Restoration and Repair of Historic and Contemporary Brick Masonry

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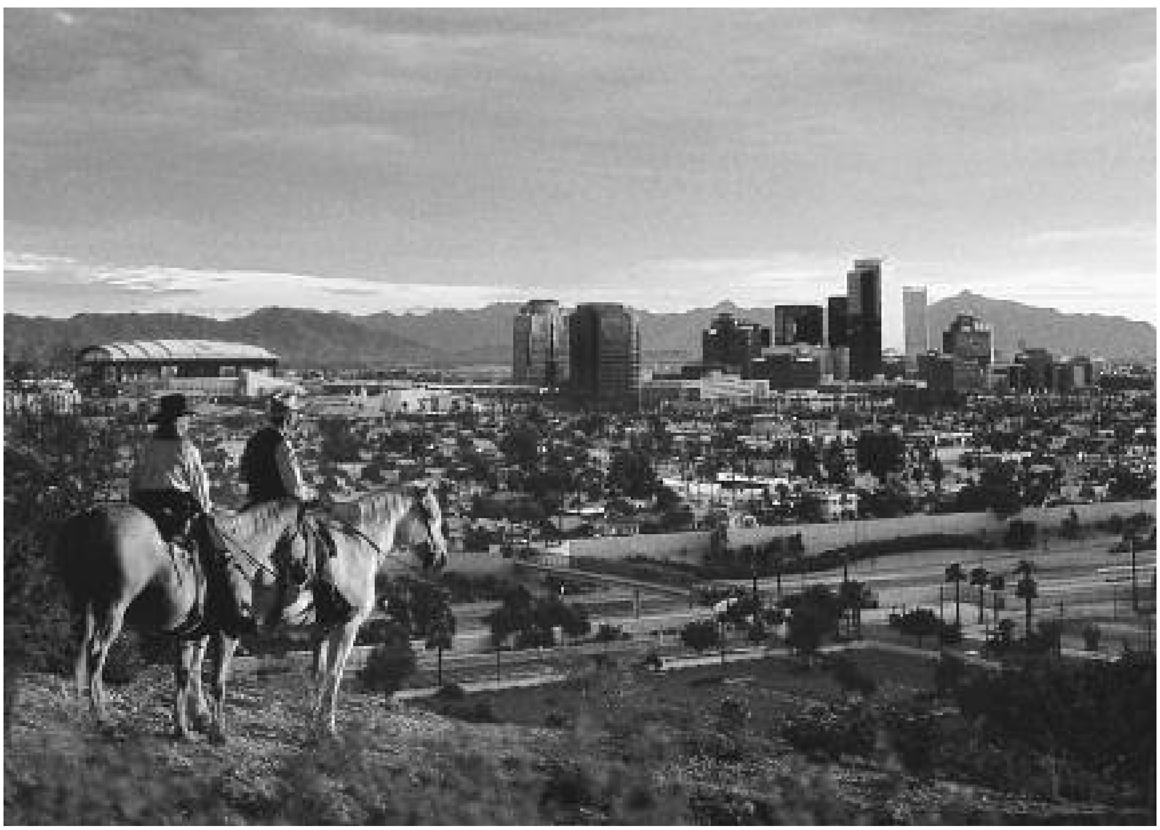

Roof Consultants Institute

ABSTRACT

This paper will initially discuss the history and development of brick masonry. Different exterior wall types will be evaluated. The manufacturing of brick will also be presented. Material properties of the fired clay product and the resulting stress will be explained.

The paper will then highlight the different visible signs of masonry distress that consultants should look for when evaluating brick masonry. Water infiltration problems and testing methods will be discussed. Masonry repairs will also be presented. The discussion will conclude with detailing problems encountered at roof-to-brick masonry interfaces.

SPEAKER

DOUGLAS STIEVE specializes in the diagnosis and repair design of historic and contemporary structures. Since joining WJE in 1991, Mr. Stieve has provided professional services for over 600 structures throughout the northeast United States. He has experience with many types of materials, including brick, concrete masonry, stone, EIFS, roofing, and waterproofing. Mr. Stieve also provides consulting services to architects and building developers during new construction.

