Practice Points NUMBER 09

Nondestructive Evaluation: Structural Performance of Masonry

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Introduction

Masonry is one of the world's most durable construction materials. Masonry structures can remain in service for hundreds or even thousands of years. Masonry structures often outlive their designers, their original design documents, and their original functions. When historic masonry structures are evaluated for preservation, adaptive use, or additions, there are numerous questions that may arise about the construction and the condition of the brick, stone, concrete block, and mortar.

One of the first questions typically asked by the design or investigation team is "How is it performing?" It is important to understand observed distress, such as cracks, corrosion, and surface erosion. Often the cause and/or extent of distress can play a major role in rehabilitation work and in determining what other types of nondestructive evaluation are required. Another common question about masonry is "How strong is it?" In order to conduct a structural evaluation, an engineer must have at least some information about the strength of the masonry. A related question often asked next is "How was it constructed?" Masonry characteristics such as ties, voids, headers, and embedded items are often hidden from view, but these items are critical to understanding how the assembly will perform. Finally, in some cases it is important to ask "What is it doing right now?" It can be vital to understand what types of loads and stresses the masonry is currently experiencing, especially in order predict future performance under new or different loads. Other questions regarding moisture permeability, acoustic properties, or thermal behavior of masonry may also arise.

This Practice Point focuses on these fundamental questions by providing a summary of current nondestructive-evaluation tools available for the assessment of historic masonry. While case studies and descriptions of specific nondestructive test methods are fairly common, this article provides an overview of numerous techniques, both listing the technologies available and helping in the selection of an appropriate method. A wide range of evaluation methods are available for use, and many claims are made regarding the accuracy of different methods. Some methods were developed specifically for masonry evaluation, but many approaches are "borrowed" from archeology, aerospace, or other construction-material applications. Table 1 summarizes evaluation methods and conditions and lists methods available to answer these questions. Since some methods provide more detailed or accurate information than others, the table gives each applicable method an effectiveness grade. Cost, complexity, and effectiveness grades are based on the authors' experience with each method and are intended only as general guidelines. All of these items can vary significantly based on numerous factors including location, accessibility, schedule, and scope of investigation. Typically, an investigation involves the use of multiple complementary evaluation techniques. Investigations should be planned carefully to include appropriate methods with minimal disruption to the existing structure. A list of nondestructive-testing techniques and associated ASTM and RILEM test specifications is provided in Table 2.

Fig. 1.
Spalling, efflorescence, and surface deterioration is visible at stone surfaces between the arched openings and wall caps. Damage results from the soft nature of sandstone, water infiltration along the top of the wall, and environmental exposure. All photographs by Atkinson-Noland & Associates.

Table 1. Appropriate test methods to evaluate or investigate various masonry conditions.

	Test Method for Investigating Condition													
	Destructive		Nondestructive w/ Minor Repairs			Nondestructive								
General	Sampling (Cores)	Bond Wrench Test	Flatjack / Shearjack	In-situ Load Testing*	Petrography	Visual / Optical**	Ground Penetrating Radar (GPR)	Ultrasonic Pulse Velocity (UPV)	Impact Echo (IE)	Rebound Hammer / Surface Tests	Metal Detection (Induction)	Radiographic	Infrared Thermography (IRT)	Half-Cell Potential
Relative Cost ($, $$, or $$$)	$$	$$	$$	$$$	$$$	$	$$$	$$$	$$$	$	$	$$$	$$$	$$
Complexity/Experience Needed (L=Low, M=Medium, H=High)	L	M	M	H	H	M	H	H	H	L	L	M	M	L
Condition														
In-place strength?	G	G	E	E	A			A	A	A				
In-place uniformity?	G		G		G	A	G	G		G		G	G	
In-place deformability?			E	E				A	A	A				
In-place stress?			E											
Crack location?						A		E	E			G		
Crack movement?									G					
Performance under load?		E	E	E										
Rebar size, location, cover?	E						G				E	E	A	
Anchor and tie locations?								E			E	E		
Voids in grout?						A	E	A	A			E	G	
Voids in masonry?						A	E	A	A			E	G	
Corrosion of rebar?						A								G
Durability problems?				E		A		G						

E = Excellent information, reliable method
G = Good information, somewhat variable or vague results
A = Approximation only, highly variable or inexact

* Generally Load Testing is conducted at service levels that do not result in significant damage to the structure. If loads are taken to levels near failure, more significant repairs may be required.

