Chapter 16 – Table of Contents

Chapter 16 – Table of Figures

Chapter 16 - Masonry Bridges

16.1 Common Types of Masonry Bridges and Masonry Bridge Elements

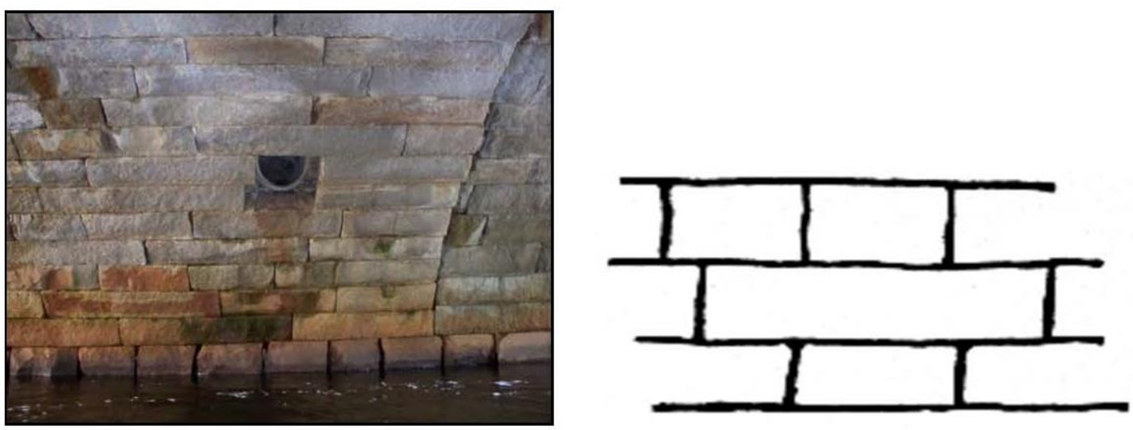
Masonry bridges are an early bridge type, and many are still in service. Many of these bridges have historic and cultural significance to the community and are on, or eligible for, the National Register of Historic Places. The intent of this chapter is to offer guidance on maintaining and preserving masonry structures.

16.1.1 Arches

Masonry arches come in three main types (i.e., coursed ashlar, random ashlar, and rubble) and can be constructed of either brick or stone.

16.1.1.1 Coursed Ashlar Masonry

Most brick arches and many stone arches are this type. Ashlar stones have neatly dressed edges. The joints are of a consistent thickness and blocks of the same size are used throughout, as shown in Figure 16.1. The horizontal joints are consistent over the length of the arch. To be considered ashlar masonry, the joints between the stones should be small and consistent. The joints can either be mortared or dry-laid.

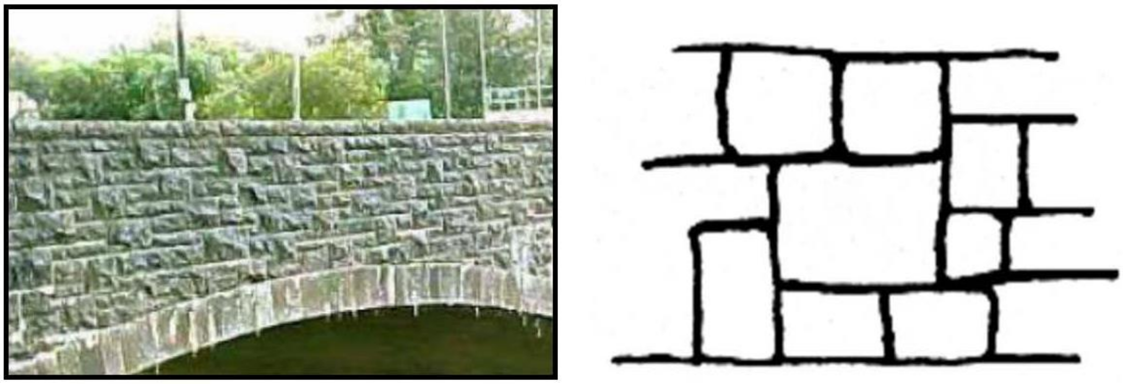


(a) (b)

Figure 16.1 Coursed Ashlar Masonry (a) Photo and (b) Schematic

16.1.1.2 Random Ashlar Masonry

Random ashlar masonry is comprised of dressed stones or brick, where only the thickness of the masonry units and the longitudinal placement varies along the arch ring (arch stone) or wall face (spandrel), as shown in Figure 16.2. This type of construction is more common in vertical walls (e.g., substructure units) than in arches.

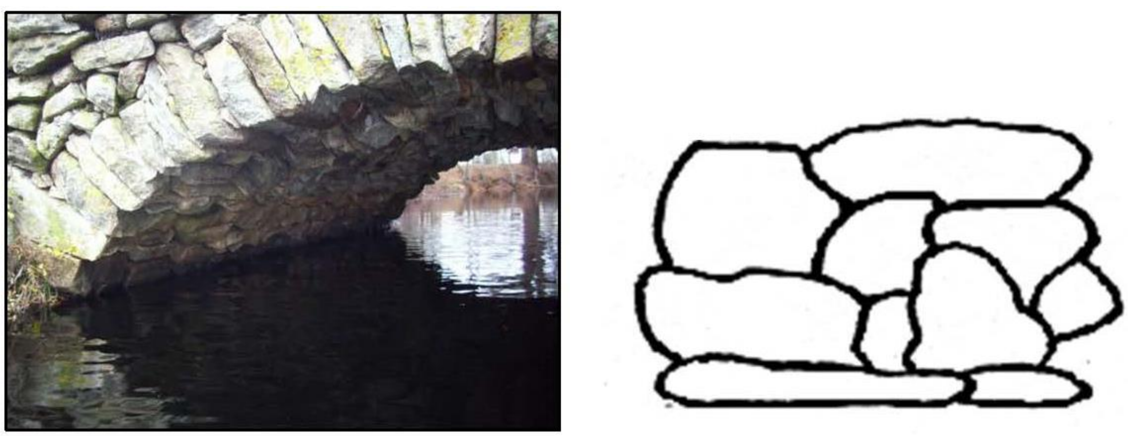


(a) (b)

Figure 16.2 Random Ashlar Masonry (a) Photo and (b) Schematic

16.1.1.3 Rubble Masonry

Rubble masonry is comprised of undressed or roughly dressed stones. Figure 16.3 shows squared rubble masonry along the face stones (spandrel wall). The interior of the arch (intrados) in Figure 16.3 is constructed of stones that have not been squared and are placed in random coursing. Rubble masonry can be coursed or random, similar to ashlar masonry. It can also be grouted or dry-laid.



(a) (b)

Figure 16.3 Rubble Masonry (a) Photo and (b) Schematic

16.1.1.4 Arch Elements

Figure 16.4 defines most of the terminology required for the discussion of stone arches. The interior of the arch barrel is called the intrados and the exterior is called the extrados. The spring line is the horizontal line connecting the furthest apart points on the intrados. The arch rise is the distance from the spring line to the underside of the keystone. Not all stone arches have a keystone. For an arch without a keystone, the crown is common terminology for the top of the arch.

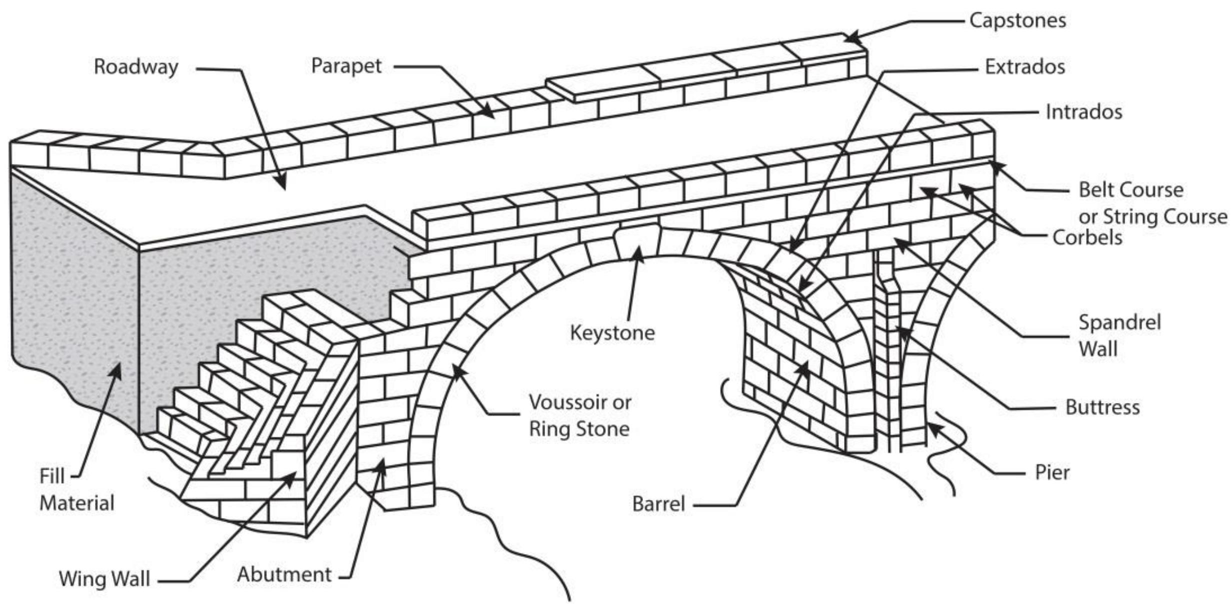


Figure 16.4 Arch Elements

Arches typically rely on the soil to provide lateral stability and to distribute the live load among the various elements. Typically a 1 foot wide section is assumed by engineers for structural analysis purposes and the soil is assumed to distribute the live load to the arch. However, if there is less than 2 feet of fill over the structure, the soil cannot be used to distribute the fill. In cases of inadequate fill depth, the length of the stones themselves becomes critical in determining the transverse width that the live load can distribute, making the minimum stone length a critical dimension in determining the structural capacity of the masonry structure.