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ABSTRACT

This paper will initially discuss the history and development of brick masonry. Different exterior wall types from older, massive, load-bearing walls to contemporary brick veneers will be evaluated. The manufacturing of brick will also be presented. Material properties of the fired clay product and the resulting stress introduced into masonry buildings including but not limited to ceramic and thermal expansion, will be explained. Different types of mortars and the various problems that can develop affecting the brick-to-mortar bond strength and water infiltration properties will be discussed.

The paper will also highlight the different visible signs of masonry distress and water infiltration that consultants should look for when evaluating brick masonry. Repairs can then be developed based on observations in the field and an understanding of the physics that affect brick masonry. Unless the underlying source of masonry distress and/or water infiltration is understood repairs may be developed that address only the symptoms of the problem. These repairs often fail, as the underlying root cause of the distress continues to degrade the wall system.

History of Brick

The first known masonry units most likely consisted of mud placed into forms, which were allowed to dry in the sun. These types of masonry units are known today as adobe. The first known fired clay masonry units date back to circa 300 BC in Mesopotamia. Heating the mud to elevated temperatures created a much harder and durable masonry unit. However, the majority of Mesopotamian masonry was still adobe.

The Romans elevated the use of brick by integrating it into some of their engineered structures such as arches and domes. Brick was also often used by the Romans as formwork for concrete or as a backing material for stone facings.

During the Industrial Revolution in the 19th century, steam engines and other machines begin to be developed to produce brick in larger quantities. This mechanism led to the mass production of brick in larger plants. Prior to this, brick was often made by hand close to the sites where the material was used.[1]

Wall Types

The earliest types of masonry walls contained multiple wythes of brick. The mass of the wall was used to bear the weight of the structure above. The taller the building, the thicker the wall became. With the advent of cast iron, structural steel, and the passenger elevator around the start of the 20th century, buildings could be constructed taller. The steel skeleton frame was designed to carry the weight of the structure. Clay masonry, such as brick, tile, and terra cotta was often used within these structures due to its fire resistance. Masonry was predominantly used as an exterior façade material. Exterior walls were still multi-wythe masonry often packed tightly between steel spandrel beams and columns. However, fired clay units were also used to form floor arches and to protect the buildings steel skeleton frame from the heat of a potential fire.

In the 1950s, brick began to be used as a single-wythe veneer with a cavity wall and back-up construction. These wall types allow rain water that penetrates through the brick veneer to drain down through the wall within the cavity. Flashings are utilized to expel water back to the exterior at the base of the walls and at other locations that impede the downward flow of water within the drainage cavity.

Brick Manufacturing

The manufacture of brick has not changed much over time. The process includes extracting the clay and/or shale from the earth; removing impurities, mixing the clay and/or shale, forming the brick unit; drying; and then firing at elevated temperatures. Firing the formed mixture to elevated temperatures of up to approximately 2,000 degrees F allows the individual clay and/or shale particles to fuse together. This critical step is what produces a durable brick product.

When the wet (green) brick is fired, practically all of the moisture in the clay is driven out of the brick and the unit will shrink. Drying the units prior to firing allows some of the moisture to escape. Firing a green brick may collapse the unit as the moisture quickly changes into steam and damages the brick as it escapes. After the brick is fired, the material seeks to reach an equilibrium in moisture content with the surrounding air and will expand. Most of this ceramic expansion occurs initially after the brick is removed from the kiln. However, the process will continue at a slower rate, which decreases with time for many years.

Early brick units were manufactured by hand. The clay was placed into a soaking pit and mixed by foot in a process called pugging. Then the clay was formed into individual brick molds, dried, and then moved to a kiln to be fired. Over the last 150 years, machines have been developed to facilitate the production of brick. Most brick are manufactured via an extrusion process in which the clay and/or shale is forced through a dye and then individual units are cut from the column of clay with wires. Molded brick are pressed into forms with hydraulic presses.

Gas-fired tunnel kilns have also been developed. Brick units are loaded onto railroad type platform cars and then pulled through the kiln. Temperatures and the speeds at which different runs of brick are fired can be controlled by the manufacturer. Fluxes are sometimes added to the clay or shale mixture before the brick units are formed to help the brick reach the desired firing temperature. Additives are also used to produce some desired colors.

