Investigation and Repair of An Improperly Constructed Masonry Barrier Wall System

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BUILDING DESIGN AND BACKGROUND

The original design of a four story apartment building built circa 1995 in California, Maryland incorporated a composite brick and block design for the exterior walls. This design required the exterior walls of the building be constructed of an exterior wythe of brick masonry attached to a concrete masonry unit (CMU) back-up by means of galvanized truss type horizontal reinforcing and a solidly filled collar joint.

Wall section designs varied from location to location in regards to size of back-up block (4" or 6") although all sections called for an approximate two-inch solidly filled collar joint. This grouted collar joint was required structurally so that the exterior wall would behave as a composite wall. An additional function of the grouted collar joint was that of creating a barrier wall system in which the collar joint would act as a barrier to any water which penetrated the exterior wythe of brick masonry. Flashing and weephole details were shown on the original drawings at window and door heads and sills.

Subsequent to the construction of the building, water penetration problems began to occur primarily along the north and east elevations of the building. Wind-driven rains would routinely result in water penetration to the interior of the building. Water penetration was sporadic although often occurred at floor levels. In an attempt to remedy the water penetration problems, a siloxane penetrating water repellent was applied to the exterior face of the building. Although the water repellent appeared to decrease the amount of water penetration into the building, it did not completely eliminate it and further investigation into the water penetration problems was deemed necessary.

INVESTIGATIVE AND SAMPLING PROCEDURES AND FINDINGS

A preliminary visit to the property allowed discussions with building personnel, review of pertinent building plans, and a cursory inspection of the building. Additional investigative procedures and requirements were developed and an in-depth investigation into the water penetration problems was subsequently undertaken. Investigative techniques included destructive testing and exploration and material sampling. Several samples of mortar and brick masonry were acquired from various areas of the building, including a brick prism, mortar segments and individual brick units.

Multiple wall deficiencies were observed during the investigative and sampling procedures. The deficiencies were all primarily the result of poor workmanship and resulted in a non-performing exterior wall system. The following describes these deficiencies and their corresponding effects on the performance of the exterior wall assemblage.

Improperly Constructed Collar Joint
The brick prism removal location revealed a partially filled collar joint. Poorly consolidated collar joint mortar was present at the upper half of the prism area above a layer of horizontal reinforcing. This configuration evidenced placement of the collar joint mortar without regard to proper filling and consolidation, often the result of a practice known as slushing (filling joints by pushing mortar into the space with a trowel). Removed brick units revealed a completely omitted collar joint at least four feet in any direction.

The effects of the improperly constructed collar joint were two-fold. First, the structural integrity of the exterior walls was compromised. A solidly filled collar joint was designed to create a composite masonry structure. The solid collar joint was intended to bond the exterior brick and interior back-up block together and help generate composite action by transferring stress between the two wythes. In effect, the combined wythes act together as a single member. Without a solidly filled collar joint, this transfer of stress did not occur and the structural integrity of the wall was significantly compromised.

The second result of the improperly constructed collar joint was the compromise of the water resistance of the exterior walls. The solidly filled collar joint was architecturally designed as a barrier to stop the inward migration of wind-driven rain. The solid collar joint functions as a barrier to repel any water which passes through the exterior brick wythe. The omission of the collar joint resulted in unimpeded water migration into the unfilled collar joint and through the interior back-up block. Partially filled collar joints typically resulted in pockets where water collected and bridged to the interior of the building.

Incompletely Filled Mortar Joints
Removal of the brick prism and brick units at three separate locations revealed incompletely filled mortar joints. Incompletely filled mortar joints result in increased water permeability,

reduce the strength of the masonry assemblage, and may contribute to disintegration and cracking due to water penetration and subsequent freezing and thawing.

Facial Separation Cracks
Widespread facial separation cracks were observed at each elevation of the building. Facial separation cracks are openings in the wall face between brick and mortar, usually 0.04 in. or less in width. They are most frequently caused by inadequate tooling of mortar joints during construction but may also be caused by thermal contraction of masonry units and mortar and less frequently by mortar shrinkage.

Brick Unit Cracking
Brick unit cracking was sporadically evident at the perimeter of the building. Brick unit cracks were typically straight and vertical and located at the center of the brick units. Brick unit cracks of the type evident at the building are typically caused by water penetration and subsequent freezing and thawing but may also be caused by inadequate quality control in the brick manufacturing process. Brick unit cracks result in an increase in the permeability of the masonry walls.