A masonry arch is made from identical wedge-shaped pieces known as voussoirs (the masonry units). The arch is built on falsework (a temporary supporting framework) since it cannot stand until the last stone is in place. Once complete, the falsework is removed and the arch at once starts to thrust at the abutments. Inevitably the abutments will give way slightly and the arch will spread.

Figure 16.5, greatly exaggerated, shows how the arch accommodates itself to the increased span. The arch has cracked between voussoirs – there is no strength in these joints, and three hinges have formed. The arch is not, however, on the point of collapse – the three-hinge (also known as the three-pinned) arch is a well-known and perfectly stable structure.

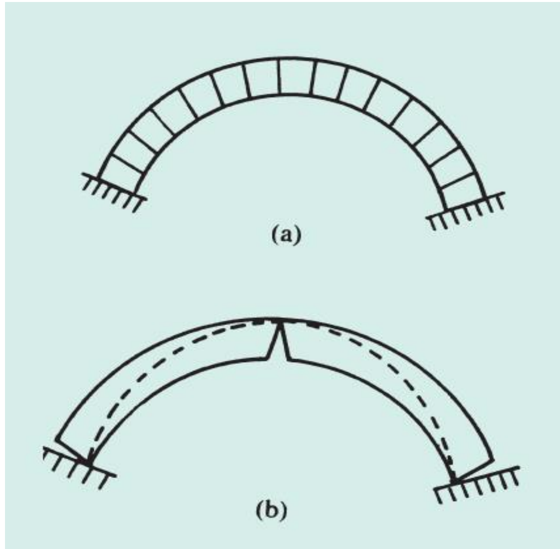


Figure 16.5 Arch Accommodation to Increased Span

If the arch is backfilled (the soil over the arch is placed) prior to the formwork being removed, then the arch will perform as one homogeneous structure (no hinges will form in the arch). The lateral earth pressure as well as the vertical earth load provide resistance to the arch thrusting at its abutments. Therefore, the arches ability to spread is severely reduced. In this case, the arch would be modeled with fixed connections at the abutments and as a homogeneous mass (although the arch ring thickness may vary) throughout the arch itself.

Both the fixed arch and the three-pinned arch are valid models for masonry arches. While the supports for a concrete or steel arch can be modeled with pinned supports (and without a hinge at midspan) this model is not valid for masonry structures as it would make the structure unstable. Additionally, the hinge at the top of the arch is almost never centered on the arch due to the presence of the keystone. The keystone is typically a wedge shaped stone that is larger than the surrounding stones. The purpose of the keystone being large is that it will be able to displace into the arch to accommodate the gap caused by the formation of the hinge at the crown.

It is sometimes difficult in the field to determine which type of arch construction was used, and plans and specifications are not typically available either. Most masonry arches will show cracking in the grout and many masonry arches do not even use grout. The most common method of analyzing these structures is to assume the masonry arch is fixed at the supports.

Typically arches that have a keystone or are an approximate half circle are modeled as fixed at the supports and the arches without keystones and flatter arches are modeled as three-pinned arches so that the passive pressure can be used to help resist the thrust of the arch.

In order to analyze an arch, careful field measurements are required. The springline, rise and shape of the arch are critical to getting an accurate representation of the arch and henceforth an accurate load carrying capacity.

16.1.2 Masonry Slab Bridges

Masonry slab bridges are typically small span structures, less than 10 feet. An example of a granite slab bridge is shown in Figure 16.6. In general, masonry slab bridges have not been constructed since the early 1900's. These structures are comprised of butted individual slabs whose ends are resting on the substructure. The width of the slabs can vary over the width of the bridge. The thickness of the slabs is typically consistent over the entire structure, however, if for some reason the thickness varies, the least thickness should be used to analyze the bridge.

Figure 16.6 Granite Slab Bridge

16.1.3 Substructure Elements

Abutment and piers can be constructed of masonry elements. The masonry units can be solid throughout the elements, or in areas where production concrete is not readily available, rubble abutments are a viable alternative. The rubble abutments are formed by dumping large quantities of masonry rubble (uncut stones, brick or even concrete rubble). The structure is then typically coated with concrete to form a cohesive structure. Another common use of masonry units in substructure is to use the masonry to form an aesthetic veneer over a reinforced concrete structure. It is common to find concrete caps and extensions on masonry substructure elements (as shown in Figure 16.7). Sometimes rebar is drilled and grouted into the masonry to attach the concrete elements; however, the concrete can also be cast against the stone with no mechanical connection provided.

Figure 16.7 Masonry Substructure

16.1.4 Brick, Stone and Mortar Characteristics

Brick

Brick is manufactured by forming clay or shale into blocks and hardening it by heating. Brick can be either molded or extruded and can vary greatly in appearance and composition. While there are standard brick sizes, bricks can also be manufactured in custom sizes and with custom finishes. Brick can be glazed to provide a different finish and to increase protection from the elements. An example of a brick arch and spandrel walls is presented in Figure 16.8.

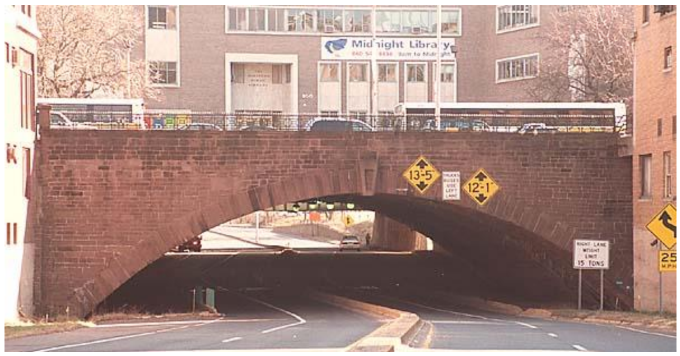


Figure 16.8 Brick Arch and Spandrel Walls

There are various ASTM standards for brick. ASTM C62 is the Standard Specification for Building Brick, ASTM C67 is the Standard Test Method for Sampling and Testing Brick and Structural Clay Tile, and ASTM C216 is the Standard for Facing Brick. There are 2 grades of brick commonly used in bridge construction. Grade SW is specified for severe weathering and also is the default type if the grade of the brick is not specified. Grade MW is specified for moderate weathering and is typically not used except in the southernmost sections of the United States.

The grades of brick can be further broken down into types. If no type of brick is specified, typically Type FBS is used. Type FBS brick is applicable for general use in masonry construction. If a higher degree of precision is required to accommodate a lower permissible variation in size, than Type FBX is required. Type FBA is specified for general use where characteristic architectural effects resulting from non-uniformity in size and texture of the individual units is desired. While there are other types of brick available, those listed above are the primary choices for masonry construction. Comparison of Type FBS and Type FBX is shown in Table 16.1.

Table 16.1 Type FBS and Type FBX Bricks

Brick Type	Waste	Chips	Cracks	Size Variation from Each Other	Warpage
FBX	Up to 10 percent	1/8 inch edge 1/4 inch corner	Any not seen from 15 feet away	5/16 inch from each other	1/16 inch for under 8 inch dimension
FBS	Up to 20 percent	5/16 inch edge 1/2 inch corner	Any not seen from 20 feet away	1/2 inch from each other	3/32 inch for under 8 inch dimension

Stone

Similar to brick, stone bridges can be constructed of several different types of stone. Igneous stone (e.g., granite), sedimentary stone (e.g., limestone or sandstone) and metamorphic (e.g., marble) are the main categories for stone. Sedimentary rock typically has little flexural strength and is therefore not used in slab bridges. All three stone categories are applicable for use in compression applications. Geological maps which show the typical bedrock profile for the area that the bridge is located are helpful in determining the type of stone used in a historic bridge. However, without testing or cleaning it is difficult to determine the stone type, as weathered stone typically has a gray appearance regardless of composition. Below is a chart with basic information on various types of stone that may be helpful in rehabilitation and repair work.

Table 16.2 Basic Information on Various Stone Types (NHI Course 134062)

Stone Type	ASTM Standard or Test Method	Absorption by Weight (percent) ASTM C 97	Density (lb./cf): ASTM C 97	Modulus of Rupture (psi): ASTM C 99	Compressive Strength (psi): ASTM C 170	Flexural Strength (psi): ASTMC 880
Marble	ASTM C 503	0.75	144 to 175	1000	7500	1000
Low-density limestone	ASTM C 568	3.0	110	400	1800	n/a
Med-density limestone	ASTM C 568	7.5	135	500	4000	n/a
High-density limestone	ASTM C 568	12.0	160	1000	8000	n/a
Granite	ASTM C 615	0.4	160	1500	19,000	1200
Sandstone	ASTM C 616	1.0	125	350	4000	n/a
Quarzitic sandstone	ASTM C 616	3.0	150	1000	10,000	n/a
Quartzite	ASTM C 616	8.0	160	2000	20,000	n/a
Slate	ASTM C 629	0.25	n/a	7200 to 9000	n/a	n/a
Travertine	ASTM C 1527	2.5	144	1000	7500	1000

Mortar

Mortar is a mixture of cement, lime, sand and water that is installed while still in a plastic state. The mixture then cures (hardens) to a solid state. Mortar is used to separate the masonry units and allows for a construction tolerance without sacrificing contact between the stones. The mortar also helps to bond the masonry units to each other and prevents water from seeping between the masonry units. The mortar should be considered sacrificial to the masonry components and designed to deteriorate sooner that the masonry. (The mortar should have a lesser strength than the masonry units that it joins.) Mortar should be designed to be more permeable than the adjacent masonry to allow water vapor to escape from the masonry units.