Mortar

The original mortar used by the Mesopotamians was mud. However, bitumen was sometimes added to the mud, presumably to increase its water resistance. Lime and gypsum were added by the Egyptians as additives for strength. Lime, aggregate, and pozzolans were used by the Romans. Lime mortars were used from the 6th through the 19th centuries. In the mid 19th century, portland cement was developed. Portland cement increases the strength of mortar, allowing for quicker and stronger construction.[1]

Today, most new masonry buildings utilize portland cement-lime mortars, which are composed of a combination of portland cement, hydrated lime, sand, color additive, and water. Masonry cements (Portland cement and crushed limestone-based mortars) and mortar cements (mortars based on other constituents) are also used. The terminology of these products is confusing. These mortars are a combination of several products – some of which are proprietary. Sand, water, and sometimes additional portland cement are added to produce the final mortar. In the author's opinion, Portland cement-lime mortars should be used so that the mortar materials are known and predictable results can be achieved.

The final strength of the mortar needs to be strong enough to satisfy the structural requirements for the particular project, yet not become a source for excessive water infiltration. Mortar should also be matched to the brick. Portland cement adds strength to the mortar. However, large quantities of portland cement will cause shrinkage cracks and lead to greater water infiltration. Hydrated lime, on the other hand, is slowly carbonated and produces a softer, more water resistant mortar. ASTM International (ASTM) Standard C270, *Standard Specification for Mortar for Unit Masonry*[2] includes proportions for different types of mortars. This document is the industry standard for mortar.

The mortar should be matched to the brick's initial rate of absorption (IRA), which is the rate at which the body of the brick will absorb or suck water from the mortar. Brick with high IRAs will absorb water quickly, leaving the mortar next to the brick with little remaining water to properly hydrate the cementitious components of the mortar. This may cause bond line separations between the brick unit and the mortar. This reduces the flexural bond strength of the masonry and increases water penetration through the masonry. Conversely, brick units with a low IRA will not readily absorb water. A small film of water may form between the brick and the mortar and the mortar may not be absorbed into the pores on the brick unit, again producing masonry with poor bond between the brick unit and the mortar.

IRA is determined by ASTM C67, *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile*.[2] There are two different IRA test methods within ASTM C67, a laboratory test and a field test. Both test methods involve placing the brick units in pans filled with water and recording the weight or volume of the water lost from the pan over a relatively short time period. This is calculated as the amount of water that is absorbed by the brick. Brick manufacturers can provide IRA values for their products. If the brick manufacturer and type are not known, units that have not been placed into service can be utilized for IRA testing. Care should be used if brick that have been removed from the wall and cleaned are used because small amounts of mortar still within the pores of the brick will influence the IRA test results.

Modes of Deterioration

Brick masonry can degrade due to a number of phenomena. Some are naturally occurring and others can be the result of improper construction, design, or both. Following are some of the more common forms of brick distress:

Water Infiltration: Water leakage problems are one of the most common reasons that repairs are made to exterior walls. With the advent of thinner walls, there is little redundancy in the façade system to resist rainwater penetration. Flashings are critical in these thinner walls. Older, multi-wythe masonry walls can also leak. Age sometimes catches up to older walls, deteriorating the mortar and brick, which can increase the potential for uncontrolled water entry.

Rising Damp: Due to its porous nature, brick walls that are constructed into grade can wick moisture up out of the ground. This mainly occurs in older masonry walls were brick was often extended into grade. These buildings are sometimes constructed with brick footings or even no footings at all. See *Figure 1*.

Freeze-thaw Distress: Brick and mortar both contain many microscopic pores. Masonry absorbs water and when it is saturated, these pores become filled with water. If the masonry freezes while it is saturated, the ice will expand as it changes from a liquid to a solid. If the pores on the brick and/or mortar are well interconnected, there is enough room to accommodate the expanding ice. If there is not enough room, stress is produced within the material and distress can occur (*Figure 2*).

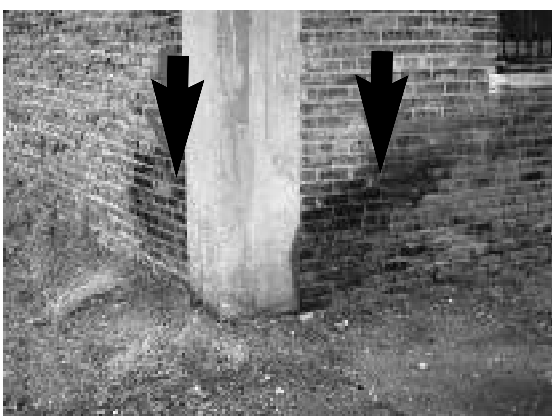

Figure 1 – Rising damp (see arrows).