** Visual / Optical Testing can involve minor repairs for borescope and small probe observations or significant repairs for larger openings.

Masonry-evaluation techniques can involve varying levels of damage or deconstruction of the masonry. Especially in historic structures, even relatively minor damage can result in expensive and difficult repairs. The use of nondestructive methods helps limit the damage caused by the testing. Additionally, gathering information about the existing masonry provides designers with confidence that they understand the current conditions and the potential causes of any distress. This knowledge and confidence typically lead to better planning and more effective designs, ultimately minimizing modifications and additions to the historic structure.

How Is It Performing?

An important aspect of evaluating historic structures is understanding the cause or causes of observed distress. Common types of masonry distress include cracks, spalls, efflorescence, and surface erosion (Fig. 1). Numerous questions can arise regarding the various types of distress and about the best method to use in evaluating distress based on the situation.

One of the most important tools in evaluating distress is visual observation by an experienced investigator. The cause of many crack patterns or surface-erosion patterns can be reasonably deduced based on surface observations alone by such an expert. Sometimes additional subsurface investigation using nondestructive evaluation, probe openings, or borescope observations may be required to determine subsurface conditions. Visual observation may also include the installation of crack monitors or tiltmeters to track movement of cracks or walls (Fig. 2).

There are several other nondestructive evaluation methods that can assist in the evaluation of cracks, spalls, and surface erosion. Crack depth and extent can often be evaluated in place using ultrasonic pulse

Fig. 2.
An installed electronic crack gage used to determine if a crack (or gap, in this case) is actively moving.

Fig. 3.
Ultrasonic pulse velocity (UPV) testing of a clay brick masonry structure. Pulses were transmitted through the wall thickness to help determine wall solidity and locate cracked headers.

velocity (UPV) (Fig. 3) or impact echo methods (Fig. 4). UPV can also be useful in evaluating surface conditions. If it is possible to obtain a small material sample, the use of laboratory-based petrography to examine the sample microscopically and chemically can provide valuable information about distress mechanisms.

Sometimes cracking in masonry is caused by corrosion of embedded metal items. A nondestructive-evaluation method known as half-cell potential can be used at the masonry surface in order to determine the likelihood of active corrosion at various subsurface locations.

The appropriate nondestructive-test methods to use in evaluating distress varies based on the situation, but evaluation should always begin with visual observations by a qualified masonry investigator.

How Strong Is It?

The most commonly desired piece of information is the compressive strength of the masonry assembly (i.e., how much force the masonry can resist in compression). Compressive strength can be used by a structural engineer to evaluate the load-carrying capacity of the existing structure. Other material properties may also be estimated if the compressive behavior is known. In historic structures, evaluating or specifying the strength of the masonry was likely not part of the design process. Even if it were, any record of the masonry strength is likely lost. Additionally, the strength of the masonry after dozens or hundreds of years is often significantly different from the original strength, due to weathering, deterioration, and the effects of long-term load application.

Table 2. Nondestructive evaluation and in-situ test standards.