There are several ASTM standards for mortar. They include C270 Standard Specification for Mortar for Unit Masonry, C780 Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry, and C1324 Standard Test Method for Examination and Analysis of Hardened Masonry Mortar.

Mortar is comprised of binders, aggregates, and water. Binders typically include Portland cement, lime and other manufactured or natural cements. The aggregates in mortar are sand and pigments if powdered pigments are used to vary color or texture. Masonry structures can be built without mortar. Mortar used in bridges that were built prior to the 1800's is typically either an earth/clay mortar or a sand/lime mortar. Portland cement mortars were not in use until the 1870's. Masonry cement (Type N, M, S & O mortars (referenced in the MBE and ASTM standards) has been used since the 1930's and ready mix mortars have been available since the 1980's.

There are several characteristics of mortar that need to be considered when designing the mix for a masonry arch. The compressive strength of the mortar should always be less than the masonry units that it is connecting. The amount of lime in the mix adjusts the strength, as well as other attributes. Increasing lime content corresponds with decreasing strength of the mix. The mortar is intended to fail before the masonry units. Mortar can be repaired; however, cracking of the masonry units is a much more involved repair.

The tensile strength of the mortar is another design consideration. It is not uncommon (although it is also not desirable) for part of the arch to be in tension. Typically this occurs at the extreme limits of the arch barrel depth, outside of the kern. The kern is defined as the middle third of the arch barrel. In cases where the combined dead and live load thrust falls outside of the kern, sections of the arch are in tension and do not contribute to the load carrying capacity of the arch. Figure 16.9 (right) visually illustrates potential areas where tension can occur due to applied load (shown by red arrow). This sketch is greatly exaggerated to illustrate the point. Imagine a very heavy load passes over the stone arch with such force the arch flattens out. It can still be stable, but the load was so large that it placed portions of the arch in tension (gaps between stones in Figure 16.9 right).

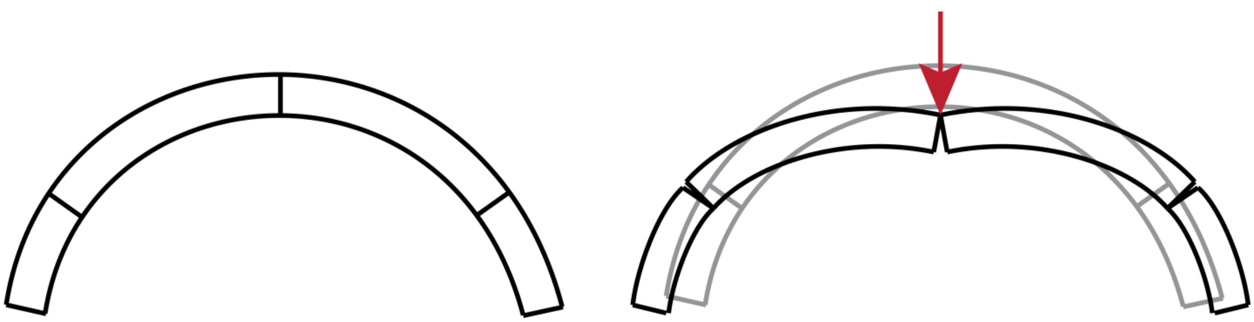


Figure 16.9 Potential Areas of Tension in an Arch

The intent is to provide a mortar that will bond the masonry units to each other if tension is present in the arch. Therefore, cohesion and bond strength of the mortar is another design consideration.

To avoid damage to mortar due to road surface runoff seepage, the porosity of the mortar is designed to be higher than that of the adjacent masonry units. It is important that the mortar accommodates the moisture before the masonry units can absorb it. If the water does seep into the mortar, the durability of the mortar also becomes another consideration. The freeze thaw cycle of water can be detrimental to mortar joints. It can cause cracking and spalling of the mortar in the joints. However, the mortar should still be designed to fail prior to the masonry units.

Several other materials can be added to mortar to adjust its characteristics. Pigments or colorants can be added to adjust the color of the mortar. One common use of pigments is to darken the mortar. This is performed on rehabilitation projects where a previously un-mortared arch requires mortar. The mortar is placed in the joints and then raked back so that the darker mortar is in the shadow of the stones and is therefore less visible. Other common admixtures include bonding agents, masonry cement components, and water repellants. However, on rehabilitation jobs, the use of water repellants in the mortar should be carefully considered so that the porosity of the stone is always exceeded.

Table 16.3 shows the typical mortar types, their compressive strengths, and their typical uses. The schematic in Figure 16.10 explains the benefits of soft mortar versus hard mortar. Soft mortar is considered to be "self-healing", but it has limited compression capacity. Hard mortar is often high compressive strength but brittle. Please refer to Figure 16.10 for further discussion of the benefits soft mortar over hard mortar.

Table 16.3 Mortar Types and Descriptions

Mortar Type	Minimum 28-Day Compression Strength	Description and Use
M	2500 psi	High compressive strength and durability for below-grade applications
S	1800 psi	High bond strength for flexural conditions
N	750 psi	For exposed masonry above-grade
O	350 psi	Soft masonry units

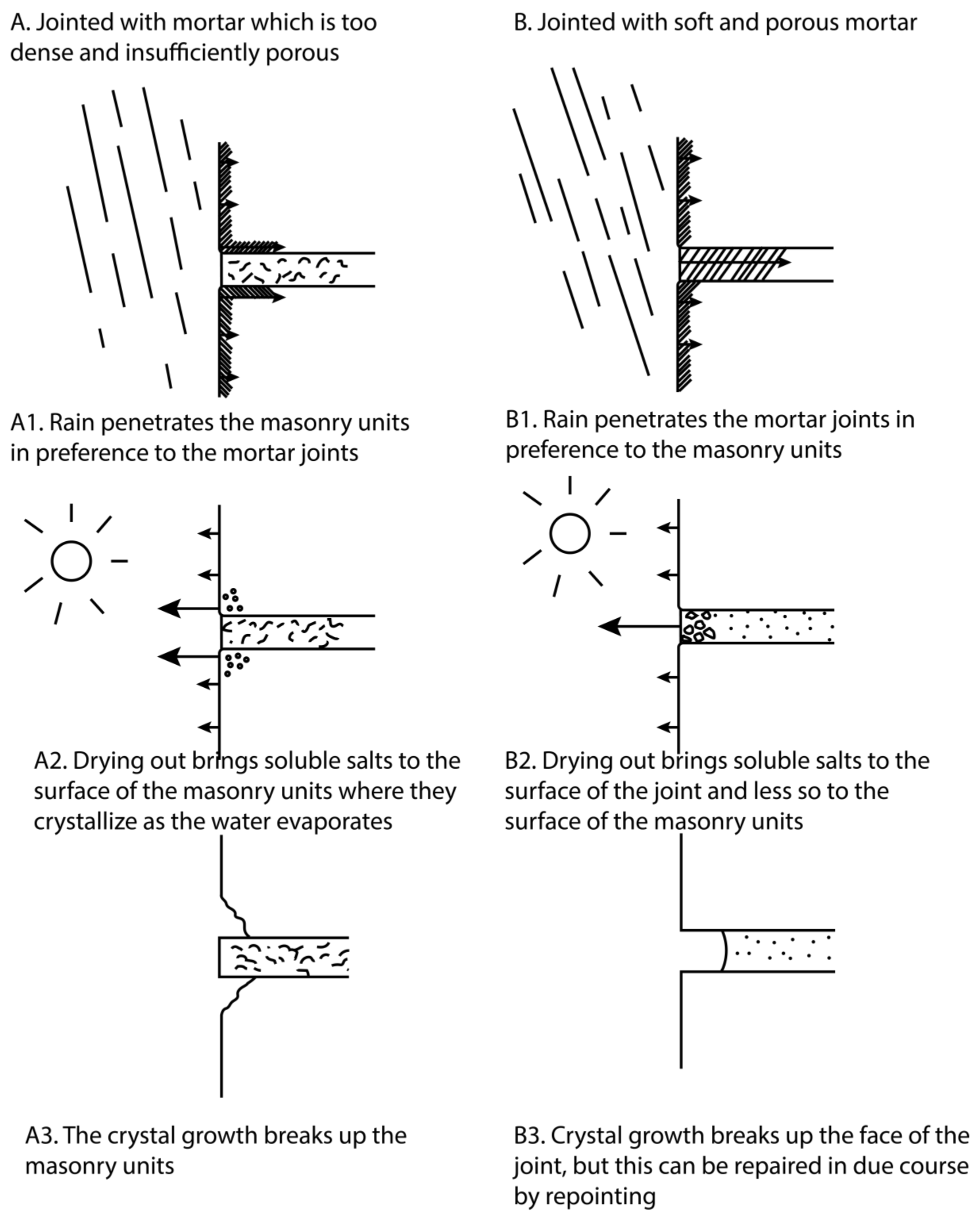


Figure 16.10 Benefits of Hard and Soft Mortar

16.1.5 Architectural Veneer

Architectural veneers are common in bridges. They are used for aesthetic purposes and typically are not a structural element. They are used to cover the structural element in order to form a more pleasing appearance.

