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Overview of NDE Methods for Masonry Structures

Micah Heide[i] and Donald Harvey[ii]

ABSTRACT

Nondestructive evaluation (NDE) can be used to provide valuable information about the current state of existing masonry structures. NDE is often chosen as an alternative to more destructive methods to preserve as much of an existing structure as is reasonably possible and to minimize damage and disruption. This is especially beneficial when assessing historic structures where the preservation of original construction is often paramount. The appropriate use of NDE typically results in better economy for building assessments without compromising the retrieval of information necessary to inform any structural interventions.

An overview of the NDE methods that can be applied to existing masonry structures as commonly conducted by Atkinson-Noland & Associates (ANA) and found in the literature are described in the associated paper. Such methods include, but are not limited to, ground penetrating radar, ultrasonic pulse echo, infrared thermography, and flatjack testing. The general procedures for each method are described and the applications to masonry investigation are presented. Additionally, field examples are included to illustrate the use and combination of NDE methods when applied to masonry structures.

KEYWORDS

NDE, investigation, brick, CMU, stone, nondestructive

[i] Engineer Intern, Atkinson-Noland & Associates, Boulder, CO, USA, mheide@ana-usa.com
[ii] Associate Vice-President, Atkinson-Noland & Associates, Boulder, CO, USA, dharvey@ana-usa.com

INTRODUCTION

Nondestructive evaluation (NDE) can be used to effectively gather information about the condition of an existing masonry structure and has been found to be useful for the investigation of both historic and new masonry construction. NDE methods are typically developed to cause minimal disturbance to the tested structure and, in some cases, don't even require any physical contact with the structure itself. This is advantageous during the investigation of historic masonry structures where preservation is often paramount. Additionally, investigation of new masonry construction with NDE methods can reveal as-built construction defects or damage that may have been otherwise hidden.

NDE methods can provide information useful to the overall assessment of a masonry structure, such as representative values of compressive strength, insight into the internal condition of a masonry assemblage, and the location of defects. A single NDE method does not typically provide all of the information required for a given assessment. However, multiple NDE methods are commonly used in combination to provide complementary results that provides a more comprehensive understanding of a structure. It is, therefore, important for an investigator to be able to assess which NDE method or methods would be most effective for a given situation (Schuller, 2003).

This paper includes an overview of NDE methods that are currently used in masonry investigations. The included methods are those that are commonly used by Atkinson-Noland & Associates (ANA) and those that are described in the literature. Each of the methods described herein may be applicable to brick, concrete, stone, and/or adobe masonry. However, the proper method or methods to use in a given scenario should be chosen by a qualified professional.

OVERALL CONDITION OF MASONRY STRUCTURE

It is essential that a masonry investigation starts with knowing the history of the structure in question and the phases in which it was constructed. Materials and techniques that were used in each construction phase can help an investigator to understand the overall static behavior of the structure (Rossi, 1991). A knowledge of the different materials used for construction can also inform the scope of a structural investigation by defining the material properties that need to be quantified before an analysis of the structure can be conducted.

Initial surveys should then be conducted after the background information has been gathered and analyzed. The motivations of initial surveys and expected information to be gathered are described herein.

Visual Survey

The first NDE method that should be used on most projects is a visual survey. Visual surveys can be used to identify areas of differing masonry quality and conditions such as moisture saturation, external damage, and deterioration. Basic details such as masonry unit type, mortar soundness, building geometry and configuration, and expected structural load paths can all be documented in an initial survey (Schuller et al., 1995). Such information can be used to inform the rest of an investigation as existing conditions can necessitate specific testing and appropriate locations for testing can be revealed.

Surficial cracks that are visible during an initial survey can provide valuable insight into the behavior of an existing masonry structure. Detailed crack mapping that tracks the extent of cracks and their openings provides information about the condition of a masonry structure, instabilities, and possible causes of those instabilities (Rossi, 1991). The investigator can assess the location and form of the cracks to hypothesize if they are shear cracks, flexural cracks, related to volumetric movement, or if they resulted from some other induced stress.

In certain cases, visual surveys can be supplemented by the use of fiberoptic videoscope or minimally destructive probes to reveal additional information about the structure. For example, bricks may be removed to reveal the interior condition of a wall, or small, exploratory test pits can be excavated to investigate the state of the foundations (Rossi, 1991).

Non-destructive tests that can be conducted concurrently with a visual observation to provide supplemental results include surface hardness, ultrasonic, and mechanical pulse tests (Schuller et al., 1995). Each of these methods will be discussed further in this paper.

