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Assessment and Retrofit of Masonry Structures

Retrofit

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University of Minnesota
Driven to Discover®

CHAPTER 5

Retrofit

Masonry building retrofit

Content

Introduction

Need

- Retrofit is needed when a deficient condition is identified during the assessment process, resulting from application of diagnostic approaches, engineering analysis, and consideration of codes and guidelines. A singular generalized retrofit methodology is difficult to develop due to the varying types of masonry materials, construction typologies, structural loads, and environmental exposures that exist throughout the built environment. The designer must, instead, rely on engineering knowledge, judgment, and experience to arrive at a viable solution.
- There is a wide range of approaches to repair and strengthening existing masonry construction, and the chosen approach will depend on available budget, architectural considerations and constraints, and expertise of contractors available to implement the work. Special considerations also exist for treatment of historic masonry.

Terminology

- Different terms are used to describe interventions with existing structures depending on the need for intervention and the approach used to achieve certain performance criteria. Retrofit is used herein as a generic term to include strengthening, upgrading, repair or rehabilitation.
- More specific definitions, included in the next few slides, were developed by The Masonry Society's Existing Masonry Committee based on industry publications and popular usage.

...Terminology

- **Retrofit**: Adaptation of a system to meet contemporary requirements by addition of new materials or components not provided at the time of original construction.
- **Rehabilitation**: The act or process of restoring a structure to a state of utility through repair, alteration, or addition, which makes possible an efficient contemporary use. Portions or features that convey historical, cultural, or architectural values are preserved.
- **Repair:** To bring an item to an acceptable condition by the renewal, replacement, or mending of damaged or distressed parts, including replacement in kind with compatible substitute materials.
- **Restoration**: The act or process of accurately re-establishing the form and details of a structure, site, or artifact as it appeared at a particular time, by means of removal of later work or by the reconstruction of earlier work.

…Terminology

- **Preservation**: The act or process of applying measures to sustain the existing form, integrity, or materials of a building, structure, or artifact. These measures focus on ongoing maintenance and repair rather than on extensive replacement and new construction.
- **Conservation**: To prevent damage or loss to an item while maintaining traditional style and appearance.
- **Adaptive Reuse**: Alteration of a building or system to accommodate a new function or usage.
- **Maintenance**: The effort required to limit deterioration of an element's physical appearance or structural integrity, carried out in an effort to preserve building materials and limit the need for repairs.

….Terminology

- **Strengthening** or **upgrading** are additional terms used in the industry to describe measures to enhance structural performance.
- The term **strengthening** is used when describing measures to improve performance of the structure not satisfying the project requirements at the time of design and construction.
- **Upgrading** describes the process of enhancing performance in cases where the structure does not meet new requirements introduced after construction such as when building function is changed or when new code provisions are introduced.

General Retrofit Objectives

A successful retrofit program begins with clearly defining project objectives. Primary retrofit objectives most often concentrate on meeting life safety requirements for both structural capacity and architectural performance, as dictated by codes and guidelines. Renovations, additions, or other work may trigger the need for the entire structure to meet current building code requirements, depending on the scope of the project related to overall building worth

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…General Retrofit Objectives

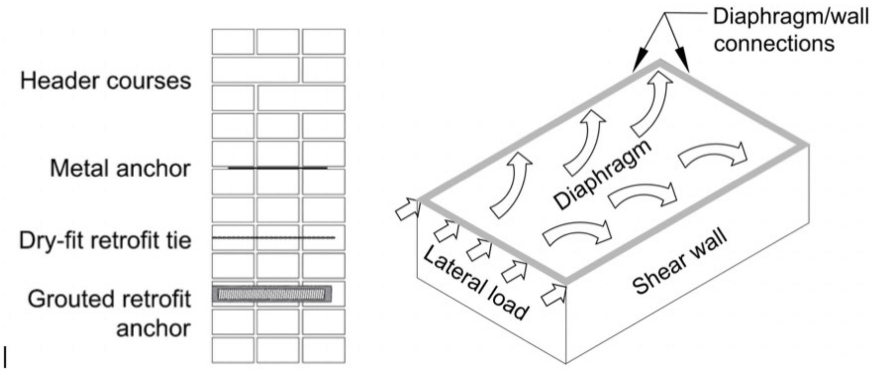
- Other important project objectives include meeting project budget and schedule, maintaining or improving serviceability, increasing energy efficiency, and addressing historic preservation requirements.

- Retrofit is sometimes required to enhance masonry strength and/or deformation capacity due to inadequate original construction, change of use, increased loads, load path modifications, and new building code requirements.

Objectives : Local/Element and Global/System

Local: With masonry construction, the primary retrofit objectives are typically related to ensuring monolithic or composite action in multi-wythe walls, providing for structural load path continuity, enhancing structural capacity from the standpoints of strength, deformation capacity, and ductility, and repairs to address damage or deterioration.

Global: Establishing load paths and ensuring composite action are accomplished primarily by ensuring proper connections at the local and global levels



(a) Wall section (b) Building layout

Increasing Seismic and Blast Performance

- When retrofitting to improve seismic and blast performance, increasing strength alone is usually not sufficient, and retrofit should focus instead on improving the structure's deformation capacity. This usually means introducing ductile reinforcing elements but may also include altering component response to deformation-controlled mechanisms rather than strength-controlled mechanisms.

- It is possible to increase strength while decreasing ductility and the retrofit process must include analysis of the retrofitted elements to determine their effect on element ductility. For example, adding vertical reinforcement to increase masonry pier resistance to in-plane flexure may result in a brittle shear mechanism controlling ultimate performance.

Improving Seismic Performance

- For static loading conditions, it is possible to individually analyze and treat structural elements and assemblages. Analysis involving seismic and other transient loads must study the response of the entire structural system to ensure adequate strength and deformation capacity, and to properly determine the distribution of lateral loads.
- Retrofit will alter local member stiffness and care must be taken to avoid introducing unwanted torsional effects due to a shift of the structure's center of rigidity. When strengthening individual structural elements, other elements are sometimes intentionally weakened or made to be more flexible to reduce torsional effects.

Historic Conservation Principles

When retrofitting historic construction, the designer has a duty to not only meet life safety requirements but to also maintain historic features. Preservation objectives are met by following conservation principles including the concepts of :

- **Minimizing interventions**
- **Material compatibility**
- **Reversibility**
- **Authenticity**

Historic Construction Guidelines

- The U.S. Secretary of the Interior's Standards provide guidelines for retrofit projects involving historic construction. These standards include requirements to retain historic features, protect and maintain existing materials rather than replacing with new, minimizing the extent of any intervention, and designing repairs to duplicate materials and appearance.
- These philosophical objectives are critical for guiding retrofits on projects involving historic masonry, but the concepts are also valid for projects involving non-historic construction.

Life Cycle Expectations

- The primary objective for retrofitting historic construction is perpetuation of the historic resource. The choice of appropriate retrofit materials and techniques is guided by a design life cycle that is often expressed in the range of 50 to 100 years or more, limiting approaches to those that have proven durability and longevity. Using new materials and methodologies with unproven durability is typically not permitted.

- Retrofit materials are chosen to match the design life cycle. For example, unprotected carbon steel is susceptible to corrosion and may deteriorate in a matter of decades. Highly durable reinforcing materials are used instead, including stainless steel, epoxy-coated or galvanized carbon steel, and fiber reinforced polymers (FRP). These materials have life cycles more closely matching the expected life of the masonry itself.

Minimum Intervention Principle

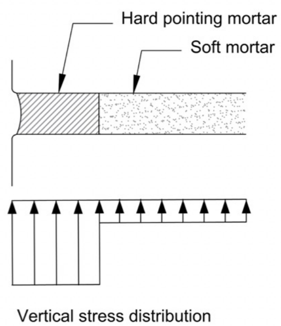
- The scope of retrofit work is optimized to meet the minimum intervention principle, reducing effects on historic materials, physical integrity, and appearance.
- This approach often requires extra engineering effort and exploring physical effects beyond normal simplifying engineering assumptions.
- Minimal interventions also consider the capacity of in-place materials, utilizing and augmenting existing construction rather than discounting the contribution of historic materials to the overall capacity.

Material Compatibility Principle

Retrofit materials and techniques must be compatible with existing construction, respecting traditional practices, where compatibility is expressed in terms of physical, chemical, and mechanical properties, Many examples exist of historic construction being permanently and irreversibly damaged when materials with properties very different from the original materials were used, and careful consideration is required to understand how new materials may affect the structure's response to structural and environmental loads.

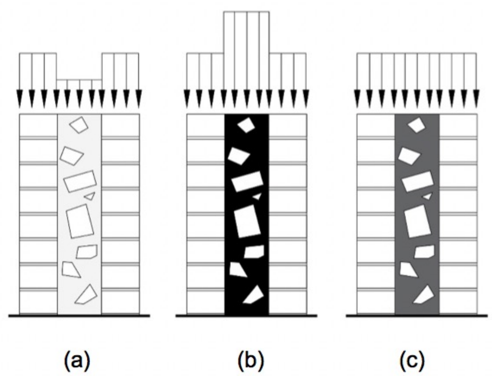
….Material Compatibility Principle

- An example of incompatibility and its damaging effect is the use of low porosity, high cement mortar to repoint over lime-based historic mortar.
- This improper approach results in stress concentrations and associated damage to adjacent masonry units at the wall face



….Material Compatibility Principle

The moisture evaporation process shifts from moisture movement through previously porous mortar joints to movement through masonry units, often leading to masonry unit degradation. This is seen when using dense repair materials and impermeable epoxies, both of which block movement of soluble salts within the wall and evaporative drying processes associated with water vapor transmission. Vapor pressures that develop at the interface with impermeable repair materials can be great enough to cause delamination of the repair layer from its substrate. These high strength, high stiffness inclusions attr



Stress distribution with (a) internal voids; (b) incompatible high modulus injection fill; (c) compatible injection fill.

Reversibility Principle

Retrofit that can be removed in the future is preferable, should the intervention be found to be non-beneficial or harmful. For example, post-tensioning is preferred over installation of bonded reinforcement because post-tension forces can be relieved, whereas bonded reinforcement is more difficult to remove. More recently, the concept of retreat-ability has surfaced as an option to reversibility, in which case an intervention should not prevent future treatments using similar or alternate methods.

Authenticity Principle

The concept of authenticity embodies protecting and maintaining existing materials and workmanship, rather than replacing with new.

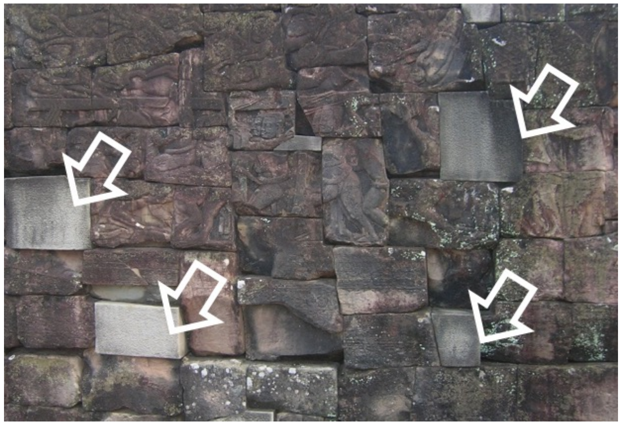
Authenticity is associated with the minimal intervention principle: work is optimized and designed to limit changes to appearance, maintaining the greatest degree of authenticity possible. Character-defining features remain in place and are stabilized or conserved where necessary.