Veneers can be mechanically attached by anchors or they can be cast into the supporting elements (see examples shown in Figure 16.11). When they are cast into the supporting element, the only element holding the masonry in place is the bond to the backing element. There is also no way to install drainage. Therefore, use of mechanical anchors is the preferred method to attach masonry veneers.

Figure 16.11 Masonry Veneer Showing Strap Anchors (left) and Under Construction (right)

Masonry anchors are widely variable. Dovetail anchors and masonry strap anchors are both common types (see Figure 16.12). One side of the anchor is attached to the concrete typically by a mechanical connection. The other side of the anchor is placed into the mortar bed between stones. Once the mortar dries, the anchors provide a mechanical connection between the reinforced concrete structural wall and the masonry veneer. An air space can be left between the reinforced concrete wall and the veneer through the use of anchors. The void between the two layers can be used to provide drainage.

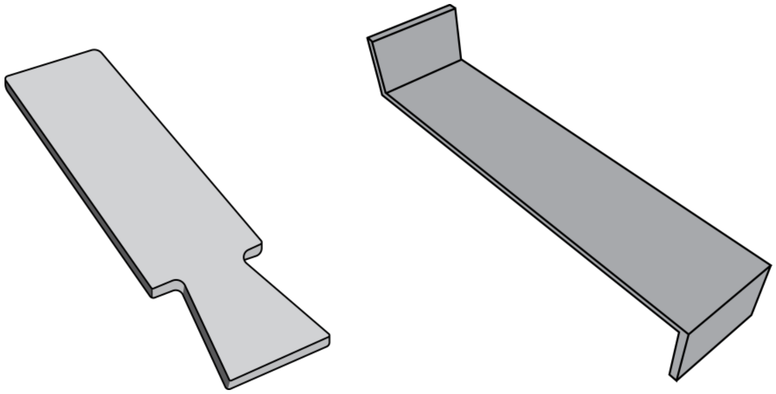


Figure 16.12 Masonry Anchor Types. Dovetail Flat Anchor (left) and Strap Anchor (right).

16.2 Preventative and Basic Maintenance of Masonry Bridges

16.2.1 Inspection

The Federal Highway Administration's (FHWA) National Bridge Inspection Standards (NBIS) require that all bridges be inspected on a two year or lesser interval unless approval from the FHWA is attained for exceeding the two year requirement for a particular bridge.

Inspection and proper documentation of masonry bridges is needed to ensure there are no signs of potential distress and to identify maintenance and preservation needs. Items to look for include:

What To Look For

- Efflorescence
- Splits and spalls of mortar and masonry units
- Deteriorated mortar, cracking in mortar and in masonry units
- Slipped masonry units
- Displacement of masonry
- Scour
- Vegetation growing in masonry
- Evidence of water infiltrating through the masonry
- Impact damage

16.2.1.1 Signs of Potential Distress

Efflorescence

Efflorescence, when present, is indicative of soluble salt migration into the masonry structure. The salt laden water typically seeps into the mortar joints first; therefore water stain and efflorescence is most likely to be first visible in the mortar joints. However, if efflorescence is visibly emerging from the masonry units, the area should be monitored for future deterioration.

Split and spall

Splitting and spalling of the mortar joints is anticipated and can be repaired by repointing if required. If the porosity of the masonry unit exceeds that of the mortar, or if the mortar is harder than the adjacent masonry units, spalling of the masonry units can occur. Both conditions should be monitored and appropriate corrective action should be undertaken when required by the field condition.

Mortar Deterioration

Mortar deterioration is expected to occur over the service life of the bridge. The deterioration itself is not necessarily an issue. However, if the contact between the stones is significantly reduced, if water infiltration is occurring, or if other signs of distress are present, repair of the joint may be required. An example of mortar deterioration is shown in Figure 16.13.

Figure 16.13 Mortar Deterioration (indicated by arrow)

Cracking

Cracking in the mortar is common and is not necessarily a sign of distress for the masonry structure. The mortar is designed to fail in order to alleviate the pressure on the masonry itself. However, if there is cracking in the masonry, there is a condition that needs to be monitored. An example of a crack in masonry is shown in Figure 16.14. Many cracks in the mortar and masonry occur either when the forms are removed or while the arch is being backfilled. These cracks should be noted, but if the condition of the crack (width or length) is not changing, there is most likely no cause for concern. However, if the crack monitoring is noting differences, the crack should be closely monitored and changes in condition should be assessed. Having an engineer review the crack and its effect on the load carrying capacity of the bridge is highly recommended.

When to Call the Engineer

Call the Engineer when an existing crack changes in appearance, either in width or length.

Masonry arches are typically load rated based on an assumed one foot unit width. Any cracks that create segment of masonry smaller than one foot should be noted.

Any cracks in the masonry of a slab bridge should be monitored. Transverse cracks indicate that failure has already occurred. Transverse cracks require immediate attention and shoring or road closure over the cracked slab should be considered, at least until an engineer can make an assessment. Longitudinal cracking in the masonry of slab bridges is not as critical. Each individual slab acts as a unit and the load is distributed over the width of the slab unit. A longitudinal crack reduces the distribution width available and is therefore important to note, but not necessarily critical to the load carrying capacity of the bridge.

Figure 16.14 Transverse Crack in Stone Arch

Slipped Masonry Units

A slipped masonry unit is a stone or brick that is lower than the adjacent stones and one that has displaced below the interior of the arch barrel (or the intrados). Examples of a slipped masonry units are presented in Figure 16.15 and Figure 16.16. Many times the stone slips during construction. This typically only occurs in un-mortared masonry arches and as brick arches are almost always mortared, it is prevalent mainly in stone arches. During a flood event, the fines and chinking stones (small stones used to fill voids between adjacent masonry units) can be washed away causing the stones to loosen in the arch ring. Therefore, monitoring of slipped stones is important after flooding. The slipped stone should be noted and monitored. An engineer should be notified if any change in the condition of the slipped stone is noted. However, the presence of a slipped stone is not typically critical to the load carrying capacity of the structure. Figure 16.15 shows multiple slipped stones, which resulted in arch deformation, this condition is more critical than a single slipped stone.

Figure 16.15 Multiple Slipped Stones

Figure 16.16 Single Slipped Stone

When to Call the Engineer

If masonry displacement is observed, the Engineer should be called prior to beginning repairs.

Missing Masonry Units

One modification historically made to masonry bridges is the removal of masonry units for the installation of utilities or drainage. Typically, the arch (or the soil in a slab bridge) is able to create an "arching effect" over the missing masonry units. The condition should be noted, but is not typically critical to the load carrying capacity of the bridge. An example of missing stones at a drainage pipe is shown in Figure 16.17.

Figure 16.17 Missing Stones in a Masonry Arch

Masonry Displacement

Masonry displacement, or arch deformation, is an indicator that failure of the masonry arch has occurred. Typically the deformation is localized, but the arch requires immediate attention. Barriers to keep traffic away from the deformed section or temporary shoring may allow sections of the arch to remain in service, but repair should be given priority. An example of masonry displacement is presented in Figure 16.18.

Figure 16.18 Arch Deformation caused by Masonry Displacement

Scour

One sign of potential distress, especially in arches, is scour. Scour is the erosion of the channel bed. Scour is critical if it occurs adjacent to the footings. If the soil behind the arch is scoured away, the integrity of the arch is compromised. The soil behind the arch is used to resist the thrust from the arch and prevent the arch footing from kicking out. As many masonry bridges do not have mortared stones, scour holes can provide a weakness in the foundation that allows the foundation to displace, therefore causing a displacement in the arch or and slab bridge foundation. Undermining can also occur to the foundation elements if scour is allowed the go unchecked.

Stream beds are dynamic and it is not uncommon for scour holes to form during high flow condition and then be filled back in by material suspended in the water settling back out during normal flow. If silt deposits are found during wading, probing and/or underwater bridge assessment, further investigation may be required to determine if a scour condition is present.

Scour should be closely monitored or repaired depending on its severity.

16.2.1.2 Condition Assessment

Visual Inspection

Visual inspection is very important for masonry bridges, as most of the potential signs of distress can be discovered with a visual inspection. During the inspection, it is also important that vegetation be removed or noted for future removal.

Wading/Underwater Inspection

Underwater inspection is used to determine stream bed erosion. Scour, and eventually undermining of the footings, can occur if the erosion is allowed to continue. Scour monitoring charts which document the stream bed condition over time are an important tool for inspectors. Scour monitoring charts consist of stream bed profiles taken upstream and downstream of the bridge and in other critical locations to monitor any changes in the stream bed profile.

Test Pits

Test pits are recommended for masonry structures for condition assessment and composition determination. As masonry structures are typically old, it is uncommon for plans to be available. If adequate determination of the structure cannot be made from below, then a test pit is recommended. Masonry units are sometimes used as a veneer over a reinforced concrete arch. Without the test pit, the inspector would have limited information to determine what the structural components actually are. The thickness of the arch ring is another component that a test pit is used to discover. Often times, the outside ring of the arch is decorative and may not be made of the same material or thickness as the interior part of the structure. Test pits are also used on masonry substructures to determine the limits and the presence of a batter. A batter is a vertical slope to the masonry structure that has a horizontal component. Probes, borings and cores can also be used to determine the extents of an existing masonry substructure. An example of a test pit is shown in Figure 16.19.

