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Nondestructive testing and damage assessment of masonry structures

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Abstract

Recent advances in nondestructive testing technology have lead to mainstream use of several methods for evaluating masonry construction. Nondestructive approaches such as rebound hardness, stress wave transmission, impact-echo, surface penetrating radar, tomographic imaging, and infrared thermography are useful for qualitative condition surveys as well as identification of internal features such as voids or areas of distress. In situ test methods are also available for determination of engineering properties. Flatjack methods are used to measure the state of compressive stress and compression response. Masonry bed joint shear stress may be evaluated using an in situ shear test, and mortar-unit bond strength is tested using an adaptation of the bond wrench approach. Standardized methods exist for many of the evaluation approaches and efforts to develop additional testing standards are ongoing with committees of ASTM and RILEM.

1. Introduction

With the many recent technological advances in nondestructive testing, the masonry industry now has the means to accurately assess in-place condition. Nearly unheard of prior to the mid 1980's, masonry evaluation using nondestructive and in situ methods is now becoming commonplace, with standardized test methods developed for many of the techniques. The basis for many nondestructive test (NDT) procedures arises from the medical, aerospace, and geophysical fields, adapted for the widely varying conditions that may be present in masonry construction. The NDT and in situ methodologies described herein are established but there is a need to improve existing methods or develop new technology. For example, it has become fairly straightforward to identify anomalies that exist within a wall section, but it remains difficult to accurately locate features in three-dimensional space as well as identify material property variations with the precision required for engineering studies.

Nondestructive test (NDT) methods are often used to provide preliminary information for concentrating further investigative efforts or repair procedures. Nondestructive approaches will not disrupt the materials being evaluated and are particularly relevant for historic preservation purposes, where the value of historic materials can not be compromised. Destructive investigative approaches, such as removal of masonry at probe holes for visual examination, may not be eliminated but will be reduced through the use of NDT procedures.

Studies of existing masonry structures are usually conducted to determine as-built and current conditions, engineering properties, or for quality control purposes. NDT has a role in each of these processes.

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1. *As-built conditions*
   In the absence of original detail drawings, many evaluations concentrate on simply defining how the structure was initially constructed. Information on wall thickness, the nature of internal wall construction, and location of brick header courses or stone bond courses can all be obtained through the use of NDT procedures.
2. *Current condition*
   All building materials undergo changes in response to applied loads and environmental conditions. Damage from seismic action, building movement, freezing cycles, and salt crystallization can be identified with nondestructive testing. The effect and location of major condition variations is the focus of many studies.
3. *Engineering properties*
   Engineering analysis requires accurate information on masonry mechanical characteristics as well as the nature of the loads being resisted. The traditional approach to determine masonry material properties has been to remove samples from a wall for destructive laboratory testing. In situ test procedures provide a viable alternative and serve to minimize disruption to the area of interest.
4. *Quality control*
   Confidence in the use of NDT has reached the point that some techniques are put into regular practice to evaluate recently completed work, whether for new construction or following repair or strengthening procedures. Nondestructive methods are commonly applied to evaluate pointing mortars, identify grout presence and solidity, and locate embedded reinforcement or ties.

1.1. Standardized Methods

Development of nondestructive and in situ test standards for masonry is ongoing with ASTM Task Groups C12.02.07 (mortar evaluation) and C15.04.06 (unit masonry evaluation) as well as RILEM Committee 177 MDT. Another group, RILEM Technical Committee 127 MS, developed a number of masonry evaluation standards from its inception in 1991 to completion of its mission in 1997. Ongoing and previous efforts for standardizing masonry evaluation techniques include the following:

ASTM C12.02.07
- Standard Test Method for the Determination of the Rebound Hardness of Masonry Mortar (in progress)

ASTM C 15.04.06
- ASTM C 1196, *In situ compressive stress within solid unit masonry estimated using flatjack measurements*
- ASTM C 1197, *In situ measurement of masonry deformability properties using the flatjack method*
- ASTM C 1531-02, *Standard test methods for in situ measurement of masonry mortar joint shear strength index*
- Future standards development: considering draft standard language for sonic pulse velocity testing and radar evaluation of masonry

RILEM 127 MS (completed)
- MS.D.1 Measurement of mechanical pulse velocity of masonry
- MS.D.2 Determination of masonry rebound hardness
- MS.D.3 Radar investigation of masonry
- MS.D.4 Measurement of E’, Dynamic stiffness of masonry
- MS.D.6 In situ measurement of masonry bed joint shear strength
- MS.D.7 Determination of pointing hardness by pendulum hammer
- MS.D.8 Electrical conductivity investigation of masonry
- MS.D.9 Determination of mortar strength by the screw (helix) pull-out method
- MS.D.10 In situ measurement of moisture content by drilling

RILEM 177 MDT

In progress:

- MDT.D.1 Indirect determination of the surface strength of unweathered hydraulic cement mortar by the drill energy method
- MDT.D.2 Deep drilling test method
- MDT.D.3 Determination in situ of the adhesive strength of rendering and plastering mortars on their substrate
- MDT.D.4 Coring and borescope techniques
- MDT.E.1 Radar moisture test method
- MDT.E.2 Infrared thermography

2. Nondestructive Test Methods

Nondestructive methods provide a means to evaluate masonry without causing observable damage. NDT methods do not provide a direct measure of material properties, such as strength or stiffness, and correlations between NDT results and material properties are often based on tenuous relationships. It is possible to gain a general understanding of the relative quality of the material being investigated based on experience and comparative results between areas having visually observable quality variations. Such qualitative analysis forms the basis for application of most nondestructive test results.

Useful methods for differentiating between regions of varying quality include rebound hardness, ultrasonic and sonic stress wave velocity, impact-echo, microwave radar, tomographic imaging, and infrared thermography. In spite of the recent advances in NDT technology, it is important to understand that, at the present time, there is no single technique that is appropriate for all situations, and that careful application of complementary techniques often provides the most useful information [1].

3. Rebound Hammer

Surface hardness is measured using a rebound hammer, commonly referred to as a Schmidt hammer, as shown in Figure 1. Widely used for evaluating concrete, the method is also used for identifying variations in masonry material uniformity. Testing for rebound hardness is rapid and requires only a few seconds for each reading. Applications include delineating zones of fire damage or otherwise deteriorated masonry, and identifying differences in unit hardness that may indicate deficiencies or previous repair efforts. Past studies have shown sensitivity to the mortar surrounding the test unit and the degree of bond between brick and mortar. With careful laboratory calibration, it is possible to relate

Figure 1 The Schmidt rebound hammer is used to provide an indication of surface hardness.

rebound hardness to the elastic properties of the masonry or compressive strength [2].

