better, but size of hole increases too. For masonry a diameter of 8 to 10 mm is best (hole can then be drilled through the mortar joint).

Limitations

- Too much should not be expected from optic probes. Often only gives limited information. For example they can be used to look at the condition of wall ties and fixings but a tie in good condition within the cavity does not mean the same is true of that portion of the tie embedded in the wall. In addition the portion of the tie within the cavity may be covered with mortar droppings.

Equipment

- *Borescopes & Fiberscopes* (Olympus) Rigid scopes $5,000; flexible scopes $12,000; light source $5,000
- *Videoimagescopes* (Olympus) $40,000+. Flexible scope with image chip at end of scope. Diameter 11 to 17 mm; lengths 1.5 to 22 m.
- *Technoscope* Rigid scope. (SDS)

PHOTOGRAMMETRY

Applications and advantages

- gives accurate, detailed photographs from which dimensions can be obtained.
- photographs taken at different time intervals can provide information on movement of cracks and on surface deterioration.
- stereo photography gives best results.

Limitations

- requires a clear view of the building or building element.
- requires people experienced in photogrammetry

Further information

Chambers 1985, Mangio 1992, Stevens 1992

PHOTOGRAPHY

Applications and advantages

- Still cameras (35mm, Polaroid) provide slides & prints for a pictorial record of conditions.
- Video is good for preliminary surveys, quick playbacks, dynamic motions and long term monitoring. Small video sensors are available which can be lowered into openings such as chimneys.

MISCELLANEOUS TOOLS

The following simpler items are useful in surveys.

Binoculars

Binoculars and telescopes are useful for preliminary viewing of the condition of the exterior of buildings, or for more detailed inspection where access is not available by ladder, scaffolding or abseiling. For models with higher magnification, a variable magnification is useful because it will easier to close in on a given area [Holland et al 1992].

Compass

For building orientation.

Flashlight

Ones with quartz or halogen light & focusing ability best.

Magnifying glass

Magnifying glasses and pocket microscopes are useful for close up viewing of surface deterioration and cracks. Some come with an integral light source (Elcometer, MTI).

Mirrors

Inspection mirrors are useful for looking behind objects and within openings. The optical probe is an alternative. Various inspection mirrors are available (Elcometer).

Plumb bob

A plumb bob is a simple means of checking bowing or tilting in walls up to one or two storeys in height. If many readings need to be taken, a theodolite is easier to use if it can be set up to give an uninterrupted field of view. Electronic plumb bobs are also available. [BRE 1989b]

Pocket knife

For scratching surfaces and scraping off surface finishes.

Stud sensors

Simple handheld sensors to locate wood studs behind drywall. Either detects metals (nails & screws) or changes in density. Available at most hardware stores. Cost approx $30.

Thermometers

Used to measure air and surface temperature. Also see spot radiometers under thermography

3.2 STRENGTH, PHYSICAL PROPERTIES AND INTEGRITY

ACOUSTIC EMISSION (stress wave method)

Background and principles

This method is used to detect stress waves emitted by a structure under increasing stress. Any developing crack releases strain energy in the form of sonic or ultrasonic waves. The technique is able to identify sudden increases in microcrushing or cracking, indicating possible or imminent failure. Parameters measured are peak amplitude, signal duration and signal energy. It has been used mainly in the laboratory.

Applications and advantages

It can be used to

- monitor the degradation of loaded specimens.
- ascertain the extent of microscopic damage long before there are any visible signs of damage.
- within certain limits, to locate developing cracks, to evaluate their size and to follow their propagation.

Limitation

- care is required to ensure the signal levels from damage due to the applied loads are not obscured by other actions (service loads, temperature, moisture changes etc).
- method is expensive for monitoring the performance of large components because of the high cost of installing a multi-channel data acquisition system.
- although its field use is being investigated, the method is still primarily a laboratory technique since there is little information relating the characteristics of acoustic emissions to the different types of load that can occur in actual structures.
- acoustic emissions only occur under increasing loads (increased loads may be impractical to attain in real structures).

Examples of use

- One example is the detection of cracking in a masonry specimen subjected to an increasing compressive load in the laboratory.
- Possible uses in existing structure are to monitor crack development under load initially caused by freeze-thaw cycles and alkali aggregates [Ohtsu 1992, Taylor 1990].

Equipment

- *Locan AT* (Physical Acoustics).

Standards

None known. ASTM E1316 gives standard definitions of terms related to acoustic emission.

Further information

Hoiseth 1988, Kimura et al 1989, Mindness 1991, Ohtsu 1987 & 1992, Ohtsu et al 1991, Rossi et al 1989, Taylor 1990

AUDIBLE IMPACT (stress wave method)

Background and principles

The audible ring induced by a sudden impact indicates whether there are any voids close to the surface of the member in question.

Applications and advantages

- The ring induced by an impact from a hammer can be used to check on tile adhesion, delamination of coatings or laminations within brick or concrete.
- Chains dragged over concrete slabs are used to detect delamination.

Limitations

This method is very approximate and requires experience in use.

Examples of use

- Snell [1978] states experienced persons can use hammer taps on concrete block masonry to distinguish between grouted and ungrouted cells. This will probably only distinguish between grouted and completely empty cells.

Further information

Litvan 1982 (describes chain drag), Snell 1978

BEDJOINT SHEAR STRENGTH (for masonry)

Background and principles

Commonly known as the shove test. It was developed in California to give an indication of the shear capacity of unreinforced brick walls in earthquake zones. The test measures the shear strength at the brick-mortar interface of a brick in an existing wall.

Application and advantages

- it is used as one of the indexes for checking the seismic capacity of older unreinforced masonry buildings in western USA.
- it gives an indication of the mortar quality.
- the test is fairly easy to carry out. One brick, next to brick to be tested, needs to be removed so a small hydraulic jack can be inserted. Mortar at the ends of the brick under test must also be removed. Jack load then applied to this brick until sliding occurs.
- can also be used in conjunction with flat jacks to give shear strength at the brick mortar interface under varying levels of compressive stress [Noland et al 1990].

Limitations

- brick removed needs to be replaced and mortar joints filled
- suitable for masonry with lower strength mortars only (1:2:9 or less). With stronger mortars it is difficult to remove a brick without damage, and during the test delamination of mortar joints may occur in areas other than the tested brick [Noland et al 1990].
- its only direct use is to check seismic capacity in accordance with the Uniform Building Code for Building Conservation.
- test gives the pure shear strength of the joint. It should not be directly related to the overall shear strength of the wall without prior calibration.

Standards

UBC UCBC, UBC 24-7

Further information

Epperson 1989, Noland et al 1990

BOND WRENCH (for masonry)

Background and Principles

Originally developed in Australia, the bond wrench is an accurate and simple method of determining the strength of the bond between a masonry unit and mortar (flexural tensile strength). A long lever is attached to a masonry unit free on all sides except the bottom face which is still attached to the mortar joint in a masonry wall or wallette. An increasing load at the free end of the lever applies a bending moment to the unit until failure occurs at the joint.

Applications and advantages

- used for investigating suspect masonry, for quality control during construction and for laboratory investigations of bond.
- simple test.

Limitations

- in the field, access is required to the top, front and back of the unit to be tested, thus a temporary opening usually needs to be made in the wall.
- minor damage occurs which has to be repaired

Equipment

- *Brench* (ELE) $8000. A portable device developed for field use. It can be attached to masonry units 75 to 215 mm in thickness. [see BRE 1991a]

Standards

- ASTM C1072 & UBC 24-30 (test meant for laboratory use but describes principles so can be adapted to field use)
- AS 3700

Further information

BRE 1991, Brown & Palm 1982, Hughes & Zsembery 1980, Marquis & Borchelt 1986, Noland 1990

BREAK-OFF TEST (for concrete)

Background and principles

Test was developed in Norway in 1976 as a measure of the in-situ flexural tensile strength of concrete. A core cutting drill is drilled 70 mm into the concrete. The drill is then removed leaving a 55 mm diameter concrete cylinder, which is still attached at the bottom. A lateral load is then applied to the top of the cylinder causing a flexural failure near the bottom in a plane parallel to the concrete surface.

Applications and advantages

- determining in-situ strength of new concrete for form removal
- strength correlates well with the compressive strength
- the test is easy to use, safe and fast

Limitations

- leaves a 60 mm circular hole, 70 mm deep, which needs to be filled in
- not for use in concrete where the maximum aggregate size exceeds 19 mm
- concrete member should be at least 100 mm thick

Equipment

- *Scancem* break-off tester (SDS)

Standards

ASTM C1150

Further information

Naik 1991

CORES AND DRILL DUST

Background and principles

A drill is used to cut out a sample for further testing and analysis.