Clogged Weepholes
Mortar clogged weepholes were present at multiple flashing locations surrounding the building. Weephole installation was detailed in combination with flashing installations to properly drain any water collected on the flashing. Mortar clogged weepholes prevent the proper drainage of water from within the wall assembly and can result in water infiltration into the building and disintegration and cracking of the brick units.

MATERIAL TESTING AND ANALYSIS
Collected masonry and mortar samples were laboratory tested in order to detect any material defects and to verify specified mortar proportioning. The brick prism, five unsealed brick unit samples, and a sample of collar joint mortar were packaged and shipped to a testing laboratory. The laboratory was authorized to perform a petrographic examination of the mortar, a chemical analysis of the mortar, and determine the water absorption characteristics of the brick units.

Analysis of the laboratory test results revealed mortar proportioning and mixing was adequate. The petrographic and chemical analyses revealed mortar composition consistent with Type S mortar, as was specified for use on the project. The hardened mortar properties were acceptable although brick-mortar boundaries exhibited weak bonds. This was evidenced by easy fracture at brick-mortar interfaces and excessive depths of carbonation at bedding surfaces. Patchy accumulations of yellow-brown soils on the brick surfaces may have contributed to said weak brick-mortar bond and subsequent water infiltration. These accumulations evidenced poor handling of materials prior to use. Organic chemical analysis of the bed joint mortar did indicate the presence of minor quantities of glycerol or related diols. The presence of glycerol typically indicates the addition of anti-freeze to the mortar to improve workability in cold conditions or to act as an accelerator. The trace amounts of glycerol found in the bed joint mortar samples were minor and should have had no deleterious effects on the mortar. Water absorption testing of the five unsealed brick units indicated saturation coefficients and absorption characteristics acceptable for grade SW facing brick units, as were specified for use on the project.

PRELIMINARY REPAIR STRATEGIES AND TEST PANEL CONSTRUCTION
Based upon the above investigative and laboratory findings, the primary requirement for repairing the deficient wall system was the restoration of the structural integrity of the wall. In order to accomplish this goal, the empty collar joint must be solidly filled with a load bearing material as was originally intended. The second repair goal was the elimination of water infiltration into the building. This goal should also be met by the filling of the collar joint in that the barrier wall system originally intended will be restored.

The most effective method of accomplishing these goals is grout injection. This well researched method for repairing and strengthening masonry walls involves low-pressure injection of a fine cement-based grout into the collar joint. The injected grout is formulated to completely fill the empty collar joint and bond the exterior brick and interior back-up block together and restore composite action between the two wythes. In addition, the grout solidifies to a dense layer to prevent moisture passage to the wall interior while still permitting some level of vapor transmission through the wall system.

A test panel was constructed in order to test the grout injection procedure and performance. Prior to construction of the test panel, borescopic inspections of the building's internal wall conditions were conducted. The borescopic inspections further revealed extensive voids within the collar joint. Partially filled areas or "mortar patties" within the joint were observed in multiple locations although their locations did not appear to follow any pattern. These areas of partially filled collar joint complicate grout injection in that the grout may not be able to completely fill all voids and cracks within the mortar patties and that the patties can cause air pockets to form during the injection process. These expected complications can typically be addressed through grout injection procedures.

Based upon the desired material properties, performance criteria (i.e. strength, bond and waterproofing) and in-place conditions (i.e. cavity size and mortar patty size and location), a grout mix formulation was developed for use in the test panel construction. The test panel grout formulation, consisting of Portland cement, sand, fly ash, lime, water reducing admixture, and water, has the material properties shown in Table 1.

Table 1: Grout Material Properties

Gelman Water Retention (ml water collected)	< 2.0 ml
ASTM C940 Bleeding Test (5)	0
ASTM C939 flow (seconds)	8 to 14
ACE Flow (puddle diameter, inches)	7-1/4"
ASTM C1019 Grout Compressive Strength (psi)	3100 @ 28 days
Typical Shear Bond Strength Range (psi)	74 to 170

The formulated test grout was injected under pressure through ports into the collar joint cavity at an approximate 60 s.f. area at the south end of the building. Borescopic examination of this area revealed a primarily empty collar joint with small mortar patties located at the top of the test area. Prior to grout injection, expandable foam was injected into the collar joint on either side of the test area in order to provide an end dam to prevent unwanted lateral grout flow. A borescope was utilized to monitor grout flow through the cavity. The test grout injection successfully filled the empty collar joint, although as expected, additional injection ports and effort were required to inject the grout at the partially filled collar joint area.

