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In-Place Stabilization of a Stone Masonry Facade

M. Schuller[1], W. Ruth[2]

Abstract
A 100-year old stone masonry facade was visibly displaced and in danger of collapse due to inadequate support, poor initial construction, moisture infiltration, and related freezing action. Rather than demolish and rebuild the facade, a scheme was developed for in-place stabilization using a combination of shoring, grout injection, and anchoring. A cementitious grout was used to fill internal voids and stabilize the facade and adjacent shear walls, followed by installation of a series of 1.6 m anchors tying the facade to the shear walls. Nondestructive testing, utilizing ultrasonic pulse velocity measurements, was used to characterize the masonry prior to the work and to verify the effect of grout injection following stabilization. This project demonstrates that severely damaged walls can be saved from demolition with the careful application of appropriate techniques and associated quality control testing.

Keywords
Stone, facade, repair, anchor, grout injection, nondestructive testing, ultrasonic.

Introduction

In recent decades the U.S. has seen a renewed interest in our cultural heritage, leading to an increase in preservation efforts directed at salvaging historic buildings for adaptation to contemporary use. In years past, buildings with serious problems were often demolished for construction of new, modern structures in their place. By applying relatively new technology for evaluating the condition of historic buildings, coupled with adaptation of traditional repair techniques, it is feasible to repair damaged buildings and provide confidence in the capacity of restored masonry. These approaches permit society to retain our masonry heritage as an important part of our communities.

A project to evaluate and stabilize a five-story façade is described. The buildings, located on the main downtown street of Baltimore, Maryland, were originally constructed in 1903 as two adjacent mansions. The granite stone façade was built in a broken-range ashlar pattern, with the raw product transported from the local Ellicott Mills quarry and faced and dressed on site by Italian stone masons. These masons were in plentiful supply due to the railroad construction centered in Baltimore. Their skill to transform this difficult material into such beautiful detail is practically irreplicable today. Hence, an important part of this city's' heritage lay literally leaning toward demolition before the grout team was contacted.

The building had seen several uses through its life. A recent project was undertaken to renovate the building for use as modern office space. The street facade, as shown in Figure 1, was attractively built with rough-hewn granite facing stones and decorated with ornamental stone carvings at the roof line.

[1] Atkinson-Noland & Associates, Inc., 2619 Spruce Street, Boulder, Colorado, 80302, USA.
[2] Masonry Solutions, Inc., P.O. Box 1036, Sparks, Maryland, 21152, USA.

Figure 1. Street elevation of the building, showing the façade before stabilization.

The building was constructed in 1903 as two private residences and is being converted to modern office space. The façade is supported by steel beams at the second floor, installed several decades ago when the first floor masonry was removed in favor of a glass store front.The supporting wall was modified several decades ago by removal of the first floor masonry and installation of a glass-panel storefront. A series of steel beams were added to support the facade and the bay window, which cantilevered out from the main wall section. Years of moisture infiltration, in combination with changes to the structure supporting the stone façade, led to deterioration of building materials. As a result, a 50 mm separation had opened up between the granite facing and the brick backup, with an additional separation of the façade from supporting masonry shear walls by up to 50 mm. By all indications, the stone facing was in danger of collapse and required emergency shoring and bracing. The historic nature of the building, beautiful stone façade, and costs associated with rebuilding the facade led to the recommendation that the stone be stabilized in place rather than demolished.

The adjacent masonry shear walls had long since relinquished their structural stability. As the plaster walls ... leterioration was revealed. Extremely late in the ... ed decision makers toward demolition of the remaining ... uld save the façade, it was reasoned, the party walls were ... with one's bare hands! All of this was nearly invisible on the occasion of the recent purchase of the building. The owner had contracted with a structural engineer for a pre-purchase inspection, but even this tremendous amount of deterioration was not discernable under the layers of plaster, paint, and mouldings which shrouded the deterioration immediately below.