Another philosophy is to deliberately highlight new elements to avoid giving a false sense of authenticity. Retrofit is left in plain view, to give a sense of the history of interventions. The example given in Figure 5.4 shows a condit

…Authenticity Principle

- The authenticity concept is interpreted differently by different designers. One philosophy is to hide all evidence of an intervention. This approach, adopted by the U.S. Secretary of the Interior's standards, requires new work be designed to duplicate existing materials and appearance.

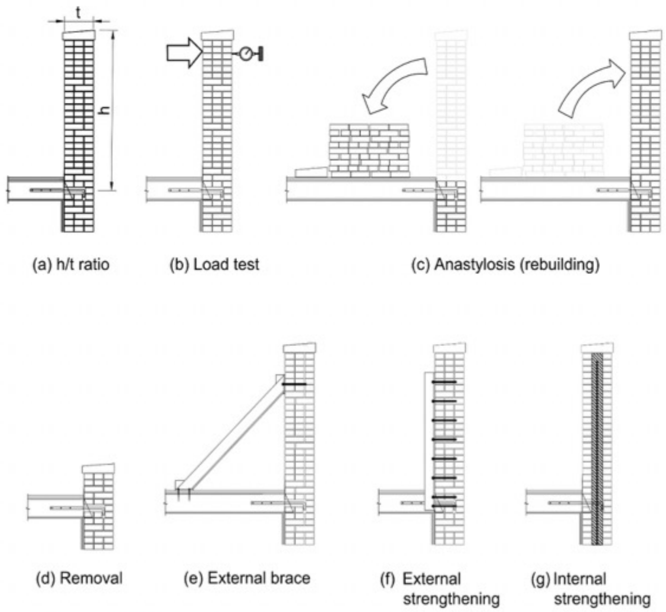
- Another philosophy is to deliberately highlight new elements to avoid giving a false sense of authenticity. Retrofit is left in plain view, to give a sense of the history of interventions.



Retrofit Strategy

- Design and implementation of retrofit follows study of the history of original construction and prior interventions, site evaluations to carry out a condition survey, use of in-place and laboratory diagnostic procedures, and structural analysis.
- Retrofit design is often an iterative process, requiring separate analysis of different retrofit options to understand how the selected approach affects local and global response, and to assure that the chosen retrofit avoids actions that negatively impact strength or deformation capacity and long-term material durability.
- Often, there are few options to choose from. These options have to be evaluated to choose the most appropriate (meeting retrofit objective) and cost-effective

Retrofit Approaches- Parapet Example



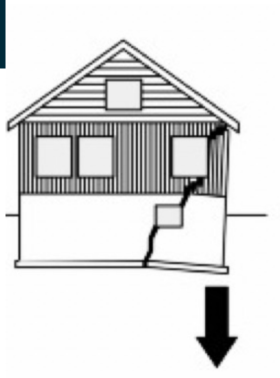
- Analysis
- Monitoring
- Rebuild
- Removal of inadequate arch elements
- Strengthening
  - Modifying supporting conditions
  - External strengthening
  - Internal strengthening

Foundation Retrofit

Introduction

- Foundations are retrofitted to address movement, new loads, or inadequate initial construction. Soil can be locally overstressed due to excessive vertical loads, or existing foundations (such as wood piles) may have deteriorated.

- Many historic buildings have no foundation, in the modern sense, with the wall simply terminating at or slightly below grade, and new foundation elements may be necessary to extend to frost depth or soil strata with better bearing capacity.



Choice of Foundation Retrofit

- The choice of a foundation retrofit approach depends on many factors, and designing a foundation retrofit requires knowledge of underlying soil characteristics including groundwater conditions, soil expansion and consolidation potential, and depth to competent bearing. Where competent soils exist near-surface, a shallow-depth retrofit may be used. Installation of micro-piles, drilled piers, and helical piers are better options for deeper applications.

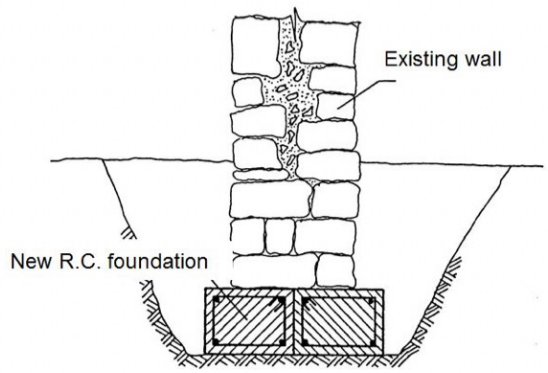
- Historic sites and areas with sensitive archeological conditions require special considerations, where soil disruption is minimized by limiting the extent of excavations.

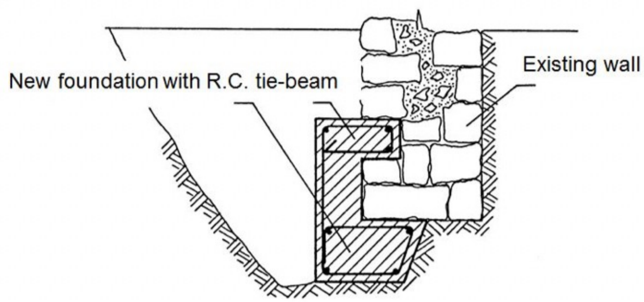
Soil Moisture Condition

- Foundation movements are commonly related to changes in soil moisture conditions. Some soil types expand when wetted, leading to uplift or heaving and associated cracking. Soil may also shrink as it dries during prolonged periods of drought, resulting in cracks forming in rigid masonry walls.
- Before embarking on an invasive foundation retrofit project, measures are first taken to prevent localized saturation and stabilize soil moisture conditions. Roof drains are evaluated for proper operation and configured to direct runoff well away from the foundation.
- Finished grade is sloped at least 10 percent for the first 1.8 m adjacent to foundations to promote surface drainage. Water and sewer pipes are also examined for leaks. Soil moisture content can take many months to stabilize, requiring movement monitoring be carried out over a period of at least one year to determine if measures have halted foundation movement.

Adding a New Footing

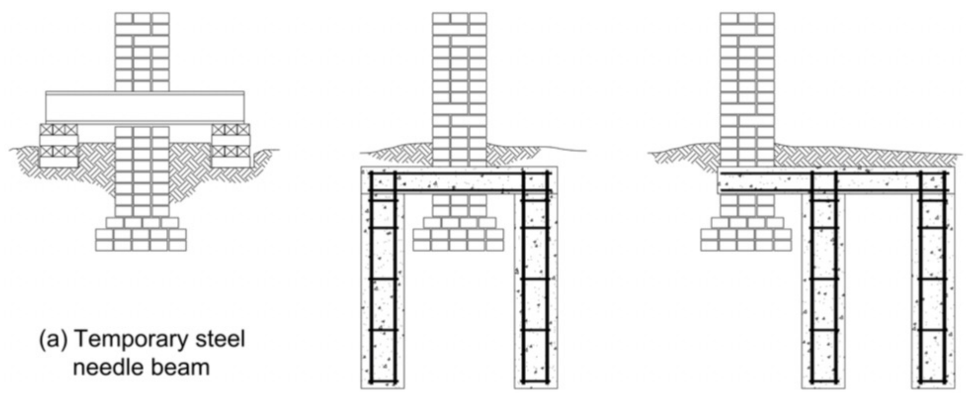
The most common way of strengthening a masonry wall foundation is to add a new reinforced concrete footing. The new footing may either be continuous or discrete at intervals.





Needle Beam Support

Supporting walls with needle beams involves installing a series of short beams penetrating the wall at regular intervals and supported by props on both sides of the wall. Needle beams may be used to provide temporary support during rebuilding work or may remain in place as part of the permanent underpinning system.



(a) Temporary steel needle beam

(b) Concrete needle beam

(c) Cantilever needle beam

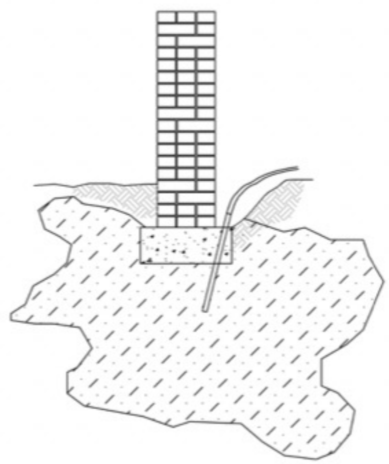
Soil Improvement

Soil injection, compaction grouting, or jet grouting consolidates and strengthens poor soils to provide a foundation retrofit with high stiffness and high-end bearing capacity. Soil injection introduces low-viscosity grout at low pressure into open fissures and loose soil formations.

The method works best with poorly-consolidated

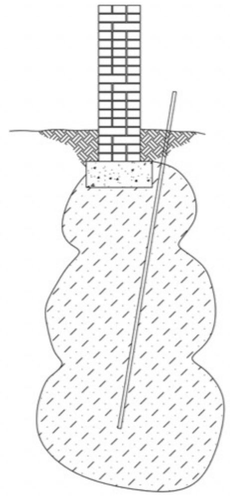
granular soils, including sands and gravels, and is most often used for relatively shallow repairs extending less than 4.5 m below grade.

Soil injection grouts may be cementitious or chemical-based, using sodium silicate, acrylates, or urethanes as the main binder.



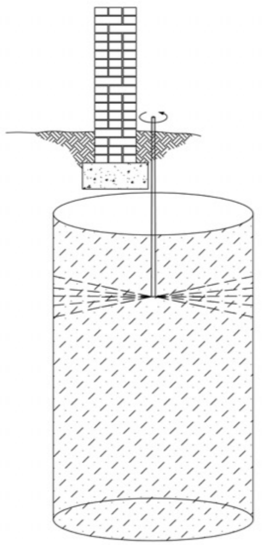
Compaction Grouting

Compaction grouting involves installing a drill casing into a hole bored to the design depth. Cement-based grout is pumped in at high pressure as the casing is withdrawn, forming a series of overlapping grout bulbs that densifies the surrounding soil to improve bearing capacity. Injection grout fills voids in weak soil while at the same time fills spaces that open under pressure in poorly-consolidated soils. The method may be used in conjunction with grouted micro-piles at deeper depths.



Jet-Grouting

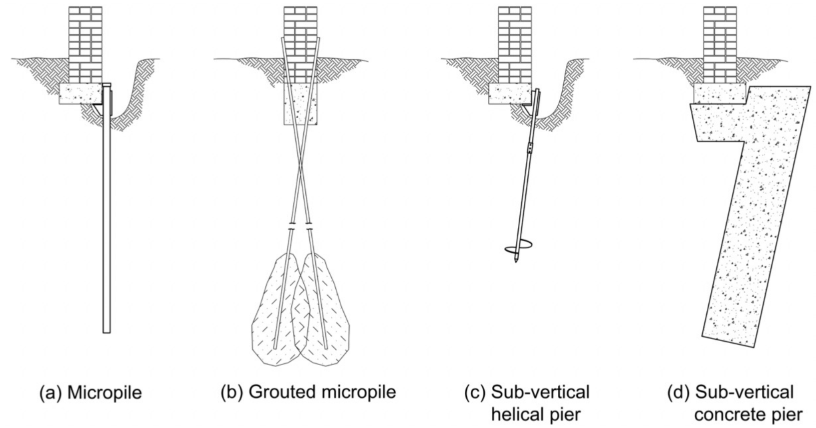
Jet-grouting forms a series of cylindrical jet-grouted columns or planar jet-grouted panels. The jet grouting process involves drilling a small-diameter borehole, followed by cementitious or polymer grout introduced at very high pressure of up to 31 MPa through a series of orifices in the side of the drilling tube. Soil disturbed by the high-pressure jet mixes with grout, forming a stabilized matrix as the grouting rod is rotated and drawn up out of the borehole.