FIELD ADAPTED ASTM E514 TESTING PROCEDURES AND RESULTS

In order to assess the performance of the proposed repair strategy with regards to water permeability, field adapted ASTM E514 testing was performed. The grout injection test panel was subjected to a field adapted moisture penetration test described in ASTM E514 before and after (four days to allow for grout curing) injecting the collar joint with grout. The test involved clamping a pressure chamber to the face of the wall and applying water at a rate of 40.8 gal/hr. The entire chamber was pressurized to 10 psf and the test was continued for a minimum of four hours. Information recorded during the test included water loss through the wall assemblage and appearance and location of moisture at the inner back-up or at brick units adjacent to the test area (lateral migration).

Results of the field adapted ASTM E514 tests showed that fully grouting the collar joint with the chosen grout formulation significantly reduced water penetration through the wall. Flow rates prior to grout injection were measured at 2.69 gal./hr. while post grout injection rates were measured at 0.24 gal./hr, equating to a 91% reduction in water penetration.

Empirical standards of performance have been developed through the accumulation of historical data for the Field Adapted ASTM E514 Test. These standards are presented in

Table 2. As can be seen, prior to grouting, the masonry wall assemblage would be rated poor in regards to service, materials and quality of construction. Subsequent to filling the collar joint by means of grout injection, the wall assemblage achieved a rating of excellent in each category.

Table 2: Field Adapted ASTM E514 Empirical Standards of Performance

Water Loss Rate (gal./hr.)	**Service Performance Rating**	**Materials and Quality of Construction Rating**
< 0.5	Excellent	Excellent
0.5 to 1.0	Expected	Standard
1.0 to 2.0	Questionable	Questionable
> 2.0	Poor	Poor

Source: Hoigard Et Al., "Including ASTM E514 Tests in Field Evaluations of Brick Masonry," Masonry: Design and Construction, Problems and Repair, ASTM STP1180

REPAIR IMPLEMENTATION

As a result of the effectiveness of the test panel construction with regards to restoration of the structural integrity of the wall and elimination of water infiltration into the building; grout injection was chosen as the appropriate repair method for the improperly constructed barrier wall system. A specialized masonry repair contractor was retained to effect the wall repairs through grout injection.

Pre-Injection Evaluation and Analysis

Due to the complexities involved in the grout injection process and the random nature of the masonry deficiencies at the building, additional evaluation of the entire structure (including masonry ties, flashing details, collar joint profiling, moisture infiltration locations, lintel conditions and expansion joints) was required prior to grout injection. The first stage of this evaluation required a personnel lift to reach the upper levels of the fully-occupied structure. Three-eighths inch diameter holes were drilled at mid-points in the head joints of the oversize brick into the collar joint area in order to allow for borescopic investigation of the wall system. These observation points were provided in the following locations around the structure:

- Parapets
- Heads and sills of windows
- Returns

- Changes in wall profile
- Sealant joints
- Apparent moisture infiltration
- Reported moisture infiltration
- Areas of efflorescence or staining
- Changes in designed wall width
- Window and door perimeters
- Walls adjacent to flashing
- Weep hole locations

Notably, facial separation cracks and improperly filled collar joints and masonry head joints were observed throughout. Facial separation cracks would be filled during the grout injection process by the injected materials moving to the face of the wall from the collar joint side. Improperly filled head joints would be filled from their backside when adjacent to the collar joint cementitious injected fill, or at locations of the drilled injection ports.

In addition to the borescopic observations, physical observations were made at the underside of the wood-framed roof, particularly at the intersection of the roof and the exterior wall. Observations were recorded as to the moisture infiltration frequencies and locations at each elevation, each floor, and each unit in order to compare and analyze the moisture related problems with physical conditions of the structure.

A pachometer was utilized to scan a representative portion of the building for joint reinforcement. The reinforcement was expected to be present at 16"o.c. vertically, as indicated in the construction documents. The presence of joint reinforcement could not be determined with the pachometer where structural steel was present. Such areas, which comprised approximately 20% of the region inspected, were inspected using a borescope. Of the regions where joint reinforcing could be inspected by pachometer, the total expected linear footage of reinforcing was 831 lineal feet, however the amount of joint reinforcing present was 394 lineal feet. This finding confirmed the need to augment the wall with ties prior to the cementitious injected fill process.

Compilations of the data from these investigations were analyzed to determine areas of potential anomalies and deviations from standard cementitious fill procedures. Of particular concern were areas of mortar entrapment and "patties" within the collar joint area. These areas needed to be identified and the protocol modified so that air entrapment during the injection process would be avoided.