The approach for building stabilization, described below, was conducted using the following sequence:

1. Initial evaluation to determine material properties, wall sections, and deterioration.
2. Stabilization of the three shear walls with a fine grout injection.
3. Temporary shoring of the façade to the newly stabilized shear walls.
4. Anchoring the façade to the shear walls, using 1.6 meter anchors.
5. Stabilization of the granite façade brick backup.
6. Pinning the granite to the newly stabilized backup.
7. Grout injection of the granite-brick façade.
8. Removal of the temporary shoring.
9. Post-repair nondestructive testing.

Additional work related to the facade but not discussed here included: replacement of rotting wood nailers, roof supports, and floor framing, rebuilding of severely deteriorated brick masonry at the roof line, window sills, and window jambs, construction of a new reinforced masonry wall at the first floor with footing to support the facade, and addition of new sections to existing steel beams supporting the facade.

Temporary Shoring

One of the keys to success of the project was an innovative temporary shoring scheme, designed to use the mass of interior shear walls as a temporary support for the failing facade. Visible leaning and cracking at the facade supports suggested that some remedial measures would be required, but observations during the initial stages of construction prompted the installation of emergencing shoring to prevent wall collapse. Removal of surface finishes had revealed a complete separation of the facade from adjacent shear walls. The entire facade actually moved perceptibly in response to traffic vibrations and construction operations at the rear of the building.

The shoring scheme was developed to hold the facade in place during the stabilization process. Temporary frames were designed to hold the front wall together by clamping the wall through window openings. These frames were tied back laterally with 1.2 cm cable and turnbuckles, anchored approximately 6 m back with cone-type expansion anchors into the newly stabilized shear walls. Prior to the shoring, one could actually move portions of the façade wall. The shoring provided a level of security for the workers, and unimpeded safety for the pedestrians in the busy street below. Following completion of the facade stabilization, shoring frames were removed to provide access for the remainder of interior renovations.

Initial Evaluation

A condition survey was conducted to determine as-built construction details, current condition, and typical material properties. The evaluation was conducted primarily by visual observation, augmented by investigations using a borescope, inserted into holes drilled in mortar joints, to determine the internal wall configuration. Through-wall ultrasonic pulse velocity tests were also conducted at two areas to determine wall solidity and to provide a set of baseline measurements for post-repair tests.

Masonry walls were built in running bond, with full header brick installed every 8 courses. Interior shear walls were 3 wythes thick at the first and second floors, reducing to 2 wythes at the third through fifth floors. The front facade was built with 3 wythes of brick masonry, faced with granite stones ranging in thickness from 5 to 8 inches. Laboratory tests on samples removed from the wall revealed the brick to be soft and porous, likely poorly fired, with a high suction rate.

Brick were set in a lime-based mortar with poorly filled joints. The photograph in Figure 2 shows the typical internal wall construction. Observation of the wall interior was conducted using a borescope at 42 locations, verifying that walls were poorly constructed with many unfilled mortar joints. Many individual brick were actually loose within the wall and could be removed by hand.

Brick masonry was suffering from the effects of years of moisture infiltration. Water entered directly into masonry walls via a leaking roof gutter system, around window frames, and through roof leaks. A downspout which had been missing for years actually dumped water into the façade, exacerbating problems due to open mortar joints and poor roofing. The walls had many interior voids, as shown in Figure 2, that contributed directly to the

Figure 2. Typical section through interior shear walls, showing many internal voids and incompletely filled mortar joints. Interior voids were channeling water from gutter and roof leaks throughout the wall, resulting in mortar deterioration and related freezing damage.

masonry deterioration: once within the wall, water was able to travel within the large void network of unfilled internal mortar joints. The effect of the moisture infiltration was twofold: 1) deterioration of brick and mortar at the material level; and 2) freeze-thaw cycling, which successive increased separation of the stone facing from its brick backup. With portions of the rotting wood frames missing, visible displacement exceeding 12 cm were clearly seen, as well as additional movement of the granite's brick backup from the shear walls. A secondary deterioration pattern can be attributed to salt crystallization, and efflorescence was noted at some heavily deteriorated areas.