Geometric Survey

Geometric surveys can often be done simply by using a tape measure or with other tools of varying complexity, but the result should always be the same: an increased dimensional understanding of the structure. Geometrical study of a structure can help to identify irregularities from the intended structural form which could have resulted from either poor workmanship or movement over time (Rossi, 1991). Bulges in walls and sags in beams that may not be noticed with a visual survey can be quantified during a geometric survey. Additionally, comparison of dimensions taken on site can be compared with historical or structural plans to determine the accuracy of those documents or subsequent changes.

A survey method that is becoming increasingly popular, with increased accessibility to the necessary technology, is LiDAR (light detection and ranging). LiDAR scanners use lasers to record sets of precise geometric measurements that would not be practical to gather by hand. These measurements are typically stored in the form of 3-dimensional models which can be used to assess surface damage to masonry elements and inform the development of analytical models. Investigators have even used LiDAR results to recreate structural elements of an existing building in a laboratory to a sufficient level of accuracy for representative testing (Nowak et al., 2022). However, LiDAR can be limited by the resolution of the scan as it determines the spacing between measurement points and the size of surface defects that can be detected. The level of detail required for an investigation, roughness of the surfaces, and the resolution capabilities of available equipment should, therefore, be considered before conducting a LiDAR scan.

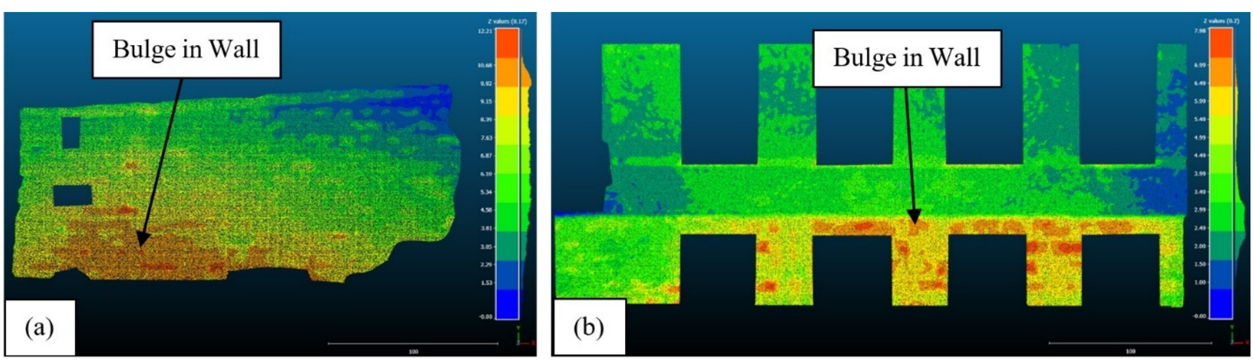

Figure 1: LiDAR contour plots: (a) of a stone masonry retaining wall and (b) of a brick masonry wall.

LiDAR Field Example: Elementary School

One useful way to use LiDAR is to create contour plots of planar masonry elements such as walls. This technique was used by ANA during a condition survey of an elementary school to identify areas where the walls bulged outwards. Figure 1 shows contour plots that were created using scans taken of two walls that were suspected to be bulging outwards. Figure 1(a) shows a stone masonry retaining wall with a bulge in the lower left region as shown in orange, and Figure 1(b) shows a wider bulge in the windowed region of a brick masonry wall as shown in yellow and orange. These contour plots were used to quantify the amount that the walls had deformed out-of-plane and, furthermore, to establish where repair interventions were necessary to address the deformation.

CONSTRUCTION TYPE AND INTERNAL CONDITION OF MASONRY

Observations made beyond the surface of masonry are often necessary during the investigation of a structure. Non-destructive methods can be used to characterize the internal condition of a masonry element and to identify internal features such as chases, chutes, and reinforcement. Such information can help to identify the construction methods that were used for a masonry structure to provide a better understanding of structural form and intended load paths. Additionally, locations where internal deterioration or damage has occurred can be identified for future repair. Non-destructive methods that can be used for the investigation of internal conditions are described herein.

Infrared Thermography

Infrared thermography (IRT) was first developed by the military in the 1960s (Schuller, 2003), but has been used for masonry applications for many years. IRT can be conducted using either long or short wave infrared cameras. Short wave cameras are useful for detecting large temperature differentials while long wave cameras can detect much smaller temperature differences, as small as 0.08°C. These cameras measure the infrared radiation emitted by surfaces and display those measurements in the form of 2-dimensional heat maps. The amount of emitted radiation from a surface is in part dependent on the emissivity of the particular material, which is a measure of the efficiency of the material to act as a radiator (Clark et al., 2003). Knowledge of the expected emissivity of the surface material to be evaluated is therefore necessary to obtain accurate temperature. However, relative thermal properties are often sufficient for masonry investigations.