Applications and advantages

Cores drilled out of walls or floors can be used to

- determine compressive strength
- determine composition, moisture content
- to check depth of carbonation of concrete

Dust from drilled holes can be used to

- to measure water content, salts and composition

Limitations

- coring and drilling leaves a hole which must be repaired.
- drilling equipment for cores is more expensive. In most cases renting is more economical.
- masonry cores with weak mortars likely to be damaged.
- it is not always easy to analyze composition of cores or dust samples. For example, chemical analysis of mortar can be very inaccurate especially in cases where the original ingredients are not available and no check can be made for soluble lime or silica compounds in the aggregate [de Vekey 1991].

Examples of use

- cores cut out of a brick wall were reinserted to monitor long term moisture content due to rain [Newman 1975]. Cores were taken out at regular intervals and weighed.
- BRE [1981] describes a method for sampling drill dust to determine moisture content and hygroscopicity in masonry. Latter is assessed to see whether moisture in the wall could have been absorbed from the atmosphere. Low speed drill with 9 mm bit. Normally drill into the mortar joint. Sample taken over depth from 10 to 80 mm. Heat produced by drill bit does not cause enough evaporation of moisture to significantly affect the results provided the drill bit is sharp and the material not so hard as to make drilling difficult. Samples placed in small glass bottles for subsequent weighing and checking for hygroscopicity, or moisture can be measured immediately using a carbide meter.

Equipment

- *Corecase & Crackcase.* (Germann; ELE) $2000 Corecase with 75 mm drill bit
- *KwikCore.* Model 75 (James) $2400
- *Chloride test system.* (James) Determines chloride concentration from drill dust.
- *Speedy moisture tester* (ELE) The moisture content of a sample of drill dust is measured by mixing it with carbide, and measuring the pressure induced by the gas produced.

Further information

BRE 1981

CRACK GAUGES

Applications, advantages and limitations

Comparators incorporating a magnifying glass are useful to measure crack size. Tell-tales consisting of cement or plaster patches across a crack, or a glass strip glued across a crack should not be used. At the most they only tell whether a crack has moved but not how much. Avongard, a plastic tell-tale, and hand held gauges such as the Demec, Whittemore and vernier calipers can measure the change in movement across cracks between readings. Demecs measure movements as small as 0.001 mm but have a small range (a couple of millimetres). Crack movement can also be continuously recorded using electronic gauges (LVDT for example) or a scratch gauge.

Equipment

- *Crack width meter* (SDS) Scale to measure crack widths.
- *Illuminated scaled magnifier* (MTI)
- *Plastic tell-tales* (Avongard). $5-15? Each part of the tell-tale has a grid in millimetres.
- *Demec gauge* (Mayes) $600+. Handheld gauge; lengths from 50 to 2000 mm.
- *Digital caliper gauges* (MTI)
- Also see movement gauges (miscellaneous)

Further information

BRE 1989, Koski 1992, Stockbridge 1986

FLATJACK (for masonry)

Background and principles

The flatjack was first used with masonry in Italy to determine in-situ deformation properties and the existing compressive stress in masonry. The jack is a thin metal diaphragm formed from two sheets of steel welded at the edges with two openings to allow oil to be pumped into it (sheets usually rectangular or semi-circular). The flatjack is thin enough so it can be inserted into a slot cut into a mortar joint. A handheld strain gauge is used to monitor the deformation across the slot before and after it is cut into the wall. The compressive stress in the masonry can be deduced from the oil pressure in the flatjack when the strain gauge reading returns to its original value. Calibration of the flatjack is required beforehand.

Applications and advantages

- its greatest use has been in historic masonry structures but it has also been successfully used with modern masonry cladding.
- it determines the compressive stresses in masonry walls (within 15%)
- the jack can also be used to determine the in-situ compressive strength (destructive test) and the stress-strain relationship

Limitations

- the maximum stress it can measure is approximately 7 MPa
- not generally used with hollow masonry units
- masonry units with cores need extra precautions (plates to span the cores or two extra flatjacks to ensure a flat surface for the main flatjack).
- the slot cut into the wall needs to be repaired

Equipment

- *Stressjacks* (Atkinson-Noland)

Standards

ASTM C1196 & C1197

Further information

de Vekey 1991, Epperson 1989, Noland et al 1990, Rossi 1982, 1985 & 1990

IMPACT-ECHO METHOD (stress wave method)

Background and principles

- A stress pulse is applied to the surface of the member by mechanical impact. In contrast to an electromechanical transducer (ultrasonic method) the energy is much less directional and spreads into the member in all directions but the energy is usually much larger. The pulse or stress wave propagates within the member and is reflected at material discontinuities (cracks, voids, member boundaries). The reflected waves are measured at the impact point or at a number of different points.

- The time of arrival and the amplitude of the reflected wave can be determined. If the pulse velocity in the material is known, the depth to each reflected object within the member can be estimated from the arrival (travel) time of the reflected waves. This works best on piles and thin members which confine the waves.
- Alternatively the frequency content of the returning signal can be analysed. The waves caused by the impact reflect at internal discontinuities and surface interfaces. The impacted surface is also an interface, thus the pulse will propagate back and forward between the surface and each internal discontinuity. These repeated surface reflections will produce a decaying periodic surface response which is monitored by placing a transducer close to the point of impact. The frequency content of this periodic response is then calculated. Knowing the wave velocity, obtained from an unflawed section of known thickness, the presence and depth of discontinuities can be determined from the frequency content of the surface waveform (depth = wave velocity / 2x frequency of the surface waveform).

Applications and advantages

The method has been extensively used on concrete structures. Because both the transmitter and receiver are generally located on the same surface, the method is extremely useful when only one surface of a component is accessible.

The method has been used to

- measure component thicknesses
- determine severity of spalling or delamination
- locate cracks, faults and defects
- uniformity of a material within a building or within a structural component

Limitations

- resolution is dependent on the wave velocity in the material and the frequency of the pulse. High frequency pulses are required to detect small defects or dimensions. Resolution (pulse wavelength) = wave velocity / frequency
- reflected response may be complex when the component geometry is not simple and the pulse produced by the hammer impact propagates equally in all directions.
- much depends on operator knowledge and experience

Examples of use

- detect delamination in bricks due to frost damage
- integrity of wooden joists and poles [Anthony & Bodig 1990]
- determine integrity of cast in-situ concrete piles during construction or later.
- detect ungrouted voids in hollow block masonry.
- determine below-grade depth of masonry wall foundations
- Lemaye [1988] found it gave good results to detect the thickness of concrete members. Gave an example of a concrete cooling tower which varied in thickness from 150 to 450 mm.
- Noland [1990] used a 30 kHz transducer to record vibrations induced in a masonry wall by a Schmidt impact hammer.
- Carino [1984, 1986] used a conical broadband displacement transducer as a receiving source to detect location of cracks in concrete. Pulse introduced by dropping small hardened steel balls (4 to 12.7 mm dia) from a height of 0.1 to 0.2 m (basis for DOCter impact echo equipment). Shorter contact time causes wider frequency range; the higher the range the smaller the flaws which can be detected but at same time less penetration.

Pulse source and receiver placed close to each other to reduce interference from surface waves.

Equipment

Basic equipment needed are an impact hammer, a digital storage scope and a high-frequency receiving transducer (accelerometer). Equipment available commercially includes:

- *DOCter: impact-echo* (Germann) $32,000 Field instrument for locating defects in concrete structures. Uses lap-top computer.
- *Ultrasonic impact hammer* (Sakata) Detects voids in grouted blockwork.
- *Mechanical pulse equipment* (PCB)
- Consultants are available to evaluate timber in structures using impact echo equipment. (EDM)

Standards

RILEM draft (for masonry)

Further information

Anthony & Bodig 1990 (application to timber), Berra et al 1992, Carino 1984, Carino et al 1986 & 1992, Epperson 1989, Forde et al 1987, Limaye 1988, Lin & Sansalone 1992, Noland et al 1990 (application to masonry), Sansalone & Carino 1988, Sansalone & Carino 1991 (evaluation of this method for concrete), Sansalone & Poston 1992

IMPULSE-RESPONSE METHOD (dynamic properties)

Background and principles

This method is used to determine the dynamic characteristics (natural frequencies, modal damping ratios and mode shapes) of structures (buildings, bridges) and structural elements (beams, slabs). The vibrational response is measured under ambient conditions (e.g. wind loading, traffic induced loads), or as a result of an artificially induced load such as an impact from an instrumented hammer or electro-dynamic shakers. Artificially induced loads produce more accurate results as these loads can be accurately measured. The vibrational response of the member or structure is measured (eg by accelerometers). The response gives an indication of the general condition since dynamic characteristics are dependent on the mechanical properties of component materials and connections to adjacent elements.