Pulse velocity measurements are useful for identifying voids, cracks, and other anomalies within masonry walls (Suprenant 1994). Ultrasonic pulse velocity tests were conducted through walls at the 3rd and 4th floors to determine construction variability within individual wall panels and to provide comparative data for post-repair quality control testing. Input pulses were generated using 50 kHz ultrasonic transducers. Due to the highly attenuative nature of the soft, poorly constructed masonry, an input energy of 1000 volts and high-gain amplification was necessary. Through-wall travel times were calculated at 120 locations using software developed in house and automated to determine pulse arrival time. Typical pulse velocities ranged from as low as 400 m/s to 2300 m/s. High velocities typically were recorded at through-wall header courses; lower velocities correlated to large internal voids and severely deteriorated brick.

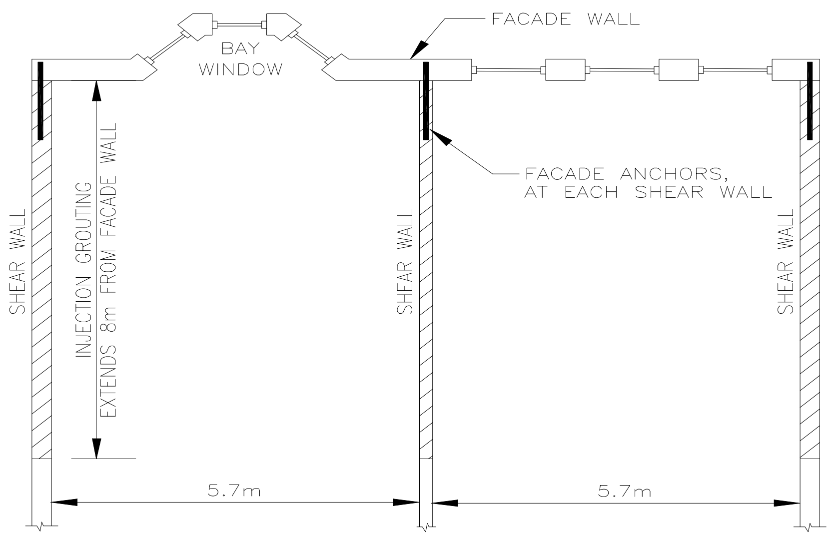


Figure 3. Building plan, showing injection areas at shear walls and façade anchors.

Shear Wall Stabilization
As shown in Figure 3, three cross walls comprised the main load-bearing structure of the building. These walls were an essential component of the stabilization scheme and were designated to function in two different capacities: 1) for attachment of temporary shoring to hold the facade in place during repairs; and 2) to provide anchorage through connection with the main facade wall. In their current condition, with many frequent internal voids and deteriorated masonry, masonry bearing walls did not possess the capacity for either role. The first step of repair implementation was enhancing the capacity of these walls to resist brace and facade loads. Injection of specially formulated cement-based grout into internal voids and fractures was specified to bond together wythes of the masonry wall system to better resist applied loads.

Grout injection techniques have been the subject of several recent research projects investigating the potential of different materials and approaches for repairing seismic damage (Manzouri 1996), strengthening multi-wythe masonry (Binda 1992) and stabilization of load-bearing masonry (Tomazevic 1992). Research results, in conjunction with experience applying injection procedures to building repair projects, shows that it is possible to stabilize and strengthen poorly constructed or damaged masonry.

Repairs must be carried out carefully, however, using compatible repair materials applied by trained technicians and thorough quality control testing.

Prior to grout injection, a series of permeability tests were conducted to characterize the void structure in terms of injectability. This approach, adapted from the field of rock mechanics (Houlsby 1982), follows a procedure first recommended by Lugeon in 1933. The “Lugeon Test” measures the in-place permeability of fractured rock masses by determining the rate of water flow at a given pressure into the rock. Equipment to deliver water at a set pressure and to measure flow rate was developed for application to masonry wall structures. This approach, when calibrated on site, is capable of delineating injectable zones within a wall. Lugeon tests conducted on this project revealed a high injection permeability at nearly all areas, indicating typical void structures that exceeded 3 mm in size. As a result, a single coarse grout formulation was used for injection at all areas.