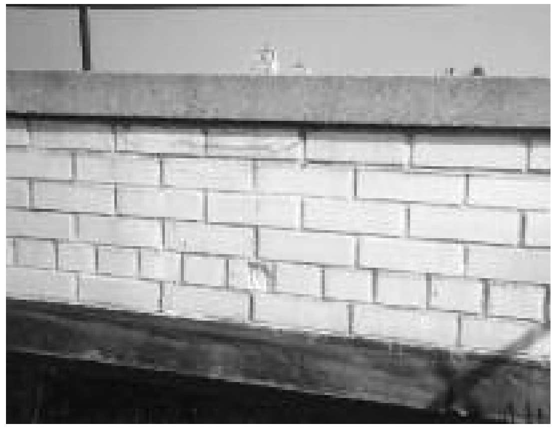

Figure 2 – Freeze-thaw distress at parapet.

Rust Jacking: Masonry is often placed in intimate contact with structural steel lintels, outriggers, and spandrel beams. Steel will expand as it corrodes, often to volumes several times greater than that of the original steel. The expanding rust produces large stresses, which can exceed the tensile strength of the masonry. Cracks, deflection, and spalling of the brick can all occur due to rust jacking (*Figure 3*).

Ceramic Expansion: This phenomenon is also known as moisture expansion. As brick regains moisture after the masonry is fired, its volume will increase. Most of the volume increase occurs directly after the brick is removed from the kiln. However, fired clay products will continue to expand at a slower rate for several years. Earlier construction did not recognize this movement and the stresses produced often led to spalling and cracks in the masonry. This form of deterioration can also become evident in newer construction if expansion joints are inadvertently filled with mortar.

Thermal Expansion: Temperature differences affect all materials. New construction standards require expansion and control joints. Older buildings with multi-wythe masonry walls and steel skeleton structural frames are also affected by differential thermal movement between the outer wythe of brick and the steel structure, which is better protected from temperature swings by the mass of the wall (*Figure 4*).

Figure 3 – Rust scale on structural steel.

Figure 4 – Bowing due to restrained thermal movement.

Structural or Lateral Movements of Building: There are many other types of stresses that can affect a brick wall. These include but are not limited to settlement of foundations and lateral wind and seismic loads. Missing wall ties or improperly installed wall ties can reduce the lateral resistance of a masonry veneer. Wire brick ties should be used and have been recommended by the Brick Industry Association (BIA)[3] for some time. Corrugated wall ties can stretch and pull their fasteners out of the back-up. This was recently documented by FEMA during its evaluation of the damage caused by Hurricane Ivan.[4]

INVESTIGATION

The purpose of the investigation is to determine why the distress or water infiltration has occurred. The investigator must determine the mode(s) of deterioration in order to properly detail a repair.

The first component of a brick investigation is an overall visual survey of the building façade. This initial survey is often performed from grade level with the aid of binoculars and telephoto equipment. Anomalies should be recorded on building elevation drawings and with photographs. Patterns of distress that are recorded can provide insight as to the root cause(s) of the distress. Close-up observations at representative areas of the façades should then be performed. Many small cracks and spalls are often detected up close that could not be seen from grade level. The close-up investigation can also provide a different viewing angle of the walls, such as a downward view of a sill or water table that was impossible from grade level. Water leakage areas and/or recorded patterns of distress such as extensive cracking at lintels, efflorescence stains under shelf angles, or at grade level are symptoms of distress.

Probes should be made into the brick at representative locations to observe conditions and record anomalies that are hidden from view. The locations of these exploratory openings are determined after the condition survey is complete. It is important for the investigator to be present and observe the opening as the masonry is removed. Sometimes underlying flashings can be damaged during masonry removal or the mason can remove debris within the wall cavity that is important to document. The author prefers to take many photographs during probing and often instructs the mason to start and stop work as required to document conditions observed as the work progresses.

