Evaluation and Repair of Masonry Construction

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***Abstract* – Many existing masonry buildings require repair or strengthening to address long-term deterioration effects, structural deficiencies, or concerns regarding seismic performance. This paper follows a project to retrofit an historic masonry building as a case study to present the process of evaluation and repair. Nondestructive and in-place test methods are used to evaluate existing construction to identify as-built conditions and masonry engineering properties. Load-bearing capacity of walls are then augmented by installation of internal reinforcing bars and injection of voids using a Compatible Injection Fill (CIF). Unique to this application is installation of a series of diagonal stitching bars to confine the masonry and enhance masonry compression response.**

***Keywords* - nondestructive evaluation, masonry, injection, reinforcement, stabilization, repair**

I. Introduction

Masonry is the world's most common building material, existing as adobe, brick, concrete masonry, and stone construction. These types of masonry units have been used for thousands of years for both utilitarian and monumental structures, most often as load-bearing walls in building structures, as masonry arch bridges, or as retaining walls. Unreinforced masonry has excellent resistance to compression loads but can suffer dramatic and brittle failure when subjected to lateral shear forces which may develop due to seismic loading or high winds.

Engineering for historic construction must follow basic preservation theory including the principle of minimal intervention, the concept of authenticity, and the principle of material compatibility. Strengthening measures used with historic structures must be optimized for each building to minimize the work and to avoid altering any visible character-defining features. Internal strengthening approaches are preferred, rather than structural overlays or external strengthening that may hide or otherwise change the historic appearance. Dismantlement and rebuilding destroys a building's authenticity and is usually avoided in order to maintain the building's appearance and workmanship of the original construction.

Particularly important with preservation projects is the concept that any materials used to repair historic construction must have engineering properties similar to those of the original materials. The engineer has to carefully consider repair materials to ensure the stiffness, strength, moisture absorption, and water vapour transmission characteristics match those of the original substrate materials. Use of modern high strength, high stiffness materials such as epoxies can be detrimental to durability and structural response of historic masonry construction [1].

This paper discusses the general process of masonry evaluation and strengthening by following a project to reinforce an historic masonry building. With a renovation program underway, this multi-story heritage building located at a prominent U.S. university campus was found deficient in capacity to withstand new design loads. The proposed retrofit scheme included a change of use that required larger open spaces within the building; subsequent changes to roof and floor framing led to the introduction of large structural loads at discrete points throughout the exterior building envelope. Concern regarding the stability of these walls and the ability of the poorly-constructed brickwork to carry new structural loads led to the decision to retrofit the walls through a combination of internal reinforcement and stabilization with compatible injection fill.

II. Structural Evaluation

Most projects involving heritage construction prohibit specimen removal for laboratory testing and opening of destructive probes to investigate internal wall construction. Construction and design professionals may turn to nondestructive and in-place evaluation methods to obtain critical information on as-built conditions, location of cracks or other deterioration, and material engineering properties [2,3].

A. As-Built and Existing Condition

A wide range of nondestructive and in-place methods are available for evaluating existing masonry construction.

Rebound Hardness: Measures surface hardness of masonry units or mortar; useful for evaluation of relative material properties.

Metal Location: Magnetic or eddy-current probes are used to locate embedded metals such as reinforcement, ties, and anchors. Equipment permits accurate location and depth of metals and an estimate of the relative size of embedded metals.

Stress Wave Transmission: Low frequency sonic waves are often used to evaluate masonry by evaluating the velocity, frequency, and energy content of waves passing through a wall section. Ultrasonic pulse velocity (UPV) methods may be used with competent masonry; historic construction is often too attenuative for UPV methods. Data from stress wave techniques can also be processed with tomographic imaging software to provide 3-dimensional representation of internal anomalies.

Impact-Echo: Evaluation of stress waves in the frequency domain permits identification of sub-surface features such as cracks or voids and the thickness of individual masonry wythes.

Surface Penetrating Radar (SPR): Microwave energy is reflected at boundaries between materials having varying dielectric constants, thus providing information on the location and depth of embedded anomalies [4]. SPR is particularly useful for locating metals, internal voids, and wall thickness.

