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Non-destructive Evaluation of Masonry Materials in Structures

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Non destructive test (NDT) methods applicable to masonry structures are defined, classified and reviewed in the context of the type of information required to suit different problems, which tests are appropriate to which application and when they should be used. Some of the more promising techniques are discussed at greater length in the light of current research at the Building Research Establishment.

1. Introduction

In Europe there is a long tradition of building with masonry, and applying ceramic finishes. Structures range from the humble boundary wall through housing, warehouses, factories, commercial buildings, to large institutions, great cathedrals and the many civil engineering uses such as tunnels, retaining walls, waterways, aqueducts and bridges. Many of these structures have lasted hundreds or even thousands of years and are frequently still performing their original function or have been adapted to a new use. Many other masonry structures are preserved for their beauty or historical significance and their role in culture and tourism.

Masonry has a role in modern buildings as well although less often as the main structural form and more frequently as an attractive and durable facade or cladding element. Structural use of masonry continues in the UK, however in the form of reinforced and prestressed retaining walls and diaphragm walls used for large single storey structures such as sports halls. Recently the masonry arch bridge is being reconsidered because of it's durability and attractiveness and a significant new one was built in 1993.

In the purest sense Non-destructive evaluation (NDE) is a method of obtaining information about materials or composite structures without visibly affecting the materials or the structure in any way. Such tests are based, in most cases, on some form of electromagnetic or other radiation at intensities (amplitudes) below the damage threshold for the materials. Examples are given in the upper part of Table 1. It is convenient to class these as radiative NDE techniques and they can give valuable information about invisible subsurface structural form and limited information about the condition of materials.

Unfortunately, the pure radiative techniques are not very effective at giving information about the structural performance (e.g. strength) of the materials or assemblages (masonry) nor about the stresses which are acting nor the resulting strains that may have occurred. For this information it is necessary to use a technique that interacts physically with the materials at significant intensities. These mechanical/chemical interaction techniques do cause localised, but reparable, damage to materials but can be limited such as to not prejudice the integrity of the whole structure nor cause significant aesthetic damage. Examples, in rough order of severity, are given in the lower half of Table 1.

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2. Technical Applicability of NDE to Masonry and Ceramic Products

Increasingly structures are being preserved for cultural and functional reasons and many are being re-used often with different loadings or subject to more demanding codes and standards or in changed external conditions. It is essential, in order to maintain or develop them safely and effectively that data is obtained about their form, design, materials etc., particularly those predating the application of any design codes, regulations and standards for materials.

Whenever NDE is considered the questions usually being asked are:

(1) WHAT IS PRESENT ? i.e.what are the materials, what is the subsurface structure, is the structure homogeneous or does it have different materials below the surface, is it solid, hollow, reinforced, tied, bonded or unbonded? etc.

(2) WHERE IS IT ? i.e. what is the bonding pattern below the surface, if voids or hollow features are present where are they located, if metal components are incorporated where are they?

(3) WHAT CONDITION IS IT IN ? Is there any chemical or mechanical deterioration of unit materials, tiles, mortar, adhesive, plaster coatings or the bond between them; what state are any metal components in; have cores been leached or settled.

(4) HOW STRONG, WET, STIFF ETC. IS IT ? i.e. if redesign is required what are the relevant design data for the structure and materials as found?.

The first two questions form a group to which some generalised test methods apply, the third and fourth questions usually require specialised methods and equipment. Despite an increase in interest and research on NDE tests for masonry there are still no widely accepted in-situ tests for the strength of the units and mortar and the standard test is to remove mortar by drilling and to evaluate by chemical analysis and to evaluate whole units after removal from the wall. A RILEM committee, 127MS, is attempting to lay down embryo international standards for such tests wherever there is a sufficient basis of laboratory and field data.

Table 1 gives an overview of the available techniques and attempts to give guidance about applicability and cost. Well

Table 1. NDE methods.