Figure 16.19 Test Pit

As the top of the masonry structure is typically exposed to more salt (that migrated from the roadway above) than the underside, the test pit can also be a way to determine the condition of the extrados of an arch bridge or top of a buried slab bridge. If efflorescence is present on the underside, test pits to expose the top should be considered.

Inspection Openings and Cores

Masonry arches are sometimes comprised of multiple layers. Sometimes the layers are all of the same material, but other times the material visible from the outside is only a veneer. Inspection openings can be used to determine the material composition of the structure. The inspection opening is created so a visual assessment and measurements can be made. The opening is then patched. An example of an inspection opening is presented in Figure 16.20.

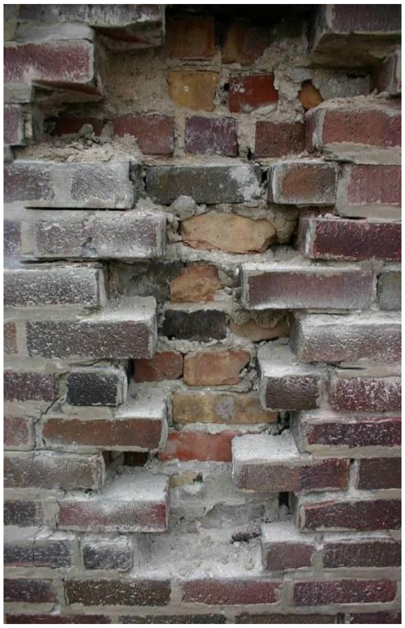


Figure 16.20 Inspection Opening

Cores can also be used to determine the thickness and the material composition of a masonry structure. If the core is taken along the joint of masonry units, the contact area can be determined. Cores can be tested to determine the strength of the masonry units and the degree of contamination (chlorides, etc.) in the masonry if applicable. An example of core removal is shown in Figure 16.21.

(a) (b)

Figure 16.21 Masonry Cores (a) Removing the Core and (b) Finished Masonry Core

Non-destructive Testing

Non-destructive testing can also be used to determining the composition and quality of the masonry structure. Typical methods for non-destructive evaluation of masonry structures include impact echo testing and ground penetrating radar, as described below.

Impact echo testing is a common method of evaluation for both concrete and masonry structures. Impact echo testing uses impact generated sound/stress waves. The waves pass through the structure until they are interrupted by either internal flaws in the structure or by the structure ending. Impact echo can be used to determine the thickness of the masonry unit. Impact echo can also be used to find cracks, delaminations, voids, or other deficiencies in the masonry structure. Impact echo testing principles and in practice are shown in Figure 16.22.

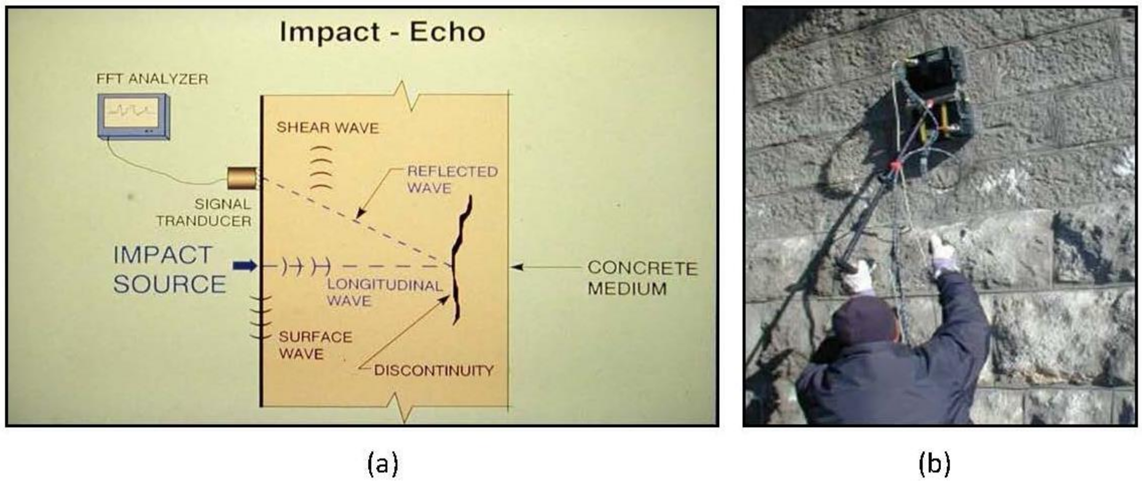


Figure 16.22 Impact Echo Testing (a) Schematic and (b) In Practice

Ground penetrating radar is another common method of non-destructive testing for masonry bridges. Ground penetrating radar is similar to impact echo except that it uses electromagnetic radiation, as opposed to sound waves, to generate its data. Ground penetrating radar can also be performed from the ground surface where impact echo requires application of the impact to the masonry structure. An example of ground penetrating radar application is presented in Figure 16.23.

Figure 16.23 Ground Penetrating Radar Testing

16.2.2 Maintenance

Removal of Foreign Material / Vegetation

One of the most important maintenance procedures on masonry bridges is the removal of foreign material and vegetation. Dirt and debris can trap moisture and accelerate the freeze / thaw deterioration cycles. Vegetation also causes problems with the continued performance of the structure. The roots are destructive as they can grow through the structure in their search for water. They can cause displacement of the stones. Additionally, when trees fall, they can further damage the masonry structure. An example of vegetation growing through masonry joints is presented in Figure 16.24.

It is also important that vegetation and foreign material be removed from the stream, if applicable. This material can cause the stream to re-route causing potential scour and undermining problems. Additionally, the foreign material can cause the stream to flow at a higher elevation which can erode the mortar (or fines) between the stones. The water can also overtop the roadway, causing displacement of the spandrel walls as well as accelerated deterioration to the structure.

Figure 16.24 Vegetation Growing Through Masonry Joints

Cleaning

Cleaning of masonry structures is important to remove efflorescence and soluble salts from the surface of the masonry units and mortar. Cleaning can also be an important tool in determining the type of stone used in the masonry structure. Over time, most stones weather to a gray color similar to that of granite. By cleaning the stones, the true surface of the stone can be exposed. It is recommended that several stones are cleaned (a wire brush and water are typically adequate) and assessed prior to determination of material composition. Low pressure power washing (less than 400 psi) is also acceptable, however the use of high pressure water is not recommended as the high pressure water (over 400 psi) can actually damage the masonry structure and the mortar joints. An example of cleaning with low pressure water is shown in Figure 16.25.

Figure 16.25 Cleaning with Low Pressure Water

Arresting Water Infiltration

When water seeps from the surface of the roadway to the masonry structure, it brings salt and other contaminants with it. These contaminates can shorten the surface life of the structure. Cleaning out adjacent drainage structures, removing debris that may be impeding the travel of runoff from the bridge, and patching the pavement are all routine maintenance procedures that can increase the service life of the masonry structure. A possible result of water infiltration is shown in Figure 16.26.

Figure 16.26 Evidence of Water Infiltration

16.3 Repair and Rehabilitation of Masonry Bridges

The intent of repair and rehabilitation of masonry structures is to extend the service life of the bridge, correct a deficient condition, or to bring the bridge up to current standards (such as changing the crash barrier). As many of the structures are historic, it is important to match the existing structure or to repair it in a way that is sensitive to the historical significance. However, public safety is still the first priority.

16.3.1 Repointing of Mortar

Mortar is a sacrificial element of a masonry bridge, and it is anticipated that it will need to be repointed over time. However, keeping the mortar in good repair is an essential aspect of extending the life of a bridge.

Depending on the age of the structure and the preferences of the designer or mason, a variety of binders could have been used in the original construction. The type of binder significantly affects both the characteristics and the performance attributes of the mortar. For example, mortars made with lime binders tend to have a lower compressive strength, lower bond strength, and greater permeability than mortars made with Portland cement as the binder. Mortars with a high lime content also have the ability to re-seal small hairline cracks. This allows the mortar to provide greater resistance to rain penetration and allows the moisture to escape after it has penetrated. However, the high lime content also delays curing of the mortar and the time it will take for the mortar to reach full compressive strength.

When designing the mortar mix, it is very important that the new mortar have a lower compressive strength than the units that it will be connecting (as previously mentioned). The mix must have a greater porosity than the adjacent masonry units. As not all of the mortar is removed in the joints, it is also important that the proposed mortar be compatible with the existing mortar. It is recommended that the mortar be replaced only if there is evidence of deterioration. Therefore, it is also important that the proposed mortar have a similar cured appearance to the existing mortar, especially if aesthetics are a concern.

Recommended repair method is as follows:

Suggested Procedure

Mortar Repointing

1. It is recommended that 2 to 2-1/2 times the thickness of the mortar or a minimum of 3/4 inch (whichever is greater) be removed for repair. This will ensure the replacement mortar has adequate bond area. The mortar should be removed using hand tools or a small pneumatic chisel. The use of power tools such as a grinder is not recommended because it is difficult to control and can result in damage to the adjacent masonry units. Square cuts at the limits of the removal are recommended. Figure 16.26 demonstrates the recommended mortar removal.
2. Debris should then be removed from the joint. This can be accomplished using a nylon brush, low pressure compressed air (40 to 60 psi) or low pressure water (less the 400 psi). Care should be taken during the removal of the debris to ensure that additional mortar depth is not removed by the debris removal process.
3. Any loose stones should be carefully removed, cleaned, and re-set prior to repointing.
4. Mortar used for repointing should be stiff, as stiff mortar will shrink less as it cures. Mortar should not be allowed to dry out during use and should be reworked at intervals prior to being placed in the joints. Retempering (or adding additional water) to the mix is not allowed. Repointing should not be done if the temperature is below freezing. To help control suction and evaporation of the water from the new mortar, the existing stones and mortar should be wetted to Saturated Surface Dry (SSD) prior to the placement on any new mortar.
5. The mortar should be applied by hand and in 1/4 inch lifts (especially in the last 1-1/2 inch to be repointed) as shown in Figure 16.27. Thicker lifts and use of a pressure gun (or grout gun as shown in Figure 16.28 and Figure 16.29) to apply the mortar (or grout) can be used behind the final 1-1/2 inch if required. All lifts should cure to thumbprint hardness prior to the application of the next layer as shown in Figure 16.30.