Either active or passive thermography may be conducted and are appropriate in different scenarios. Active thermography is conducted by forcing temperature changes (Rossi, 1991) and then recording areas with different sensitivities to temperature change as they provide indications of varying subsurface conditions. Passive thermography is conducted by recording the sensitivities of surfaces to typically occurring heating and cooling cycles (Rossi, 1991) which are often most prominent when conducting IRT outside. For example, sunshine in the morning provides a natural heating cycle which can be used to conduct passive thermography. Whether actively imposed or passively observed, masonry must generally be in the process of heating up or cooling down to conduct an effective IRT survey.

IRT can be applied to a masonry application to locate internal discontinuities by observing the sensitivity of the surface to temperature change. This is especially effective at locating areas with near surface voids, cracks, delaminations, or incipient spalls (Abrams and Matthys, 1991; Schuller, 2003) as such areas are more sensitive to surface change than intact regions. Similarly, areas with internal openings such as chases or chutes typically have lower thermal mass than more solid masonry areas and are, therefore, more sensitive to temperature changes. When applied to concrete masonry, IRT has been found to be capable of locating missing regions of grout, accumulation of grout in otherwise hollow regions, and locating damage to walls from shear loading using passive thermography (Khan et al., 2015). Other applications of IRT that are relevant to masonry include detecting variations in moisture content, finding locations of air leakage, and locating regions of missing or displaced insulation (Schuller, 2003).

IRT can be advantageous as the cameras are typically lightweight and highly portable, it can be conducted either close-up or at a distance from the surface under investigation, and a large amount of data can be gathered in a short time (Clark et al., 2003). These factors make IRT ideal for investigating hard to reach surfaces or historic masonry that cannot be disturbed, such as masonry surfaces hidden by plaster or frescoes that cannot be removed (Schuller, 2003). However, disadvantages of IRT include that the effective test depth is limited as only surface radiation is recorded (Rossi, 1991), environmental factors provide many challenges to IRT being conducted outside (Clark et al., 2003), and passive thermography is time sensitive as the time of day affects the data that can be gathered (Hussain and Akhtar, 2017).

Recently, infragrammetry has emerged as a method of viewing and analyzing IRT data. This method involves overlaying infrared images onto a 3-dimensional model. Such models are typically obtained using LiDAR scanning. Infragrammetry is advantageous for analyzing IRT data gathered on structures with atypical shapes or for communicating IRT investigation results.

Ultrasonic Pulse

Ultrasonic pulse velocity (UPV) is a NDE method that utilizes high frequency ultrasonic waves and is often be used to evaluate cracks, voids, and delaminations in masonry assemblages (Abrams and Matthys, 1991). A transmitter that emits ultrasonic waves and a receiver that records the waves are used in a timing sequence to assess the internal condition of a test material (Schuller, 2003). Direct UPV tests are conducted with a transmitter and a receiver located on opposite sides of a masonry assemblage. Alternatively, indirect UPV tests can be conducted by placing the transmitter and receiver on perpendicular faces of the masonry assemblage or far apart on the same face (Silman, 1996). For both the direct and indirect methods, the time that a wave emitted by the transmitter takes to travel through the masonry and be recorded by the receiver can be used to determine the wave velocity. Voids and discontinuities within the masonry reduce the wave velocity. Areas where wave velocity is lower, therefore, indicate lower quality masonry. Further information can be obtained if the amplitudes of the received waves are evaluated.

Ultrasonic pulse echo (UPE) testing uses a UPE array which is a relatively new technology that contains multiple transmitters and receivers in a single unit. Ultrasonic waves emitted by the transmitter reflect off of any internal voids or discontinuities and are recorded by the receiver. The depth of the discontinuities can be determined from the recorded reflection time. UPE testing is more suitable than UPV testing when only one surface of a masonry element is accessible. Figure 2(a) shows a UPE array being used to investigate the presence of delaminations at the bottom of granite pavers. Figure 2(b) shows five scans that were recorded on different pavers. The red portions of the scans indicate locations where the ultrasonic waves reflected off of discontinuities and indicate delaminations.