Underpinning

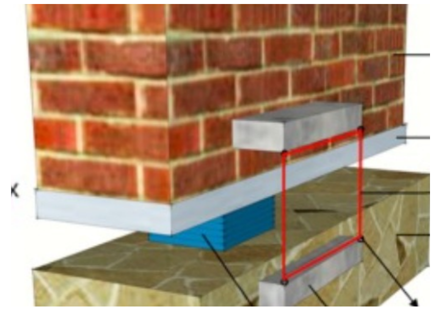
Underpinning methods involve adding new drilled or driven piers or piles, installed to carry loads down to competent soils beneath existing foundations.

Steel or reinforced concrete brackets connect the underpinning to the existing stem walls. The bearing capacity of the underlying strata will determine the number, diameter, depth and spacing of piles used.



Techniques Related to Reducing Demand

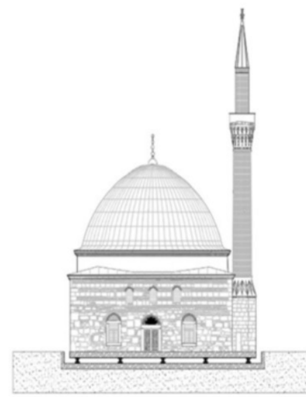
Base Isolation

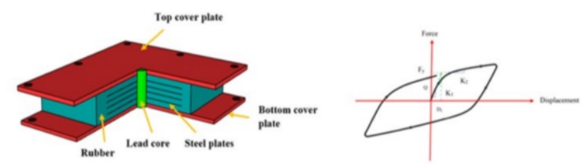


- Seismic base isolation technology involves placing flexible isolation systems between the foundation and the superstructure effectively isolating the structure from ground movements

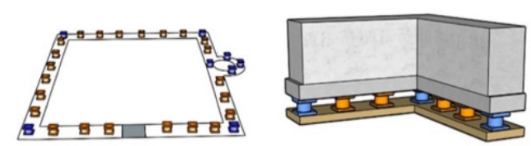
- By means of their flexibility and energy absorption capability, the isolation systems reflect and absorb part of the earthquake input energy before this energy is fully transmitted to the superstructure, reducing its energy dissipation demand.

- Both energy dissipation and deformation capacity demand are reduced. It is an effective technique, but very expensive. Therefore, it is more suitable to critical and historically significant structures.





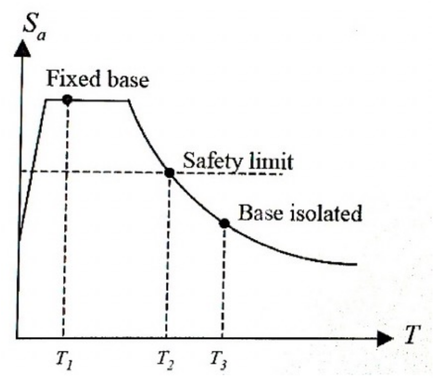
Schematics and force–deformation characteristics of the LRB isolation system.

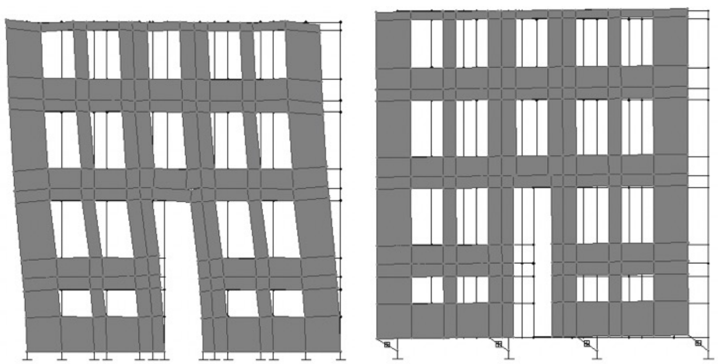


… Base Isolation

Base isolation causes the natural period of the structure to increase resulting in increased displacements at the isolation level and reduced accelerations and displacements in the superstructure during an earthquake.

Base isolation not only provides safety against collapse but also largely reduces damage.





(b) Non-isolated building (c) Base-isolated building

… Base Isolation- Early Forms

- Early forms of base isolation include pouring sand or gravel under the foundation or leaving a soft layer under the foundation and installing pieces of wood between the ground and the foundation.
- Application of this technique goes back to the 4th Century BC when a primitive base isolator was first used in the Tomb of Cyrus in Iran
- In this tomb, several layers of smoothed stone without any mortar or other high-friction material between them form a kind of base isolation.
- Another example of this technique is the foundation of the Aqsa Mosque in Jerusalem with three layers of large base stones and one layer of timber acting as a base-isolator system.

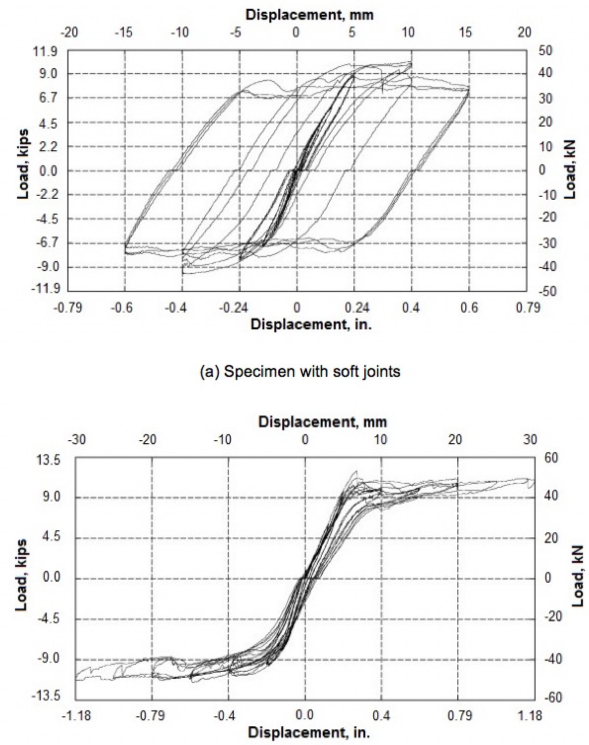
Friction Sliding Isolation (Soft Joint)

- Recent efforts to implement soft joints at the base of unreinforced masonry (URM) walls show promise as a form of structural isolation. It has been demonstrated that the engineering of a "soft" layer in terms of its friction coefficient and deformation capacity can achieve the following performance goals:
  - Minimal or no damage in frequent earthquakes when the structure is expected to remain elastic.
  - Controlled damage and preservation of the gravity load-carrying capacity in design-basis earthquakes. Desired performance is achieved through controlled lateral sliding deformation and elongation of the structural response period due to low stiffness in the sliding regime.
  - Collapse prevention in beyond-design-basis earthquakes through engagement of the full shear strength of the structural masonry walls.

…Friction Sliding Isolation (Soft Joint)

Soft joints installed as layers of rubber, cork, plastic, or composite material dissipate energy through friction, reducing seismic energy transmitted to the structure above.

Overall seismic response of URM with a friction sliding isolation system was concluded to be better than the response of conventional URM subjected to the same earthquake excitation.



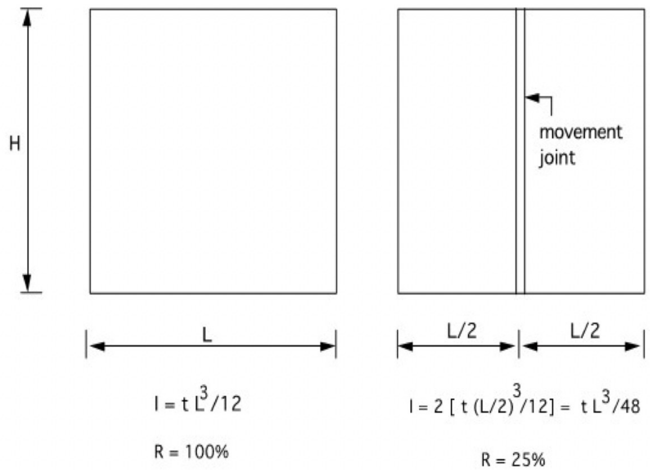
(a) Specimen with soft joints

(b) Specimen without soft joins

Reducing Torsional Effects

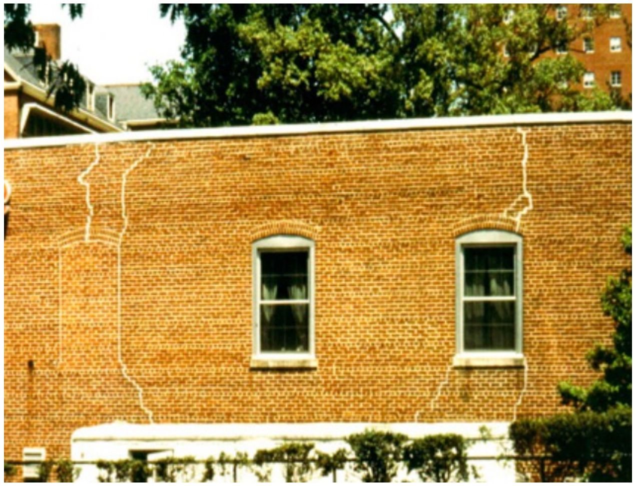
- Higher demand on end shear walls due to torsion from unequal stiffness distribution may be reduced or eliminated by introducing vertical movement joints in solid walls, thereby reducing their in-plane rigidity. The objective is to adjust wall stiffness such that the building center of mass coincides with its center of rigidity as nearly as possible, reducing torsional effects.

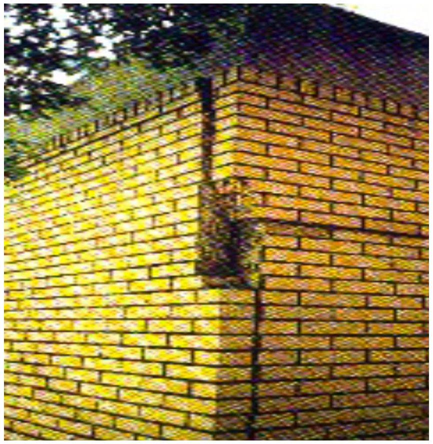
- Introducing a vertical joint in the middle of a solid masonry wall reduces its flexural rigidity *R* (proportional to EI) by 75 percent. Hence, wall stiffness may be balanced throughout a structure by judicious placement of movement joints.



Reducing Stresses/Preventing Cracking of Masonry Veneer

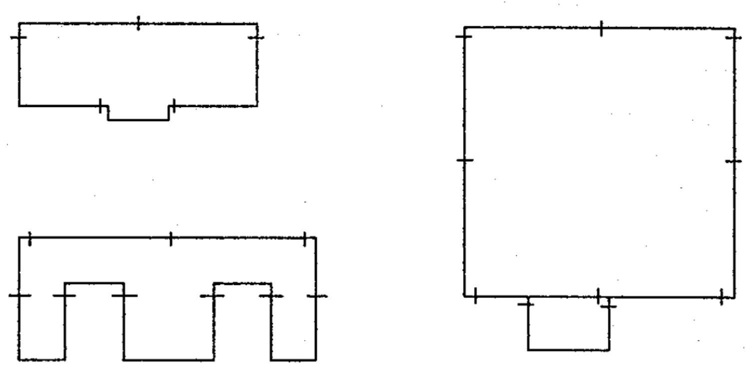
Changes in temperature and/or moisture content can cause cause cracking of brick veneer due to thermal movement/moisture expansion.