Applications and advantages

The dynamic characteristics obtained from this method can be used to

- verify the structural behaviour and integrity of a structure
- gauge the condition of structures and their components
- compute the structural response of a system to other dynamic forces, i.e. earthquakes
- monitor the variation in condition of a structure by repeated testing at regular intervals (variations may be caused by changes in the structural integrity and/or material properties)

Limitations

- dynamic characteristics are not very sensitive to changes in material properties or structural integrity. Often it may not be possible to assess damage from changes in dynamic characteristics. May give better results if results compared to a mathematical model, or if such a model is used to determine what measurements to take.
- the method is expensive for most civil engineering structures (eg bridges & buildings) as a considerable amount of instrumentation is required to obtain a reasonable estimate of a structure's dynamic characteristics.

Examples of use

- Stockbridge [1988] measured the natural frequencies and damping of the masonry spires on a cathedral under ambient excitations. He then carried out a random decrement analysis to obtain the dynamic *signature* of the spires. It was used to indicate whether any significant structural changes were occurring while a tunnel was being excavated nearby.

Equipment

- Equipment can be purchased from a number of manufacturers.
- Some companies manufacture a full line of measurement and analysis instrumentation and therefore can supply a complete impulse-response system. (Bruel & Kjaer)
- An investigation of the dynamic characteristics of a structure requires the following measurement and analysis instrumentation.

  Measurement
  - impact hammer, electro-dynamic or electro-hydraulic shaker
  - transducers (accelerometer or velocity transducer)
  - signal conditioners (amplifiers and filters)
  - storage device (FM tape recorder, computer with A/D board etc)

  Analysis
  - dual or multi channel structural analyser, or computer based modal analysis system

Standards

RILEM draft (for masonry)

Further information

Ellis 1992 (gives a good overview for buildings), Ewins 1984 (gives principles and applications but not for buildings), Noland et al 1990, Sansalone & Carino 1991, Stockbridge 1988

LOAD TEST

Background and principles

Load tests, known as proof loads, are used to show that a structure or structural member can resist a given load.

Application and advantages

- its objectives are to predict safe load capacity and to assess the real behaviour, usually of a structural element or part of the structure rather than the entire structure. The deflection under loading and unloading is also measured.
- such loading is normally only feasible for floors and roofs, and sometimes to test thinner, modern walls under lateral load.
- care is needed to ensure that the test will yield information realistically applicable to actual service performance.

Limitations

- load tests are expensive and time consuming.

Further information

Armer 1987, BRE 1991b, Holland et al 1992, ISE 1989, Stockbridge 1986

MAGNETIC FIELD METHOD

Background and principles

A magnetic field is induced in the reinforcement. This field is wholly contained within the reinforcement but if defects occur such as cracks then the field will be disrupted locally and extend beyond the reinforcement. This can be detected by a handheld probe on the surface of the concrete member.

Applications and advantages

- this is a method under development by the US Federal Highway Administration to detect deterioration in reinforcing steel of prestressed concrete highway bridge members [Lauer 1991].
- can locate loss in section and cracks in reinforcement even if surrounded by a steel duct.

Limitations

- equipment still under development

Equipment

None available commercially.

Further information

Lauer 1991

MOVEMENT GAUGES (electrolevels)

Applications, advantages and limitations

Electrolevels, with appropriate instrumentation and calibration, can accurately sense rotations less than 1 second of arc. The electrolevel is similar to the common glass level except that it contains a conducting fluid and metal contacts to monitor the position of the fluid. Movement in a structure can be calculated from the measured rotations (as small as 0.02 mm). They have been used to monitor movement in buildings undergoing extensive structural renovations, or located close to excavations or tunnels under construction.

Equipment

- *Electrolevel* (Applied Geomechanics) $900 Level for long term monitoring of displacement and tilt; measures tilt over a range of 12 degrees; repeatability of 2 arc seconds.
- *Electrolytic tilt sensors* (Fredericks) Manufacturer of electronic bubble levels. Additional electronic equipment needed to be able to use them.

Further information

BRE 1992, Crossan 1991

MOVEMENT GAUGES (electro-optical devices)

Principles and applications

These devices measure change in location of a light ray (halogen light, laser) or change in distance (laser, infra-red). Used to monitor static and dynamic movement in structures.

Examples of use

- Stockbridge [1988] used an electro-optical device (halogen light) to monitor the relative lateral movement between the top and bottom of a 45 m high lighthouse. Movements of 0.025 mm could be measured.
- Dalgliesh [1978] used a laser to monitor the lateral movement of a 57 storey high building in Toronto. Movements as small as 2 mm could be measured over a height of 250 m.

Further information Anon 1989a, Dalgliesh & Rainer 1978, Stockbridge 1988

MOVEMENT GAUGES (miscellaneous)

Also see Crack gauges.

LVDTs and potentiometric gauges

Applications, advantages and limitations

These electronic displacement gauges are useful to monitor local movements within a building (for example across cracks) and differential movements between two building components.

Equipment

- LVDT's (Schaevitz)
- Potentiometers (Penny)

Sonar devices

Principles and applications

Ultrasonic range finders can be used to monitor movement from a distance (eg Polaroid ultrasonic range finders).

Further information Kuc 1990 discusses the theory.

Strain gauges

Applications, advantages and limitations

Electric resistance strain gauges glued onto the material under investigation can sense changes in strain over a small area. This in turn can be used to determine the stresses within the material. Vibrating wire gauges are also frequently used in field instrumentation (reliable for long term measurements).

Examples of use

- Stockbridge [1986] has used electric resistance gauges to estimate existing stress in terra-cotta cladding. The gauges were glued to the terra-cotta. Sections with the gauges were then cut out of the wall and the change in strain gave an indication of the stress level. But it does not take into account possible flexural strain relief within the terra-cotta unit (gauges only attached to the outside surface).

PENETRATION TEST (PROBE)

Background and principles

The depth of penetration of a steel probe into concrete or masonry gives an indication of compressive strength. A standard power charge or spring can be used to drive a steel probe into concrete or mortar. An example is the Windsor probe, developed in USA, which uses a powder charge to fire a pin into the concrete.

Application and advantages

- to estimate strength of new concrete for form removal
- to estimate compressive strength of concrete and mortar
- assess the uniformity of concrete and mortar
- fast and simple to operate

Limitations

- probes with smaller penetrations (lower power) more affected by surface conditions
- to obtain absolute values of concrete compressive strength, separate calibration charts are needed to account for type of concrete, size of aggregate, aggregate type and age of concrete.
- it is best at estimating strength of concrete up to 28 days old
- for use with concrete strengths less than 30 to 40 MPa depending on the power of the probe

- leaves a hole up to 8 mm in diameter; may cause minor cracking
- not reliable in estimating strength of mortar in masonry
- safety glasses required

Examples of use

- Nasser [1987] developed a spring loaded probe for concrete (PPR meter). It gave good results for the concrete he tested, lightweight and normal concrete up to 28 days old. Separate calibration curves required for each type.
- Noland et al [1990] used a Densicon probe to fire 6.3 mm diameter pins into masonry mortar joints. The results were very variable.
- Tests in Britain on mortar joints also gave poor correlation with strength for cement:lime:sand mortars and no correlation with air entrained mortars [de Vekey 1991].
- Pume [1989] mentions the successful use of a 4 mm diameter pin, driven into the mortar joint. Strength is related to the number of 1 Joule impacts required to drive the pin in 5 mm.

Equipment

- *Densicon penetrometer* (Densicon)
- *PPR meter* (James) $1400 Spring loaded [see Nasser 1987, Al-Manaseer 1990]
- *Windsor penetrometer* (James) $1500 Powder charge; used with masonry.
- *Windsor probe* (James) $1900 Powder charge; used with concrete [see Swamy 1984]

Standards

ASTM 803 (the Windsor probe conforms to this standard)

Further information

Al-Manaseer & Nasser 1990, de Vekey 1991, Malhotra & Carette 1991 (good overview), Nasser 1987, Noland et al 1990, Swamy 1984

PENETRATION TEST (DRILL)

Background and principles

The resistance to the penetration of a drill bit moving at a constant rate into a material is used as an indication of strength and composition of the material.

Applications and advantages

- to give an indication of the strength of concrete or mortar
- to determine variation in material properties across a wall

Limitations

- drilled hole needs to be repaired
- still in the development phase but probably useful as an indication of the variation in properties across a wall or floor.