Test	Type Code	Equpt. Cost	References Reviews	porosity/permeability	crack location	void location	damp location	metal location	metal size/shape	metal corrosion	density of materials	strength of materials	bond strength	shear strength	stress	elastic properties	overloading	salts content	moisture content	chemical content	mineral content	carbonation depth
Visual inspection	RPS	$/$$	3,5,10		✓	✓	✓	✓	✓	✓							✓					
Microwave transmission	TQ	$$$	4,5,10															✓	✓			
Pulsed Radar reflection	RP/S	$$$$$	5,6-10		✓	✓	✓	✓	✓													
X-Radiography	TPS H	$$$	5,10		✓	✓	✓	✓	✓	✓												
Gamma radiography	TP/S H	$$$	10		✓	✓	✓	✓	✓	✓												
Gamma radiometry	TQ/C H	$$$$	10		✓	✓	✓	✓	✓	✓	✓											
Gamma ray back-scatter	RQ H	$$$$	10								✓											
Neutron absorption	TQ H	$$$$$	10															✓	✓	✓		
Infra-red thermography	T/EPS	$$$$$	5,10,11-13		✓	✓	✓	✓	✓													
electromagnetic	RDP/S	$/$$	5,10,14					✓	✓													
ultrasonic pulse velocity	TQ/C	$/$$	5,10,15-17		✓	✓		✓	✓			✓										
Half cell potential	Q	$	10, 18							✓												
Surface resistivity	RCQ	$	10			✓												✓	✓			
Fluid flow	TQ	$/$$	10		✓																	
Resonance (continuous)	EQ	$/$$$	19-21													✓						
Mechanical Pulse echo	RP	$$	16		✓	✓																
Mechanical Pulse response	EW	$$	22		✓				✓							✓						
Acoustic emission	EW	$$$	10												✓		✓					
Penetration resistance	C	$	5,23	✓							✓	✓										
Internal fracture test	CQ	$	23,24,25									✓										
Pull-off test	CQ	$	10,26									✓										
Helix pull-out	CQ	$/$$	5,23,27								✓	✓										
Dynamostratigraphie	C	$$	23,28								✓	✓										
Rebound hammer	C	$	5,10,16,29									✓										
Flat jack	Q	$$	5,10,16,30-32																✓			
Dual flat jack	Q	$$	5,10,16,30-32													✓				✓		
Bond wrench	Q	$/$$	5,23,32-35									✓	✓									
Shove test	C (Q)	$$	16									✓	✓	✓								
Coring and testing cores	Q	$$	16	✓	✓	✓		✓	✓	✓	✓	✓			✓	✓		✓		✓	✓	✓
Drilling dust	Q	$	10,36															✓	✓	✓	✓	
Phenolphlalein test	Q	$	10																			✓
Small sample petrography	Q	$$$	10	✓																	✓	
Chemical analysis	Q	$/$$$$$	10															✓	✓	✓	✓	
Scanning Electron micro- -scopy / x-ray fluorescence	REQPS	$$$$ - $$$$$	10	✓	✓					✓								✓		✓	✓	

TYPE CODES:	
T =	transmission - technique requires access to two sides
R =	Reflection - technique requires access to only one side
E =	emission - technique requires access to only one side but may require stimulation
Q =	quantitative - technique gives absolute data about a parameter if calibrated
C =	comparative - technique gives data about local variability of a parameter but not absolute values
D =	detection† - technique signals the presence of a feature or material
P =	positional† - technique gives information about position of a feature or material
S =	scalar† - technique gives information about size and/or shape of a feature or material
	† the feature or material may not be visible on the surface
H =	hazardous - technique involves radiation harmful to life and thus requires special precautions.
COST CODE	$=<$500, $$=$500-$3000, $$$=$3000-$15000, $$$$=$15000-$50000, $$$$$=>$50000

known techniques are not described individually but more comprehensive references are given in Table 1.

3. Interpretation of Data from Tests

In most cases the reason for carrying out a test is to enable a decision to be made or a dispute to be settled. Tests on masonry materials are inherently variable, even in wellcontrolled laboratory conditions, and in-situ tests have been shown to be more variable than laboratory tests by Suprenant and Lin [1] and de Vekey [2]. Even the simplest tests tend to be labour-intensive, and thus expensive, for site applications. Problems increase it the building is in a remote location or if the access is difficult thus a lot of care must be taken to select viable, cost effective and relevant tests. At the outset the specifier must have a clear idea of how the results are to be applied and whether the variability is acceptable. if the results of the test, however conclusive, will not be accepted or used because of non-technical reasons it is pointless to carry them out! Remember that engineering judgement will usually be necessary as tests rarely produce a clear-cut answer. If a repair or alteration, which meets any conservation requirements, can be carried out at lower than or equivalent cost to a test to establish its necessity, then only test if there is some risk of deleterious side-effects from the proposed treatment.