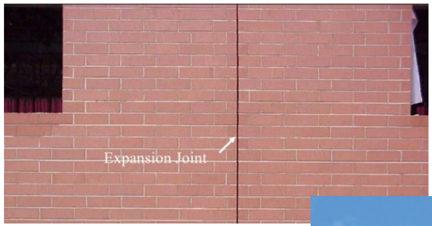




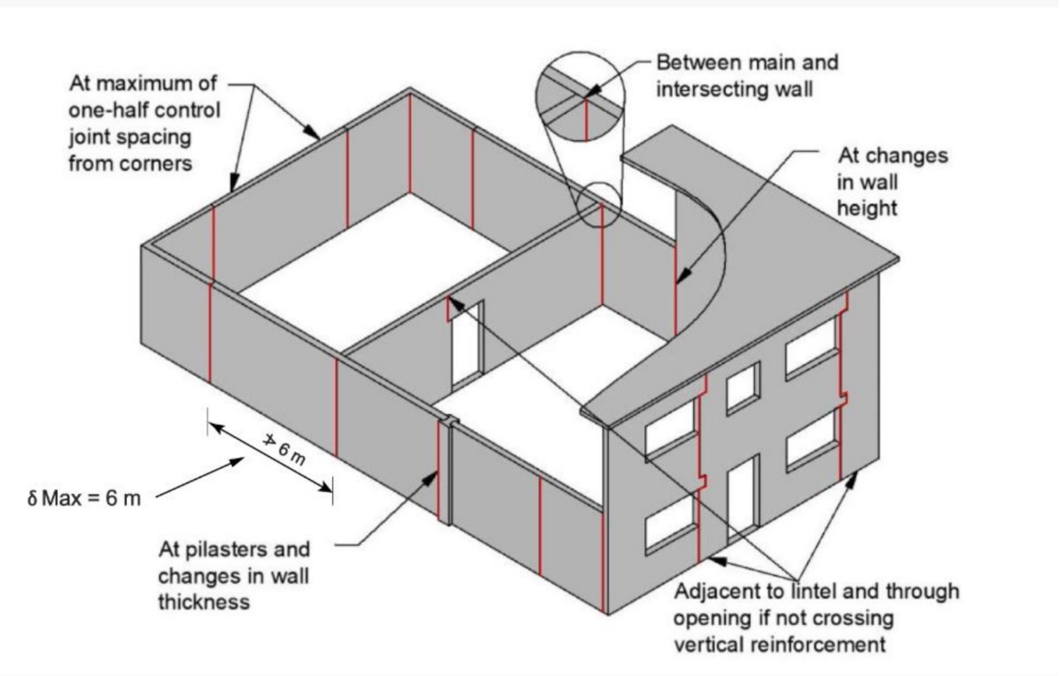
...Reducing Stresses/Preventing Cracking of Masonry Veneer

- Introducing movement joints at key locations (corners, around openings and offsets) can relieve stresses and eliminate cracking.





Locations of Movement Joints



Techniques Related to Element Resistance

Introduction

- There are many different options for enhancing a masonry element's load resistance and deformation capacity. The choice of an appropriate technical solution depends on the type and quality of the masonry construction, the degree of existing damage, and the level of strengthening or upgrading required.
- When strengthening historic construction, options may be limited to those incorporating traditional materials and techniques.
- Modern materials including cement, metal or polymer reinforcement, and concrete offer many advantages, but these materials must be used judiciously to avoid compatibility issues.

Introduction-Methods

- Load resistance and deformation capacity of masonry elements is enhanced using external or internal methods. External methods are usually more cost effective and more easily reversible, but are visible. The primary advantages of internal methods are that masonry appearance remains unchanged, with new elements hidden within masonry sections, and new internal members do not encroach on floor space.
- Furthermore, internal methods enhance element resistance by acting compositely with existing masonry. Internal techniques are, however, not easily reversible nor are they distinguishable from original construction.

Attachment of an Additional Wythe, Conversion of Nonloadbearing Walls to Structural Walls, and Adding Elements

- Individual walls with insufficient axial or lateral load capacity can be strengthened with an additional masonry wythe. The new wythe increases axial load capacity and flexural strength through an increase in the effective section, The new wythe can also be a convenient way to introduce tensile reinforcement, either in the collar joint or in the cells of the new wythe.

- Depending on interior and exterior finishes, the additional wythe can be introduced at either the inside or outside of external walls. If the new masonry is expected to act compositely with the existing wall, it must be attached and bonded using anchors and grout.

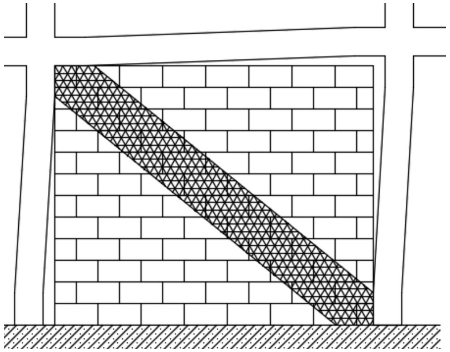
- This may entail removal of surface finishes or layers, air and vapor barriers, and insulation.

Grouting Void Spaces

- Wall capacity can also be improved by grouting void spaces in multi-wythe masonry or open cells in hollow unit masonry walls. Grout is introduced by pouring or pumping through holes cored in the wall face or by injection.
- Grouting the cavity between the wythes (or grouting the cells of hollow units) may be difficult near the top of each story without drilling access holes through the floor above.

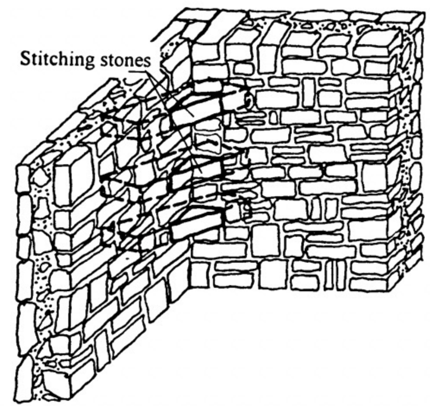
Conversion of Nonloadbearing Walls to Structural Walls

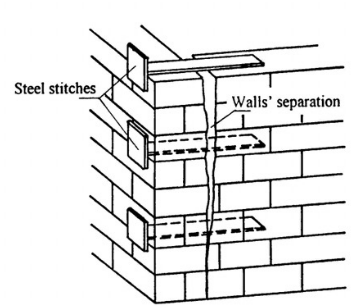
Non-loadbearing partitions and infill frame panels can be converted to participating structural walls by providing attachment to the surrounding frame.

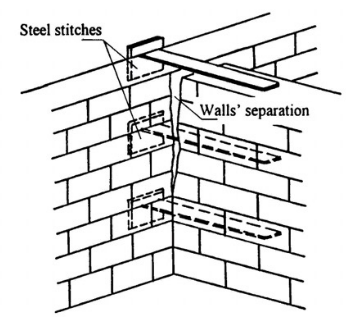


Flanged Walls

- Other possibilities for improving the lateral load resistance of masonry construction is to ensure that intersecting walls are properly attached to produce flanged sections.
- This approach requires careful consideration and analysis, as modifying shear walls may also shift wall in-plane load response from a deformation-controlled rocking mechanism to a strength-controlled shear mechanism.

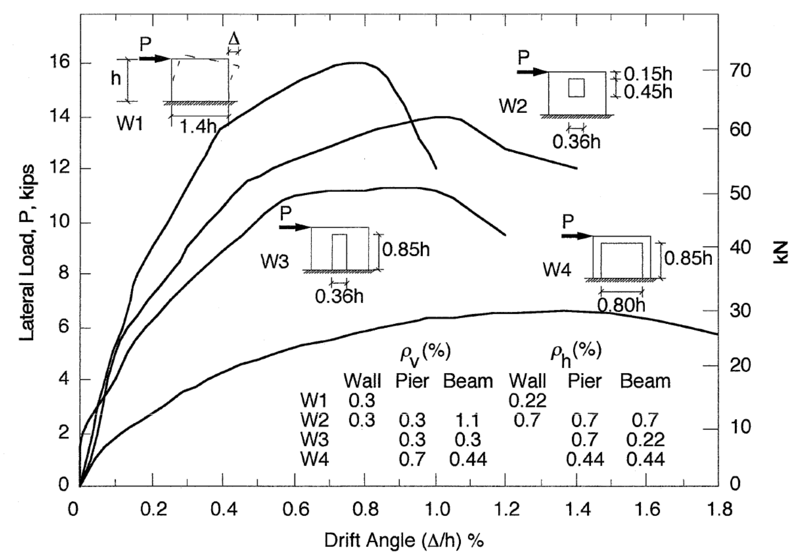






Closing Wall Openings

- Openings reduce Lateral stiffness depending on location and size of openings.
- Therefore, Tightly infilling openings in masonry shear walls will increase the lateral stiffness of these walls.



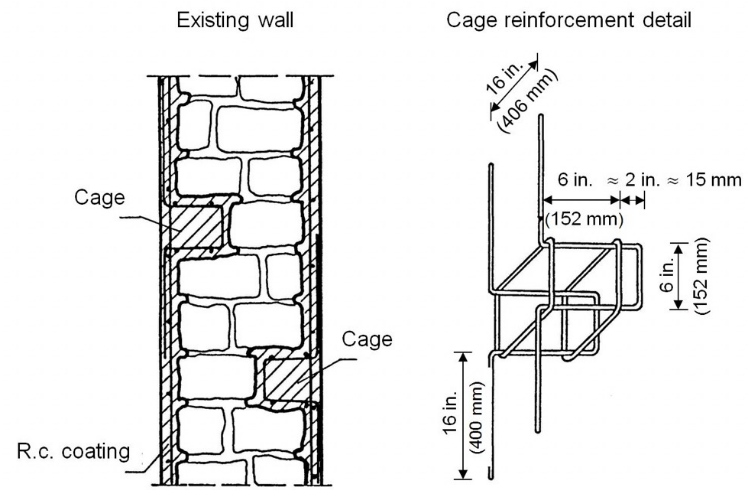
External Reinforcing Overlay

Where the aesthetic change resulting from covering masonry with a surface layer is not a controlling concern, such as with non-historic structures, use of an external reinforcing overlay can be an effective retrofitting technique for increasing the strength of unreinforced masonry walls.