Rebound hardness measurements are affected by a number of variables, including surface roughness, specimen mass and geometry, vicinity of nearby edges, and hammer orientation. A methodology for conducting rebound hardness tests is provided by RILEM MS.D.2, *Determination of masonry rebound hardness*. The approach is essentially nondestructive but can leave small depressions in softer brick or deteriorated stone.

4. Metal Location

Equipment for locating metals embedded in masonry walls are based on either magnetic or eddy-current principles. Commonly termed "pachometers," these devices have been used since the 1970's for investigating reinforced concrete and for locating wall ties, reinforcement, or structural steel members within masonry sections. Equipment was originally developed considering the objectives of concrete investigations, with reinforcement cover depths in the range of 2 to 8 cm, and early pachometers did not have the penetration depth needed for typical masonry applications. Devices are now available with maximum working depths in the range of 12 to 30 cm which are useful for most situations, but there are occasions where a greater detection depth would be useful. For example, with massive stone construction or where structural steel members or utilities are embedded in masonry walls, metals may be found 1 m or deeper within the wall section. More powerful metal detectors are used to identify metals at depths of 60 cm and more, but accurate sizing and exact location of metals at these depths is difficult.

5. Stress Wave Transmission

Pulse transmission techniques involve measurement of the time needed for an induced stress wave to pass through the material of interest and subsequent calculation of the characteristic wave velocity. First applied to masonry in 1967 [3], the pulse velocity approach is useful for investigating the internal construction of multi-wythe walls, locating header courses, determining void and spall locations [4], and identifying masonry damage [5,6]. Applications for new construction include verification of grout solidity in reinforced masonry construction and control of grout injection procedures [6].

In a homogeneous material, stress wave velocity is related to the material's dynamic stiffness, Poisson's ratio, and material density. Laboratory research has shown a relationship between pulse velocity and compressive strength [7], but the method is best used for qualitative purposes. In the evaluation of a wall, very little energy travels through air voids or gaps within the wall and, as a result, the apparent straight-line velocity decreases as the wave travels around internal voids or discontinuities. Stress wave transmission is not significantly affected by the presence of reinforcement or moisture. Recent work in analysis of frequency content and amplitude of received waveforms shows some promise for evaluation of construction materials [8].

Measurement of pulse velocity is a point-by-point process using a gridwork set up on the wall surface. Through-wall velocity offers the most meaningful data, where the source and receiver are located directly opposite one another on either side of a wall. Data points can be interpreted individually or an entire data set can be used to generate a contour plot of through-wall velocity. A typical velocity contour plot, shown in Figure 2, is used to identify internal anomalies or changes in wall construction.

The choice of optimal waveform frequency depends on the investigation's objectives: high frequency waves are more sensitive to small flaws and voids, but lower frequency waves penetrate through thicker cross sections. High frequency waves in the ultrasonic range (20 to 100 KHz for masonry evaluation) are attenuated rapidly in masonry construction and are most useful for evaluating thinner walls and modern grouted masonry construction. Low frequency sonic waves (usually 1 to 5 kHz) are used for investigating massive masonry or sections with little continuity between wythes [9].

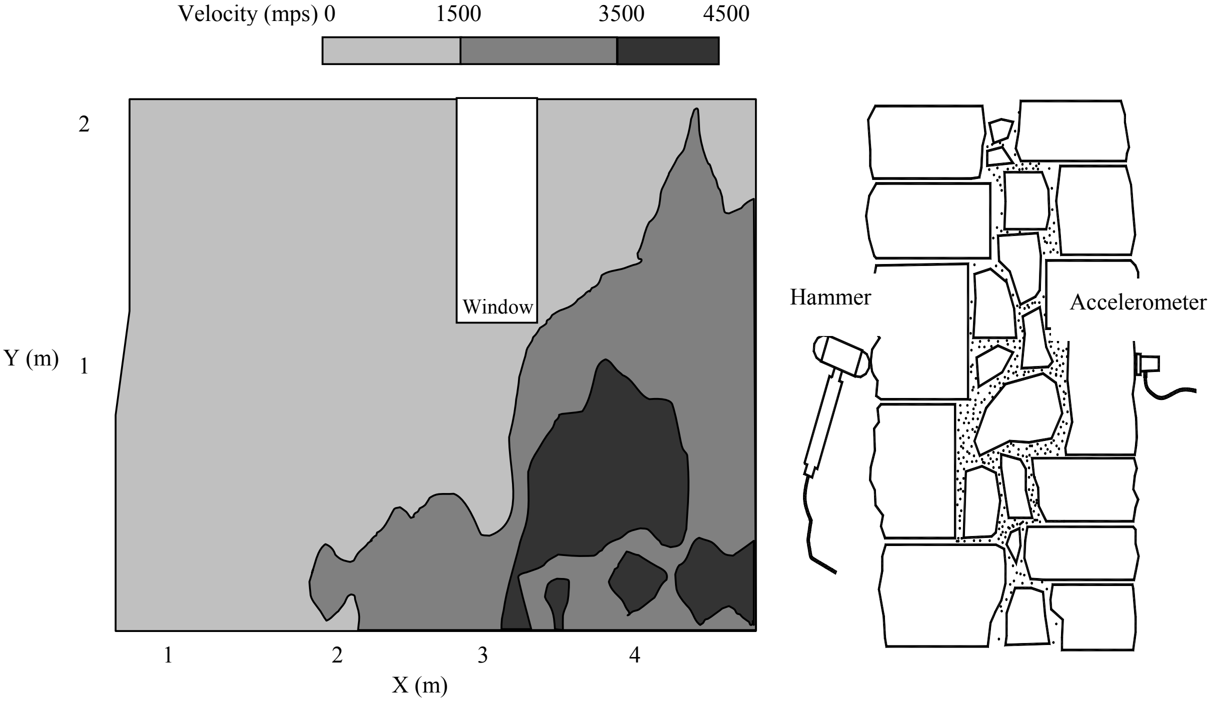


Figure 2 This contour plot of through-wall sonic pulse velocity was generated to evaluate solidity of the internal wythe of a stone bell tower using the sonic pulse velocity method as shown on the right. The higher velocity zone at the lower right is representative of relatively solid construction; the low velocity region to the left and top of the image represents internal separation or voids between the wythes. Areas identified as having low velocity were subsequently repaired by grout injection.

6. Ultrasonic Velocity Testing

Commercial equipment for ultrasonic velocity testing is available from a number of sources. An ultrasonic pulser/receiver unit initiates a timing circuit as it sends an electrical signal to the source transducer, which in turn uses an internal piezoelectric crystal to generate a low-energy, high frequency stress wave. Transducers are coupled to the masonry surface using silicon sheets or gels for maximum energy transmission. The wave travels through the section where the receiving transducer converts the wave energy back to electrical energy. Pulse transmission time is displayed in microseconds on a readout display.