Examples of use

- The penetration of an 8 mm diameter drill bit into a mortar joint after 10 impacts at a constant pressure of 150 N gives a measure of the strength of the mortar [Pume 1989].
- Trials are being carried out on the resistance to penetration by a drill in masonry by measuring the power consumption of the drill [de Vekey 1991], or the force required to drive in the drill at a constant displacement rate [Chagneau 1989]. Chagneau [1989] has also tried it on concrete. This procedure shows up the variation in properties over the drilled depth. It is still in the development stage but preliminary results are promising.

Further information

de Vekey 1991, Chagneau 1989, Pume 1989

PENETRATION TEST (INDENT)

Application

This is an impact test to check the quality of cement/sand screeds placed directly onto a solid floor. A weight is dropped onto a circular, 25 mm anvil lying on the screed. The indentation caused by the anvil is then measured.

Equipment

- *BRE Screed Tester* (ELE)

Further information

Pye 1984

POTENTIAL-DROP TECHNIQUE

Background and principles

An electric potential is applied between two points on an electrically conducting element such as a reinforcement bar. Any faults, such as cracks or reduction in area due to corrosion, will increase the measured resistance. Direct or alternating current can be used. High frequency alternating current sent out in pulses will cause reflections at defects which enables the location of defects to be determined.

Applications and advantages

- main application with post-tensioning cables in concrete
- can give an overall idea of the condition of reinforcement
- can detect breaks and reductions in section.
- detects ungrouted sections in pre-stressed cable ducts
- determines the location of defects
- best in monitoring change in behaviour over time

Limitations

- requires access to at least one end of steel bar or cable so that an electrical connection can be made.
- does not differentiate between anomalies in tendons and the metal duct enclosing them.
- if there are many defects in a cable, this method will only detect the closest ones.
- experienced personnel needed to interpret results.

Equipment

- *RIMT* (Cordec) Available on rental basis. RIMT (reflectometric impulse measurement technique) was recently developed in Switzerland to evaluate rock anchors and the condition of post-tensioned cables in concrete. Accuracy of estimating defect location of the order of 8%. [see Chiesura & Nava for more information]

Further information

Chiesura & Nava 1991, RIMT brochure (from Cordec), SRI 1988,

PULLOFF TEST

Background and principles

Measures the tensile adhesive strength (bond) between two layers (eg new concrete on top of existing concrete). In concrete a core drill cuts past the interface of the new and old layers. A metal plate is then glued onto the surface of the core and pulled away.

Equipment

- *Bond Test* (Germann)
- *Bond test* (James)
- *Pull-off tester* (Proceq) $2900-3700

Further information

Heidrich 1990, Hindo 1990 (describes Lok-Test)

PULLOUT TEST (for concrete)

Background and principles

A metal insert is pulled out of the material under test to give an indication of its compressive strength. The pull out force is correlated to compressive strength. A variation of this test is the use of a expanding anchor which causes fracture within the material.

Applications and advantages

- the main use is in new concrete members to establish strength for removal of formwork.
- good correlation with compressive strength of concrete

Limitations

- a cone of material may be removed during this test
- correlation needs to be established between pull-out load and type of concrete under test

Equipment

- *Lok-test* (Germann; ELE) Standard version $3500; automatic (lighter) version $4700. For new construction. Insert cast into the concrete 25 mm from surface. [see Peterson 1984]
- *Capo-test* (Germann; ELE) Expanding anchor inserted into an 18 mm diameter hole drilled 50 mm into the concrete [see Peterson 1984]
- *Expanding wedge anchor* No commercial version. Initial results show a reasonable correlation between the maximum torque applied to an expanding wedge anchor and the compressive strength of concrete [Chabowski 1980]. It has also been tried on concrete blocks but a recent test program gave very poor correlation to strength [Grundy 1986; de Vekey 1991].

Standards

ASTM C900 (for inserts in concrete)

Further information

de Vekey 1991, Carino 1991 (detailed review), Chabowski 1980, Peterson 1984

PULLOUT TEST (for anchors and bolts)

Application

Anchors and bolts attached or embedded in concrete, masonry or timber can be tested to a proof load to check their design tensile strength.

Equipment

- *Pull-out tester* (SDS) To test anchor bolts, dowels and other embedded or bonded devices.

Standards

ASTM E488

PULLOUT TEST (for mortar)

Background and principles

The pullout resistance of a self tapping helical stainless steel tie (6 mm diameter), inserted into a 4.5 mm diameter hole drilled into masonry mortar joints and concrete blocks, gives an acceptable indication of the compressive strength in the range 2-10 MPa for mortars and aerated concrete blocks. This test is still under development in Britain.

Further information

de Vekey 1990, 1991

RADAR

Background and principles

Short pulse (impulse) radar is the electromagnetic analog of sonic and ultrasonic pulse-velocity methods. Electromagnetic waves travel through the material and are reflected or refracted where the dielectric constant of the material changes (dielectric constant reflects a material's ability to store charge when an electric field is applied to it). Such changes occur with a change in material, density or water content. A radar pulse is transmitted into the material. When a variation in the ground's electrical properties is reached, part of the incident wave is reflected back to a receiving antenna. The radar penetration is highly dependent on the conductivity of the material being investigated. The longer the wavelength the greater the penetration but less resolution. Moisture attenuates and diffuses a signal and reduces the level of response. Steel acts as a complete barrier.

Applications and advantages

Radar is very useful for detecting defects and voids within concrete and masonry construction. It is used in a similar way to a metal detector in that it can be operated by a single person using a combined transmitting/receiving antenna from one side of the wall or structural element. It has an advantage that it gives more information than a metal detector, for example it is capable of finding plastic ties. It can locate the following:

- cavities, voids, flaws and delaminations
- location of metal components in concrete and masonry
- boundary between good and poor concrete
- boundary between concrete and nonmetallic building materials (insulation)
- boundary between dry and wet concrete (masonry)
- areas of high chloride concentration

Limitations

- poor depth penetration in wet or saturated specimens; in dry concrete maximum penetration about 1-2 m for longer wavelength pulses
- resolution decreases as wavelength increases (greater penetration). Approximately a 5 mm limit for discontinuities and voids.
- a continuous metal mesh acts as a barrier to the radar (metal is a complete barrier to radar).
- interpretation of output not easy. Considerable experience is required. Modern digital signal processing in colour is improving ease of interpretation.
- equipment is expensive.
- the generator and recording devices are bulky and heavy; the transmitting/receiving antenna is connected to them by a cable.

Examples of use

- Pitt [1992] used it to check that voids in concrete floors were adequately grouted, to check thickness of concrete slabs (pavements), and to locate reinforcement.
- Lim [1990] used it to locate ungrouted voids in concrete masonry and to give an approximate indication of chloride levels in concrete decks (such areas have increased conductivity causing greater loss of radar signal).
- In the UK, University of Liverpool is investigating its use for concrete, and Edinburgh University for masonry [see Montgomery 1991].

- With experience, information can be gained about the type and state of ties in masonry cladding and of any voids such as perforations in bricks or holes in hollow blockwork [BRE 1988].

Equipment

- *Pulse radar* (Geophysical Survey) Cost of complete system with digital radar, software and computer about $90,000.
- *PulseEKKO IV* (Sensors & Software)

  In most cases it will be more economic to rent the equipment. Analysis software can be bought separately.

Standards

RILEM draft (use with masonry)

Further information

Armer 1987, BRE 1988, de Vekey et al 1989, deVekey 1988, Forde 1984 & 1987, Ground-Scan 1991, Lim & Olson 1990, Manning & Masliwec 1990 (applied to bridge decks), Pitt 1992

RADIOGRAPHY (GAMMA RAYS)

Background and principles

Gamma rays are produced by radioactive sources such as cobalt-60, cesium-137, iridium-192, thulium-170, and ytterbium-169. Penetration depth of the rays depends on the energy of the source. Cobalt-60 with an energy range 1.17 to 1.33 MeV can penetrate 20 mm thick steel or 70 mm thick concrete (intensity of rays reduced by half over those thicknesses). The lower the density the more gamma rays are transmitted.

Applications and advantages

- detect material defects such as cavities, areas of reduced density and thicknesses.
- determine density of concrete or mortar
- can traverse greater thicknesses than X rays (for a given energy level?) [Le Devehat 1993]. Mitchell [1991] states it can traverse up to 0.5 m in concrete while X rays up to 1 m. Probably because much higher power sources are available for X rays.
- less expensive and easier to operate than X ray
- portable equipment
- no power required thus can be used on remote sites.

Limitations

- needs access to both sides unless backscatter technique is used.
- quality of image not as good as X rays
- long exposure times for images; up to 2 hours per location
- needs protection against radiation; requires more shielding and safety features than X ray because it is a continuous radiation source.
- expensive
- qualified personnel
- requires a license to operate

Equipment

- *Nuclear moisture/density gauge* (Humboldt, Troxler)

Standards

- ASTM C1040 (density of unhardened and hardened concrete).
- NT Build 123. For checking the proper compaction (density) of the mortar filled joints under precast panels and columns. Joints to be at least 20 mm high and depth no more

than 300 mm. Needs access to both sides of the joint. Mean density determined with an accuracy of ±5%.