Type of Test	Purpose	Standard
Brick prism testing	Compressive strength of brick assembly	ASTM C 1314
Brick shear testing	Shear strength of brick assembly	ASTM E 519
Flatjack deformability test	Compressive strength and/or stiffness of brick assembly	ASTM C 1197
Push or shove test	Shear strength of brick assembly	ASTM C 1531
Ultrasonic Pulse Velocity (UPV)	Crack and deterioration location	ASTM C 597 Concrete*
Impact Echo (IE)	Crack and debond location	ASTM C 1383 Concrete*
Rebound hardness of mortar	Approximate mortar condition	ASTM C12.02.07 (In Progress)
Rebound hammer	Surface hardness	ASTM C 805 Concrete*
Probe penetration	Surface hardness	ASTM C 803 Concrete*
Petrography	Physical and chemical characteristics of mortar	ASTM C 1324
Borescope	Visual observations below surface	None
Ground Penetrating Radar (GPR)	Subsurface voids and embedded items	ASTM D 6432
Radiography	Subsurface voids and embedded items	None
Infrared Thermography (IRT)	Surface temperature differences suggesting voids or delaminations	ASTM C 1060
Metal detection	Location of reinforcing or other embedded metals in subsurface	None
Half-cell potential	Location of areas with high likelihood of active corrosion	ASTM C 876 Concrete*
Flatjack stress test	Determination of in-situ compressive stress in masonry	ASTM C 1196
Bond wrench test	Masonry flexural bond strength	ASTM C 1072
Mechanical Pulse Velocity (MPV)	MPV of masonry for voids and discontinuities	RILEM MS.D.1
Radar investigation	GPR of masonry	RILEM MS.D.3
Push or shove test	Shear strength of brick assembly	RILEM MS.D.6
Pendulum hammer	Hardness of pointing mortar	RILEM MS.D.7

*Items marked as concrete are standards intended for use in concrete materials but are also applicable or can be adapted for use with masonry.

Fig. 4. (top left) *Impact-echo testing of clay tiles to determine thickness of dome and dome geometry.*

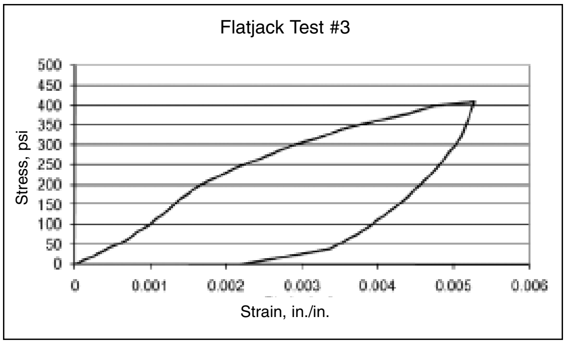

Fig. 6. (top right) *Flatjack test results (stress vs. strain).*

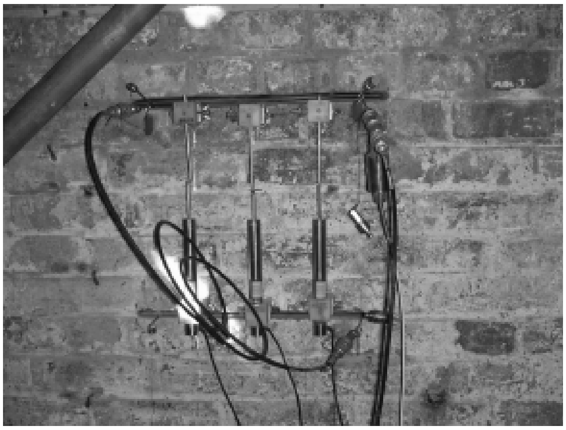

Fig. 5. (bottom left) *A flatjack deformability test used to determine compressive strength and/or stiffness of an existing masonry assembly.*

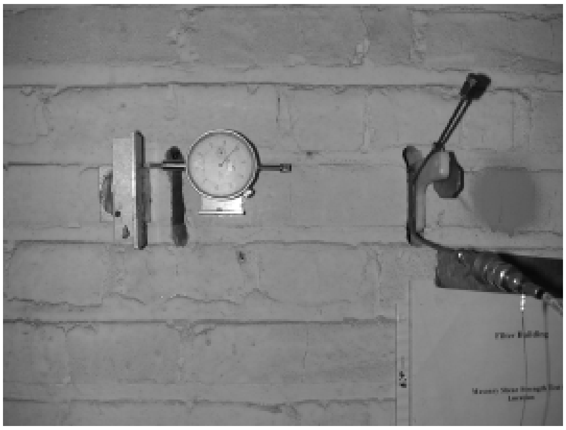

Fig. 7. (bottom right) *A shearjack test on painted clay brick masonry. The shearjack on the right inflates to push the brick to the left, where head joint mortar has been removed.*

It can often be important to understand the shear strength of the masonry as well. Shear-strength information is required by some building codes (such as the International Existing Building Code) to evaluate a structure's ability to resist lateral loads, such as wind and earthquake forces.