7. Sonic Velocity Testing

Lower frequency sonic stress waves are generated using an instrumented hammer (Figure 2). The mass and hardness of the rubber hammer head define the energy and frequency content of the initial wave. The onset of the hammer pulse triggers an attached oscilloscope or digital data recorder to begin compiling data, as sensed by an accelerometer held against or attached to the wall at the receiver position. Converting wave trace data into velocity information is time consuming and must be conducted in a meticulous manner to obtain reliable results. Data analysis may be automated but no commercially available software exists. Equipment and test procedures are described further in RILEM MS.D.1, *Measurement of mechanical pulse velocity*.

8. Impact-Echo

First developed for evaluating concrete [10], the impact-echo approach is a variation of the stress wave transmission method that uses a frequency-based analysis of wave echoes propagating within the masonry to locate internal discontinuities [11]. A transient stress wave is generated at the face of the wall, typically using a hammer hit or other mechanical impact. Wave energy is reflected at impedance variations, or discontinuities, within the wall, such as at an air void, the boundary between a masonry unit and adjacent grout, or at a crack. Multiple wave reflections set up vibrational frequencies within the section, which are in turn recorded using a piezoelectric displacement transducer. The resulting waveform is then analyzed in the frequency domain to identify dominant frequencies. Knowing the characteristic compression wave velocity, the depth to discontinuities can be identified as a function of frequency, where depth is equal to the velocity divided by twice the frequency. Impact-echo approaches are attractive because access is required to only one wall face. Typical masonry applications include locating brick header or stone bond courses, identifying grouted cells in reinforced masonry construction, determining cross-section thickness, and locating voids in multi-wythe construction.

One disadvantage of the technique is that essentially all stress wave energy is reflected at air boundaries, and no information can be obtained on materials beyond an initial void or delamination. The method also provides limited localized information, requiring a series of point-by-point measurements to map larger regions. Recent hardware developments speed data collection [12] and permit scanning over a two-dimensional surface with many closely spaced points.

9. Surface Penetrating Radar

Known also as ground penetrating radar, georadar, or microwave radar, surface penetrating radar (SPR) techniques use reflections of wave energy to identify internal anomalies. Unlike the impact-echo approach, data is analyzed in the time domain, rather than converting to the frequency domain. Whereas impact-echo and ultrasonic signals are unable to penetrate any air interfaces within a section, microwave energy travels well through air spaces and the SPR approach is able to provide information beyond the first disbond, crack, or other flaw.

Used as early as 1975 in archaeological surveys [13], the method is currently being used for investigating a number of masonry conditions:

- detecting inclusions, voids, and other defects [14]
- characterizing multi-wythe walls [15]
- locating bond stones and header courses
- determining thickness of retaining walls
- locating grout in reinforced masonry construction [16,17]
- identifying horizontal and vertical reinforcing bars or embedded structural steel members [17]
- determining effectiveness of repair techniques [18]
- qualifying the state of internal damage or deterioration in walls
- measuring moisture content [19,20]
- locating regions with high salt content [20, 21].

A standard method for investigating historic masonry with radar has been developed by RILEM committee 127-MS as MS.D.3, *Radar investigation of masonry*, which provides information on the required apparatus, procedure, test locations, limitations, test report, and interpretation of test results. RILEM Committee MDT also has an ongoing effort to develop a method for determining moisture content and distribution in masonry using microwave radar.

Equipment for conducting an SPR survey includes a radar control unit, antenna, and data storage device. The radar control unit sends an electrical pulse to the transmitter to generate the electromagnetic wave and at the same time signals the storage device to begin recording data. The shape, size, and configuration of the transmitting antenna define wave frequency and the shape of the transmitted wave. After transmitting the pulse, the antenna switches to receive mode and energy reflected from internal discontinuities is picked up and passed back to the control unit, which converts the signal to digital form. Individual radar pulses are generated and reflections are recorded continuously at a rate chosen by the user, but typically many pulses are recorded each second. The subsequent series of reflected waveforms are analyzed by the equipment operator, ranging from characteristic hyperbolic shapes for reinforcing bars to planar reflections from larger discontinuities. Alternatively, data may be stored on the processor for later analysis in the office.

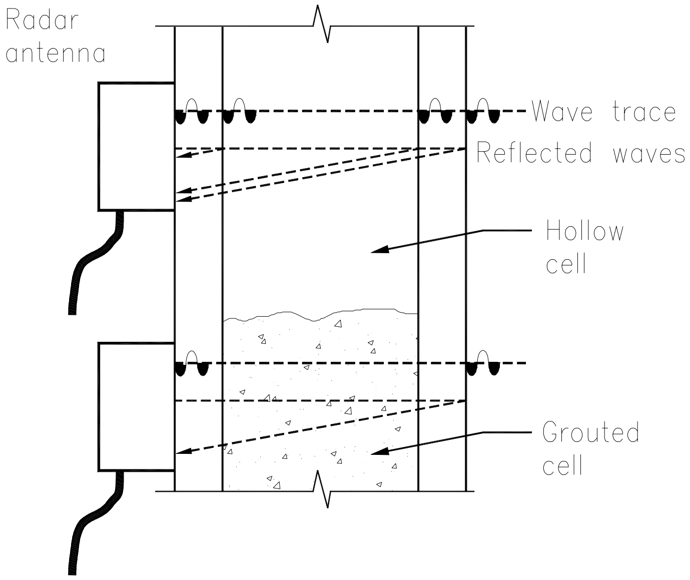
SPR resolution and penetration depth is dependent on the wave frequency, which typically is in the range of 200 MHz to 1.5 GHz for masonry investigations. The optimal frequency is chosen based on a reasonable consideration of the investigation's objectives: lower frequency waves penetrate deeper into the host material, whereas higher frequency waves give greater resolution. Lower frequency antennae are used for investigating massive masonry sections where maximum penetration depths of up to 4 m are required; use of higher frequencies gives the capability to resolve near-surface and internal features on the order of about 1 cm in size.

The most common approach for evaluating masonry sections is to record reflected wave energy, where a single antenna operates as both the transmitter and receiver. Analysis of reflection data concentrates on the time passing between the onset of the initial pulse and the reflected energy. Knowing the characteristic wave velocity through the material being tested, the depth to the discontinuity can be calculated.

Data may be analyzed as a one-dimensional "wiggle" trace or scan, generated at each pulse of the transmitting antenna (see example in Figure 3). More practical is the recording of multiple wiggle traces as the antenna is moved along a line, thus generating a two-dimensional view of the cross section as shown in Figure 4. Three-dimensional images can be produced by recording a series of adjacent two-dimensional traces. Though requiring considerable time to record data as well as extensive computational effort, three-dimensional representations are most easily recognizable by the general public.