Ferrocement

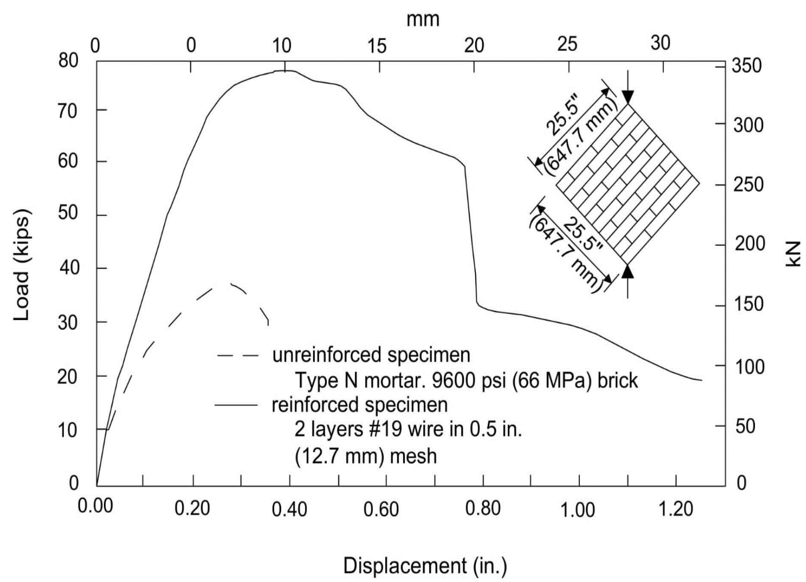
Ferrocement is the most common overlay, installed as an orthotropic system consisting of high-strength cement mortar typically 13 to 25 mm thick, reinforced with layers of fine steel wire mesh and a reinforcement volumetric ratic ranging from 0.5 to 5.0 percent.

Overlays must be properly connected to act compositely with the masonry. The reinforcement mesh is tied to the masonry wall at intervals using reinforced cages or with 6.4 mm diameter wires spaced at 200 to 500 mm.



…. Ferrocement

Test results confirm the effectiveness of the ferrocement overlays for increasing the diagonal tensile strength and for producing significant improvement in stiffness and deformation capacity.



.....Ferrocement

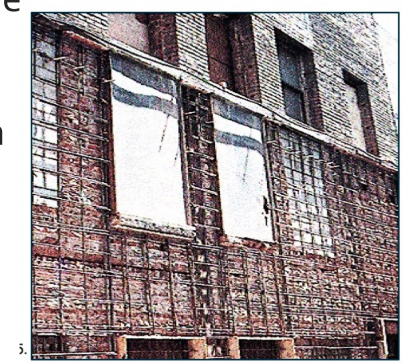
- The overlay must be properly detailed and installed to avoid damaging separation and detachment under load.

- Problems associated with improper installation of ferrocement include:
  1. Failure due to insufficient steel mesh overlapping
  2. Insufficient transverse ties for confining action
  3. Lack of connection between nets,
  4. Absence of proper connectors

(a) (b) (c) (d)

Shotcrete

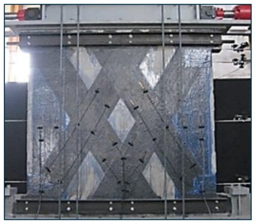
- ***Shotcrete***, also referred to as ***sprayed mortar***, ***gunite*** or ***jetcrete***, is used as an overlay to repair and strengthen masonry walls.
- In the wet process, all the materials are mixed prior to being placed in the spraying system.
- Alternatively, dry-mixed cement and sand are fed using compressed air to a nozzle where a separate line delivers water and admixtures, if any, to the nozzle that provides the final mixing. In some cases, fibers are introduced in the mix, whereas in othe
the reinforcement.
- Overlays often have a thickness of 150-200 mm



Externally-Bonded Composite Systems

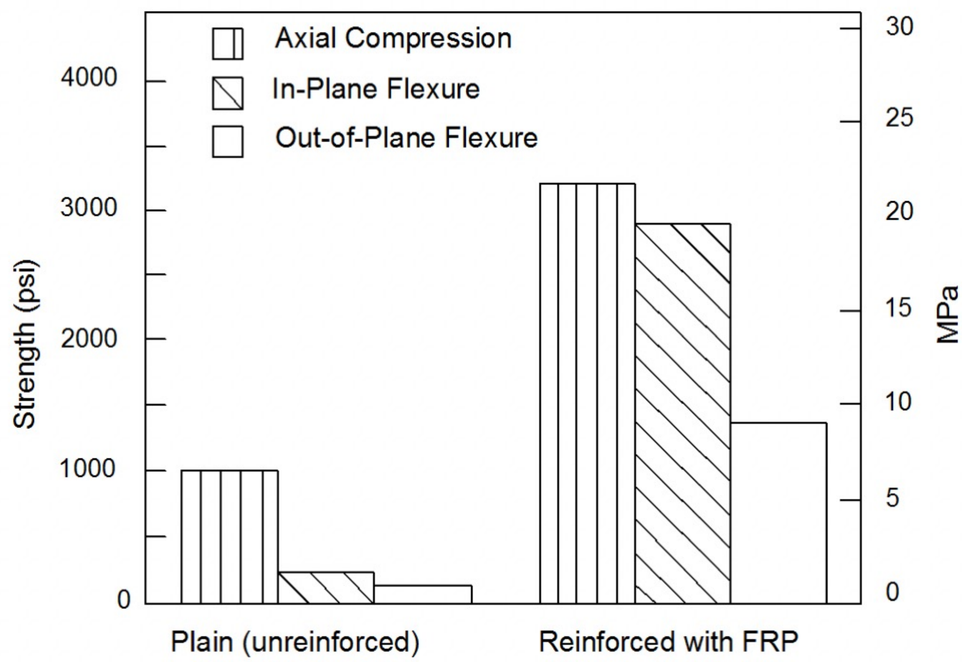
- ***Externally-bonded composite systems*** include fiber reinforced polymer (FRP) and fabric reinforced cement matrix (FRCM) techniques for seismic retrofit, repair or strengthening of masonry walls.
- FRP laminates are made of a continuous bi-directional mesh of glass, carbon, or Kevlar fibers bonded to the masonry with a resin polymer matrix.
- The laminates used in FRP and FRCM systems are lightweight, have high stiffness and tensile strength, excellent fatigue properties, and are highly corrosion resistant.





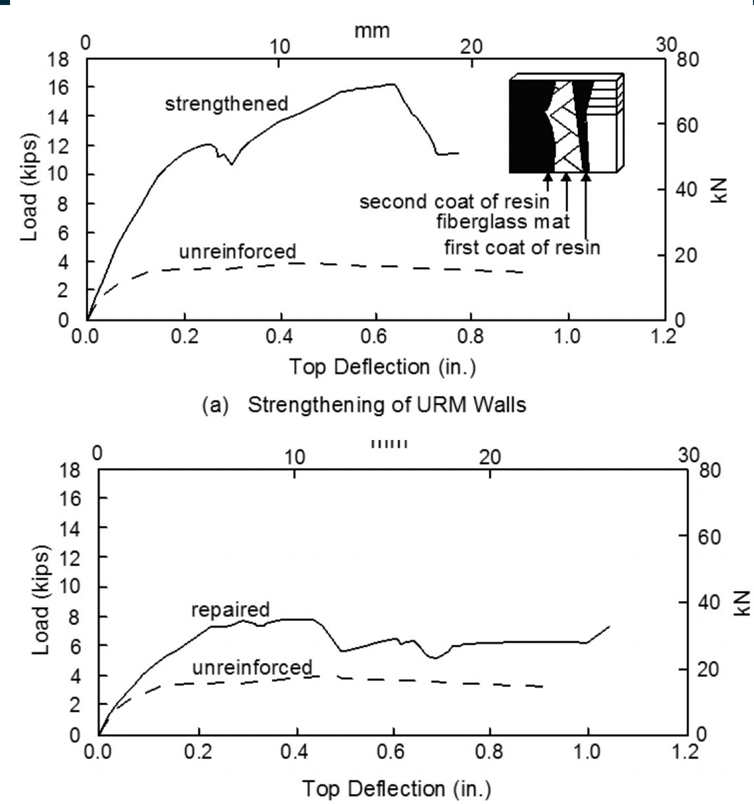

FRP Laminates

Tests of FRP-strengthened small-scale concrete masonry wall assemblages demonstrate a significant increase in compressive strength and both in-plane and out-of-plane flexural strength.



…FRP Laminates

- Wall tested under in-plane shear forces showed the effectiveness of FRP glass laminates in
  - strengthening undamaged walls
  - repair of damaged walls



(a) Strengthening of URM Walls

(b) Repair of Damaged URM Walls

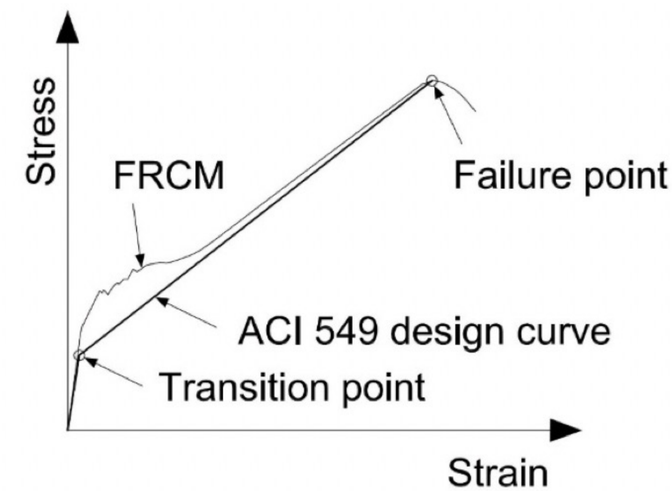
FRP Laminates-Challenges

- One challenge of using FRP laminates is their susceptibility to premature delamination under large deflections. Attempts have been made to address this problem by providing an anchoring system to prevent or delay delamination.

- Another difficulty is developing FRP strength at connections such as at the wall-floor interface. Laminate strength is developed by extending the overlay beyond the connection zone, wrapping fabric around isolated structural members, or using a series of discrete anchors tying the fabric to the substrate

Design of Resin-Bonded FRP

- Design of resin-bonded FRP systems follows ACI 440 Standard ·which limits the overlay capacity based on the ultimate tensile strain that can be developed in the fibers, considering a linear elastic tensile response to ultimate capacity. Failure typically initiates as brittle debonding of the overlay from the masonry.

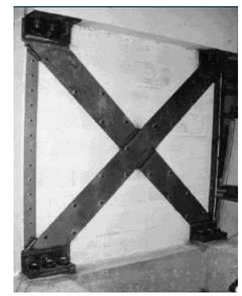


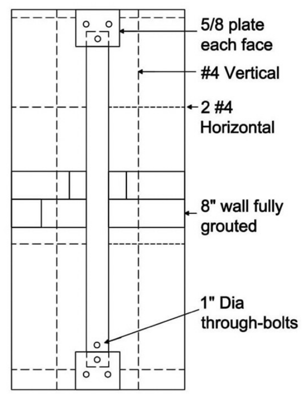
Material Properties of Fiber Filaments

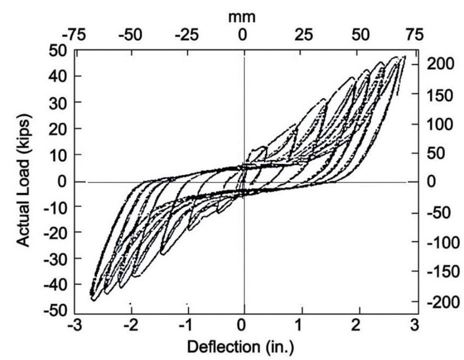
Mechanical Property	Fiber Type			
	Alkali-Resistant Glass	Basalt	Carbon	PBO Polymer
Ultimate tensile strength, ksi (MPa)	180 (1,241)	380 (2,620)	550 (3,790)	850 (5,860)
Modulus of elasticity, ksi (MPa)	10,500 (72,400)	12,500 (86,180)	33,800 (233,000)	39,600 (273,000)
Ultimate tensile strain	0.018	0.030	0.016	0.025

External Reinforcing with Steel Plates

- Steel plates have been used to increase the lateral shear resistance of unreinforced masonry walls.
- Proper anchoring of the steel plates is a key to develop the full tensile strength capacity of the steel plates if composite action between the steel plates and the masonry is desired.
- Coupled with the simplicity and ease of installation, the enhanced strength and displacement ductility of this retrofit scheme has merit for retrofit of masonry walls subjected to out-of-plane flexure.