Further information

Le Devehat 1993, Mitchell 1991, SRI 1988

RADIOGRAPHY (X RAYS)

Background and principles

X rays are produced in a vacuum tube which contains a target anode, comprising a tungsten disk, which is bombarded with high energy electrons originating from a heated element. For steel the energy range is typically from 50 keV which will penetrate steel as thick as 10 mm to 8 MeV which will penetrate 300 mm (eV = electron volts). X ray sensitive paper is placed behind the object during the test.

Applications and advantages

- detect reinforcement, voids and other items within walls
- can penetrate up to 1 m concrete
- wall thicknesses and coverings can be calculated
- good quality image
- digital X-ray equipment allows processing the image on computer and allowing reconstruction of images.

Limitations

- access required to both sides of the member
- high cost
- can be very slow (depends on power of X ray and thickness of member); up to 2 hours per location
- precautions required to protect the operators and the public against the X rays when the equipment is switched on
- qualified personnel
- requires license to operate (radiation safety)

Examples of use

- Fidler [1982] used 3 keV X-rays to examine timber walls. 4 keV should be adequate for masonry walls (dependent on exposure time).
- A system developed in France, Scorpion II, is used for the evaluation of prestressed concrete bridges to examine quality of grouting and concrete and for establishing the location and condition of prestressing cables [Mitchell 1991].

Equipment

- *X-ray radiography equipment* (Staveley)

Further information

Fidler 1982, Guinez 1989, Hart 1977, Le Devehat 1993, Mitchell 1991 (use with concrete), SRI 1988

SPECTRAL ANALYSIS OF SURFACE WAVES, SASW (stress wave method)

Background and principles

This is a method which uses surface waves to determine stiffness profiles and layer thicknesses in layered systems, such as pavements. Work is ongoing to investigate its potential to detect delamination and voids in concrete. At the moment its use in buildings is limited.

Further information

Bay 1990, Nazarian 1990, Olson 1992, Sansalone & Carino 1991

SURFACE HARDNESS TESTS

Background and principles

Surface hardness is estimated by measuring the rebound of a hammer impact on the surface of the material being tested. The rebound distance is an indication of the compressive strength of the material. Hammers with varying degrees of impact energy are available. Materials ranging from plaster to concrete can be tested.

Application and advantages

- The Schmidt hammer is the best known example. It is has a spring activated plunger.
- Assess the uniformity of in-situ concrete or masonry in a structure.
- Detect zones or regions of poor quality or deteriorated concrete or masonry
- A pendulum hammer has been adapted to assess the quality of the mortar within the outer part of the mortar joint (pointing mortar). The mortar can be divided into 6 classes varying from *Very weak/soft* to *Extremely strong/hard.*
- Simple to use and quick.

Limitations

- Difficult to calibrate directly against material strength because it is too sensitive to surface structure. Should not be used for the determination of the compressive strength of a material.
- Can pit softer surfaces. This may be avoided by using a hammer with a lower impact energy.
- Only gives an indication of condition near the surface of the material tested.

Examples of use

- Pume [1989] said the hammer determines the quality of a brick in a wall to a depth of 50 mm. If five to ten bricks are removed from the masonry and tested beforehand to provide a calibration factor, the strength of the bricks remaining in the wall can be estimated.

Equipment

- *Schmidt hammer* (Proceq) $500; plus test anvil $300. Three typical energy levels are 0.74, 2.2 & 29 Nm.
- *Digi-schmidt* (Proceq) Electronic version of the hammer; digital readout.
- *Pendulum hammer type PM* (Proceq) For hardness of pointing mortar [see Klugt 1991].
- *H meter* (James) 2.2 Nm impact energy

Standards

- ASTM C805 (impact hammer on concrete)
- BS 1881 Part 202, RILEM draft (for masonry)

Further information

Feldman 1977, Klugt 1991, Malhotra 1991, Noland et al 1982 & 1990

ULTRASONIC PULSE VELOCITY (stress wave method)

Background and principles

An electromechanical transducer transmits a high frequency pulse into the member under investigation. The time it takes the pulse to reach another point on the member, or the time it takes to return is measured. If the distance between the points is known, the pulse velocity can be calculated. The velocity is a function of the dynamic modulus of elasticity, Poisson's ratio and the density of the materials through which it passes. If there are defects such as voids or low density areas the pulse is reflected and refracted which lowers the velocity and attenuates the amplitude of the transmitted wave. This method is used extensively to investigate the properties and condition of homogeneous continuous materials such as steel. Frequencies of 1 MHz and higher are used for steel. Lower frequencies are used for concrete (200 kHz or less; a common value is 54 kHz). Heterogeneous solids such as concrete or masonry strongly attenuate higher frequencies.

Applications and advantages

- assess uniformity and relative quality of concrete and masonry
- successfully used to measure the thickness of plate elements such as concrete pavements, and integrity testing of rod like elements such as piles.
- detect cracks, voids and areas of poor compaction
- detect progressive deterioration of a material with time (eg increase in cracks)
- estimate dynamic modulus of elasticity and Poisson's ratio
- assess strength and quality of concrete particularly repaired areas where comparative techniques can be applied (i.e. for quality assurance).
- computer modelling can show the position and shape of boundary layers that induced the reflection. This will improve interpretation of experimental data.
- sonic tomography helps interpretation (contours of equal velocities are plotted onto a plan of the member under investigation).

Limitations

- cannot be used to estimate compressive strength unless it has been correlated with compressive tests on the same material.
- steel reinforcement may influence the measured pulse velocity in concrete [see Naik & Malhotra 1991]
- best results achieved if both sides of member are accessible (e.g. slab thickness).
- interpretation of data requires skill and experience; the more complex the member's geometry the more difficult the interpretation.
- a higher penetration is attained by decreasing the pulse frequency but as the frequency decreases (longer wavelength) the resolution also decreases (i.e. smaller defects not detected). Too high a resolution may also be detrimental if the wavelength gets down to the size of the aggregate in concrete for example; the waves will then reflect of these interfaces too.
- in inhomogeneous materials such as masonry the pulse is affected by joints and voids which rapidly attenuates the signal reducing the depth of penetration (open joints present an impenetrable barrier to the ultrasonic waves). It also makes the signal much more difficult to interpret because of the many reflections and refractions. It may give better results in detecting cracks within individual bricks (i.e. those caused by frost damage).
- pulse velocity changes when specimen becomes wet. Especially noticeable if there are cracks since water helps bridge the cracks.

Examples of use

- Armer [1987] found best results if there is access to both sides of the member under investigation.
- Sullivan [1991] used it to estimate the compressive strength of concrete with high alumina cement. Results cross-checked with core tests.
- 50 kHz gives a useful range in concrete but less so in masonry especially where lower strength mortars are used [Noland et al 1990; they recommend trying a lower frequency].

- Abrams [1989] used the method to calculate the transit times between two points in a masonry wall under test in the laboratory. Ultrasonic wave length was too short relative to the dimensions of the masonry components plus problem with attenuation (1.5 m maximum penetration). With impact-echo method longer distance (approx 2 m).

Equipment

- *Pundit and similar ultrasonic units* (ELE, Soiltest, Germann, James) 54 kHz standard transducer; options 24 kHz to 1 MHz. $3-4,000 [Naik & Malhotra 1991 give a brief description]
- *High power pulsed RF* (Matec) Main use in laboratory.
- *Sonic, ultra-sonic instruments.* (Staveley, Physical Acoustics, Sierra Matrix)
- *DM2E Digital thickness meter.* (Krautkramer) [described by Kayser 1992]
- *Mu-gage* (MTI) Digital thickness meter
- *Panametrics Epoch II A-scan meter* Displays visual record of the return echoes. [described by Kayser 1992]
- *Ulcon (Ultrasonic Concrete Tester)* (Krautkramer) Approx $30,000

Standards

- ASTM C597 Test method for pulse velocity through concrete (10-150 kHz range).
- ASTM E797, BS 1881 Part 203, RILEM draft (for masonry)

Further information

Abrams 1989 (application to masonry), Armer 1987, Calvi 1988, Epperson 1989, Figg 1992, Forde 1987 (application to masonry), Hobbs & Wright 1988, Kayser & Miller 1992 (application to steel), Matec 1989, Naik & Malhotra 1991 (evaluation for concrete), Noland 1990 (evaluation for masonry), Sansalone & Carino 1991, Sullivan 1991

3.3 MOISTURE AND ASSOCIATED PROBLEMS

CONDENSATION SENSORS

Background and principles

Condensation sensors are used to measure time of wetness, or detect dew point temperatures. One type acts as an electrochemical cell, producing a small voltage when it becomes wet. Another more sensitive one, detects condensation on a mirror.