Care must be taken when interpreting radar traces due to the many reflective interfaces present in masonry construction. Mortar and grout interfaces, as well as geometric interfaces, will refract microwave energy, having a tendency to mask energy reflected from targets of interest. The multiple echoes and localized reflections resulting from this effect can be only partially overcome by data processing. Embedded metals reflect all radar energy, creating a shadow zone directly beneath the metal and effectively hiding features behind the metal. Masonry with a high concentration of soluble salts, generally found near the base of

Figure 3 Schematic representation showing reflection of microwave energy by discontinuities within grouted and hollow concrete masonry wall sections. Each set of wave reflections constitutes a "wiggle trace" for subsequent evaluation.



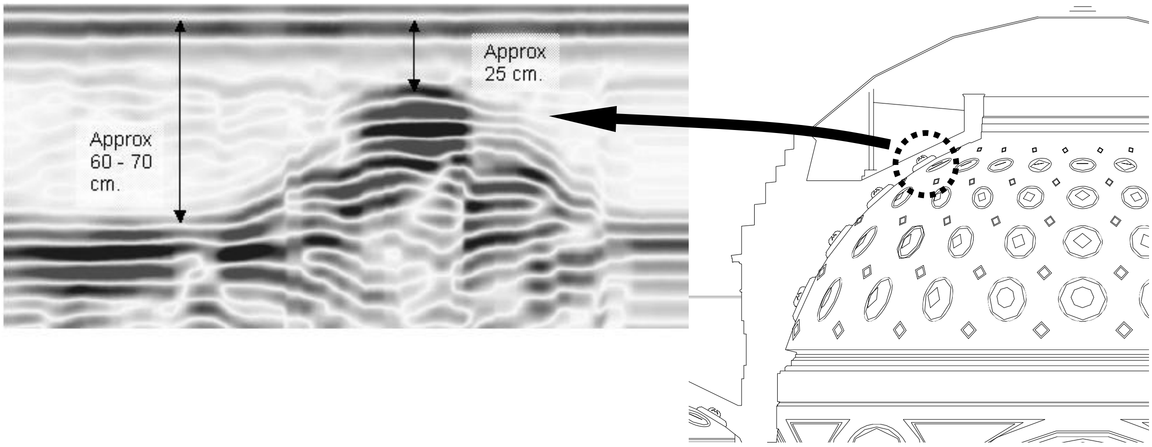


Figure 4 Surface penetrating radar was used to scan through the top of the brick masonry dome at the Basilica of the Shrine of the Immaculate Conception in Baltimore [43]. The image on the left shows a series of radar traces as the antenna was moved over the coffer; the thickness of the main dome and the reduced thickness at a coffer was readily observable. Line drawing courtesy of John G. Waite Associates.

the wall in zones of rising damp, has a high electrical conductivity and rapidly attenuates radar energy [21].

Data from radar surveys is often used to complement results of other nondestructive test methods [1]. For example, microwave radar waves are highly affected by moisture and salt content of embedded materials and results obtained in the presence of moisture can be misleading. Sonic velocity tests are not as affected by moisture; hence the use of such techniques is complementary.

10. Tomographic Imaging

Data from ultrasonic, sonic, or radar testing can be used as input to tomographic reconstruction algorithms to provide a cross-sectional representation of internal properties. Tomography is the practice of reconstructing a cross sectional image of an object from transmissions of energy through the object [22]. Procedures developed for geophysical exploration have been adapted for use with masonry and stone and the approach has been shown to provide a reasonable approximation of the size and extent of internal anomalies [23]. Internal features such as voids, cracks, and deterioration can be located and sized using tomographic imaging and recent efforts investigating the use of attenuation-based tomography shows an increased sensitivity to internal anomalies [8]. Tomographic analysis techniques involve considerable effort for acquiring the required large data set. A typical ray path distribution and tomographic velocity reconstruction is shown in Figure 5.

11. Infrared Thermography

Infrared thermographic imaging provides a visible representation of infrared energy radiated by an object. Scanning with infrared cameras is a truly “global” approach, permitting rapid evaluation of large regions without requiring direct access to the wall. In a state of heat flux, differences in surface temperature will exist in the vicinity of materials with different densities, heat capacities, and/or thermal conductivities; these variations in surface temperature are measured using special cameras sensitive in the infrared range from 0.76 to 30 μm. Originally developed by the military in the 1960’s, in recent years infrared thermography has seen wide application to evaluating features of masonry building envelopes [24], including:

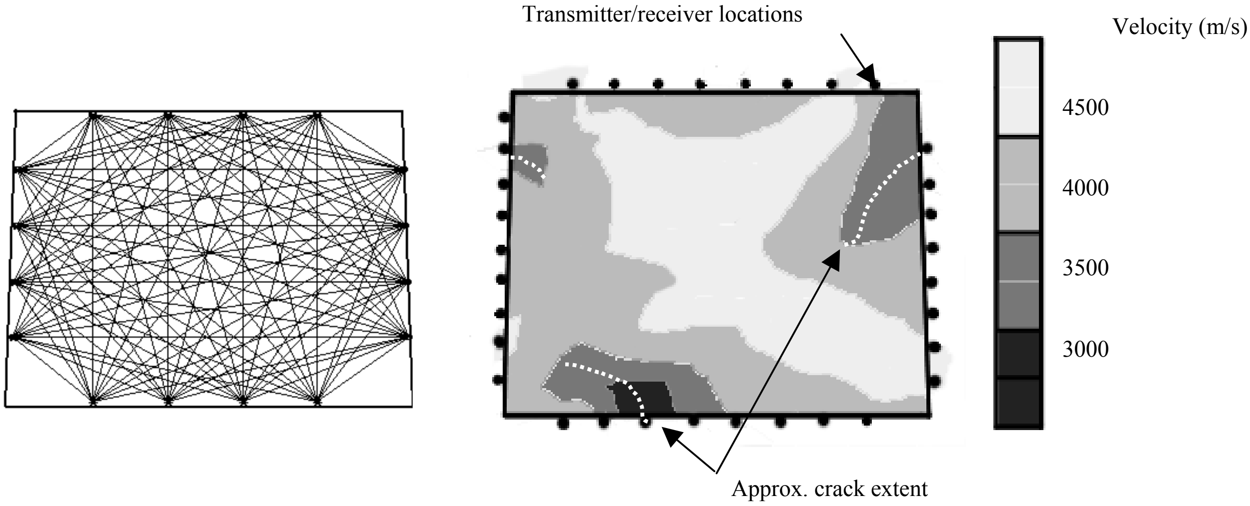


Figure 5 Tomography results are shown here as a velocity profile through a cross section of a stone monument. The stone measured 1m square. Ultrasonic pulse velocity measurements, taken along the ray paths shown at the left, were used to calculate the velocity reconstruction to estimate the penetration depth of surface breaking cracks as shown on the right.