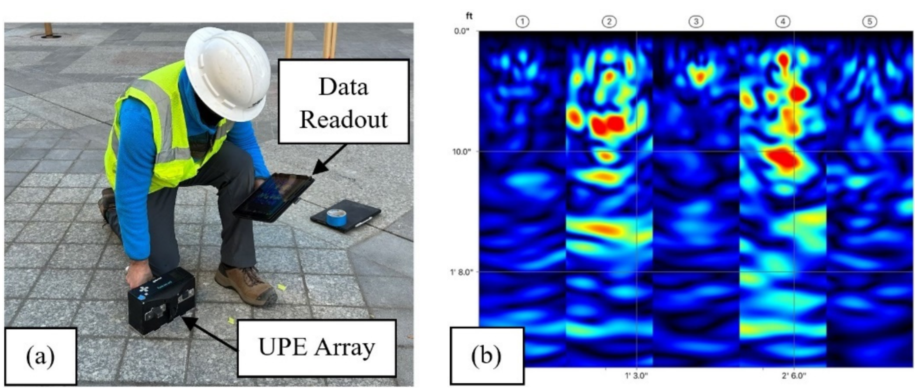

Figure 2: UPE testing: (a) conducting test and (b) results showing discontinuities in red.

The high frequency ultrasonic waves used in UPV and UPE testing are sensitive to narrow cracks and discontinuities and, therefore, have a limited effective depth range (Schuller, 2003). This limited depth makes ultrasonic techniques most useful in evaluating thinner sections or solid continuous sections. Ultrasonic techniques have been found to be particularly useful in locating internal damage or discontinuities in fully grouted concrete masonry walls as they are generally solid (Khan et al., 2015). It is important to know the moisture content of the test material that is being investigated using ultrasonic methods as wave velocity tends to increase with moisture content. This affects the interpretation of gathered results as a recorded high wave velocity can indicate good quality masonry or result from lower quality masonry simply being wet (Hussain and Akhtar, 2017).

Mechanical Pulse Velocity

Mechanical pulse velocity (MPV) tests can be used to investigate the internal quality of masonry assemblages with a concept similar to UPV testing. MPV tests are conducted by tapping a hammer on a surface and recording the stress waves that travel through the test material with an accelerometer. The mass and hardness of the hammer head used for tapping the material surface define the energy and frequency content of the initial wave (Schuller, 2003). Couplants, such as water or oil, are typically applied at the interface between the accelerometer and test material to maximize energy transmission to the accelerometer (Hussain and Akhtar, 2017).

MPV tests use lower frequency waves in comparison to ultrasonic tests. These waves are able to travel through small discontinuities to allow for an increased depth range. This often makes MPV testing more useful in investigating historic masonry with weak mortar and numerous flaws and cracks (Atkinson, 1993) or for investigating thicker masonry sections.

Contour maps are often used when MPV testing is conducted on masonry walls to assess the relative condition of the masonry (Atkinson, 1993). Areas where the waves travelled slower through the masonry or lost more energy are typically areas of lower quality, more discontinuities, and possibly lower strength.

Impact-Echo

Impact-echo tests use equipment similar to that used for MPV tests but, similar to UPE tests, only require access to one face of a masonry assemblage. Impact-echo tests can be used to find internal discontinuities that are parallel to the test surface such as delaminations and cavities (Schuller et al., 1995). A stress wave is generated at the face of a wall and reflects off of internal discontinuities or interfaces between high-impedance and low-impedance materials, such as the interface between brick and air (Hussain and Akhtar, 2017). The reflected waveforms and frequencies are then recorded with a piezoelectric transducer. The depths of internal features are then determined by using known wave characteristics (Schuller, 2003).

The application of impact-echo testing to brick masonry is limited as interpretation of results becomes complicated due to reflections off of mortar joint surfaces and mode shapes of brick units. Therefore, it is often recommended that impact-echo testing be used on more solid materials such as prismatic stone masonry or fully grouted concrete masonry (Hamid and Schuller, 2019). Impact-echo testing can be used for investigation of concrete masonry and can be used in quality control programs to identify flaws or defects, to detect damage caused by fire, and to look for voids in grouted cells (Hussain and Akhtar, 2017).

Electromagnetic Detection

Tools that use electromagnetic detection can be useful for the location of metallic objects embedded in masonry (Abrams and Matthys, 1991). Pachometers are one such tool that can be used to investigate the presence of reinforcement and to locate wall ties, reinforcement, shelf angles, and steel sections in masonry. Equipment typically has a maximum depth range from 12 to 30 cm which is sufficient for most masonry applications (Schuller, 2003). Pachometers can locate reinforcement in a wall without any supplemental information but cannot generally reliably be used to determine the depth and size of a reinforcing bar without knowledge of either the depth or size first. Therefore, pachometers are often used in modern masonry investigations in combination with other methods.

Note that different metal detection devices use different technologies and have different capabilities. For example, eddy current induction pachometers can detect non-ferromagnetic metals, but devices using magnetic sensors cannot.