Various forms of material studies conducted within a laboratory and in-situ testing can be performed to aid in the investigation. Again, the purpose is to gain a better understanding of the problem. These tests include but are not limited to:

Material Tests:

Freeze-thaw testing per ASTM C67, *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile.*[2] Brick units are repeatedly dried, saturated with water, frozen, and thawed to mimic actual freeze-thaw cycles. The results are utilized to provide a basis to determine future performance of the brick.

Absorption testing per ASTM C67, *Standard Test Methods for Sampling and Testing Brick and Structural Clay Tile.*[2] These tests are used to determine how much water the brick may absorb. This can be used to aid in water penetration resistance studies. These tests can also be used to determine how susceptible a brick may be to freeze-thaw damage. Two different tests are performed. One is a cold water test and one is a test performed with boiling water. The ratio of these test results is known as the "saturation coefficient "or the" c/b ratio." This value is an indication of how well connected the microscopic pore structure is within a brick. If the saturation coefficient is low, the pore structure is well connected and there will be more room on a microscopic level for ice to advance without producing excessive stress within the brick. Care should be used when using cleaned brick for absorption tests because the remaining mortar left in the pores of the brick will influence the test data.

Petrographic studies. These are observations of the masonry under a high-power microscope. An experienced petrographer can observe the pore structure with the brick and mortar, microscopic cracks, and the important bond line between the brick and the mortar

Scanning Electron Microscope (SEM). This can be used to determine the elements of a material and can aid in the identification of stains or deleterious inclusions within brick such as pyrites (rust stains) and calcium (lime pops).

In-Situ Strength Tests:

Strain Relief Testing. This in-situ test can be performed if excessive compression of the masonry (usually from ceramic expansion is suspected). Strain gauges are mounted to the masonry and then the stress is relieved by saw cutting the mortar bed (horizontal) joints. This relaxes the masonry. The strain gauges record the microscopic expansion of the brick as the stress is relieved. This can be performed with a flat jack per ASTM C1196, *Standard Test Method for In Situ Compressive Stress within Solid*

Unit Masonry Estimated Using Flatjack Measurements[2] or just by cutting out the mortar bed joints while recording movement of the brick (*Figure 5*).

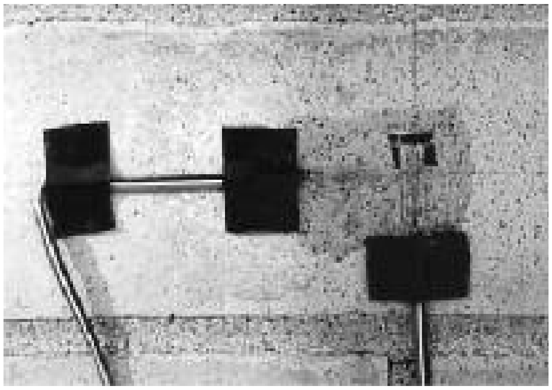

Figure 5 – Strain gauge mounted to masonry.

Bond Wrench Test. Based on a modified field application of ASTM C1072, *Standard Test Method for Measurement of Masonry Flexural Bond Strength.*[3] This can help determine the flexural bond strength of the masonry. Masonry is removed from around the test specimen and a large calibrated wrench is used to break the brick from the bed joint while recording the peak load (*Figure 6*).

Figure 6 – Bond wrench test.

***In-Situ* Water Tests:**

Water Spray Rack. Water is sprayed on the wall surface area via a water spray rack. The size of the spray rack can be adjusted to suit field conditions. Portions of the wall can be masked off with plastic sheathing to limit the testing to just the masonry or to eliminate other variables such as windows and/or mechanical louvers. The flow of water and spray nozzle sizes are based on ASTM E1105, *Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Cyclic Static Air Pressure Difference*[2] (*Figure 7*).

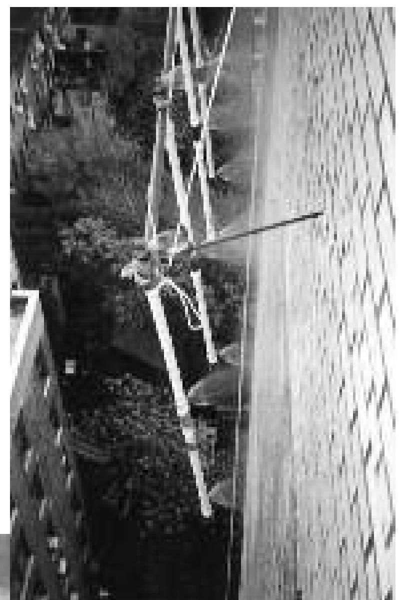

Figure 7 – Spray rack.