There are various methods for determining strength properties of a masonry assembly. The most obvious and direct method is to obtain samples from the structure and test them in a laboratory (in compression and shear, as needed). There are several significant problems with this approach. First, obtaining appropriately sized samples that remain intact throughout the removal and transportation process can be extremely difficult. Second, obtaining samples causes significant damage to the structure, and extensive repairs may be required. With most historic structures the damage and disruption caused by sample removal is simply unacceptable.

If the masonry cannot be taken to the laboratory, there are strength-evaluation methods that bring the laboratory to the masonry. In-situ evaluation of masonry strength can be performed using flatjacks, thin stainless-steel bladders that are inserted into slots in the masonry and are inflated to exert force on the masonry. The most common type of flatjack testing is shown in Figure 5. In this test, the compressive strength and/or stiffness is determined by pressurizing two jacks and monitoring the deformation of the masonry between them (Fig. 6). Typically, the flatjacks are placed in horizontal mortar joints so that only minor repointing of joints is required after the test is completed. This same concept can be applied horizontally to evaluate shear strength. Smaller shearjacks are placed in head joints and inflated to push a unit sideways (Fig. 7). This push, or shove, test can also be conducted using a more conventional hydraulic jack, but this method requires the removal of a masonry unit in order to insert the jack. The building shown in Figure 5 was undergoing renovation, including a new roof and modified floor loads. The building shown in Figure 7 was a government building undergoing a seismic retrofit. In both cases the material properties of the masonry were required for engineering analysis.

Several other methods can provide some approximation of masonry strength properties. Ultrasonic wave methods, such as ultrasonic pulse velocity (UPV) and impact echo (IE), can be used to evaluate wave propagation speed through the masonry. This wave speed can be approximately correlated to stiffness properties, which, in turn, can be approximately correlated to strength properties. These results give some general indication of material properties but are generally not sufficiently precise for structural design. Similarly, there are several methods of testing surface hardness, such as rebound hammer and probe penetration, which can be used to give a loose correlation to material strength. Petrographic examination of mortar and masonry-unit materials may also be useful in determining a general category of performance. However, particular caution should be used with pressure wave, surface hardness, and petrographic methods to predict masonry strength. Research has shown poor relationships between these methods and masonry strength properties. Nevertheless, these methods may be able to provide estimates of approximate strength as being either weak, of average strength, or strong. Often, such simple approximations are appropriate for simple structures or preliminary evaluations. Accurate measures of masonry strength properties are best obtained using in-situ tests.

For historic structures flatjack and shearjack testing are often the strength-evaluation methods that provide the most meaningful information with the least amount of damage and disruption.

How Was It Constructed?

While certain aspects of historic masonry construction are visible at the surface, other problem areas may be hidden from view. When original construction documents or related documents are available, they can provide valuable information about the original design. Even when original design information is available, though, it is important to verify that existing conditions match the original design intent. This process can be challenging for conditions such as blind headers or discrete veneer headers that tie wythes of masonry together but are not readily visible. Determining the type, size, and spacing of these headers is an important aspect of many building investigations. Similarly, there may be questions about how solidly the collar joint between wythes of masonry is filled, either for structural or waterproofing reasons, and about the presence of steel or other embedded items. Sometimes it is possible to observe these subsurface conditions directly, either by making probe openings or by observing conditions through small holes using a borescope (Figs. 8 and 9). However, direct visual observation of the subsurface generally provides information only about a small area and can require expensive repairs. Visual observations should be used in conjunction with other methods to minimize damage and disruption.

A relatively modern nondestructive-testing method that can help provide information about subsurface construction is ground penetrating radar (GPR), also known as surface penetrating radar. This technique transmits pulses of microwave energy (electromagnetic waves) into a material and then monitors for reflections of these waves (Fig. 10). Wherever the wave encounters a significant change in dielectric constant, typically caused by an embedded item or a void, a reflection is visible to the operator. The depth of the feature can be estimated based on the pulse travel time. This method is particularly adept for locating air voids and embedded metallic items. Before-and-after scanning can be used to determine if voids were successfully filled during compatible injected fill (CIF) repairs (Fig. 11). GPR can also be used to locate blind headers, discrete veneer headers, and significant changes in moisture content (Fig. 12). GPR uses very low energy pulses, and it is safe to use in occupied buildings. The operator can get information along the line of a GPR scan instantly and adjust further investigation accordingly. The frequencies used for masonry evaluation generally provide useful information to a depth of approximately 24 inches or less. Because GPR-device output requires significant interpretation by the operator, its effectiveness depends largely on the experience and expertise of the operator.