4. Individual Radiative Tests

4.1. Visual inspection and crack monitoring

Applications are well known. Borescopes can be inserted into small crevices via specially drilled holes to examine the interior by means of fibre optics. BRE Digest 361 [3] gives much information and illustrated examples of cracking relevant to visual diagnoses.

4.2. Microwave transmission

Research was carried out at BRE in the 1950s and 60s on the determination of moisture content of walls by Watson [4]. Further references are given in an earlier review [5]. Microwaves in the wavelength range 10 - 3 cm are absorbed strongly by water and salt solutions thus the water content of materials can be calibrated against microwave absorption as the basis of a moisture content test. The method is more suitable for well-defined laboratory or manufacturing industry applications than for field measurement because of the problem of the both water and salts being present in most materials (i.e. two independent variables) and because the scanning of the transmitter and receiver are difficult to coordinate. Dissolved salts also lead to variability. If the water content is constant then the amount of soluble salts may be determined and vice versa.

4.3. Radar (reflected pulse radar)

In earlier trials the power and sensitivity limitations prevented the use of reflected radar. Recent advances in the solid state transmitter/receivers, antennae, and signal processing software have made one-side access reflected radar into a potentially powerful diagnostic tool for civil engineering structures and buildings.

The principle of operation is that a timed radar pulse is transmitted and the time of flight (equivalent to depth) and the amplitude of reflections (equivalent to the character of the object) are recorded. By scanning the transmitter head (antenna) in a line or plane a two or three dimensional image can be built up of what lies below a surface. Reflection occur at any significant boundary between materials having different dielectric constants.

Botros et al [6], Carr and Cuthbert [7]. have demonstrated the detection of hidden objects such as pipes in masonry walls, Transbarger [8] tried the method for tunnels where information on delamination of arch rings and on the formation of voids in the masonry and the surrounding strata can be obtained. Baston-Pitt [9] has discussed its use for investigating historical buildings and archaeological sites. At BRE the technique, applied to a typical UK cavity wall, gave information about the thickness of the units and the width of the cavity plus accurate information on the position of metal wallties and less reliable data on the type of ties. The method is also likely to give data on: interfaces in walls between plaster or drylining and masonry, between masonry and cavities containing air, insulation or rubble fill, voids in masonry units e.g. frogs or large voids in hollow ware, between dry masonry and wet masonry e.g. either side of a dpm. Additionally metals give a signal so ties, straps, fixings, metal dpms and any reinforcement may be located.

The method is unlikely to work in water-saturated masonry and damp, newly-built masonry nor for material beyond a sheet of metal or fine metal mesh due to attenuation problems. The accuracy is reduced because the radar beam is divergent and quantitative estimation of pulse time is difficult in multilayer structures because the velocity varies with the dielectric constant.

4.4. X and gamma - radiography

The principle used is the same as that used for medical radiography in that a beam of high energy radiation generated by electrical means or from decay of unstable isotopes is passed through the structure and the signal is detected photographically on the remote face. Information is derived about the presence, position and size of objects having a different absorption characteristic to the main material. The main advantage is that the 'X-ray' is fairly pictorial and is thus easily interpreted by someone familiar with structures. In masonry it can be used to investigate metal fixings, cracks and voids up to a limit of 1.5m thickness. Problems are the need for both-side access, radiation danger and long exposure times. Most of the literature references concern concrete but the principles apply equally to masonry. In earlier reviews, de Vekey [5,10] gives several references.

4.5. X and Gamma ray (transmission) radiometry and (Gamma) Back-Scatter radiometry

Similar to radiography but detected with a geiger counter or scintillation detector. Without calibration the method is only suitable for comparative work. Back-Scatter radiometry is similar but the detectors are positioned on the same side of the specimen and are separated by a lead shield.

4.6. Neutron absorption measurement

Neutrons from either a portable low energy source, for in-situ work, or from an atomic pile, as a laboratory technique, are passed through materials or thin components and the attenuation of the beam is mainly due to absorption by water. This technique can be used either as a transmission method to measure bulk content or in backscatter mode to measure the same parameters in thin surface layers.

4.7. Infra red thermography (IRT)

This is a technique for observing the emission of heat from objects. It has a many uses in medicine and industry. Paljak [11] suggested that the technique could be used to observe heat leakage from walls of buildings and it is now an accepted method for checking the thermal performance of buildings and individual materials [12].