Videoscope

Videoscopes can be used to visually survey the internal characteristics of masonry assemblages and are often used as a confirmation of findings from using other methods. This method may be classified as slightly destructive, as a small hole, typically only about 3/8” in diameter, needs to be drilled into the masonry to allow for a small camera to be inserted. However, the hole can often be drilled into a mortar joint that can simply be repointed after the survey. The small camera typically provides a real-time feed to a display that can be observed during the survey. Videoscope surveys can be used to identify structural characteristics of the masonry, measure internal cavities, and analyze the propagation of internal cracks and measure their openings (Abrams and Matthys, 1991). Figure 3(a) shows a videoscope being operated to investigate a concrete masonry wall and Figure 3(b) shows an image captured from the videoscope probe.

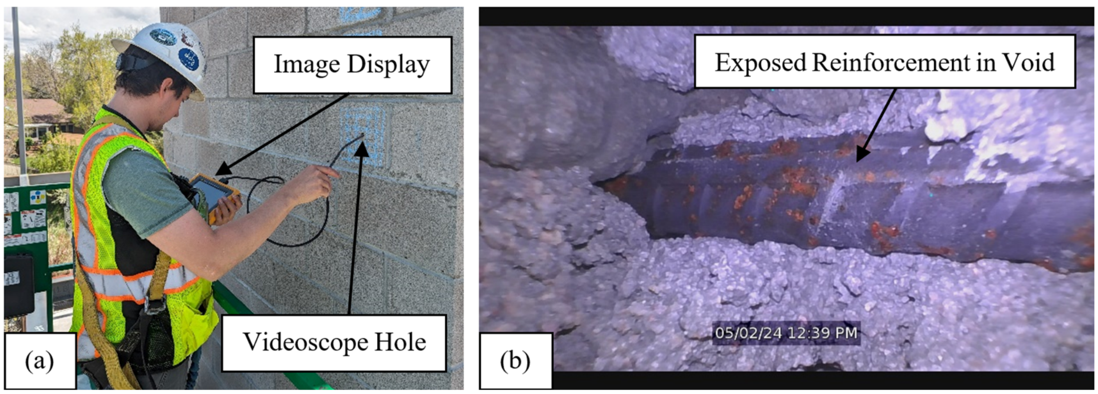

Figure 3. Videoscope probe: (a) operating videoscope and (b) videoscope image.

Ground Penetrating Radar

Ground penetrating radar (GPR) is often used in masonry investigations to characterize the internal features of masonry elements. The equipment for GPR testing includes an antenna, a data storage device, and a radar control unit which typically has a display. Some GPR systems include all of these elements in one device, while other systems allow interchanging of parts such as antennas. A transmitter and a receiver are both contained within the antenna, the size and shape of the transmitter and receiver determine the frequency of the emitted waves. Larger antennas emit lower frequency waves (typically as low as 200 MHz for masonry applications) which penetrate deeper than higher frequency waves (typically as high as 2.5 GHz for masonry applications) emitted by smaller antennas (Schuller, 2003). The lower frequency waves emitted by GPR antennas can penetrate through air spaces, such as voids, allowing GPR scanning to investigate beyond the depth that can be effectively reached with other methods (Hussain and Akhtar, 2017). Signals emitted by the transmitter reflect off of interfaces between materials that have different dielectric constants (Rossi, 1991). These reflected signals are then gathered by the receiver and sent back to the radar control unit as traces. Radar traces are collected continuously as the antenna is moved over a surface. The collection of traces are then compiled into a 2-dimensional cross-sectional view which can be analyzed by qualified personnel. Modern equipment and software can further compile data into three-dimensional models in some cases.

GPR can be used to determine wall thickness and to locate bond stones, blind header courses, internal joints in clay or stone masonry, grout in concrete masonry assemblages, and reinforcement or other internal steel sections (Rossi, 1991; Silman, 1996; Schuller, 2003). GPR is also often used to locate internal imperfections such as inclusions, voids, damage or deterioration, and delaminations (Schuller, 2003). GPR is non-invasive and is, therefore, advantageous for use in historic structures where invasive methods of investigation are not permissible. *RILEM MS.D.3 Radar investigation of masonry* (RILEM TC 127-MS, 2001) provides standard methodology for investigating historic masonry with GPR.

An important aspect of GPR scanning to know before application is that the scanning is highly affected by the moisture and salt content of a material (Schuller, 2003). High amounts of moisture and salt rapidly attenuate radar signals, thus reducing the effective depth that can be reached with this test method.