Immediately after repointing, the masonry units should be cleaned of all excess mortar. Application of a bond breaking agent, such as paraffin wax, to the face of the masonry units can aid in the clean-up process. (Figure 16.29 shows the wax on the face of the stones). It is recommended that use of metal tools or chemical cleaning agents be avoided unless tests to determine their effect on the masonry units have been performed and no adverse effect is noted.

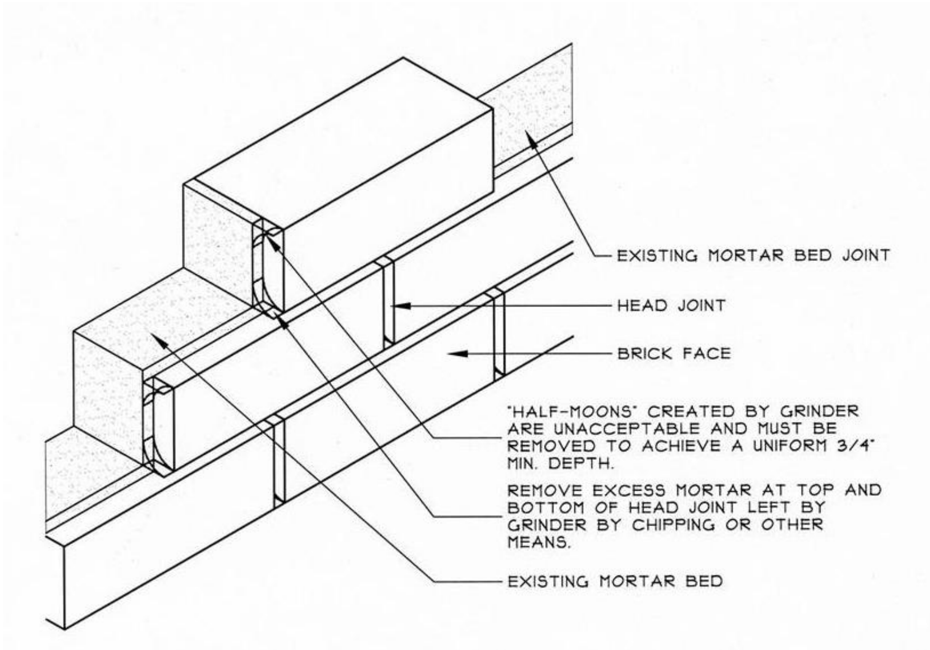


Figure 16.27 Preparation for Mortar Repointing

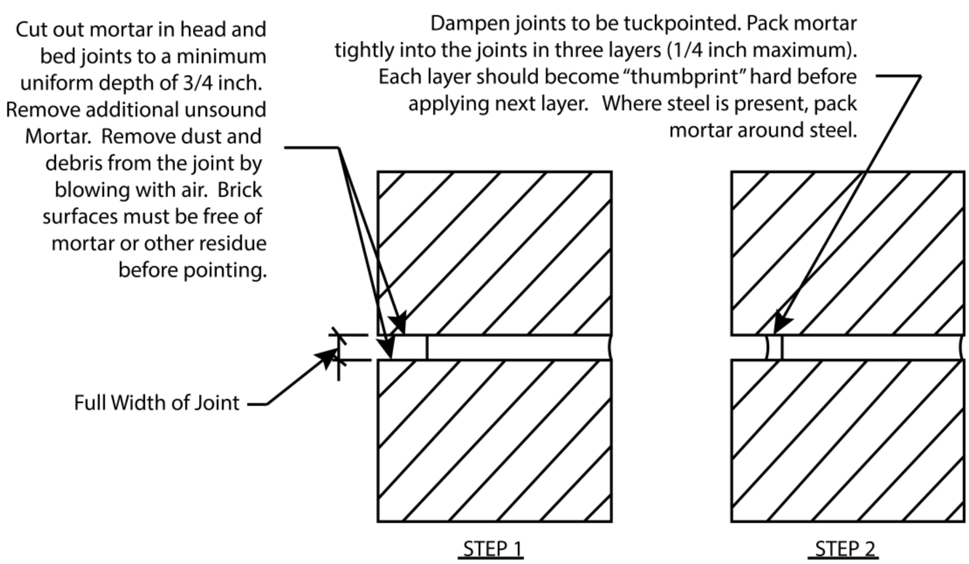


Figure 16.28 Mortar Repointing Schematic

Figure 16.29 Pressure Injection of Mortar (Note presence of paraffin wax on stones)

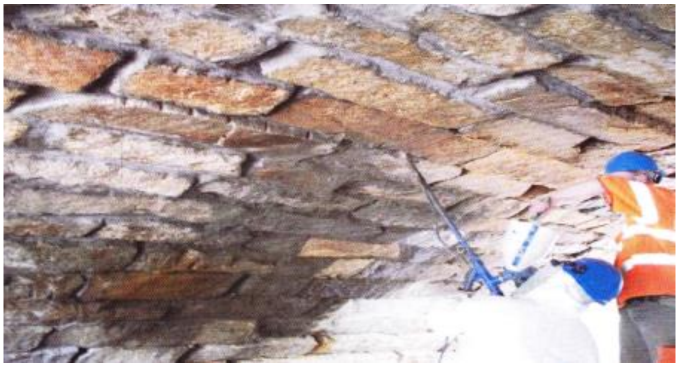


Figure 16.30 Pressure Injection of Mortar (Smaller nozzle size for neater application)

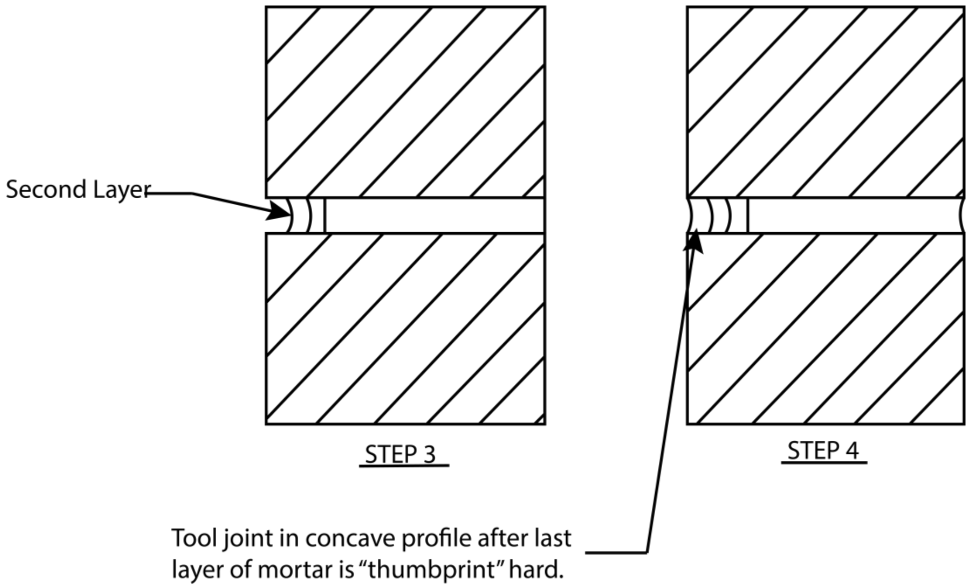


Figure 16.31 Mortar Repointing Schematic Showing Proper Geometry of Layers

16.3.2 Removal of Shotcrete Coating

The application of exterior coating, such as shotcrete, to masonry structures can trap moisture. The trapped moisture makes the structure more susceptible to frost damage. Frost can cause cracks in the coating (as shown in the example in Figure 16.32) and in the bridge mortar. The cracks then allow more moisture to enter, which then enlarges the crack during the freeze / thaw cycle. The coating can also trap moisture between the masonry units and the coating. If the coating does not allow the masonry units to dry out, spalling and delamination of the masonry units can occur. Additionally, this coating hides potential problems and signs of distress from the inspector, making visual inspection a much less effective tool.

It is recommended that gunite or shotcrete coating be removed when signs of distress are found. Wetness along the joint or efflorescence is often the first sign that the coating has water trapped behind it. Removal of the coating should be achieved through the use of hand tools or small pneumatic hammers and care should be taken to remove the coating without damaging the masonry units. Any damage that occurs to the masonry joints should be repaired by repointing.

Figure 16.32 Evidence of Degraded Shotcrete Coating. Macro View (left) and Magnified View of Inset on Left Showing Cracks and Efflorescence (right).

- Care should be taken when the coating is removed. The surrounding surfaces should be continuously monitored to ensure that the coating is not delaminating and potentially detaching, a dangerous situation which could cause a sudden collapse of a large section of the coating and injury to the workers. If any masonry units fall out during the removal of the coating, they should be replaced (see missing stone repair procedure outlined below).
- After the coating is removed, it is recommended that the surfaces be cleaned using a light abrasive blast cleaning (below 400 psi) to remove any remaining film and chisel marks. However, if damage to the masonry units is occurring, the process should be immediately stopped and another method of cleaning or a discontinuation of the cleaning should be performed. Low pressure water (preferably demineralized) should then be used to finish cleaning the surfaces. If repointing is required, follow the procedure in Section 16.3.1.