- subsurface anomalies such as voids, near-surface cracks, or incipient spalls
- variations in wall construction
- missing or displaced wall insulation
- moisture rise by capillary action [25]
- air leakage and variations in moisture content [26]
- features hidden by surface plaster or frescoes, such as blocked openings or previous repairs [18]
- internal cavities such as flues, ducts, or chimneys
- the presence of grouted cells in reinforced masonry construction [27,28]
- thermal bridging of mortar obstructions in wall drainage cavities

As shown in Figure 6, different surface temperatures are indicated as variations in color or grayscale intensity. These measurements give a measure of the disparities in heat transmission or absorption throughout a region. Temperature differences on the order of 0.1° C are detectable by modern focal plane array cameras; information is recorded digitally or continuously on videotape.

Infrared scans may be conducted using either an active or passive approach. Active thermography relies on homogeneous forced heating of the wall using an external heat source such as sunlight or a bank of heat radiators. Imaging during heating or cooling (after removal of the heat source) provides information on near-surface anomalies [29]. Passive investigations are more useful for locating defects deeper within the wall section, relying on a temperature differential across the wall section to develop steady-state heat transfer through the wall section. Through-wall temperature differentials on the order of 10° C or more will generally provide a readily recognizable thermal pattern.

Use of infrared images relies on interpretation by the user to determine the meaning of temperature anomalies. Operator experience is essential as well as an understanding of the physics behind heat transfer processes and the performance of masonry wall assemblies [26]. Under different heating and cooling conditions, for example, sections containing internal voids may show as either warmer or cooler regions. Temperature variations may also arise due to differences in material moisture content, surface texture, material emissivity, or reflections from nearby heat sources. ASTM C 1060 (1997) *Standard practice for thermographic inspection of insulation installations in envelope cavities of*

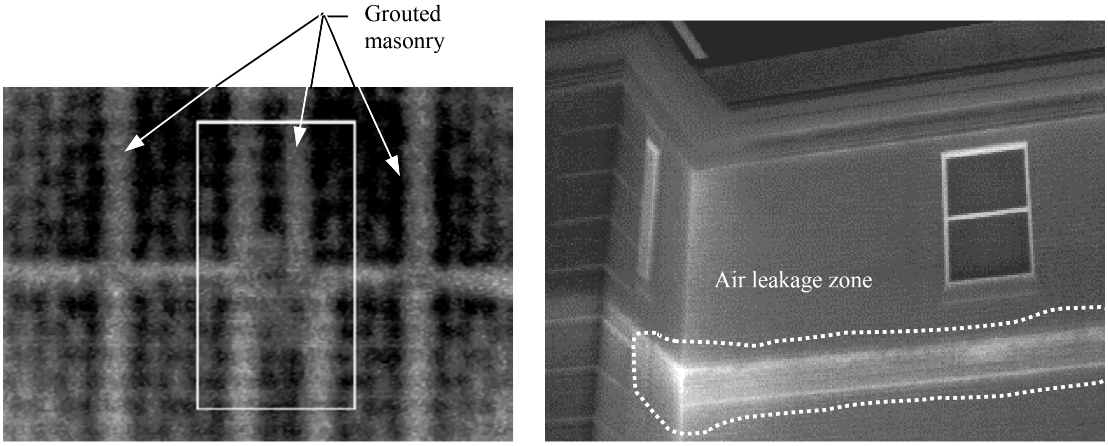


Figure 6 Results of two infrared scans are shown here as grayscale representations; lighter regions represent warm zones. The left image (courtesy of Trey Hamilton) shows a series of grouted vertical and horizontal cells in concrete masonry construction. A vertical grout column steps one cell to the left at the horizontal bond beam. At the right is an image taken to identify areas of air leakage through an exterior brick veneer. Note the warm regions at the floor line and at the wall intersection, where flashing and vapor barrier is likely discontinuous.

frame buildings, provides general recommendations on conducting an infrared inspection but was not developed specifically for masonry applications. A standard methodology for conducting masonry evaluations using infrared thermography is under development by RILEM committee 177 MDT.

The typical infrared image shown on the right in Figure 6 was taken early in the morning on a cool winter day, with a temperature differential of about 20° C across the wall section. The region of high temperature indicates either major blockage of the drainage cavity with mortar or the absence of flashing and vapor barrier behind the veneer. In this case the issue appears to be air leakage which is permitting heated interior air to flow into the drainage cavity, increasing brick temperature in the vicinity. Note also the leakage of hot air from weep holes at the flashing level located at the floor line.

12. In Situ Test Methods

Nondestructive test methods are useful for identifying relative conditions and areas of distress but do not provide information on the engineering properties of materials. In situ, or in place, test methods are used in lieu of the traditional approach of destructive removal of test specimens for laboratory testing [30]. In situ test methods require removal of mortar joints and/or units for insertion of loading devices and, while requiring repairs following tests, such work is generally limited to pointing new mortar in cleared joints or isolated unit replacement. As such, in situ methods are not truly nondestructive but do provide information not available through direct use of NDT procedures.

13. Borescope

Nondestructive methods have developed the capacity to identify anomalies within a wall, but visual verification is often needed to provide final verification. Borescopic examination is used as an alternative to the destructive process of removing mortar and units at probe holes. The borescope, inserted into small diameter holes drilled into mortar joints, provides a minimally destructive means to observe identified anomalies or defects as well as important internal wall components such as flashing, ties, and drainage cavities. Borescope devices incorporate fiber optics and an internal light source to illuminate the internal space, and some borescopes have a graduated scale in the viewfinder to aid in identification and sizing of objects. Rigid borescopes or flexible fiberscopes, some with video or camera attachments, provide a simple means to examine and record internal condition. A borescope is shown in use in Figure 7, along with a typical image.

14. Mortar Evaluation

Mortar is often evaluated by removing samples for laboratory study. Mortar may also be tested in place to determine general material properties or as a means of quality control and for identifying batch-to-batch mortar variations. The following techniques are available for in situ mortar evaluation.

- Pendulum rebound hardness (Figure 8): similar to the Schmidt hammer approach, the pendulum hammer utilizes a low energy impact and resulting rebound from the surface of a mortar joint to measure surface hardness. Rebound hardness shows good correlation to mortar type and strength [31,32]. One standardized method exists as RILEM MS.D.7, *Determination of pointing hardness by pendulum hammer*; ASTM Committee C12.02.07 also has a test standard under development.
- Pullout resistance: the force required to remove a helical tie, installed in a mortar joint, provides a measure of mortar strength. Developed by the British Building Research Establishment [33], the methodology is standardized in RILEM MS.D.9, *Determination of mortar strength by the screw (helix) pull-out method*.
- Drilling resistance: RILEM MDT.D.1, *Indirect determination of the surface strength of unweathered hydraulic cement mortar by the drill energy method* and the related standard MDT.D.2, *Deep drilling test method*, describe equipment and procedures for determining the resistance of masonry mortars to drilling. A standard drill with a carbide bit is attached to an ammeter to measure electrical energy consumed versus penetration depth into the joint [33].
- Probe penetration: the Windsor Penetrometer method uses penetration of explosive-driven pins into mortar joints as an indicator of strength. The method is difficult to apply to masonry and does not always give repeatable results [7]. An alternate approach, better suited to mortar evaluation, uses a spring-loaded apparatus to strike the mortar surface. Meticulous care is required during micrometer measurement of penetration depth.