Isolation Water Testing. This test is performed in accordance with American Architectural Manufacturer's Association (AAMA) 501.2, *Quality Assurance and Diagnostic Water Leakage Field Check of Installed Storefronts, Curtain Walls and Sloped Glazing Systems*[5]. A calibrated water spray nozzle is used to test individual joints of curtain walls or other similar structures at the suspected site of water infiltration.

Water Penetration Testing. This test conducted per ASTM C1601, *Standard Test Method for Field Determination of Water Penetration of Masonry Wall Surfaces,* can be performed to determine the amount of water that penetrates into a masonry surface (*Figure 8*). A chamber is mounted to the brick and a film of water is created within the chamber that flows down the face of the brick. The water is collected at the bottom of the chamber and recirculated. Air pressure is introduced to mimic a wind-driven rain. The amount of water lost from the chamber is recorded as the amount of water that penetrates into the masonry. This is a very useful tool to evaluate various repairs to resist water penetration, such as re-pointing and masonry sealers. Base line values for the existing wall can be compared to mock-ups of different repair methods.

Figure 8 – Water penetration test in progress.

REPAIR AND RESTORATION

Repairs should address the underlying problems, not just the symptoms of the observed distress. For instance, if cracking within a brick façade was caused by thermal movement or rust jacking, the distress will likely reoccur if only the brick is replaced.

Sometimes temporary repairs are required to stabilize the masonry until long-term repairs can be performed. Masonry distress to walls over sidewalks, driveways, and other areas accessible to pedestrians and/or vehicles are of particular concern. Access into these areas should be prevented or adequate sidewalk protection should be installed. Temporary repairs are often performed before the investigation concludes. These can involve pinning, the installation of braces (*Figure 9*), and/or netting to catch loose fragments before they can fall to the ground.

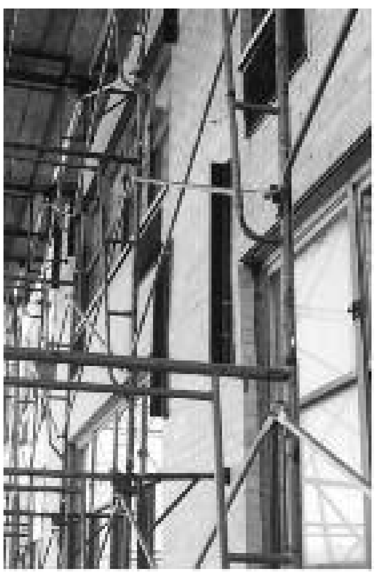

Figure 9 – Temporary bracing angles used to prevent bulged masonry between windows from falling.

To address water infiltration problems, flashing repairs or new flashing systems are often required to provide an effective barrier against the downward flow of water within a wall assembly. Often during construction of masonry veneers, mortar is inadvertently spilled into the drainage cavity, where it hardens at the base of the wall. Large amounts of mortar droppings can block weep holes. These mortar droppings should be cleared and adequate precautions provided to prevent new mortar droppings form falling into the cavity during reconstruction or repair. Pea gravel or proprietary products can be installed at the base of the cavity to catch and disperse mortar droppings. However, the use of these products should not give the mason a false sense of security. Mortar spills into the drainage cavity should still be mitigated. Flashing repairs often involve insertion of new flashing in the masonry veneer or through entire sections of the wall if a true through-wall flashing is required. The type of new flashing required will depend on the amount of water infiltration, existing conditions of the brick, and the type of wall system.

Shoring is a critical component during construction and can be provided with wood blocking or the use of steel angles inserted below the remaining brick. These angles are supported off of the lower remaining brick or connected back to the structure of the building. Masonry veneers are usually tied back to the remainder of the wall with metal ties, which have no vertical load resistance capabilities. Older multi-wythe masonry walls are usually tied together with brick header courses. These headers transfer some of the weight of the outside wythe of brick to the inside wythe(s). Often during flashing repairs, small amounts of masonry are removed, the flashing installed, and the brick is replaced before the mason proceeds to the next small section of masonry. A metal flashing that can be soldered in the field such as copper, lead-coated copper or stainless steel should be used. This will allow the small sections of flashing to be soldered together so that the end result is a complete watertight flashing system. Shoring is often a means and methods issue and will vary, depending on the repair and wall type. The existing wall should be reviewed and shoring should be designed by a licensed engineer engaged by the contractor (*Figure 10*).