16.3.3 Repair of Spalling or Delaminated Masonry Units

Spalling occurs when the exterior face of the masonry unit begins to flake or chip off. Delamination occurs when the masonry unit separates into constituent layers. If the spalling or delamination is extensive, replacement of the whole area may be required. However, if the damage occurs over a small area and there is no evidence of water infiltration, repair can be accomplished.

The recommended repair is to use mortar to patch the face. The repair is typically completed for aesthetic purposes only. If the spalling is widespread enough to be a structural concern, in the opinion of an engineer, the delaminated stones will most likely require replacement. Please refer to section 16.3.4 for information on replacing stones. The mortar mix should be designed to match the color of the adjacent stones and finished to match the texture. The face of the masonry unit to be repaired should be cleaned with a wire brush, low pressure compressed air, or low pressure water prior to the mortar being applied. After the mortar has cured, the adjacent mortar joints should be repointed. At a minimum, mortar lines should be scribed to represent the joints.

16.3.4 Repair of Missing Masonry Units

This treatment is intended to replace a single stone or small group of stones. If larger areas of stone are missing or loose, a more extensive rehabilitation or restoration of the masonry is required. Missing stones can be indicative of a serious problem with the bridge, such as water infiltration. Therefore it is recommended that the underlying cause of the missing stones be discovered and addressed prior to replacing the stones.

If the original stones can be found, it is recommended to use the original stones in the replacement. If not, it is recommended to find stones that match the original stones. Clean the area where the stone will be replaced. Apply a bedding mortar (a layer of mortar that is applied below the masonry unit to be set) in the area of the stone to be replaced. Carefully reset the stones ensuring that they are well bedded. Take care to protect the adjacent masonry units. It may be required to shore the masonry unit in place until the bedding material and potentially the mortar used for repointing have cured. After the bedding mortar has cured, repoint the masonry joints following the repointing procedure provided in Section 16.3.1.

16.3.5 Repair of Slipped Masonry Units

It is recommended that loose slipped stones be removed and replaced (see missing stone procedure above). If the slipped stone is locked into its location and does not create a structure deficiency, it is recommended that it be left in place. The mortar adjacent to the slipped stone should be repointed (or pointed) to further help secure the slipped stone.

16.3.6 Repair of Cracked Masonry Units

Slab bridges that have transverse cracks cannot be repaired. Temporary shoring can be used until a permanent solution can be found, but the cracked slab requires replacement. Longitudinal cracks in slabs and cracks in arch barrels are not typically structural detriments and can be repaired.

- If there is water leaking through the crack, if must be addressed prior to repair of the crack (see water infiltration above). Only repair the crack after water no longer escapes through it. Mortar injection can be used to repair the crack without having to excavate over the bridge.

- The joint must be cleaned using hand tools, low pressure compressed air, low pressure water or vacuuming. Mortar injection ports should then be affixed into or onto the crack. Make sure that there are ports attached at the ends of the crack to ensure complete filling. For cracks less than 1/4 inch wide, space the injection ports no further than 2 feet apart. For cracks over 1/4 inch wide, the ports can be spaced up to 3 feet apart.
- After the ports have been installed, the crack can be sealed using a stone patching grout. The injection should begin at the wider end of a horizontal crack or at the lowest point of a sloping or vertical crack. Adjacent stones should be monitored during the pressure injection to ensure there is no movement. If any movement is found, immediately stop the pressure injection.
- The grout should be placed in the first port and the filling should continue until it starts leaking out of the next port. The leaking port should then be temporarily capped and the filling should continue until maximum pressure is reached (5 psi, as shown on a pressure gauge). Only then should the pressure injection be moved to the next lowest port and the first port sealed. After the grout has cured, carefully remove the injection ports and fill the holes with grout or mortar.

16.3.7 Arch Deformation Repair

If the deformation of the arch is not detrimental to the structural capacity of the arch, as determined by an engineer, then the stones can be repointed to prevent further displacement of the masonry units. However, if the structural capacity of the arch does not meet the safety requirements for the structure, more extensive rehabilitation is required. (Presented in detail in an ensuing section)

The recommended repair for the displaced stones is the application of mortar or grout with a pressure gun to penetrate as far as possible into the joints. The last 1-1/2 inch of the joints should be repointed by hand (repointing procedure described in Section 16.3.1).

16.3.7.1 Relieving Slabs

One method of repairing an arch that had insufficient structural capacity is the installation of a reinforced concrete relieving slab, as shown in Figure 16.33. The purpose of the relieving slab is to help distribute the live load to the arch. The relieving slab distributes the live load over a wider area than either a directly applied point load (less than 2 feet of fill) or a pressure based on distribution through over 2 feet of fill. AASHTO LRFD Manual provides further information in the buried structure section, Chapter 12.

Figure 16.33 Reinforced Concrete Relieving Slab (Under Construction)

16.3.7.2 Moment Slabs

A common problem with masonry bridges is the lack of a crash tested barrier system and the difficulty inherent in attaching one. One possible solution is the use of a moment slab, as shown by the example in Figure 16.34. The moment slab can be placed over a masonry bridge if there is sufficient fill, as shown by the example in Figure 16.35, or it can be placed around an arch if the geometry allows.

Figure 16.34 Reinforced Concrete Moment Slab (Under Construction)

Figure 16.35 Moment Slab (indicated by arrow)

16.3.7.3 Repairing an Arch if Fill is Removed

Repairing an arch by removing the fill should only be undertaken if all other options have already been exhausted. A Professional Engineer should oversee be involved in the design and construction of this work. Prior to any excavation, the use of formwork should be investigated to determine its necessity. The barrel may appear to be stable when construction is first started; however, as the fill is removed over the arch, it is likely that the stones will shift. It is extremely important that the fill be removed from both sides of the arch in equal lifts as the unbalanced loading is detrimental to masonry arches. Shoring the arch can help to alleviate some of these concerns.

If construction vehicles will be traveling over the arch when fill is removed, or if the depth of fill in the final condition (after the work is complete) is going to vary from the existing condition, it is extremely critical that the arch be analyzed for the revised depths of fill. Masonry arches are very sensitive to variations in the depth of fill and even small changes can be detrimental to the structure.

One possible method of repair is to install a concrete saddle over the extrados of the arch. The concrete saddle is concrete that is poured over the arch to strengthen the arch and lock the masonry units into place. The concrete saddle can either be used over a deteriorated portion of the arch or over the full structure. However, since it is necessary to remove the soil over the arch for the installation of a concrete saddle, the preferred method of strengthening a solid structure that is structurally deficient for current loading is to install a relieving slab to help distribute the load (refer to Section 16.3.7.1). The purpose of the saddle is to reinforce the area where the saddle is applied, as well as to help distribute the load around the damaged area.

Excavation over the arch can also be required for the installation of a relieving slab or to remedy drainage and water infiltration problems. In any case where fill is removed, it is recommended that well graded fill be used to replace the existing material. Use of a geotextile material for separation is also recommended.

16.3.8 Scour Protection

Substructure failure due to channel scour can cause catastrophic collapse of a masonry bridge. The substructure of a masonry bridge is typically comprised of unconnected masonry units. The small units are much less likely to be able to span over a scour or undermining hole than a reinforced concrete footing. Masonry bridges are therefore much more susceptible to scour damage. Once the stones begin to settle into the undermined area, continuity is lost and an accelerated loss of stones is likely to occur. If unchecked, collapse of the arch barrel is likely.

Scour holes should be filled with large granular material (6 inch to 8 inch minimum stone size). The actual required stone size should be sized by a hydraulic engineer. Higher velocity streams require larger stone sizes. If undermining of the substructure has occurred, it must be repaired by placement of concrete under the undermined area or another acceptable repair.

If undermining of the arch has occurred, there are several methods that can be used to fill the voids.

- Grout bags can be placed in the voids
- Tremie placed concrete can placed in the voids
- Pressure injected grout can be used to fill the voids

- Construct cofferdam, dewater, and pour subfooting

Typically a combination of the above methods will be required by the engineer. Dewatering is required. Refer to Chapter 4 and Section 13.4.8 for further guidance on scour and undermining repair.

When to Call the Engineer

Call the Engineer for guidance on undermining repairs.

16.3.9 Repairing Masonry Veneers

Masonry veneer failure is typically more of an aesthetic concern than a structural concern. However, masonry falling out of the veneer can be a safety concern. The masonry veneer should be sounded to determine the extent of the delamination. Anchors can be installed to re-attach the veneer to its supporting wall if the veneer is delaminated, but has not yet fallen. The sketches on the following pages in Figure 16.36 through Figure 16.38 illustrate several methods to re-attach the veneer. Figure 16.37 shows an expansion anchor suitable for use in a solid backing substrate.

If a masonry veneer has fallen away from its supporting wall, then re-construction will be necessary. Prior to starting any reconstruction, it should be determined if the area surrounding the failed area is structurally sufficient. Soundings can be taken around the area requiring repair to determine the integrity of the surrounding veneer. The surrounding area should then be shored as required. After the shoring has been completed, the veneer can be reconstructed. The use of anchors is highly recommended in the replacement of the veneer. Please refer to section 16.3.4 above for additional direction on the replacement of the missing masonry units.