Other subsurface investigation techniques may be appropriate in some circumstances. Radiography (X-ray) has the advantage of providing a relatively easily interpreted image of subsurface conditions. However,

Fig. 8.
Borescope examination of stone cramp corrosion.

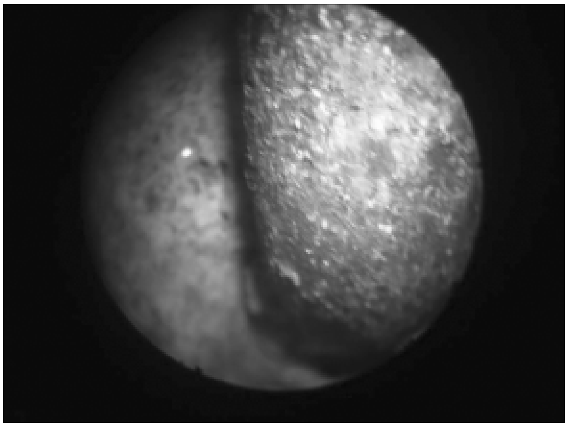

Fig. 9.
A view of the corroded anchor through the borescope.

Fig. 10.
Ground penetrating radar (GPR) scanning of exterior stone to locate headers.

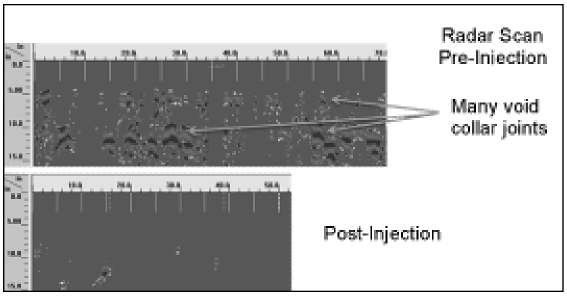

Fig. 11. GPR scans before and after injection of a masonry wall, showing the reductions in collar-joint voids.

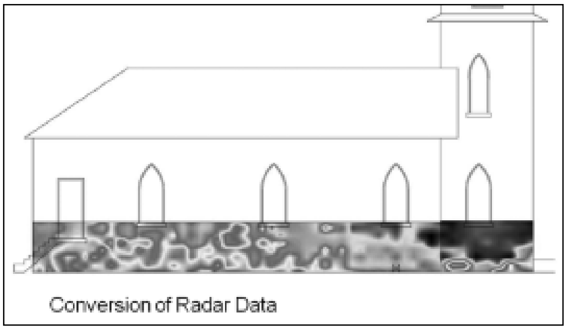

Fig. 12. GPR data after post-processing showing variations in moisture levels in an exterior masonry wall of a church.

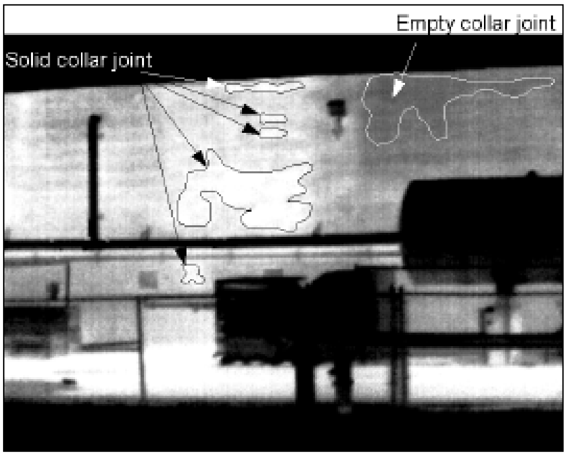

Fig. 13. Infrared thermography (IRT) image. Areas with solid collar joints appear as hot (white) zones, whereas gray and black show cooler areas.

radiography is usually effective only for small areas and is a relatively slow process for masonry construction, typically requiring evacuation of a building. Pulse methods such as ultrasonic pulse velocity (UPV), lower frequency mechanical pulse velocity (MPV), and impact echo (IE) may also provide information about subsurface conditions. However, interpretation of these results can be complicated due to reflections at the edges of masonry units. Under the right circumstances, infrared thermography (IRT) may be used to gather information about wall construction by detecting very small differences in masonry surface temperature (Fig. 13). IRT is often used to locate subsurface conditions, voids, infilled doors and windows, and variations in moisture in walls.