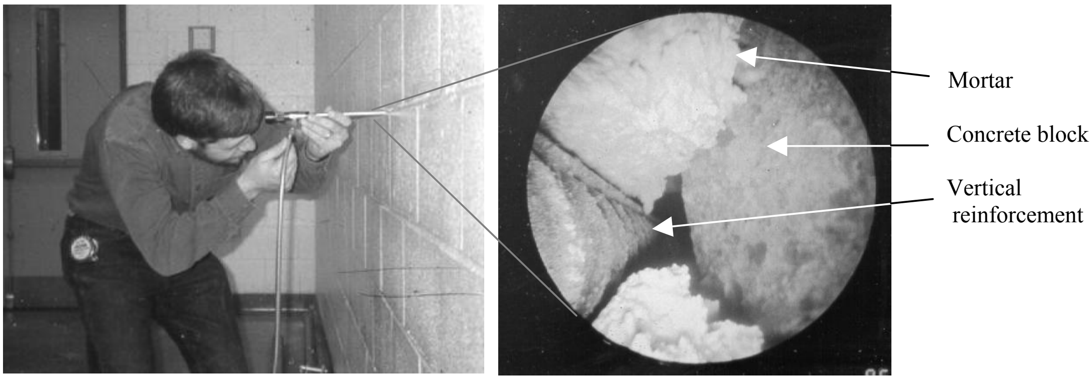


Figure 7 Borescope investigation of an anomaly found using nondestructive methods verified a grout void around vertical steel reinforcement.

Figure 8 The pendulum rebound hammer, used for evaluating masonry mortar hardness.

15. Flatjack Methods

Flatjack test methods provide reliable means for in-place determination of existing masonry stress and masonry behavior subjected to uniaxial compression. The tests are simple in principle and require only basic hydraulic and deformation measuring equipment. Flatjacks, inserted into slots cut into mortar joints, are pressurized internally to impose a stress on surrounding masonry. A flatjack is a hydraulic pressure cell manufactured to be very thin, for insertion into cleared masonry mortar joints. Various shapes and sizes of jacks are manufactured: rectangular jacks fit into slots where mortar was removed by stitch drilling; semi-circular jacks are manufactured to fit the diameter of a rotary saw used to form a slot. When pressurized, the flatjack exerts stress on the surrounding masonry and, by measuring surface deformations, information on the existing state of stress as well as the stiffness and strength of masonry can be obtained [34]. Flatjack tests are not truly nondestructive, requiring removal of a short section of mortar joint for flatjack placement. After flatjacks are removed from the wall, the slots are pointed with new mortar to restore the masonry's appearance.

Conventional metal flatjacks are durable and provide reasonably accurate results, but they have several shortcomings that could be overcome by using a new generation of "flexible" flatjacks having an elastic deformation response [35, 36]. Flexible flatjacks are able to conform to unusually shaped slots, self-deflate upon pressure reduction (which facilitates removal from the slot), and possess the deformation capacity to expand to fit wide or irregular slots without shims. Most importantly is the fact that little energy is required to deform the jack and, as a result, the stress output is very uniform and the flatjack calibration coefficient Kj approaches 1.0.

16. Flatjack In Situ Stress Test

The magnitude of vertical compressive stress present in a masonry element can be determined using a simple process of stress relief. Prior to forming a flatjack slot, the distance between gage points on opposite sides of the slot location is measured. After mortar removal, compression stress present within the wall forces the slot to close slightly. Flatjacks are then placed in the slot and pressurized to move the masonry at the slot back to its original position. The pressure required to restore the gage points to their original position, modified by the flatjack calibration constant, provides a measure of the state of compressive stress normal to the slot.

The in situ stress test represents an adaptation of methods originally developed for evaluation of in situ properties of rock masses and is standardized in RILEM D.2: *In situ stress tests based on the flatjack* and ASTM C 1196, *In situ compressive stress within solid unit masonry estimated using flatjack measurements*. Recent research on the in situ stress test [37] suggests an alternate instrumentation configuration and analysis approach to reduce the effect of inelastic deformations, such as may occur when testing low-modulus or highly stressed masonry.

Knowledge of the state of stress in masonry is important for determining applied loads, calibrating analytical models or detection of stress gradients and resulting bending moments across wall sections. The method may also be used for identifying potentially hazardous overloading situations such as the buildup of unexpected stress in masonry veneers. Data shown in Figure 9 represents results from a series of stress tests conducted on the brick veneer of a 42-story high rise building. The accumulated effects of applied loads, creep, and cement hydration led to a slight shortening of the structural reinforced concrete frame, while the brickwork had undergone expansion due to moisture and thermal effects. The brick veneer was constructed tight between concrete floor slabs with no provisions to accommodate this differential movement and, as a result, rather significant stresses developed in what was designed as a non-structural veneer. As seen in Figure 9, veneer stress generally increased towards the base of the building; test results