Additional data was derived from the use of thermal transfer technology to delineate patterns indicative of collar joint voids. The thermal imaging was verified through pulse echo imaging and borescopic investigation. These methodologies indicated "mortar ledges" at apparent scaffold heights, repeating in different wall areas. This pattern is presumably related to either dumping of mortar at the end of the work day or perhaps a visit onto the scaffold from an inspector. These "ledges" needed particular care throughout the injection process so that air pockets would not ensue.

Acquired investigative data was provided to the cementitious injected fill technicians along with the injection protocol. The injection protocol established required mixes for injected fill that would be harmonious with the original materials. In some areas, different cementitious fill mixes were specified in order to accommodate void and fissure structures within the wall. The protocol also included a pattern of injection ports relating to the insitu wall conditions and established injection procedures including the removal and clearing of sealant joints, the preparation of flashing areas, and procedures to be used at changes in wall profile.

Installation of Cementitious Injected Fill

Complete injection of all facades of the building followed. A trained and certified crew of technicians with an average experience at grout injection of over five years, worked through winter conditions, from an enclosed and heated staging, while continually monitoring the interior of the fully occupied building. Random unannounced visits by the cementitious injected fill engineer insured quality control through flow tests, physical inspection, pulse echo imaging, and material property testing.

During grout injection, several challenges and anomalies were encountered. One such anomaly was discovered at a specific area of the building while analyzing the flow of the cementitious injected fill. A membrane flashing within the wall was discovered as being installed upside-down; that is, diverting water from its high-side in the brick down to embedment in the C.M.U. backup. Complete grouting of the cavity and encapsulation of the membrane flashing in this area served to address the deficient flashing by relying on the waterproofing integrity of a properly constructed barrier wall system.

Prior to injection, the technicians addressed those areas identified as requiring additional ties through installation of retrofit anchors. Sealant joints, cleared and removed for the process, were cleaned of all prior blockages and after injection, resealed. Special treatments were provided to eliminate leakage particularly at window head areas, and in areas with improperly installed flashing. Furthermore, clogged weepholes were unclogged to ensure proper function.

After completion of the procedure, injection ports were re-pointed with compatible pigmented materials, and the walls and areas were cleaned of any minor spotting. Recommendations were provided to the owner of remaining roofing and window issues that needed to be addressed to effect a long term solution.

Finally, thermal imaging was again employed to verify the filling of all voids. Some small areas, a handful in all, were identified as a suspected void condition. These areas were re-injected with an appropriate cementitious injected fill, and re-tested to insure their integrity.

CONCLUSION

The original design of the subject building required the exterior walls of the building be constructed of an exterior wythe of brick masonry, a solidly filled collar joint, and a concrete masonry unit back-up. This system was required structurally to provide a composite wall which would transfer stresses between the two wythes and architecturally to create a barrier to stop the inward migration of wind-driven rain. This is an acceptable wall system design and by all accounts was properly designed and specified.

Investigative procedures revealed multiple construction deficiencies which resulted in the non-performance of the masonry wall system at the building. Of primary concern was the omission of a solidly filled collar joint. This omission resulted in a compromise of the structural integrity and water resistance of the exterior walls. Material testing and analysis revealed mortar and brick unit properties consistent with specified standards although further evidence of poor construction techniques was identified.

In order to properly repair the deficient wall system, the structural integrity of the walls needed to be restored. In order to accomplish this goal, the empty collar joint needed to be solidly filled with a load bearing material as was originally intended. The most effective method of accomplishing this goal was grout injection. In addition to restoring the structural integrity of the walls, grout injection reduced the water permeability of the exterior wall system by restoring the barrier wall design and filling incompletely filled mortar joints, facial separation cracks, and brick unit cracks.

Field Adapted ASTM E514 testing in combination with test panel grout injection proved successful in filling the empty collar joint and reducing water penetration through the wall by 91%. The water permeability levels attained subsequent to grout injection rate excellent with regards to service performance considering minor infiltration is expected due to material absorption and occurred as a result of an air pocket within the collar joint.

The repair of the deficient exterior wall system was subsequently performed. Building-wide evaluations specific to the grout injection process were conducted using advanced techniques including fiberoptic observation, pachometer testing, thermal imaging, and pulse echo imaging. Acquired investigative data was provided to the injection technicians along with an injection protocol which established required mixes, injection port patterns, and injection procedures.

Although several challenges were encountered during the repair procedure, the improperly constructed barrier wall system was successfully repaired using grout injection. At the conclusion of the repair, thermal imaging verified that the collar joint had been completely filled, thus restoring the structural integrity and reducing the water permeability of the exterior wall system.

American	**SI**
1.0 s.f.	0.09290 s.m
1.0 in.	2.54 cm
1.0 ft.	0.3048 m
1.0 gal.	3.785 l