Figure 10 – New through-wall flashing at setback wall. Note header brick course (arrows).

Reducing the amount of water that penetrates a masonry surface curtails water infiltration into the building and also helps reduce freeze-thaw distress and certain types of staining. Repointing is a very effective repair to lower the rate of water penetration into and/or through a brick masonry wall. Older, softer mortar joints or mortar exposed to severe wind exposure such as those in high-rise buildings can erode and are candidates for repointing. The existing mortar should be removed to a minimum depth of at least 3/4 inches or to sound mortar in a manner that will not damage the brick. Mortar should be packed tightly and tooled into the joints in multiple lifts so that the mortar is tightly compressed against the existing mortar and brick. The compressive strength of the new pointing mortar should match the existing mortar and not be stronger than the brick. This is particularly important for historic projects. If distress reoccurs, the goal is for the mortar to crack before the brick. Mortar joints can be more easily repointed where historic brick would have to be matched and replaced. Also, if the new mortar is stronger than the existing mortar or the brick, there will be a tendency for spalls to develop in the face of the brick as compressive stress is concentrated at these locations. A compositional analysis of the existing mortar can be performed to determine the constituents, and thus the strength of the existing mortar.

The author recommends that penetrating sealers and coatings be avoided wherever possible, particularly in northern climates. Even the sealers and coatings marketed as breathable will reduce the overall vapor transmission of a wall system. Water concentrated at the outside surface of the masonry is more susceptible to freeze-thaw distress. Penetrating sealers also have to be re-applied every five years to be effective.

Supplemental anchors can be utilized to connect the brick masonry to back-up construction. These anchors can be expansion, adhesive, or spiral-type anchors and can be used as a temporary or long-term repair. Spiral anchors are relatively new to the market and are a cost-effective supplemental anchor. The anchor is driven directly through the masonry within a mortar joint of brick masonry walls. The small remaining hole is pointed. However, there is a possibility that the spiral anchor may tear the waterproofing or air infiltration barrier of newer, stud-framed back-up walls.

Masonry reconstruction often includes structural steel repairs. Long-term corrosion can reduce the size and strength of the remaining steel. Supplemental sections such as plates, angles, and channels can be welded or bolted to the remaining steel to strengthen deteriorated portions of the structure. Repairs at connections – particularly where older rivets occur – prevent challenges. Structural steel repairs should be designed by a licensed engineer (*Figure 11*).

Figure 11 – New steel plate being welded to existing beam.

Restoration projects often include masonry cleaning. There are many different types of cleaning methods and products for brick, including chemicals, detergents, micro-abrasives, and steam cleaning. Sandblasting and cleaning methods that utilize high-pressure water can be too aggressive and damage the masonry. There are many variables such as the type of brick, mortar, the type of contaminant, temperatures during which the masonry will be cleaned, and the skill of the contractor that can all affect the cleaning process. Multiple mock-ups should be performed to determine which method effectively cleans the brick masonry with as little damage as possible. The subject of masonry cleaning is complex. Please see the endnotes at the end of this paper for additional information related to cleaning.[6]

CONCLUSION

Brick masonry is one of the oldest known and best performing building materials. The problems that may develop can be properly corrected once the mode of failure is properly understood by the consultant. Both simple and sophisticated investigation tools and methods can be used to evaluate brick masonry. Existing repair techniques have proven to be effective if utilized properly. New technology such as carbon fiber composites currently being developed for concrete repairs and strengthening may also be developed in the future for masonry uses.

FOOTNOTES

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Walls, and Sloped Glazing Systems. AAMA, Schaumburg, IL, 2003.

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WEB SITES FOR FURTHER RESEARCH AND USE

www.gobrick.com – Brick Industry Association

www.masonrysociety.org – The Masonry Society

www.aamanet.org – American Architectural Manufacturer's Association

www.cr.nps.gov./hps/tps/briefs/presbhom.htm - National Park Service - Technical Preservation Briefs

www.fema.gov - FEMA