In cases where the character of the materials forming the envelope of the building can affect the flow of heat the technique can be used diagnostically. Typical applications are damp patches in walls - which increase conductivity relative to dry walls and delamination, e.g. splitting of composite walls at the vertical interlayer joint or debonding of render layers, which reduces conductivity relative to uncracked walling. Adderson & Hart [13] have shown that it is possible to detect the position of metal ties between layers of masonry by their heat conduction and that it should be possible to survey such ties with equipment with improved sensitivity.

In the modern form the equipment consists of an infra-red sensitive video camera capable of detecting surface temperature differences of the order of 1°C (or less with the latest systems) within the scanned image area. There has to be a difference in temperature between the remote and near face of the wall so that heat flows from face to face and then one of the faces is scanned with the IRT camera. The IR picture generated by the camera is a grey scale from black (low emission) to white (high emission) or an arbitrary colour translation.

4.8. Electromagnetic (metal detectors)

These devices depend on the interaction between a coil or coils carrying an alternating electric current and conducting or ferromagnetic (or both) materials. Various principles are utilised including the effect of ferromagnetic materials, e.g. steels, in increasing the inductance and impedance of the coil/s and the effect of eddy currents induced in conductors, e.g. various non-ferrous metals, in loading the coil/s. The geometry of the coil can be varied to control the distance range over which they work and some, such as the induction balance and the VLF phase angle systems, can be tuned to give information about the type of metal present under well-defined circumstances [14].

4.9. Ultrasonic pulse velocity (UPV)

This device measures the transit time of a sonic pulse between two transducers. The velocity of the pulse depends upon the dynamic Young's modulus, Poissons ratio and density of the material. The transducers can be placed anywhere on the component but the more complex the geometry, the more difficult is the interpretation.

Straight-line transmission between two parallel faces of a brick, wall or column offers the simplest geometry. Coupling agents, usually in the form of viscous fluids, are usually needed to make a reliable contact. Attenuation, or damping factor, can be quite high in masonry because of the microcracks at the brick-mortar interfaces but the technique will work well on the more brittle ceramics. Quantitative relationships can be established between factors such as the strength/stiffness of wall materials and the UPV in the laboratory [15] but absolute measurements are rarely possible in-situ. The technique can be used to give a comparative assessment of strength and quality, particularly between unflawed and flawed areas [16] and to follow deterioration processes such as frost damage [17].

4.10. Measurement of surface resistivity

This is normally carried out using the Wenner four probe technique, where a voltage drop is maintained between the outer electrodes and the voltage drop between the inner electrodes is measured. The affected depth may be taken as equivalent to the spacing of the probes. The resistance is related locally to moisture content, ionic salt content and temperature. It is more suitable for comparative than absolute measurements.

4.11. Measurement of half-cell potential

Measurement is made by making a good electrical connection to encapsulated steel and then forming a cell by placing a reference half cell (usually copper/copper sulphate) in contact with the surface of the component and measuring the output voltage with high impedance voltmeter. It is used for investigating condition of reinforcement and the risk of corrosion. Results must be treated with caution and require considerable experience in interpretation. A recent development by Winnett [18] using a scanned array of half cells controlled by a microcomputer gives a two dimensional picture of areas of materials.

4.12. Fluid flow and in-situ permeability tests

The flow of fluids can give information about the pore structure of materials. In the laboratory, typical test fluids are air, oxygen, hydrogen, carbon dioxide, nitrogen and water and the information depends on whether there is only physical adsorption or any form of chemical interaction between the fluid and the solid material. The field test involves drilling a small hole into the material to a depth of 30-40 mm, plugging the hole to a depth of 20mm and introducing a narrow airway through the plug. To measure the air permeability the pressure is reduced to 15kN/sq.m and the time taken for it to rise to 20kN/sq.m is taken as a measure of the air permeability. Water permeability can similarly be measured by introducing water and measuring the time taken for the meniscus to travel along a horizontal capillary tube. A new type called a poroscope automates the measuring cycle.

4.13. Resonance techniques

A prismatic sample, component or whole structure is subjected to a driving mechanical oscillation (mechanical or transducer) and the output amplitude is monitored by a transducer. Resonances of the objects either longditudinally, in bending or in torsion are indicated by large increases in amplitude. It is used to measure the dynamic elastic properties of prisms [19] and for investigating whole structure dynamics e.g. Ellis and others [20,21]. Highly damped materials are difficult to measure.

4.14. Pulse response technique

A sonic pulse is applied to the surface of a material or component and the vibration response spectrum or 'ring' is analysed. The resonant frequency signature can be used to give information about debonding of layers or components of structure. A typical application is discussed by Armstrong et al [22].