Infrared Thermography (IRT): Measurement of infrared radiation emitted from a material's surface can provide information on near-surface voids, the presence of moisture, and internal wall construction.

Borescope: While not entirely nondestructive, borescopes provide visual verification of internal anomalies detected using nondestructive methods. Borescope examination requires insertion of a small-diameter fibre optic wand in holes drilled into masonry mortar joints.

Mortar rebound hardness was used on this project to evaluate relative properties of original mortar and pointing mortar used as part of prior repairs (Fig. 1). Data from mortar rebound tests was used to specify an appropriate compatible replacement mortar and to identify locations where incompatible repair mortars were used during prior maintenance work.

Fig. 1 Mortar rebound hardness, measured here using a pendulum hammer.

Radar scanning was useful for identifying the presence of hidden diagonal header courses and also for locating internal wall voids requiring injection stabilization (Fig. 2).

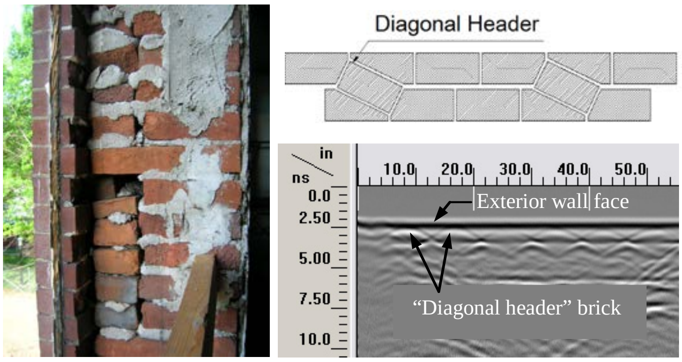


Fig. 2 Walls were built of poor quality construction (left) with many internal voids. Surface penetrating radar was used to locate voids and also identify hidden header locations. Hidden "diagonal" headers were missing at many locations, requiring remedial tie installation. The radar trace at lower right shows strong reflections at each header brick location.

B. Engineering Properties

Nondestructive test methods provide information on relative material conditions and general masonry distress but results are not directly correlated with engineering properties such as masonry strength and stiffness. In-place methods are used to measure masonry material properties.

Unique to masonry are in-place evaluation methods using flatjacks. Flatjacks are thin hydraulic bladders inserted into mortar joints. Once pressurized, flatjacks impose stress on the surrounding masonry. Surface strains during loading cycles are measured using mechanical or electronic gages.

The state of existing compression stress can be measured using a simple process of stress relief following the flatjack method of ASTM C1196. The in place stress test is useful for determining applied loads, calibrating analytical models, or detecting stress gradients across a wall cross section.

Masonry stress-strain response can be measured in-place using the deformability test method of ASTM C1197. Flatjacks are inserted into two slots, separated by several masonry courses. Flatjacks are pressurized simultaneously, subjecting the masonry between flatjacks to a state of compressive stress. A series of flatjack deformability tests were conducted at the subject building to evaluate masonry compression stiffness and strength. A test setup and typical results are provided in Fig. 3.

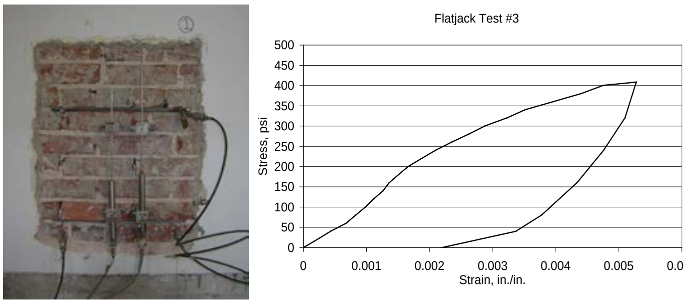


Fig. 3 Masonry deformability test conducted using the flatjack method. Test setup shown at left; at right is a typical stress-strain curve. Masonry compressive strength was measured to be in the range of 450 psi.

Masonry bed joint mortar shear strength can be measured using one of three alternative methods described in ASTM C1531. The approach is valid for masonry constructed with relatively strong units and weak mortar, where shear capacity is dominated by development of diagonal stairstep cracks through mortar joints. A field adaptation of the bond wrench method described by ASTM C1072 permits in-place evaluation of mortar-unit flexural tensile bond strength.