External Steel Frames

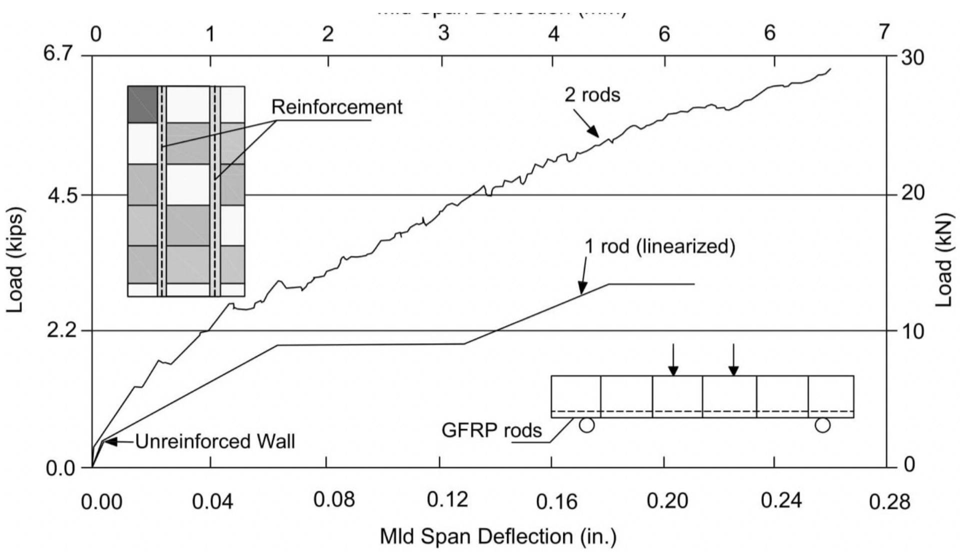
- Steel frames can be placed in visible locations at the exterior facade or at the building interior, concealed behind furred-out walls, or partially hidden within ceiling plenums. Frames are designed to carry vertical floor loads to prevent overloading fragile masonry, and braced frames or moment frames are designed to resist lateral load.
- For walls spanning floor-to-floor, placing diagonal braces between walls and diaphragm framing reduces the effective wall height

Near-Surface Mounted (NSM) FRP Rods

- Horizontal NSM rods are commonly installed in slots cut into mortar bed joints; installing vertical NSM rods requires vertical slots be cut into the wall surface.
- Rods are embedded into an epoxy resin matrix for bonding and load transfer.

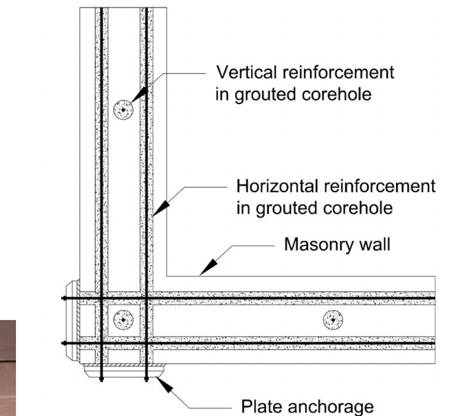
…Near-Surface Mounted (NSM) FRP Rods

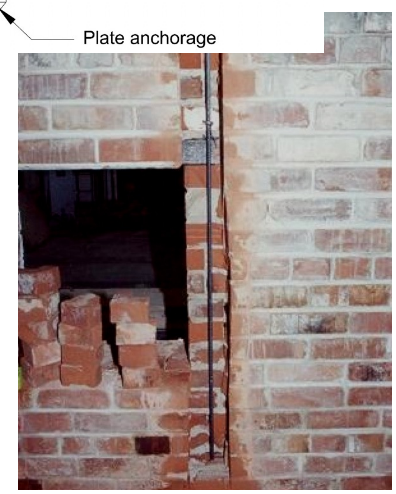
- showed that a remarkable increase in the flexural capacity of masonry block walls can be achieved by means of NSM FRP reinforcement, as the specimens strengthened with one and two GFRP rods failed at 7 times and 15.7 times the load of the control specimen, respectively.



Internal Reinforcing

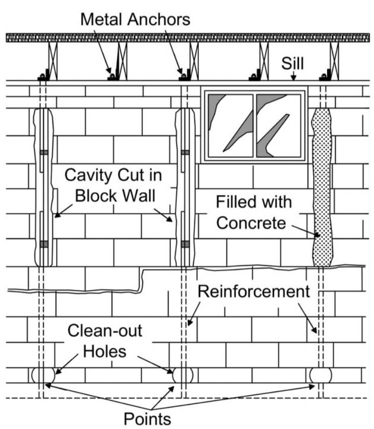
Internal strengthening involves addition of reinforcing steel in slots cut into existing masonry or in longitudinally drilled holes. Vertical and horizontal reinforcement installed in walls is used to increase resistance to vertical and lateral loads and improve deformation capacity of unreinforced or under-reinforced systems. Internal reinforcing has the advantages of being versatile, structurally effective, and does not alter interior spaces.

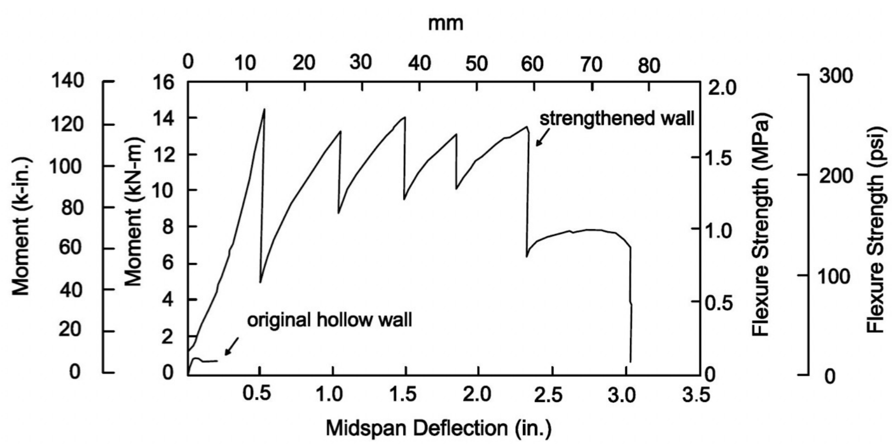




Internal Reinforcing of URM Walls using FRP Rods

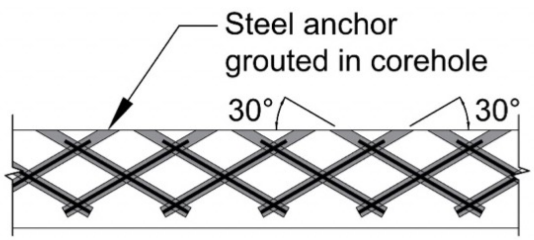
- The effect of FRP reinforcement can be be highly beneficial for reinforcing CMU walls.
- Using FRP rods instead of carbon steel may be preferred because of their ease of handling and inserting into the wall and greater corrosion resistance





Drill and Bond Method

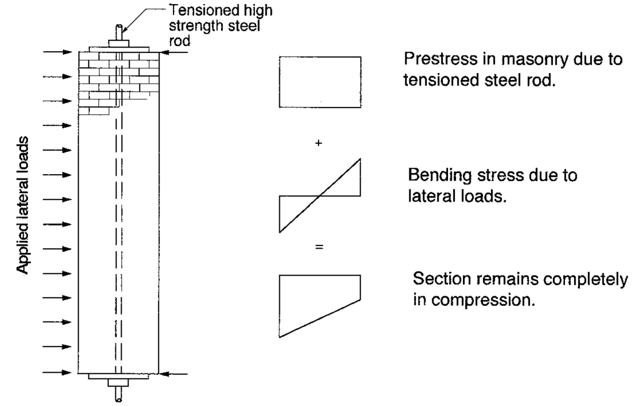
- The drill and bond method distributes tension demand among interweaved reinforcing bars installed in a 3-dimensional pattern.
- Individual anchors are grouted into holes, with anchors in alternating rows installed at 30 degrees upward and 30 degrees downward from horizontal.
- The size and spacing of diagonal stitching anchors is designed based on the expected tensile stress developing within the cross section and the degree of connectivity desired.



Plan View

Post-Tensioning

- Unbonded rods are post-tensioned to apply axial compression, taking advantage of masonry's good compression capacity to enhance its flexure and shear resistance.
- The applied compression stress offsets tension that develops in unreinforced masonry from either in-plane or out-of-plane flexure and diagonal tension, subsequently increasing the bending moment and shear required to produce tension.



Post-Tensioning Strands

- The most common internal post-tensioning system for retrofitting masonry walls is the unbonded monostrand system. The high strength steel monostrands are typically 15 mm in diameter, greased and coated with extruded plastic for maximum corrosion protection.

Advantages

- A solid and durable plastic or galvanized steel duct around the monostrand tendon provides a third layer of protection.

Advantages

- Internal post-tensioning has the advantage of only minor disruption to the existing structure. It does not require new foundations, does not reduce useable space, and, particularly important for seismic retrofit, it does not add significant mass to the building, thereby resulting in no significant increase in seismic forces. Installation of internal post-tensioning is somewhat reversible and the strand forces can be removed, if desired, by releasing the anchorage.
- Many post-tension retrofit systems are designed with accessible anchorages to permit periodic verification and adjustment of the post tension force, should the strand relax due to movement or creep.

Design

- From a design standpoint, **ASCE 41 Standard** considers post-tensioned masonry to act as an unreinforced system with increased vertical compressive stress. ASCE 41 Standard also provides design guidance for calculating losses due to creep and shrinkage.

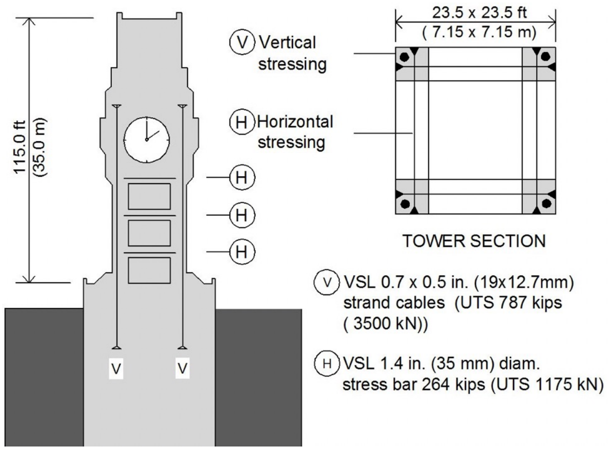
Normal stress = -P/A + My/I

Shear stress =

$$\tau = \tau_0 + \mu\sigma_n$$

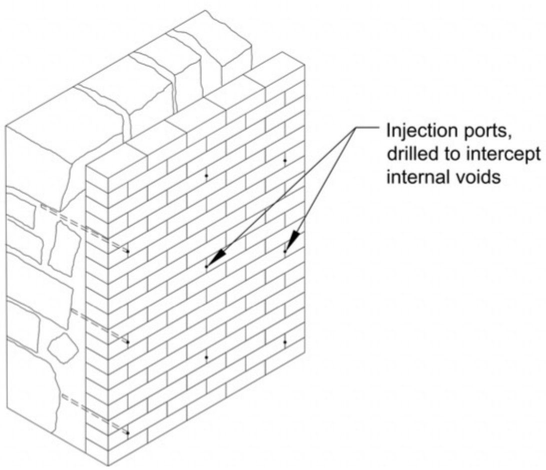
Applications

- One successful example of the unbonded post-tension approach is the VSL system, used to strengthen the GOP tower of the General Post Office in Sydney. The Post Office is constructed of sandstone masonry and is more than one hundred years old.
- was strengthened with four vertical post-tension tendons, comprised of 13 mm diameter strands each, and 35 mm diameter horizontal post-tension tendons at floor levels. The vertical tendons were placed in 100 mm diameter holes drilled from the top through sandstone columns at the tower corners.
- Special steel chairs were used to anchor the tendons and spread the 1,770 kN anchorage forces.