GPR Field Example: Pullman Shops

ANA conducted a condition assessment and investigation of the Pullman Shops (Figure 4(a)) in Chicago, IL, using NDE methods to identify the construction type and internal condition of masonry walls. The Pullman Shops were constructed in the late 1880s and are made up of stone foundations, masonry walls and pilasters comprising multiple wythes of clay brick masonry, and a steel truss roof structure.

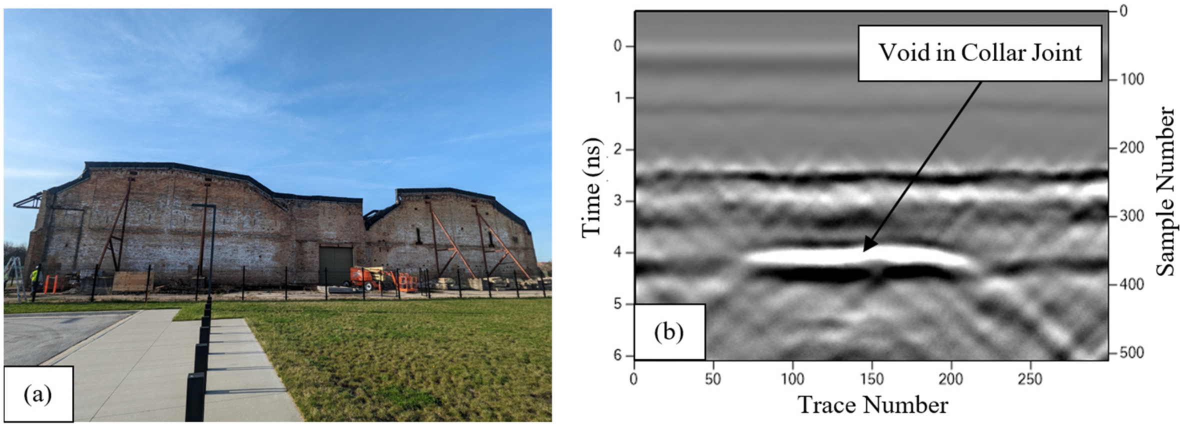

Figure 4. Pullman Shops investigation: (a) Pullman Shops and (b) sample GPR scan.

The primary NDE method used for this project was GPR scanning. GPR was used to determine wall and pilaster thicknesses throughout the structure and to locate blind headers connecting masonry wythes, steel truss bearing plate anchor pins, and voids between masonry wythes. Figure 3(b) shows a sample GPR scan of a wall with a substantial void at a collar joint. The void is visible as a relatively strong reflection with notable length. The GPR data was used to determine both the depth and length of this void.

Electromagnetic detection and videoscope probes were utilized to validate GPR findings. Electromagnetic detection was used to confirm the location of anchor pins at truss bearing locations and to investigate the presence of reinforcement. Videoscope probes were used to determine void size, confirm number of masonry wythes, and to explore existing separations between pilasters and walls to investigate the connection between the two. The use of these methods to validate results from scanning was of the utmost importance. The uncertainty that is often associated with the results of using a single NDE method can be substantially reduced by utilizing other NDE methods to validate those results. The use of multiple NDE methods is, therefore, often essential to provide a reasonable level of certainty to NDE investigations.

MASONRY STRENGTH

Masonry strengths are essential parameters for the accurate structural assessment of existing masonry structures. Estimates of in situ masonry strengths can either be estimated using conservative assumptions or be obtained through field or laboratory testing. Masonry strength estimates available in code books are typically conservative, which, when used for analysis, often result in overly conservative designs that do not account for substantial structural contribution from masonry elements. In some cases, masonry prisms or units can be sampled from a structure and tested to provide a more accurate estimate of masonry assemblage strength. However, such sampling is not always possible, especially in historic masonry structures where prisms generally cannot be extracted or transported without significant damage or total deterioration. Therefore, non-destructive or minimally destructive test methods often become the best or only available option for accurate masonry strength estimation. Such methods and described herein.

Surface Hardness

Surface hardness tests, also referred to as rebound tests, conducted using a Schmidt hammer, pendulum hammer, or Waitzmann hammer can be used as a non-destructive method to investigate relative masonry strength. Quantitative measurements of masonry strength can also be made if the test method is sufficiently calibrated with masonry prism testing (Rossi, 1991). Hammer weight must be selected based on the expected hardness of the test material as it determines the energy level of the hammer blow (Schuller et al., 1995; Atkinson, 1993). It is especially important to select low-energy hammers for weaker historic brick masonry to not cause damage to the material surface (Hussain and Akhtar, 2017).