III. Structural Strengthening

Structural adequacy of historic masonry construction is typically limited by geometric constraints and stability issues rather than strength. Historic buildings were built with massive wall sections and perform well structurally if a) there is adequate connection between wythes; b) walls are connected to floor and roof diaphragms; c) applied compressive stress is limited to no more than 20 percent of the masonry strength; d) applied tension and shear stresses are low. Strengthening may be required to address deficiencies in the original construction, the accumulated effects of years of weather exposure, or to enhance the structure's ability to resist seismic excitation and high wind loads [5].

A. Strengthening Methods

Dry-fix remedial ties are often used to provide connection between masonry wythes; these ties require drilling a pilot hole and insertion of a helical stainless steel tie using a hammering action. Anchors are used to resist structural loads. Anchors grouted in place using cementitious materials are preferred over chemical epoxy anchors for their fire resistance and compatibility with historic building materials.

Internal voids are often found in historic masonry construction, appearing as construction defects or resulting from movement of masonry units over time. Injection of Compatible Injection Fill (CIF) at low pressure (less than 1 bar) is the predominate method used to fill internal voids and ensure monolithic behaviour between masonry wythes [5,6]. CIF materials are formulated to be compatible with historic materials, having similar strength, stiffness, and water vapour transmission to the substrate. Injecting internal voids with CIF also enhances a wall’s ability to resist moisture penetration [7].

Structural strengthening typically requires adding steel reinforcement to masonry walls, installation of external steel frames, or use of concrete overlays. Internal reinforcement schemes are preferred for use with historic construction to avoid changing the building’s appearance.

Stainless steel reinforcement may be inserted into slots cut in mortar joints. Thin stainless steel or galvanized wires are often used in such a fashion to stitch walls together at cracks. Structural enhancement to increase masonry flexural strength, shear strength, and ductility requires installation of large-diameter bars in holes cored within masonry walls [6]. Reinforced cores are injected with CIF to bond reinforcement to surrounding masonry, completing the repair.

B. Strengthening Approach

Radar scans located many voids throughout the masonry construction and a lack of appropriate header courses connecting brick wythes. These deficiencies were addressed by a combination of pinning and CIF injection. A series of helical pins were first installed to tie face brick to backup masonry at locations where header brick were missing. Hydrated lime and cement-based CIF was used to fill cracks and voids within the historic walls to ensure composite action between the multiple wythes at bearing walls. CIF formulations were custom developed to be compatible with the host wall constituent materials. No polymers or epoxies were utilized. The main function of the CIF in this case was to bond the masonry backup to the exterior brick facing. In addition to the structural benefits of internal void filling, water penetration from wind driven rain was reduced as a result of the injection.

The building was being renovated to include large open spaces to meet the University’s educational needs. At areas of new concentrated loads a novel stainless steel stitching program was utilized in conjunction with injection remediation to augment the masonry’s inherent compressive capacity throughout the new load paths. Research with historic masonry shows that creep effects can be a consideration at stress levels as low as 0.2 times the masonry compressive strength, and that creep effects are considerable when applied stresses exceed 0.6 time the masonry compressive strength [8]. The structural design called for compressive stress in excess of 0.4 times the compressive strength and a diffused network of thin, vertical cracks was observed below some existing roof truss bearing locations. Hence there was a concern that new structural loads could lead to future instability.

Horizontal confinement reinforcement was installed within masonry walls to enhance compression response in the vicinity of new structural bearing points. At some locations confinement reinforcement was installed in mortar joints. At locations were conventional reinforcement was not possible, addition of new stainless steel reinforcing followed a diagonal stitching method. The “drill and bond” method distributes structural tension demand among reinforcing bars [9]. The method has been used on dozens of buildings throughout Europe, the Middle East, and Japan, and this project represents its first use within the United States.

The size and spacing of diagonal stitching anchors was designed based on the expected lateral spreading that occurs in the presence of compression stress as a result of the Poisson effect (Fig. 4). New confinement reinforcement was designed to resist all the resulting lateral tension. Thousands of discrete reinforcing pieces of varying geometries were accurately positioned within the historic walls (). The combination of injection and new internal reinforcement effectively confines the highly stressed masonry sections, offering new possibilities for augmenting historic masonry construction in situations where it must resist new loads.