Equipment

- *Sereda moisture sensor Model SMMS-01* (Epitek) $45 When moisture condenses on the sensor it activates a copper-gold electrochemical cell producing a small voltage (20 to 40 mV).
- *Chilled mirror sensors* (General Eastern) Expensive.

Standards

ASTM G84 (measurement of time-of-wetness with Sereda type sensors)

Further information

Sereda et al 1982

DOGS

Applications, advantages and limitations

Dogs have been trained to detect the dry rot fungus (serpula lacrymans) in wood.

Further information Hutton 1991

HALF-CELL POTENTIAL

Background and principles

This test is used primarily with reinforced concrete. When steel rusts it acts as an anode of a galvanic cell (there will be a current flow from the anodic areas to cathodic areas). The potential (voltage) generated can be detected using a reference half-cell moved along the surface of the concrete. The concrete acts as an electrolyte (moisture and salts). The magnitude of the measured voltage is an indicator of the likelihood of corrosion activity. Half-cells are usually made of $Cu/CuSO_4$ or Ag/AgCl.

Applications and advantages

- estimate the risk of corrosion of steel reinforcement in concrete floors and decks.
- from a plot of equipotential contour lines, likely areas of uniform and localized corrosion of reinforcement can be deduced.

Limitations

- this test on its own does not indicate the rate of corrosion.
- a direct electrical connection is required to a reinforcement bar
- the surface of the concrete must be exposed

Examples of use

- Stockbridge [1986] has used it to detect areas of active corrosion in steel embedded in terra cotta cladding. He does not state how successful it was.

Equipment

- *Half-cell corrosion test kit* (ELE)
- *Blood-Hound* (Germann) [see Moller 1992]
- *Corroscan system.* (James) Potential using Ag/AgCl half-cell.
- *Concrete corrosion mapping system* (Miller)

Standards

ASTM C876 for concrete.

Further information

Ali 1990, Lauer 1991, Litvan 1982, Moller 1992, Stockbridge 1986, Vassie 1984

HUMIDITY SENSORS

Background and Principles

Humidity can be measured by sling psychrometers (accuracy 0.3 to 3%), hygrometers based on the dimensional change of an organic material such as hair (accuracy ±3%), a variety of handheld electronic sensors (accuracy 2 to 5%), and simple crystal sensors which change in colour with changes in humidity.

Applications and advantages

- interior and exterior humidity
- indirect indication of moisture content in materials. A probe is inserted into a drilled hole. The humidity within the hole is an indication of the moisture level in the surrounding material.

Limitations

- needs recalibration at regular intervals

Equipment

- *Handheld electronic sensors* (General Eastern, Vaisala, Elcometer) With digital readout
- *Electronic sensors for monitoring* (General Eastern, Vaisala)
- *Sling psychrometers* (Elcometer)

- *Hygrothermograph* (Geneq) Pen continuously records temperature and humidity on paper attached to a revolving drum for periods of 1 day, 1 week or 1 month. Modern units are battery powered.
- *Hum-Meter* (Germann) A simple crystal sensor which measures humidity within a hole drilled into a concrete member (range 40 to 95%; stated accuracy ±3%). From this concrete moisture content is estimated.

Further information

Kulwicki 1991, McKenna & Munis 1989

MOISTURE METERS (capacitance type)

Background and principles

These sensors produce a high frequency of the order of 12 MHz to measure the dielectric resistance of the material with which it is in contact. Water has a much higher dielectric constant (80) than dry roofing materials (4), dry concrete (10) or air (1.0). Capacitance sensors can therefore be used to detect moisture.

Applications and advantages

- detect moisture and thickness of pavements
- detect moisture in roofs
- in contrast to the resistance moisture meter, not affected by salts
- most useful for giving comparative values

Limitations

- needs calibration for with same material if used to get absolute values of moisture.
- it can determine moisture content of wood to ±5% if corrected for wood species and temperature
- measures moisture in surface layer (max penetration 30 to 50 mm)
- sensor should be placed on a plane surface so that there is good contact with the electrodes (rubber covered).

Equipment

- *H_2O meters* (James) $850 For moisture content of masonry, concrete and wood.
- Other capacitance meters available from A-Tech and Tramex/United [see McKenna & Munis 1989]

Standards

ASTM D4444 (moisture meters for wood)

Further information

Anon 1985, Lauer 1991, McKenna & Munis 1989, Otto 1990

MOISTURE METERS (resistance type)

Background and principles

Meters which measure electrical resistance give an indication of moisture content and distribution (resistance decreases with increasing moisture levels). The electrodes are usually in the form of pins.

Applications and advantages

- can accurately determine the moisture content of wood (within ±0.5 to 2% if corrected for wood species and temperature). Insulated pins can be driven into wood to give moisture levels below the surface.

- For concrete and masonry, they can indicate variations in moisture content at the surface. A plastic sheet laid over the surface will cause surface moisture levels to approach those further within the member.
- Combined with the half-cell potential test, the resistance meter can be used to give an indication of the corrosion rate of reinforcement in concrete; the more moisture the higher the potential rate of corrosion where it is shown to be possible by the half-cell test. A four point resistance probe should be used (Wenner type).

Limitations

- misleading low resistance (high moisture) readings may be obtained if salts are present in the moisture.
- measures moisture levels at or near the surface
- does not give absolute values of moisture content in concrete and masonry.

Equipment

- *Resistivity meter* (CNS) Designed to measure the resistivity of concrete using a Wenner linear four-probe array; measures a.c. & d.c. resistance using a.c. circuits; developed by Taywood Engineering.
- *Resistance based moisture meters* (Delmhorst, ELE, Lee Valley) $190-$700. Resistance meters calibrated to give moisture content of wood. Some models can also be used to check relative moisture levels in concrete, masonry & plaster. An extensive selection of meters available.
- *Protimeter dampness kit* (Sheen) $1700. A portable kit containing various pieces of equipment for checking dampness problems in buildings.

Standards

ASTM D4444 (moisture meters for wood)

Further information

Anon 1985, Lauer 1991, Millard 1991

NEUTRON ABSORPTION (radiographic method)

Background and principles

Neutrons are scattered by hydrogen nuclei more strongly than by any other chemical element present in masonry or concrete. Thus this method gives a good indication of moisture present in the material. A large back scatter or low transmission indicates a high moisture level. Americium-241:Beryllium and Californium 252 are used as neutron emitters.

A neutron-gamma ray technique is also available which measures the gamma rays emitted when a material is bombarded with neutrons. Analysis of the gamma rays can show what elements are present in the material.

Application and advantages

- in buildings main use to detect trapped moisture in built-up roofs.
- gives a good indication of moisture content.
- portable equipment available for field use
- used in the laboratory to get accurate indications of moisture distribution within a material.

Limitations

- no data found regarding accuracy in use on roofs.
- grid system must be laid out on the roof and readings taken at each intersection. This slows down the survey but does produce an accurate map of the moisture distribution in the roof.

- limited penetration into the material (of the order of 100 mm, depending on material and surface water content)

Examples of use

- Livingston et al [1986] used the neutron-gamma ray technique to map the relative distribution of moisture and salt in a masonry wall.

Equipment

- *Nuclear moisture/density gauge* (Humboldt, Troxler)
- *Roof moisture meters* (Seaman)

Further information

Anon 1985, Groot 1989 (application to masonry in the laboratory), Heidt & Stade 1988, Livingston et al 1986, McKenna & Munis 1989 (application to roofs)

PERMEABILITY (initial surface absorption)

Background and principles

The rate of absorption of air or water per unit area is measured (either under constant pressure, or time of absorption of a given quantity of water).

Application and advantages

- test is useful in giving comparative values as an indication of variations in concrete porosity which may affect durability and resistance to ingress of moisture (affecting carbonation and corrosion).
- simple gauges based on graduated cylinders attached to the material under test have been used to measure water absorption of concrete, individual masonry units and leakage at the interface between mortar and masonry units.
- assess the effectiveness of water repellant treatments.

Limitations

- can help experienced investigators assess the resistance of a masonry wall to rain penetration but cannot be used as an absolute indicator.

Standards

RILEM test 11.4 (simple water gauge)

Equipment

- *GWT* (Germann; ELE) Water permeability
- *Poroscope* (James) Air and water permeability [description by Figg 1991]
- *Concrete tightness tester* (Schupack) Measures air leakage through the material or joint it is attached to.