The grout mix used for injection was formulated to complement existing brick and stone materials but not exceed the stiffness of either material. As a result, a cement-based grout with moderate compression strength (in the range of 16 MPa) was chosen. The mix design contained only mineral components with a relatively low cement content and a fine sand aggregate. Tests conducted on cores removed from sample panels showed the grout to have shear bond strengths of 0.5 MPa to granite and over 1.3 MPa to brick masonry. The mixture was highly fluid, able to be injected through 12 mm holes drilled into mortar joints at a 20 cm vertical spacing and 60 cm horizontal spacing. Low injection pressures of less than 0.7 bar were used to avoid damaging the fragile masonry walls.

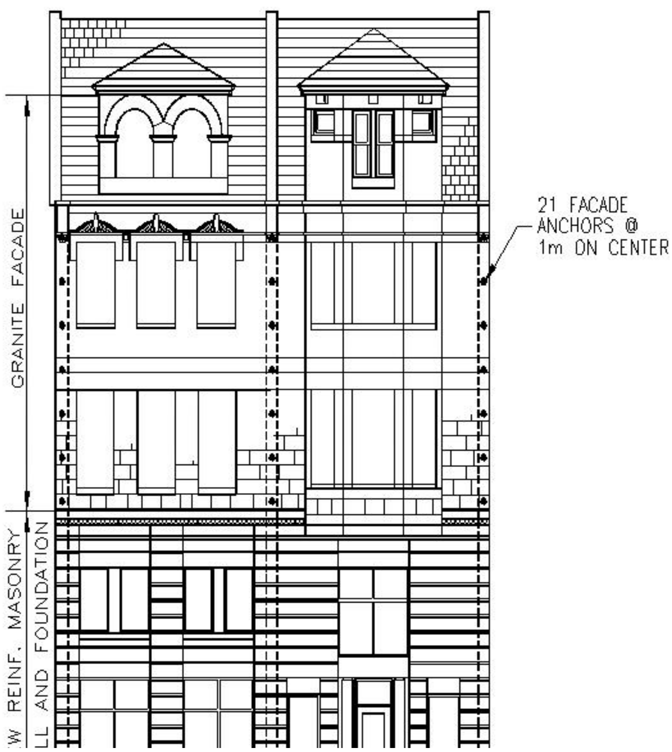


Figure 4. Building elevation. Three lines of grouted anchors were used to tie the façade to shear walls.

Shear walls were injected for a distance of 8 m from the facade wall, as shown in Figure 3. A large quantity of grout was required to complete the injection, and records of grout quantities injected showed that interior mortar joints ranged from 60 to 80 percent void. In the portions of the shear wall which were stabilized, several abandoned chimneys were located. These flues were isolated from the injection work, so that only the brick walls were filled.

Facade Anchoring

A series of grouted anchors was used to connect the facade wall to adjacent shear walls. As shown in Figures 3 and 4, 21 total anchors were installed to tie the brick and stone facade to the newly injected shear walls. The anchors themselves were 16 mm diameter stainless steel rods, inserted into 38 mm diameter holes cored 1.6 m into the walls. These anchors were placed in sequence, only after the shear walls and façade backup was stabilized, and the granite anchored back to the stabilized brick. Anchors were designed to carry loads from the facade resulting from wind and eccentricities in vertical load due to leaning of the walls. Embedment into the shear walls was longer than necessary, by a factor of about 2.5 times, to mobilize more of the shear wall mass to further anchor the facade wall and guard against future movement.

Coring of the 1.6m holes for insertion of facade anchors required a great deal of care, both in positioning of the drilling apparatus and in coring into the wall. The drilling rig was mounted on a set of adjustable rails, anchored to the wall, and carefully aligned to drill along the longitudinal center line of the interesecting shear walls. As drilling progressed in each hole, extensions were added to the core bit. The anchors themselves were made of 16 mm diameter rods that were grouted in place at each core hole. Each anchor had a surrounding fabric sock, which acted to contain grout injected around the anchor.