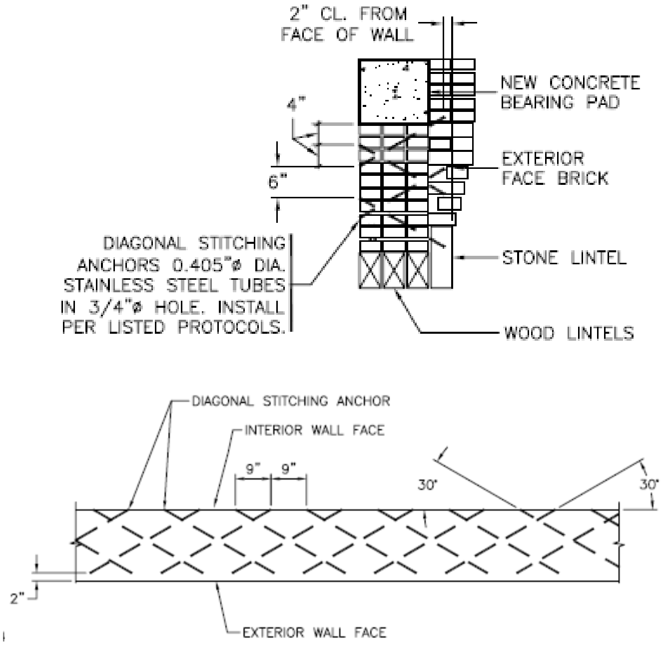
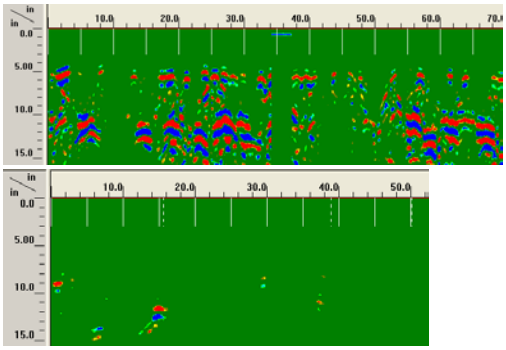


Fig. 4 Design detail showing diagonal stitching installed as confinement reinforcement: wall section (top) and horizontal plan section (bottom). Stainless steel tubes inserted into drilled holes were injected with CIF to bond new reinforcement to surrounding masonry.

C. Post-Repair Quality Assurance

Internal strengthening measures are by their very nature hidden from view and advanced quality assurance measures must be adopted to ensure project objectives are met. Nondestructive evaluation methods are useful for determining the quality of internal strengthening measures. The location of added reinforcement, anchors, and ties can be verified using a pachometer or SPR. SPR was also used in this case to verify internal voids were properly filled by CIF injection. Radar traces taken before and after injection of an historic masonry wall are shown in Fig. 5. Prior to injection, many internal voids are noticeable. After injection, radar returned almost no reflections from internal anomalies, indicating the solid nature of the repaired wall. The fully strengthened and renovated building retains its original historic appearance (Fig. 6).



Pre-injection; many internal voids

Post-injection; internal voids filled

Fig. 5 Sample radar traces showing internal masonry wall condition before injection (top) with many internal voids as indicated by multiple reflections within the radar trace. Following injection the radar trace shows the wall to be essentially solid (bottom) with no significant reflections.

Fig. 6 The building's final appearance remained unaltered after all structural strengthening measures were completed.

IV. CONCLUSIONS

Engineering efforts involving heritage masonry construction require a unique approach. Heritage preservation projects are by nature multi-disciplinary, requiring close collaboration between the design-side (architects and engineers) and the construction side (injection professionals) to develop materials and protocols suitable for use with the historic building. Nondestructive evaluation and in-place test methods are used extensively with historic construction to avoid damaging sensitive and culturally significant materials. Repair materials used with historic construction must be custom-developed for compatibility to match the strength, stiffness, and moisture vapour transmission properties of historic materials. In this case the aesthetics of the heritage masonry were unchanged despite the extensive nature of the wall injection, stitching, and the structural enhancement.

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