Further information

Gale 1989, Brüning 1989, Farahmandpour 1990, Figg 1991, Montgomery 1991, Whiting 1992

WATER LEAKAGE (through walls)

Background and principles

Water is sprayed onto a wall to measure its resistance to leakage. Frames allow measured amount of water to be sprayed onto the wall; the air in the frame is under pressure to simulate wind driven rain. Water not absorbed by the wall is collected and recirculated; loss of water is a measure of water going into the wall.

Applications and advantages

- a comparative check on water penetration through a wall

- used for quality control to check effectiveness of repointing a wall or adding a water resistant sealer.

Limitations

- cannot be used to specify a water leakage rate through walls
- test is very approximate

Examples of use

- Stockbridge [1988] used a frame with water spray to assess a suitable mortar for repointing a masonry wall, and then used it to assess the quality and consistency of the repointing.

Standards

ASTM E514

Further information

Krogstad 1990, Stockbridge 1986 & 1988

WATER LEAKAGE (through roofs)

Background and principles

An electrically conducting grid detects moisture ingress.

Application and advantages

- a moisture detecting grid is used to detect leaks in built-up roofing. When a leak occurs an alarm is set off and the location of the leak is shown.

Limitations

- these systems are installed beforehand during construction or renovation.

Equipment

- Moisture sensitive electric grids (Aquaveyor, MID)

APPENDIX 1

ADDRESSES OF MANUFACTURERS & SUPPLIERS OF NDT EQUIPMENT

Agema Infrared Systems
5230 South Service Rd, Suite 125, Burlington, Ont. L7L 5K2
tel (416) 637 5696 fax (416) 639 5488

Applied Geomechanics Inc
1336 Brommer St, Santa Cruz, CA 95062, USA
tel (408) 462 2801 fax (408) 462 4418

Aquaveyor System
UK

Avongard
UK
Agent in Canada is R.S.

Bales Scientific Inc
1620 Tice Valley Boulevard, Walnut Creek, California 94595
Agent in Canada is CANDET

Brainard-Kilman
2175 West Park Court
PO Box 1959, Stone Mountain, GA 30086, USA
tel (404) 469 2720 fax (404) 498 2841

Bruel & Kjaer
90 Leacock Road, Pointe Claire, Quebec H9R 1H1
tel (514) 695 8225 fax (514) 695 4808

Calculated Industries
22720 Savi Parkway, Yorba Linda, CA92686
tel (800) 854 8074
In Canada, Lee Valley sells their electronic tapes

CANDET (Canadian NDE Technology Ltd)
18 Canso Rd, Rexdale, Ontario M9W 4L8
tel (416) 243 3456 fax (416) 243 1354

Carsen Medical & Scientific Co Ltd
151 Telson Road, Markham, Ont. L3R 1E7
tel (416) 479 4100 fax (416) 479 2595

CNS Electronics Ltd
61-63 Holmes Road, London NW5 3AL, UK
tel 071 485 1003

Coe Manufacturing Company (Canada) Ltd
Moore-Canada Division, 1 Pleasantview Avenue

PO Box 68, Brampton, Ontario L6V 2K7
tel (416) 451 4990 fax (416) 451 6206

Cordec International Inc
1390 Prince of Wales Drive, Ottawa, Ont. K2C 3N6
tel (613) 224 5012 fax (613) 224 1642

Delmhorst Instrument Co
51 Indian Lane East, Towaco, NJ 07082, USA
tel (201) 334 2557 fax (201) 334 2657
Agent in Canada is Coe

Densicon Inc (taken over by James Instruments)

Durham Instruments
PO Box 426, Pickering, Ontario L1V 2R7
tel (416) 839 9960 fax (416) 420 1962

EDM (Engineering Data Management Inc)
4700 McMurray Avenue, Building A, Fort Collins, Colorado 80525
tel (303) 223 0457 fax (303) 223 0484

Elcometer Instruments Ltd
Edge Lane, Droylsden, Manchester M35 6BU, UK
tel 061-370 7611 fax 061-370 4999
Agent in Canada is Geneq

ELE International
Materials Testing Division
Eastman Way, Hemel Hempstead, Hertfordshire HP2 7HB, England
tel 0442-218355 fax 0442-52474
Agent in Canada is Hoskin

International **Epitek** Inc
100 Schneider Rd, Kanata, Ont K2K 1Y2
tel (613) 592 2240

Exergen Corp
One Bridge St, Newton, MA 02158, USA
tel (617) 527 6660? fax (617) 527 6590
R G (Dick) Graham has some of their equipment
sensIRscan, Thermography Incorporated
109 Acacia Ave, Ottawa K1M 0P8 tel (613) 749 0051

FaAA Products Corp [Failure Analysis Associates Inc]
149 Commonwealth Drive, Menlo Park, California 94015
tel (415) 326 9400

Geneq Inc
7978 Jarry East, Montreal H1J 1H5
tel (514) 354 2511 fax (514) 354 6948
223 Signet Drive, Weston, Ont M9L 1V1
tel (416) 747 9889 fax (416) 747 7570

General Eastern
50 Hunt St, Watertown, MA 02172, USA
tel (617) 923 2386
Agent in Canada is Willer

Geophysical Survey Systems Inc
13 Klein Drive, PO Box 97, North Salem, NH 03073-0097
tel (603) 893 1109 fax (603) 889 3984

Germann Instruments, Inc
8845 Forest View Road, Evanston, Illinois 60203-1924
tel (708) 329 9999 fax (708) 329 8888
Much of their equipment also available from ELE

Heath Consultants
100 Tosca Drive, PO Box CS-200, Stoughton MA 02072-1591
fax (617) 341 4359
[sells NDT equipment; type unknown]

Hoskin Scientific Ltd
4210 Morris Drive, Burlington, Ont L7L 5L6
tel (416) 333 5510 fax (416) 333 4976

Hughes Aircraft Inc
Agent in Canada is Optikon

Humboldt Scientific Inc
5510 Pylon Drive, Raleigh, NC 27607
tel (919) 832 6509 fax (919) 833 5283
Agents in Canada are Sartell & Geneq

Inframetrics
16 Esquire Rd, North Billerica, MA 01862, USA
tel (508) 670 5555 fax (508) 667 2702
Agent in Eastern Canada is TPInc

Intertechnology Inc
1 Scarsdale Road, Don Mills, Ontario M3B 2R2
tel (416) 445 5500

James Instruments Inc
Non Destructive Testing Systems
3727 North Kedzie Avenue, Chicago, Illinois 60618
tel (312) 463 6565 fax (312) 463 0009

Krautkramer Foerster Japan Co. Ltd
Shintaiso Bldg. 10-12 Dogenzaka 2-chome, Shibuya-ku, Tokyo 150, Japan
tel (03) 476-5941 fax (03) 476-0211
Agent in Canada is CANDET

Kyowa Electronic Instruments Co. Ltd
Japan. tel (03) 3502 3553 fax (03) 3502 3678
Agent in Canada is Omnitronix

Lee Valley Tools Ltd
1080 Morrison Drive, Ottawa, Ontario K2H 8K7
tel (613) 596 0350 fax (613) 596 6030

M&L Testing Equipment Co Ltd
27 Dundas Street East, Hamilton, Ont. L9J 1B1
tel (416) 689 7327 fax (416) 689 3978

Matec Instruments Inc
75 South Street, Hopkinton, MA 01748
tel (508) 435 9039 fax (508) 435 5289
Agent in Canada is NDT

W H **Mayes** and Son (Windsor) Ltd
Vansittart Estate, Arthur Rd, Windsor, Berks. UK SL4 1SD
tel 0753 865103/864756
ELE sells some of their equipment

MID Moisture Intrusion Detection Systems Inc
USA/Canada. Address not found.