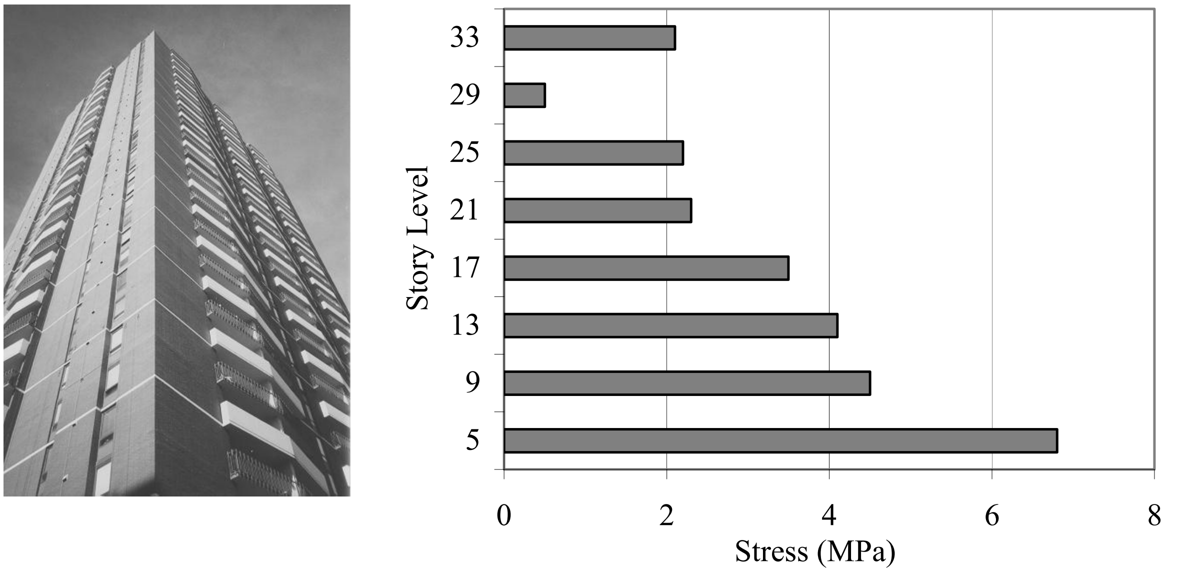


Figure 9 In situ stress tests were conducted using the flatjack method to evaluate the buildup of veneer stresses in this 42-story tall apartment building. Differential movement between the concrete frame and brick veneer led to the development of significant stresses towards the building's base.

identified a need for repairs to relieve the accumulated veneer stress.

17. Flatjack In Situ Deformability

A second flatjack test approach involves the use of flatjacks for measuring in situ masonry compression response. RILEM D.3, *In-situ strength and elasticity tests based on the flatjack* and ASTM C 1197, *In situ measurement of masonry deformability properties using the flatjack method*, describe the in situ deformability test, in which two flatjacks are inserted into mortar joints, one above the other. When pressurized simultaneously, the flatjacks impose a state of compressive stress on the masonry between them. Surface strains are measured using mechanical dial gages or electronic devices mounted at the wall face in the arrangement shown in Figure 10. To avoid boundary effects the gages should be placed toward the center of the loaded region. Analytical modeling [38] has shown that surface strains are fairly uniform and provide a good representation of masonry response over the middle quarter to third of the loaded area. In situ deformability results are typically presented in the form of a stress-strain plot, from which the masonry compression modulus can be calculated.

18. In Situ Shear Test

Masonry shear strength is determined in situ through use of the in situ shear test, sometimes referred to as the "push" test. First developed as part of the ABK methodology for evaluating seismic resistance of older unreinforced masonry [39], the method involves removal of a brick unit and head joint on opposite ends of the designated test unit. A hydraulic ram is placed in the wall and the test brick is displaced laterally, thus shearing the mortar bed joints directly above and below the test unit. The resulting mortar shear strength can be correlated to wall shear strength using a procedure outlined in Appendix Chapter 1 of The Uniform Code for Building Conservation (UCBC) [40]. The methodology is valid only for strong unit/weak mortar systems, where shear failure is dominated by bed joint sliding or diagonal stair-step cracking through mortar joints. This approach is

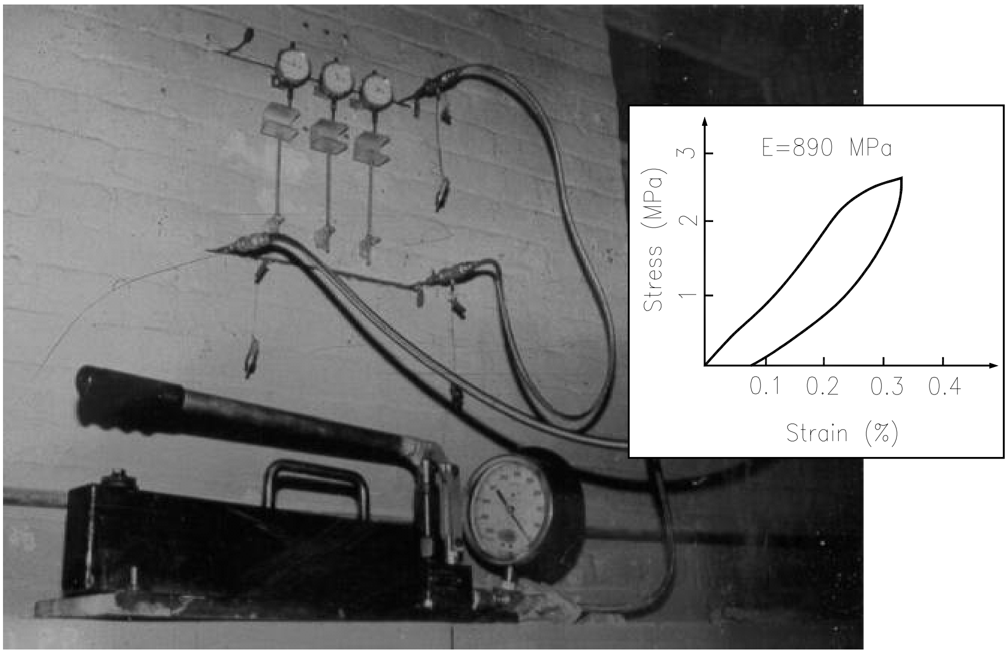


Figure 10 The in situ deformability test uses two flatjacks, placed one above another, to impose a state of compressive stress on the masonry. Measurement of applied pressure and surface strains produce a typical stress-strain response as shown on the right.

not applicable to modern concrete masonry constructed using cement-based mortars or walls containing internal reinforcement.

A new ASTM standard, C 1531-02, *Standard test methods for in situ measurement of masonry mortar joint shear strength index*, describes three alternative approaches [41]. The method includes the conventional approach, using a hydraulic ram, and a second option that uses a small flatjack, inserted into a mortar head joint to displace the test brick. The third test approach describes a procedure using two flatjacks, above and below the test area, to control the magnitude of vertical compressive stress on the test unit (Figure 11). By measuring the joint shear resistance at several levels of normal compressive stress, the mortar friction angle can be determined.