Metal detection in historic structures is also possible using devices commonly referred to as covermeters or pachometers (Fig. 14). Most modern devices use eddy current induction to detect embedded metals, a process that can detect not only mild steel and iron but also aluminum, prestressing strands, copper, lead, and other metals. The primary limitation of modern covermeters is depth of detection. Typically, metallic items are distinguishable only within 5 to 7 inches of the masonry surface. Somewhat more sensitive metal detectors can be useful in locating discrete anchors or ties, but these devices do not provide reliable information about size or depth of the metal.

Ground penetrating radar (GPR) is often the subsurface evaluation method that provides the most information about masonry geometry, embedded items, and voids.

What Is It Doing Right Now?

Sometimes the state of existing masonry stresses is unclear due to complicated load paths, building movement, or thermal and/or moisture expansion. Information about the state of stresses can be valuable in assessing whether or not a historic structure can withstand additional or modified loading. A type of flatjack testing can be used to help determine stresses in the masonry, primarily vertical compressive stresses (Fig. 15). In-situ stress testing uses a single slot cut into the masonry, typically at a mortar-bed joint. The distance between gauge points above and below the slot is measured very precisely before and after the slot is cut. Then a flatjack is inserted and inflated until the gage points reach the original separation. The pressure in the flatjack, modified by a calibration factor, is used to determine the vertical-stress state at the test location. The in-situ stress test shown in Figure 15 was conducted for a building-renovation project. The tests were performed underneath relief angles to determine whether the angles were supporting the load from the floors above as designed.

Summary

Historic masonry can provide hundreds of years of wonderful performance with limited maintenance. Many nondestructive test methods can help answer questions about material strength, construction, or distress with minimal damage to the structure. With these tools and a good understanding of masonry performance, virtually any masonry mystery can be solved, and the structure repaired if necessary, providing many more years of service and enjoyment.

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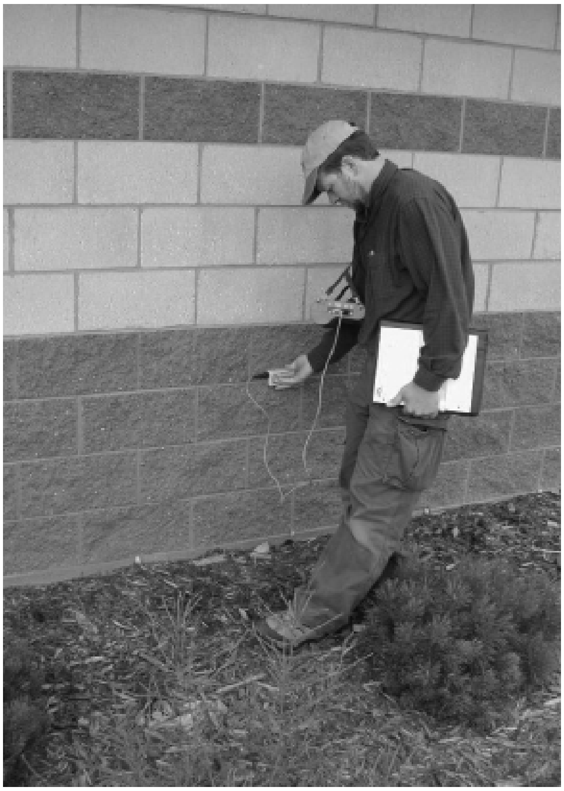

Fig. 14.
Finding reinforcement location using an eddy current induction metal detector.

Fig. 15.
In-situ stress test showing measurement of the gauge point separation after inflation of a flat-jack.

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