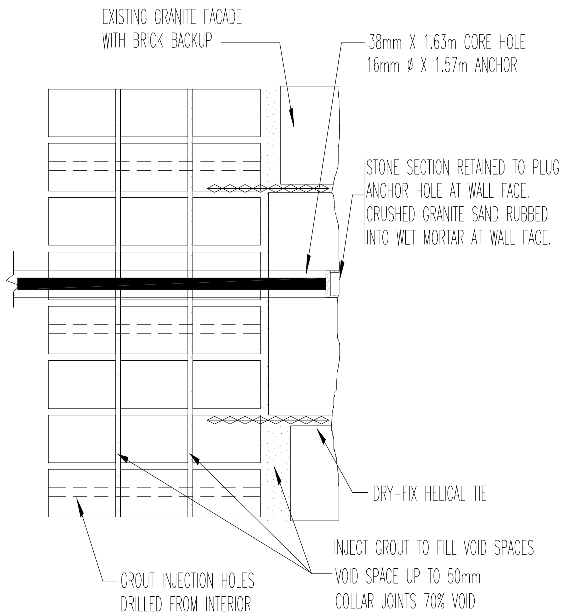


Figure 5. Façade section showing typical anchor and tie installation as well as injection of interior void spaces. Note the void space between the stone facing and brick backup, caused by inadequate structural support, years of moisture infiltration, and freeze-thaw cycling.

Facade Stabilization

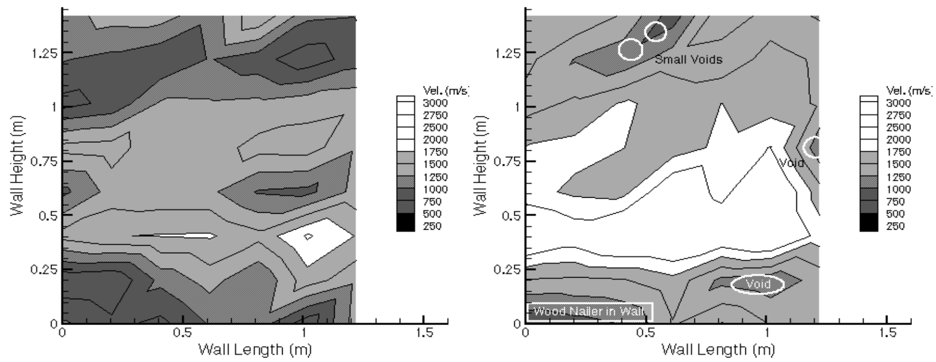
The stone facing itself was stabilized following anchorage of the facade wall. As shown in Figure 5, a gap of up to 50 mm had opened between the stone facing and its brick masonry backup due to long-term moisture infiltration and repeated freezing cycles. The facade wall was stabilized internally using a procedure combining pinning with grout injection, providing a mechanical tie as well as overall bonding to the brick backup. Six-mm diameter helical dry-fix ties, used to tie the stone to the brick backup, also served in a capacity to resist hydrostatic pressure that developed during grout injection. The ties were installed at a spacing of 30 cm on center in mortar bed joints between stones. Stones taller than 36 cm were also tied at mid-height of head joints.

Heavily deteriorated masonry was rebuilt at some areas, typically near the source of moisture entry at the top of walls and around window openings. Lugeon permeability testing again identified an internal void structure consisting of relatively large, well-connected spaces. Injection holes were drilled from the interior to intercept mortar joint voids in the brick backup as well as the space that had opened between the stone facing and the brick backup. Measurement of the total grout volume injected at the facade showed the main void space to average over 35 mm in width.