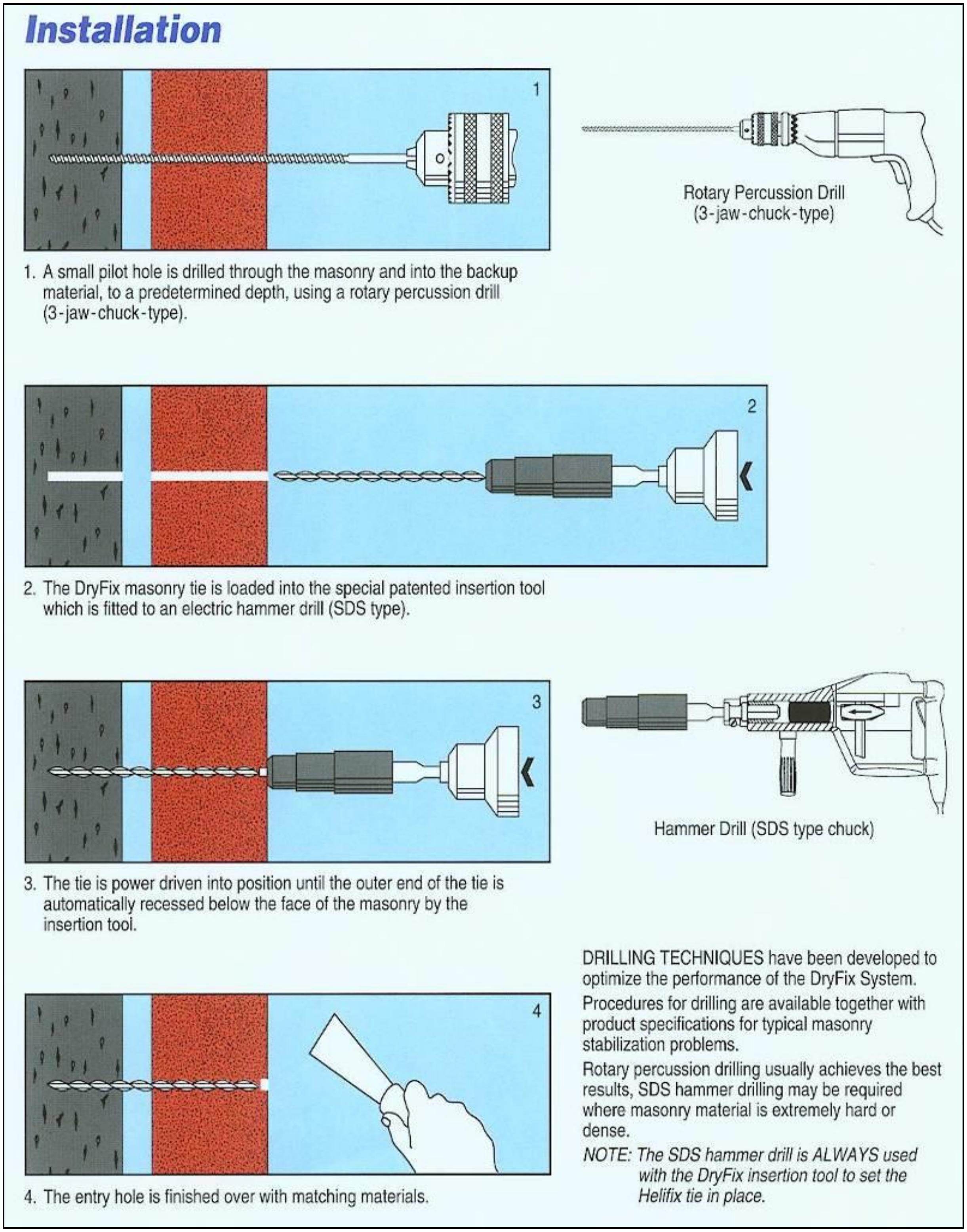


Figure 16.36 Installation of Helical Anchor

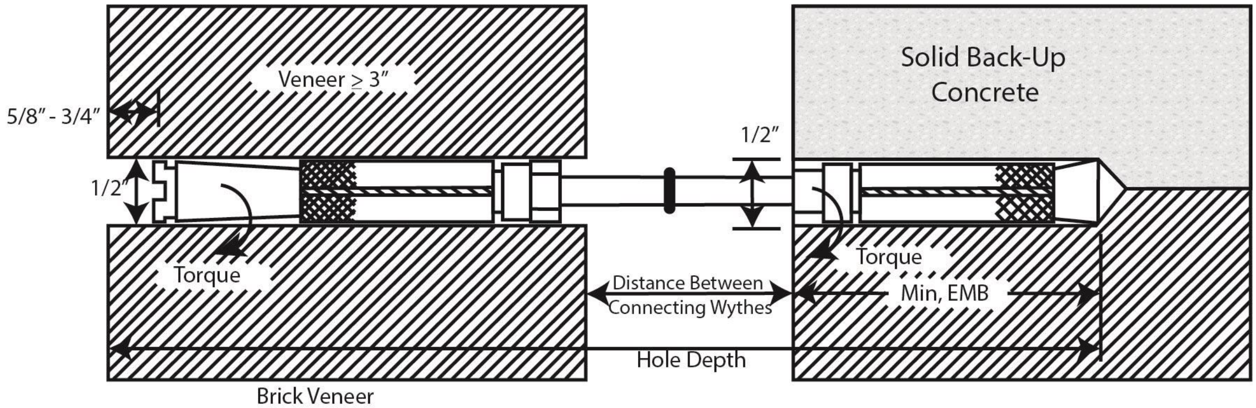


Figure 16.37 Expansion Anchor for Masonry Veneer Repair

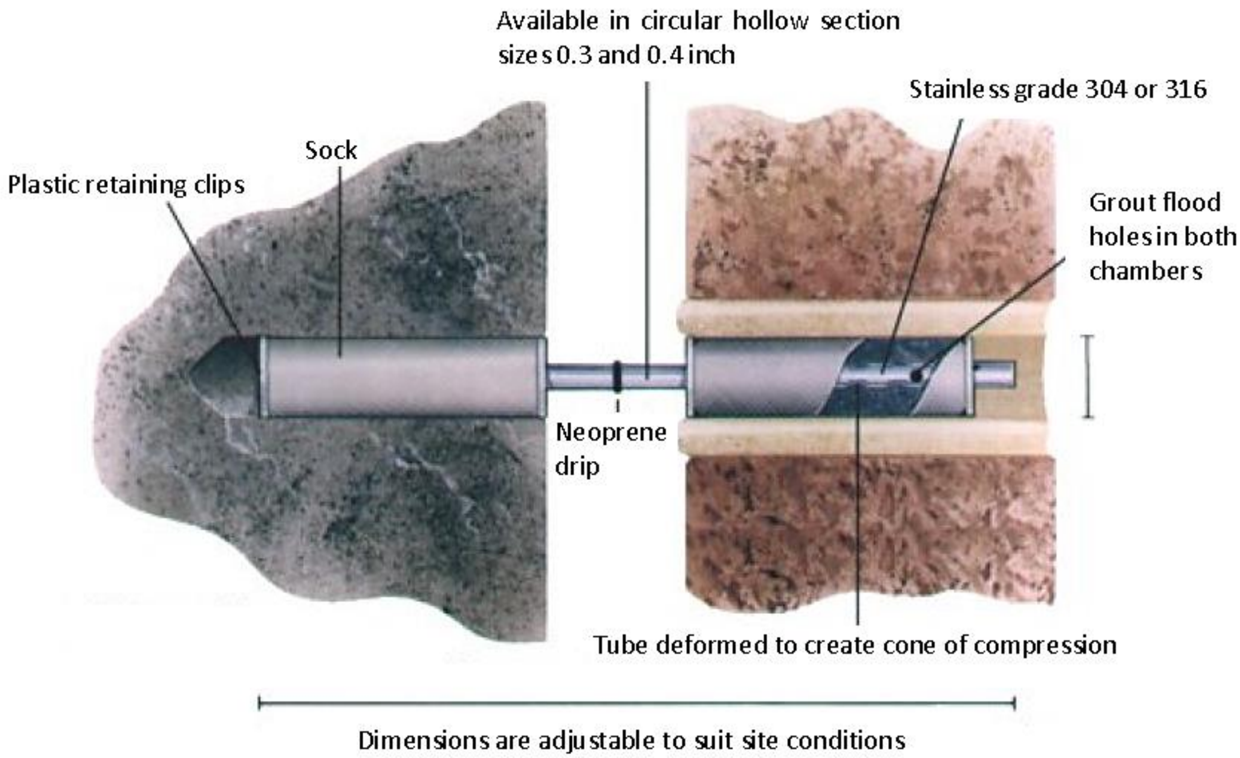


Figure 16.38 Masonry Veneer Repair with Adhesive Anchor

16.4 Chapter 16 Reference List

1. FHWA. *Bridge Rehabilitation Evaluation & Design Course.* NHI Course 134062 Instructors Guide, Publication No. FHWA-NHI-08-009. Washington D.C.: United States Department of Transportation, November 2007.
2. Ohio Department of Transportation, Office of Environmental Services. *Ohio Historic Bridge Maintenance & Preservation Guidance*. June 2010, http://www.dot.state.oh.us/Divisions/Planning/Environment/Cultural_Resources/HISTORIC_BRIDGES/Documents/OhioHistoricBridgePreservationManual910.pdf
3. Pennsylvania Department of Transportation. *PENNDOT Stone Arch Bridge Maintenance Manual.* Engineering District 6-0, October 2007.