4.15. Pulse Echo Technique (and Sonic pulse velocity)

A sonic pulse is applied to the surface of a specimen or component and the amplitude of reflections from discontinuities is measured by transducers mounted on the same surface or the velocity is measured using an accelerometer. The distance from the point of application of the pulse to the reflecting object or receiving transducer can be estimated from the velocity of the pulse and half the time of flight. it is useful where only one face is available. It is used for measuring thickness and locating faults such as delaminations cracks etc. [16]. It's main limitation is that several wavepaths are possible and may complicate the output where the geometry is not simple.

4.16. Acoustic emission

A sensitive wideband acoustic transducer is attached to a specimen or components which is subjected to some form of structural action. The method is gaining favour as an ancillary technique to laboratory load testing and, more recently, to other indirect loading tests such as frost cycling, salt crystallisation, thermal cycling etc.

5. Individual Mechanical Interaction Tests

5.1. Penetration resistance (e.g. the Windsor probe)

This is an American development based on tiring a pin into the surface of a porous material using a fixed explosive charge and relating the depth of embedment to strength, density or porosity of materials. A similar technique has been tried as an absolute test for mortar but gave unreliable results with aerated mortars in BRE tests [23].

5.2. Internal fracture test

The principle of the test is that a re-entrant object is cast or fixed into the material and then pulled out using a standard diameter reaction ring and a force measuring device. The near-surface tensile strength is measured by the force required to cause a cone failure. This version employs an expansion anchor in a cylindrical hole and can thus be used for in-situ tests on existing structures. Currently there is only a full calibration data-base for concrete cube strength [24] and attempts to calibrate for blocks and bricks have been disappointing. The method has been reviewed by Bungey [25] who proposed an alternative loading system.

5.3. Pull-off test

In which a circular steel disc is glued to the material and pulled off together with a layer of the surface. The depth of the measurement may be increased by coring over the disc provided the surface layer is stronger than the interior. It is useful for checking layers of coatings, plasters and repair compounds. It is described by McMurray and Long [26].

5.4. Helix pull-out technique

This is a simple test in which a shallow pitched helical 'screw' is self-tapped into the material then pulled out using a torque-compensated grip. A pilot hole is necessary in harder materials but not in some lightweight and aerated concretes. The cylinder of material engaged by the helix is sheared out and the force may be correlated by empirical calibration methods with other strength parameters. It is not suitable for strong materials because the steel yields. It can be applied to measure strength at varying depths by drilling a clearance hole to the depth required. The test has been described by de Vekey [23] and Ferguson [27].

5.5. Dynamostratigraphie

This is a device which measures the force require to drill a small hole into a material or component. The force may be correlated with other properties such as strength or hardness for homogeneous materials. In layered structures the changes in force indicate the layer boundaries. The applications are self evident. The method is described by Chagneau and Levasseur [28].

5.6. Rebound hammer (known commonly as the Shmidt hammer)

This is a well known technique which gives some measure of the surface hardness of materials by measuring the absorption of energy from a calibrated hammer blow. The technique is covered in a book by Malhotra [29]. There is no reason why the technique shouldn't be applied to bricks but there is little available data. In Holland the test has been developed for assessing the variation of hardness of pointing mortar.

5.7. Flat jack

A flat jack is a thin diaphragm jack formed from two sheets of metal welded at their edges and pressurised with oil. Because of the restraint from the edges and the geometry, each jack has to be individually calibrated. A single jack can then be inserted in a strain-gauged slot cut in a structural element and the stress can be assessed when the strain state has been restored to the level existing before the slot was cut. Much of the development has been carried out in Italy for assessment of Roman masonry [30] and in the USA [16, 31] and an international standard exists [32].

5.8. Dual Flat jack

Pairs of flat jacks have been used to assess the elastic modulus and occasionally the strength of the masonry between them.

5.9. Shove test

In which two vertical mortar joints are removed and the force to move a brick sideways is measured. The result is used to indicate shear-bond and robustness.

5.10. Bond wrench

The bond wrench is now accepted as a standard laboratory technique for assessing bond between bricks and mortar [33, 34]. In Australia and the UK it has also been used as an in-situ test by using an electronic measuring system [2, 35].

6. Chemical, Crystallographic & Petrographic Techniques

These are standard chemical/petrogragaphic/mineralogical techniques to back-up other tests and the applications are given in Table 1.

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