Post-Repair Nondestructive Testing

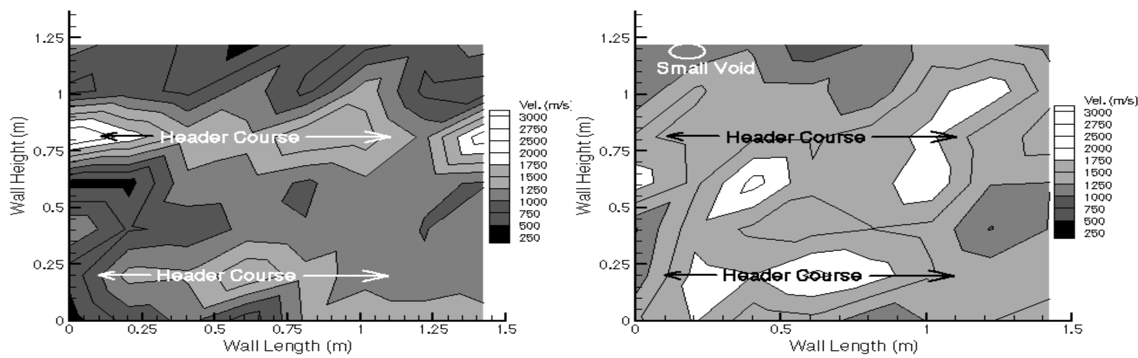
Following stabilization, wall solidity was measured using through-wall ultrasonic pulse velocity testing, conducted at the same locations as the pre-injection tests. Results of the pulse velocity testing, shown in Figures 6 and 7 as topographic velocity profiles, indicate an increase in wall solidity as measured by an overall velocity increase throughout the test areas.

General velocities were quite low due to the low density and modulus of brick and mortar. Borescope observations of wall solidity were correlated with measured pulse velocities and, for this type of masonry,



(a) (b)

Figure 6. Through-wall pulse velocity tests conducted on a wall panel at the 3rd floor. a) pre-repair and b) post-repair. Grout injection repairs increased the overall velocity. Note the 4 locations where low velocities identified voids within the wall. These areas were subsequently re-injected.



(a) (b)

Figure 7. Through-wall pulse velocity tests conducted on a wall panel at the 4th floor. a) pre-repair and b) post-repair. Header courses, which showed as regions of higher velocity before the repair, were indistinguishable from surrounding masonry after internal voids were filled by grout injection. The isolated lower velocity regions after injection, shown in (b), were mainly attributed to individual brick that were deteriorated. One small void was verified with the borescope, as shown, and re-injected.

velocities of less than 1200 m/s were found to be indicative of low density masonry or potential internal voids. Large internal voids and cracks were noted at locations where velocities were measured to be less than about 900 m/s. Prior to grout injection, the wall contained mainly low velocity zones due to sizable interior voids and poor connection between brick wythes. Individual deteriorated brick showed very low velocity readings. Following grout injection, the velocity at nearly all areas was measured to be greater than 1200 m/s, indicating the grout injection was successful at filling internal voids.

Isolated areas of low through-wall velocities were measured at some locations within the test region following injection. Tested areas having velocity of less than 1200 m/s were marked for further investigation using the borescope. Minor grout voids were observed at some locations where mortar blockage prevented grout penetration into void spaces. Locations of grout voids correlated well with results of pulse velocity tests, as shown in Figures 6 and 7. Four small voids, with typical sizes of 5 cm tall by 18 cm long by 0.8 cm wide, were located and subsequently re-injected. Observations of injected grout at the test panels and 42 other locations verified that grout was solid, with no evident shrinkage, successfully filling nearly all voids of 3 mm and larger. Remaining low velocity regions were observed to be at locations where the brick themselves were deteriorated more severely than surrounding brick.

Conclusions
New approaches to evaluation and repair of existing masonry permits building owners to salvage structures that, in the past, would have required costly rebuilding. This case study illustrates a multi-phased approach, first strengthening interior shear walls for attachment of temporary shoring, followed by anchoring and stabilization of the facade itself. The severely displaced facade wall was stabilized in place, preserving the historic appearance while maintaining structural function. The project was completed by a small work crew in 6 weeks at a cost significantly less than the alternative approach that would have involved complete demolition and rebuilding of the facade wall.

Grout injection procedures are entering the mainstream of masonry practice and, if carried out in a careful, methodical fashion, can be very effective at restoring structural integrity to damaged wall sections. Repairs of this fashion involve specialized techniques and the technicians must be thoroughly trained to recognize potential problems or conditions. Complementary nondestructive evaluation techniques such as pulse velocity measurements are well suited for defining the success of grouting operations, in addition to determining original conditions.

Acknowledgements
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