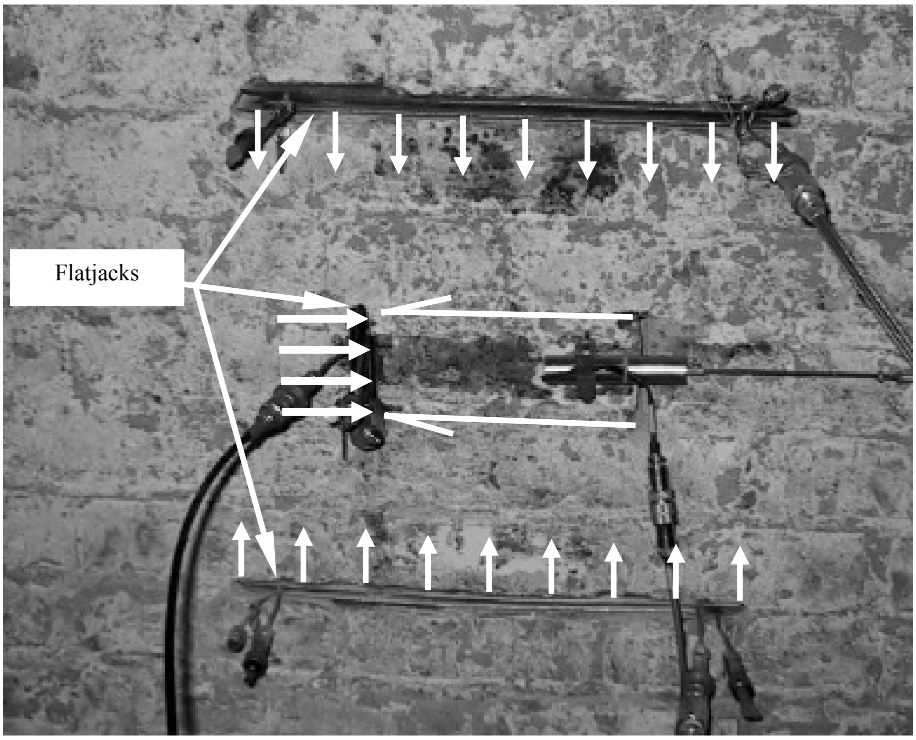
19. In Situ Bond Test

Unreinforced masonry resists out-of-plane loads through a combination of direct flexural action, rigid block response and, in some cases, arching action. Mortar-unit bond of most older masonry construction is weak compared with the tensile strength of the mortar and units themselves, hence mortar bond strength typically dictates the out-of-plane cracking strength of such walls. In lieu of assuming zero bond strength for structural analysis purposes, in situ determination of mortar-unit bond is made possible through use of a device known as the bond wrench.

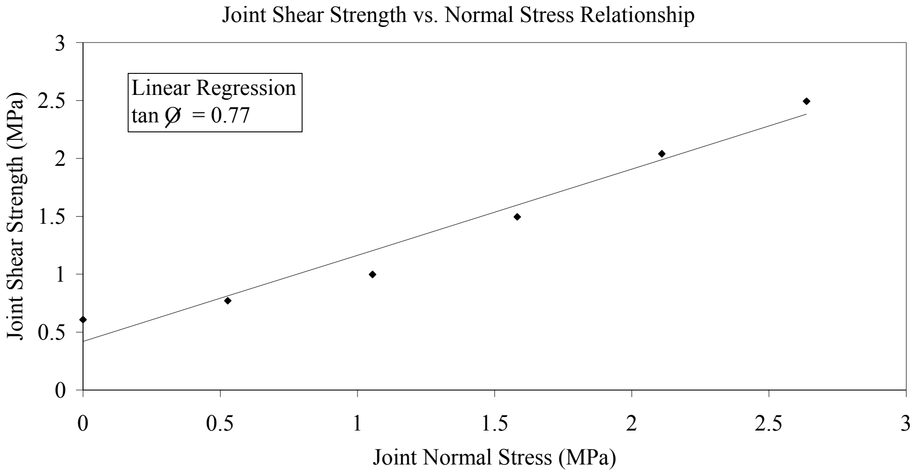
Field testing for flexural bond strength is adapted from the laboratory method described in ASTM C 1072, *Test method for measurement of masonry flexural bond strength*. One type of device, shown in Figure 12, consists of a clamping mechanism that grips a test unit within the wall, with applied loads measured by an attached torque meter. A similar device, known as the “BREnch” and developed in the U.K. by the Building Research Establishment (BRE), is available commercially. Force is applied to the end of the wrench handle until failure [42]. Resolution of applied axial and flexural forces provides a measure of flexural tensile bond strength. The test does require substantial effort for removal of units and mortar joints as well as replacement of units at the test area.

20. Conclusions

The preceding discussion provides an introduction to several nondestructive and in situ test methods that are useful for evaluating masonry. Methods such as rebound hardness are relatively simple to conduct and results can be understood on site. Most techniques, however, require proper planning and meticulous operation to provide usable results. Operator experience is essential for appropriate data analysis and interpretation of test results. Conducted and interpreted properly, these methods provide information on masonry construction as well as material properties while minimizing or, in some cases, eliminating, disturbance to the underlying material.



a) Test setup



b) Test results

Figure 11 The Uniform Code for Building Conservation permits an increase in allowable stress based on acting dead loads and a mortar friction angle of $\tan\phi = 0.15$. The setup shown above uses flatjacks to control vertical stresses, permitting in situ measurement of mortar shear strength and friction angle. In this case the shear strength was approximately 0.4 MPa and the friction angle was determined to be $\tan\phi = 0.77$. Use of the greater friction angle helped to reduce the magnitude of expensive strengthening measures.

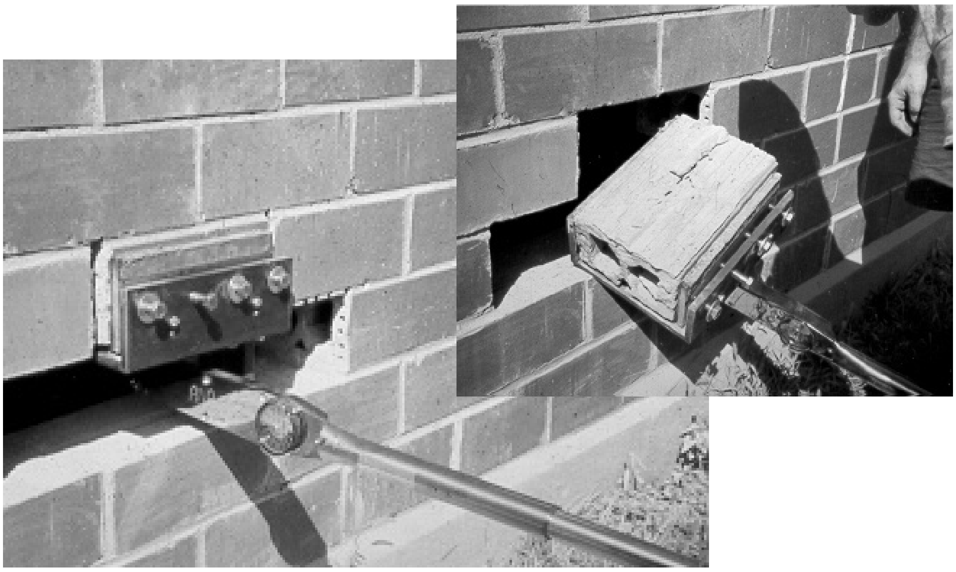


Figure 12 The in situ bond wrench test for measurement of mortar-unit flexural tensile bond. The bending moment applied to the test joint is measured by an attached torque meter.

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