M C **Miller** Co Inc
Agent in USA is SDS

MTI Corporation (Mitutoyo)
6699 Campobello Rd, Mississauga, Ont L5N 2L7
tel (416) 821 1261

NDT Technologies Inc
18900 Clark Graham, Baie d'Urfe, Quebec H9X 3R8
tel (514) 457 7650 fax (514) 457 7652

Nema Electronics BV
PO Box 7056, NL-1007JB Amsterdam, Netherlands
tel 31-20-6624583

Olympus
Agent in Canada is Carsen

Omnitronix Ltd
2180 Dunwin Drive, Unit #1, Mississauga, Ont. L5L 1C7
tel (416) 828 6221 fax (416) 828 6408

Optikon Corp Inc
300 March Rd, 4th floor, Suite 436, Kanata K2K 2E2
tel (613) 592 5207 fax (613) 592 3721

PCB Piezotronics
3425 Walden Ave, Depew, New York 14043-2495
tel (716) 684 0001 fax (716) 684 0987
Agent in Canada is Intertechnology

Penny & Gilles
Agent in Canada is Durham

Physical Acoustics Corporation
PO Box 3135, Princeton, New Jersey 08543, USA
tel (609) 896 2255 fax (609) 895 9726

Proceq SA
Riesbachstrasse 57, Postfach 491, CH-8034 Zurich
tel 01-477800 fax 01-479914
Agent in Canada is M&L; in USA is SDS

Protovale (Oxford) Ltd
Rectory Lane Trading Estate, Kingston Bagpuize,
Abingdon, Oxon. OX13 5AS. UK. tel (0865) 821277 fax (0865) 820573.
Agent in Canada is M&L, and in USA is Germann

R.S. Technical Instruments Ltd
18-1870 McLean Av, Port Coquitlam, BC V3C 4K9
tel (604) 941 9155/4848

Sakata Denki
2-17-20 Yagisawa, Hoya-shi, Tokyo, 202 Japan
tel Hoya (0424) 64-3111

Sartell Instrumentation Ltd
Mississauga.
tel (416) 890 1090 fax (416) 890 1744

Scancem Chemicals
N-3470 Slemmestad, Norway
tel 47 2852100 fax 47 2852327
Agent in USA is SDS

Schaevitz
USA
Agent in Canada is Durham Instruments

Schupack Suarez Engineers, Inc
USA [from Concrete International, Oct 90, p 93]

SDS Company
PO Box 844, Paso Robles, CA 93447
tel (805) 238 3229 fax (805) 238 3496

Seaman Nuclear Corporation
7315 S First Street, Oak Creek, WI 53154, USA
tel (414) 762 5100
Agent in Canada is Solinst

Sensors & Software Inc
5566 Tomken Rd, Mississauga, Ontario L4W 1P4
tel (416) 624 8909 fax (416) 624 9365

Sheen Instruments Ltd
Waldegrave Road, Teddington, Middlesex TW11 8LD, UK
tel 081 977 0051 fax 081 977 0855
Agent in Canada is Geneq

Sierra Matrix Inc
48890 Milmont Drive, Suite 105D, Fremont, California 94538

Soiltest
Illinois, USA.
Agent in Canada is Hoskin

Solinst Canada Ltd
2440 Industrial St, Burlington, Ont L7P 1A5
Tel (416) 335 5611 Fax (416) 335 6133

Sperry
USA

Staveley Instruments, Inc.
USA

TPInc (Totalvision Photonics Inc)
39 Vaughan St, Ottawa, Ontario K1M 1W9
tel (613) 741 1535 fax (613) 741 9750

Troxler Electronic Laboratories Inc
3008 Cornwallis Road, PO Box 12057, Research Triangle Park, NC 27709, USA
tel (919) 549 8661 fax (919) 549 0761
Agent in Canada is M&L

Vaisala Inc
2 Tower Office Park, Woburn, MA 01801, USA
tel (617) 933 4500
Agent in Canada is Hoskin

Wedge Innovations
532 Mercury Drive, Sunnyvale, CA 94068, USA
(800) 762 7853
In Canada, Lee Valley stocks their level.

Willer Engineering Ltd
6333 Chemin St-François, St Laurent H4S 1B6, Quebec
tel (514) 333 4662 fax (514) 333 8555
Also offices in Willowdale, Sarnia & Dartmouth.

Windsor Systems Inc (now part of James Instruments)

APPENDIX 2 BIBLIOGRAPHY

A2.1 STANDARDS

AS (Australian standards)

AS 3700-1988 SAA Masonry Code (Masonry in Buildings). Describes the bond wrench test method.

ASTM (American Society for Testing and Materials)

C597-83 Test method for pulse velocity through concrete

C803-82 Test method for penetration resistance of hardened concrete

C805-85 Test method for rebound number of hardened concrete

C876-87 Half-cell potentials of uncoated reinforced steel in concrete

C900-87 Pullout strength of hardened concrete

C1040-85 Test methods for density of unhardened and hardened concrete in place by nuclear methods [gamma radiation]

C1072-86 Measurement of masonry flexural bond strength

C1150-90 Test method for the break-off number of concrete

C1196-91 In situ compressive stress within solid unit masonry estimated using flatjack measurement

C1197-91 In situ measurement of masonry deformability properties using the flatjack method.

D4444-92 Use and calibration of hand-held moisture meters

D4788-88 Test method for detection of delaminations in bridge decks using infrared thermometry

E376-89 Measuring coating thickness by magnetic field or eddy-current (electromagnetic) test methods

E488-90 Test methods for strength of anchors in concrete and masonry elements

E514-86 Test method for water permeance of masonry

E797-90 Measuring thickness by manual ultrasonic pulse-echo contact method.

E1316-92 Terminology for nondestructive examinations

G84-89 Measurement of time-of-wetness on surfaces exposed to wetting conditions as in atmospheric corrosion testing

BSI (British Standards Institution)

BS 1881 Testing concrete

Part 5:1970 Methods of testing hardened concrete for other than strength.

Part 201:1986 Guide to the use of non-destructive methods of test for hardened concrete.

Part 202:1986 Recommendations for surface hardness testing by rebound hammer.

Part 203:1986 Recommendations for measurement of velocity of ultrasonic pulses in concrete.
Part 204:1988 Recommendations on the use of electromagnetic covermeters.
Part 205:1986 Recommendations for radiography of concrete.
Part 206:1986 Recommendations for determination of strain in concrete.
Part 207:1992 Recommendations for the assessment of concrete strength by near-to-surface tests
Part 208:prep Recommendations for the determination of initial surface absorption of concrete

DIN (German standards)
DIN 1048 Pt 4 Test methods for concrete; determination of the compressive strength of hardened concrete in structures and components; application of reference lines and evaluation by special methods.

ISO (International Standards Association)
ISO 6781 (1983) Thermal insulation - qualitative detection of thermal irregularities in building envelopes - Infra-red method.

NT (Nordtest Methods, Scandinavia)
NT Build 123 1981 Mortar joints: density - radiometric method.

RILEM (Réunion Internationale des Laboratoires d'Essais et de Recherches sur les Matériaux et les Constructions)
RILEM test 11.4 (water permeability)

Draft masonry standards (RILEM committee 127MS)
- Determination of masonry rebound hardness
- Measurement of dynamic stiffness for masonry elements
- Measurement of mechanical pulse velocity for masonry
- Measurement of ultrasonic pulse velocity for masonry
- Radar investigation of masonry

UBC (Uniform Building Code USA, 1991 edition)
Uniform Code for Building Conservation
Standard 24-7 In-place masonry shear tests
Standard 24-30 Standard test method for flexural bond strength of mortar cement

A2.2 BIBLIOGRAPHY

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A2.3 ELECTROMAGNETIC, SONIC AND ULTRASONIC WAVES

Electromagnetic waves

Electromagnetic waves move at the speed of light (300 x 10^6 m/sec).

Frequency	Wavelength	Description
30 MHz - 300 MHz	10 m - 1 m	TV & FM radio
300 MHz - 3 THz	1 m - 0.1 mm	Microwaves (includes radar)
300 GHz - 430 THz	1 mm - 0.7 μm	Infra-red
430 THz - 750 THz	0.7 μm - 0.4 μm	Visible light
750 THz - 5,000 THz	0.4 μm - 60 nm	Ultra-violet; ionizing radiation < 0.5 μm
30,000 THz - 300x10^6 THz	10 nm - 1 pm	X-ray
3x10^6 THz - >30x10^9 THz	0.1 nm - < 0.01 pm	Gamma ray; radioactive

Sonic and ultrasonic waves

The speed of sonic and ultrasonic compression waves depends on the material through which the waves are travelling. Speed in air 330 m/sec; in steel about 5,000 m/sec; in concrete and masonry normally in the range 2,000 to 5,000 m/sec.

Frequency	Wavelength	Description
< 20 kHz		Sonic
> 20 kHz to ~15 MHz		Practical ultrasonic range
20 kHz - 150 kHz	200 mm - 27 mm (at wave speed 4,000 m/sec)	Normal range for testing of concrete
1 kHz - 100 kHz	3 m - 30 mm (at wave speed 3,000 m/sec)	Normal range for testing of masonry
1 MHz - 8 MHz	5 mm - 0.6 mm (at wave speed 5,000 m/sec)	Normal range for testing of steel

Notes

Wavelength = wave velocity / frequency

k ilo	10^3	**m** illi	10^{-3}
M ega	10^6	μ (micro)	10^{-6}
G iga	10^9	**n** ano	10^{-9}
T era	10^{12}	**p** ico	10^{-12}

Hz 1 cycle/sec