Grout Injection

Although not reversible, injection is minimally invasive. Small-diameter injection ports drilled through mortar joints are pointed with new mortar following injection, restoring the outward appearance.



(a) Injection ports fixed into injection holes

(b) Injection nozzle self-sealing at face of wall

Grout Mix Characterization

- Injection materials are designed to meet structural and durability requirements, and for compatibility with the physical, chemical, and mechanical properties of the original masonry.
- Ideally, the grout formulation should be selected to achieve the following desirable properties:
  - High water retentivity
  - Minimum shrinkage or even slight expansion
  - High fluidity but not subject to segregation of constituent materials either when at rest or under pressure
  - Good tensile strength (greater than standard mortars)
  - Good bond to mortar and masonry units (greater than standard mortars)
  - Proper durability, considering environmental conditions to be experienced in service.

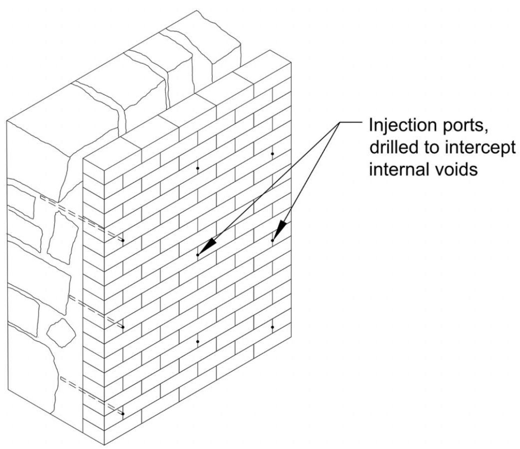
Grout Hardened Properties

Hardened properties are also evaluated to measure mechanical and physical characteristics. Specimens for hardened properties are fabricated in the laboratory, extracted from injected mockup panels, or extracted from injected masonry. Tests for evaluating hardened injection properties include the following.

- Drying shrinkage
- Compressive strength
- Bond between injected grout and surrounding masonry
- Water vapor transmission

Methodology

Port spacing of 200 mm or less is used when injecting narrow cracks and poorly-connected void spaces. Injection port spacing rarely exceeds 1.2 m, even when injecting open void spaces.



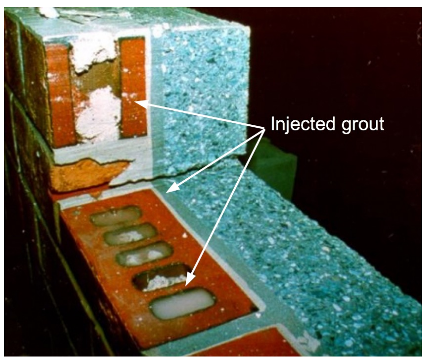
Applications

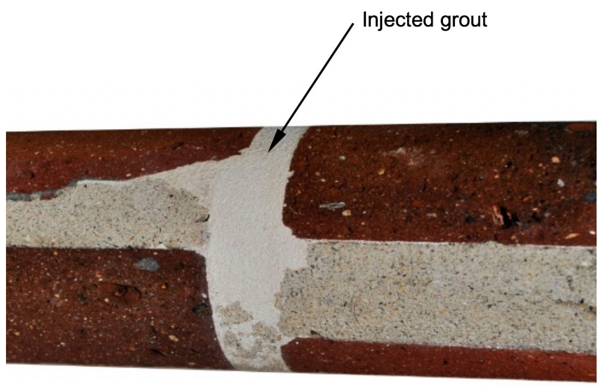
Grout Injection technique has been used successfully on many commercial applications, including:

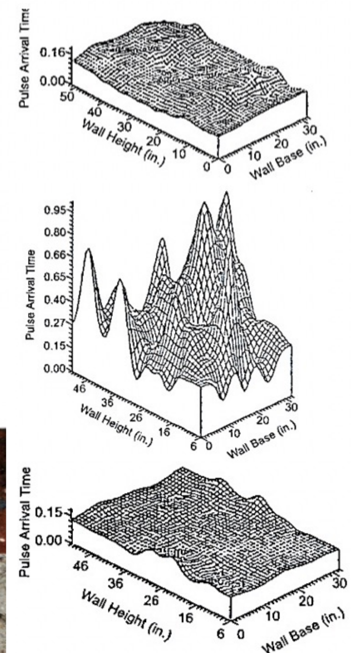
- Stabilization and re-anchoring of stone facades
- Repair of cracks in masonry buildings
- Stabilization of masonry jack-arch lintels
- Collar joint injection of buildings to reduce through-wall moisture penetration
- Strengthening of masonry arch bridges
- Correcting construction deficiencies

Effectiveness- Quality Assurance

- Non-destructive testing-Ultrasonic tests
- Destructive tests-cores







(a) Original condition, undamaged

(b) Damaged

(c) Repaired condition

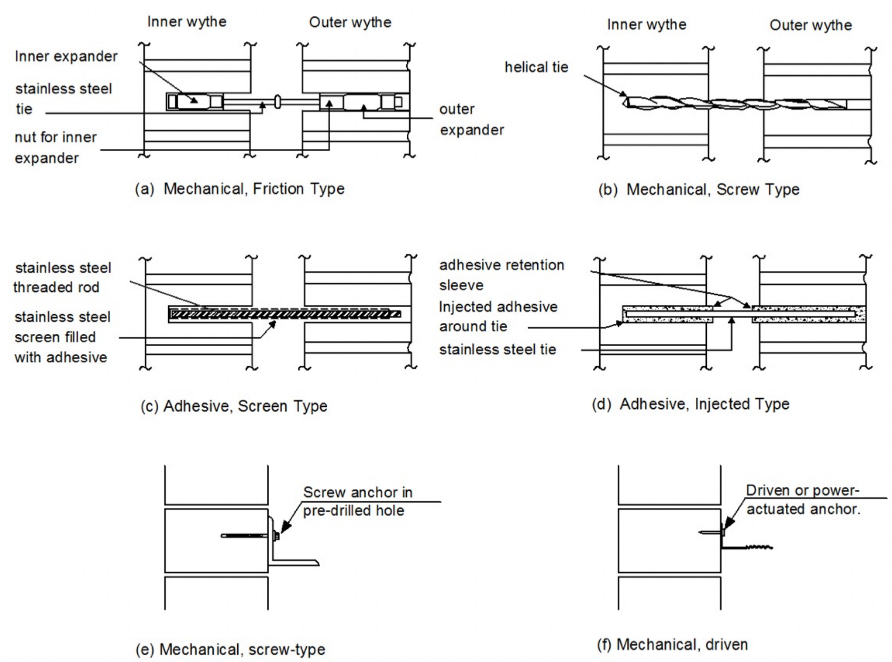
Techniques Related to Increasing System Stability and Structural Integrity

Post-Installed Anchors

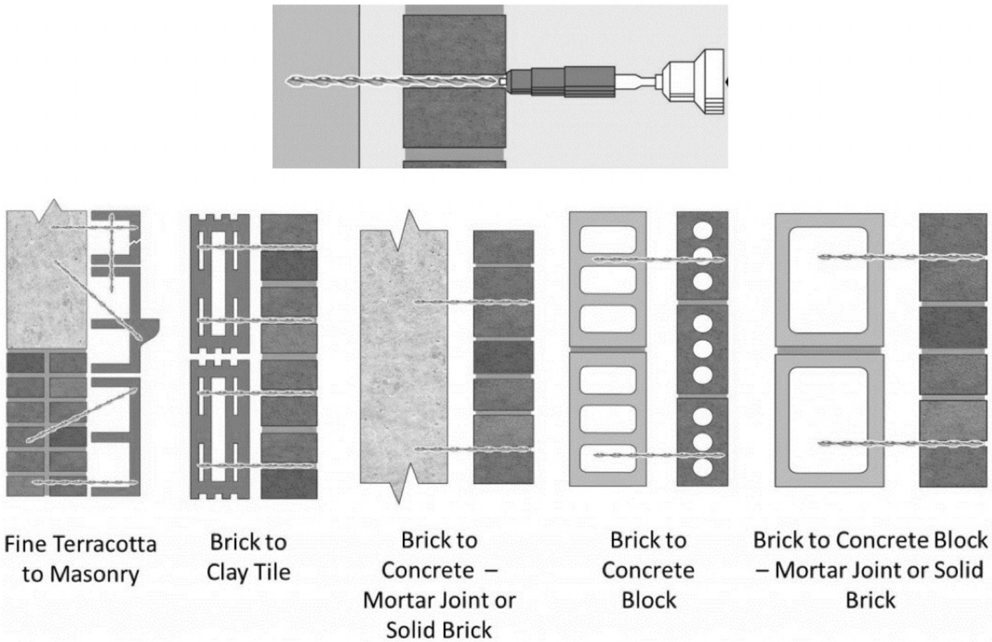
- Anchors are installed in existing masonry construction for seismic retrofit, to correct a construction or a design defect, as part of an effort to stabilize displaced masonry, or to replace corroded or fractured connections.
- Anchorages provide stability under lateral out-of-plane loading and transmit in-plane shear wall forces to floor diaphragms, enhancing overall building stability.
- Similarly, walls have vastly improved strength and stiffness characteristics if a positive connection can be made between wythes and at intersecting walls.