Surface hardness tests can provide good first indications of brick and concrete masonry strength. However, the relationship between surface hardness and material strength has been found to be imperfect (Hussain and Akhtar, 2017). Additionally, these tests have been found to be sensitive to the mortar that surrounds a given test unit and the bond between the test unit and the mortar (Schuller, 2003). Therefore, more reliable results of material strength in critical regions should be gathered through alternative test methods.

Compressive Strength and Elastic Modulus

Flatjack testing is a minimally destructive method of strength testing for use in masonry assemblages. Flatjacks are thin, metal, bladderlike devices that can be inflated to apply pressure. Flatjack deformability testing is applicable to solid brick masonry and can provide an accurate estimate of in situ masonry strength (Atkinson, 1993). *ASTM C1197* (ASTM, 2022a) provides the standard methodology for flatjack deformability testing.

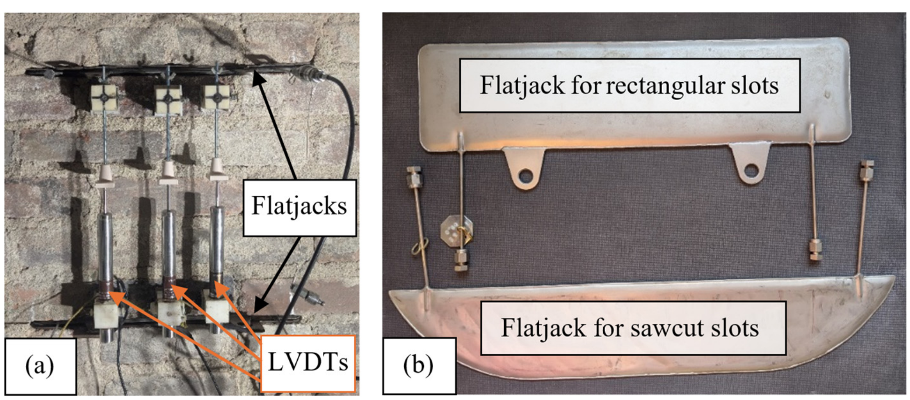

Figure 5: Flatjack deformability testing: (a) test setup and (b) typical flatjacks.

Figure 5(a) shows the typical setup for a flatjack deformability test. Wide slots are cut in two masonry bed joints that are separated by five brick courses. Flatjacks, as shown in Figure 5(b), are inserted into the cut slots and seated. Three dial gauges or linear variable differential transformers (LVDTs) are attached to the masonry between the flatjacks. The test is then conducted by inflating the flatjacks to apply load to the masonry until failure, which is defined as the point when small cracks start to develop or where the stressstrain curve becomes nonlinear. Significant dead load is, therefore, required above the test location to allow for sufficient loading to be applied to the masonry between the flatjacks. Deflection and load data are recorded during the test and are used to determine compressive elastic modulus for the masonry assemblage. The mortar bed joints that were removed for testing can typically be repointed by a qualified mason.

Masonry compressive strength can be determined from a flatjack deformability test through two methods. The compressive strength may be calculated as the maximum applied pressure if the masonry experienced failure during the test. Alternatively, the compressive modulus that was determined through testing can be used to estimate compressive strength through established relationships.

Shear Strength

Flatjack shear testing is another minimally destructive testing method that is applicable to solid brick masonry. This method can provide an accurate estimate of shear strength (Atkinson, 1993) and, unlike flatjack deformability testing, it doesn't require significant dead load above the test location. *ASTM C1531* (ASTM, 2022b) provides the standard methodology for flatjack shear testing.

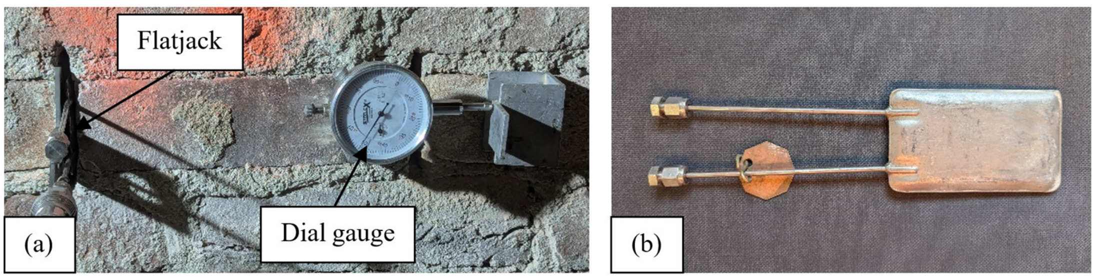

Figure 6: Flatjack shear testing: (a) test setup and (b) typical flatjack.

Figure 6(a) shows the typical setup for a flatjack shear test. The vertical head joints are removed on both sides of a test brick. A small flatjack, shown in Figure 6(b), is inserted into one of the empty head joints. A dial gauge and reaction block are attached to the masonry such that the dial gauge spans the empty head joint not occupied by the flatjack. The test is then conducted by pressurizing the flatjack and recording the load applied to the test brick at specified deflection intervals. The shear index of the masonry can then be determined from the load and deflection data that was gathered and measurement of the area of mortar bonded to the test brick. Additionally, the frictional component of shear index can be subtracted from the tested value of shear with an estimate of the dead load acting on the test location.

A recent development for flatjack shear testing includes the adaptation to rubble stone masonry (Simões et al., 2016). Changes to the described method includes the testing of an area of masonry that includes multiple units rather than testing a single unit. Also, horizontal slots are cut above and below the test area to allow for two additional flatjacks to be used to apply a known compressive stress to the test area, as described in Method A of ASTM C1531. This adapted method has been found to provide results that agree with the common flatjack shear test method when used on solid brick masonry. However, use of the adapted method on rubble stone masonry requires further development to provide consistent results (Simões et al., 2016).

Bond Wrench

The bond wrench test is a minimally destructive test method that can be used to determine the tensile bond strength between mortar and masonry unit (Abrams and Matthys, 1991). *ASTM C1072* (ASTM, 2022c) provides the standard laboratory methodology this method, which can be adapted for field use. This test is conducted by attaching a long lever arm to the top of a single brick in a masonry assembly. Load is then applied to the lever arm until the brick is pried off of the mortar below it. The load required to pry the brick can then be used to calculate the tensile bond strength between the brick and the mortar. Using this method on clay brick masonry walls requires the removal of multiple bricks to expose the top face of a single brick. The removed bricks can typically be replaced in the wall after testing is completed.

Masonry Strength Field Example: Aspen Armory

The Aspen Armory (Figure 7(a)) in Aspen, CO, underwent a structural analysis as part of an adaptive reuse project. The exterior walls of the 130 year old building are composed of three wythes of clay brick masonry. Initially, only conservative values of masonry strength from available literature could be used for the analysis as the existing strength of the masonry was unknown. As an alternative, ANA performed flatjack deformability tests, flatjack shear tests, and bond wrench tests (Figure 7(b)) to quantify the existing compressive, shear, and tensile strengths of the masonry, respectively. This provided more accurate strength values for use during the analysis to allow for more effective reuse of the existing walls and the avoidance of unnecessary retrofit measures. Overall, the result of combining multiple minimally destructive tests on a single building was a more complete understanding of the existing masonry capacity.

Figure 7. Aspen Armory investigation: (a) Aspen Armory and (b) bond wrench testing.

EXISTING STATE OF STRESS

The load paths and existing state of stress in a masonry structure cannot always be clearly determined from inspection. However, this information is often useful during analysis. The state of stress flatjack test method can be used to determine the existing state of stress in a solid brick masonry wall and is based on determining the stress that is released when a horizontal slot is cut in a mortar bed joint (Rossi, 1991). The procedures and equipment used for this test method are described in *ASTM C1196* (ASTM, 2020).

The state of stress flatjack test method begins by installing gauge points on the face of a masonry wall above and below the mortar bed joint where a slot will be cut. The distance between the gauge points is measured very precisely, then the horizontal slot is cut. A compressive stress release will most often be triggered which will result in the gauge points moving closer together. A flatjack (as seen in Fig. 5(b)) can then be inserted into the slot and pressurized until the distance between the gauge points has returned to the original value prior to slot cutting. At that point, the flatjack pressure is recorded and used to determine the compressive stress at the outer wythe of the wall (Rossi, 1991). It is important to remember when conducting this test that a stress gradient may be present for a multi-wythe masonry wall resulting in the two sides of the wall having different levels of stress. Therefore, it may be necessary to test both sides of a wall to have a more complete understanding of the current state of stress.

SUMMARY

The NDE methods presented in this paper are available for the investigation of masonry structures. Such methods can be used to provide useful information regarding overall condition, construction typology, internal features, and in situ masonry strength. It is often beneficial to use multiple NDE methods for a single investigation to gather complementary results that provide a more complete understanding of the existing condition of a masonry structure. However, knowledge of the NDE methods that are most appropriate in a given scenario is necessary to obtain the highest quality of information possible. Factors that may affect the choice of NDE method include, but are not limited to, masonry type, construction type, preservation policies in place to protect the masonry, state of masonry deterioration, and weather conditions.

NDE methods for masonry structures are constantly being improved with the availability of new equipment and the development of standards. A state-of-the-art knowledge of masonry NDE is, therefore, beneficial for investigators conducting assessments of existing masonry.

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