Types of Anchors

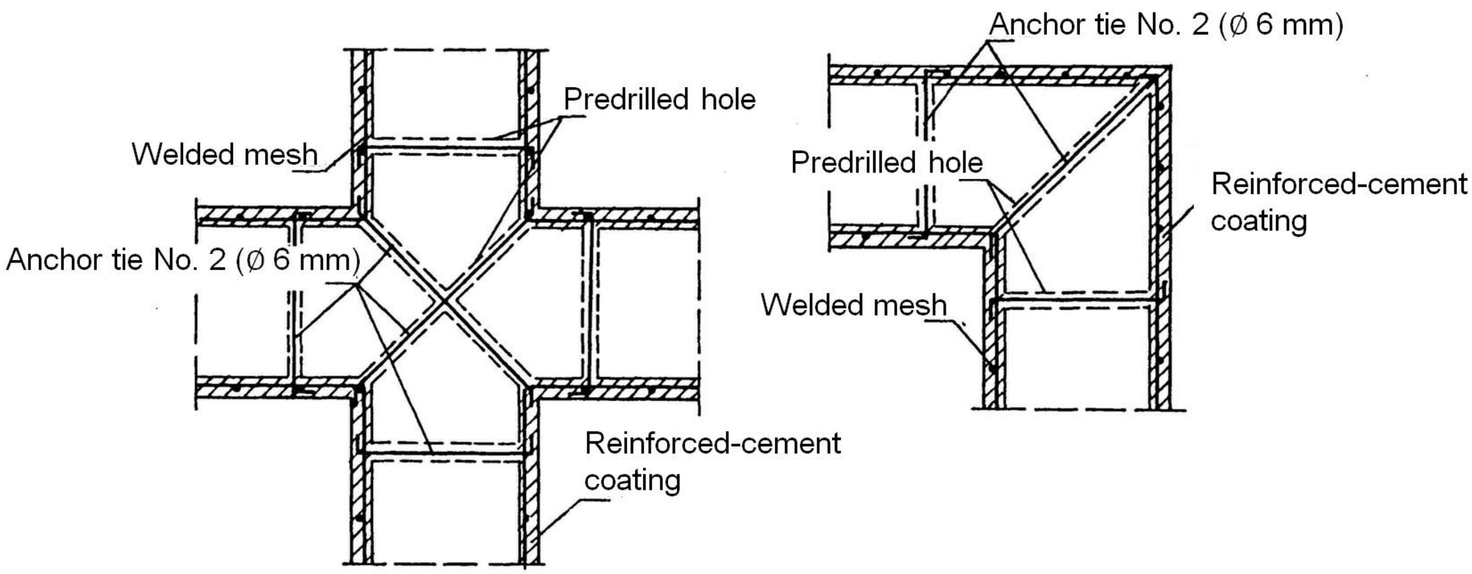
- Anchorage systems differ in terms of capacity, cost, ease of use, and other factors such as skill needed to install or weather restrictions at installation.
- Common retrofit anchors include through bolts with plates, mechanical friction expansion anchors, mechanical screw-type anchors, adhesive screen anchors, injected anchors, and power-actuated or driven fasteners



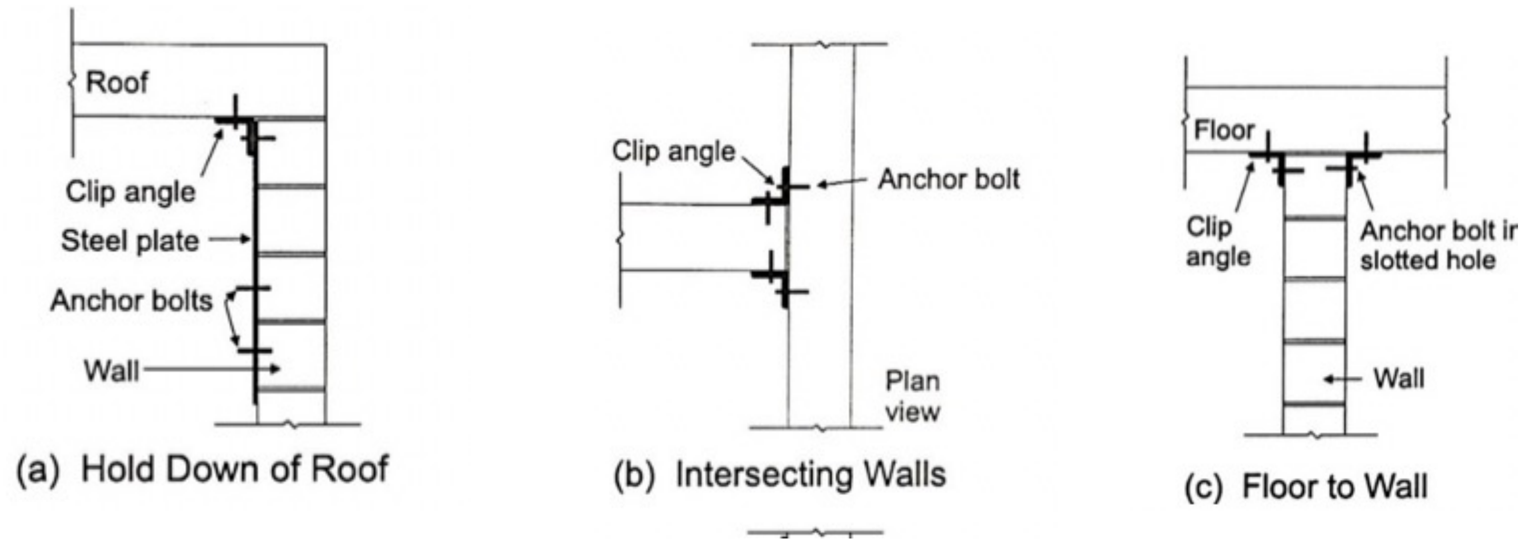
Anchoring Veneer to Backup Using Single Repair Anchors



Anchoring Reinforced Cement Coating

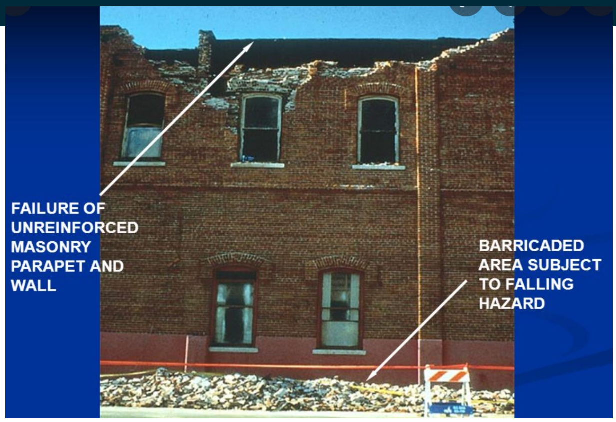


Anchoring and Tying

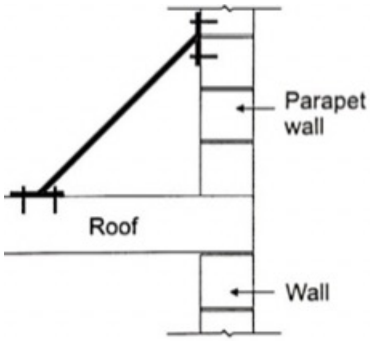


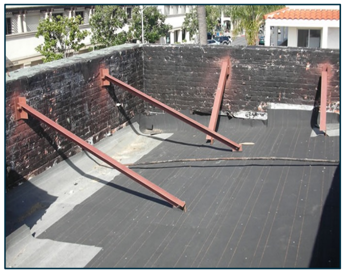
(a) Hold Down of Roof (b) Intersecting Walls (c) Floor to Wall

Bracing- Parapet Wall

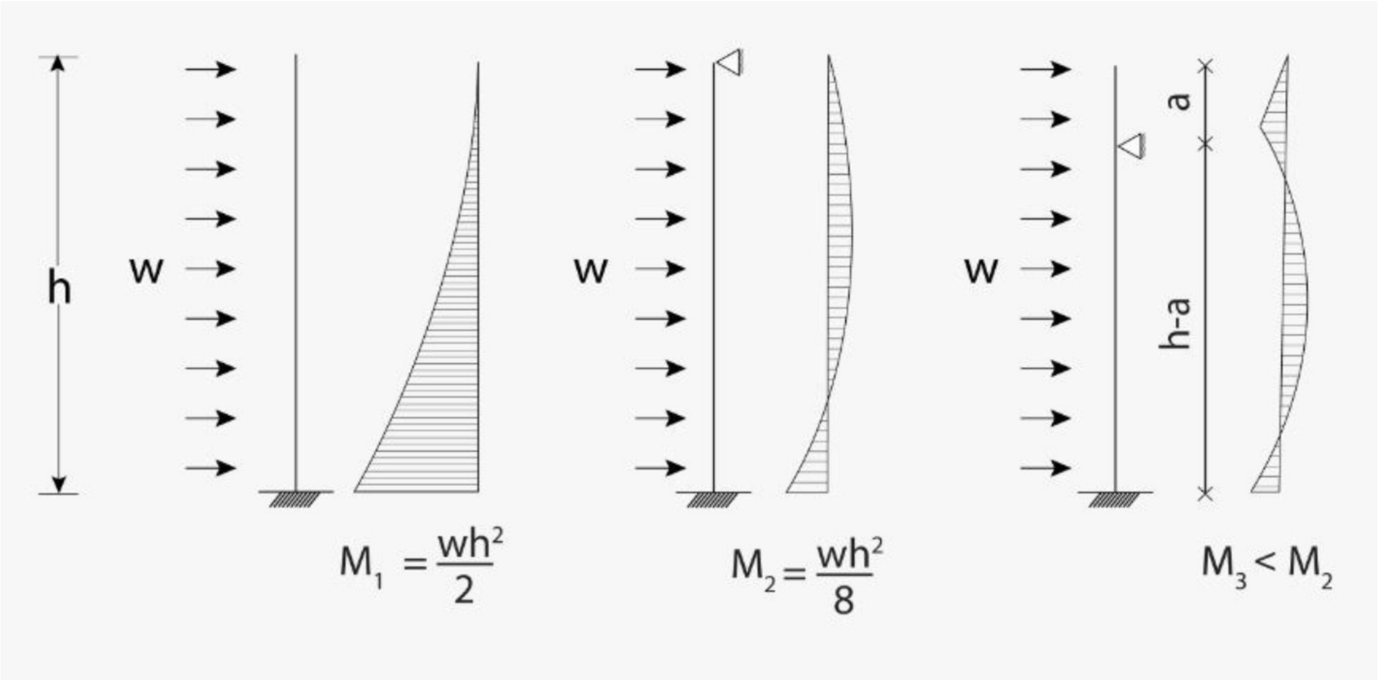


- Significant damage to unreinforced masonry (URM) buildings is attributed to parapet failures during seismic or high wind events.
- Overturning parapets cause damage not only to the building itself, but to nearby buildings as well, and poses a major risk to life safety to pedestrians. Parapet evaluation is required for seismic assessment and bracing





Bracing Locations-Parapet Wall



Bracing – Chimneys

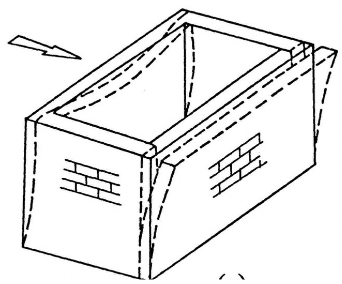
- Unreinforced chimneys are also highly vulnerable to lat loads.

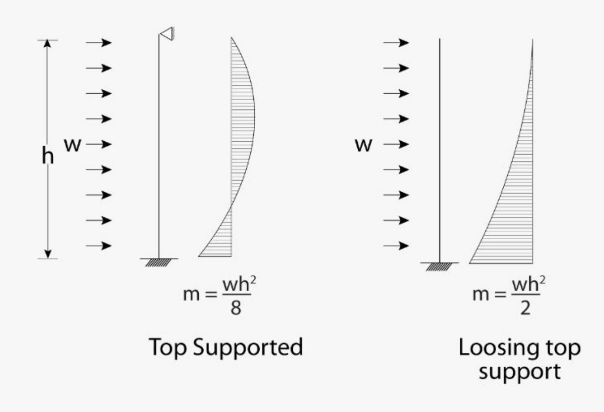
- Tying brick masonry chimneys using steel rods and straps is an effective approach for stabilizing against overturning

Connecting Floor Diaphragms to Masonry Walls

- Perhaps the most critical element for defining a masonry structure's lateral load resistance is anchorage between walls and diaphragms at the roof and floor levels. Failure to properly anchor floors and roofs to walls limits their stability under lateral out-of-plane loading.

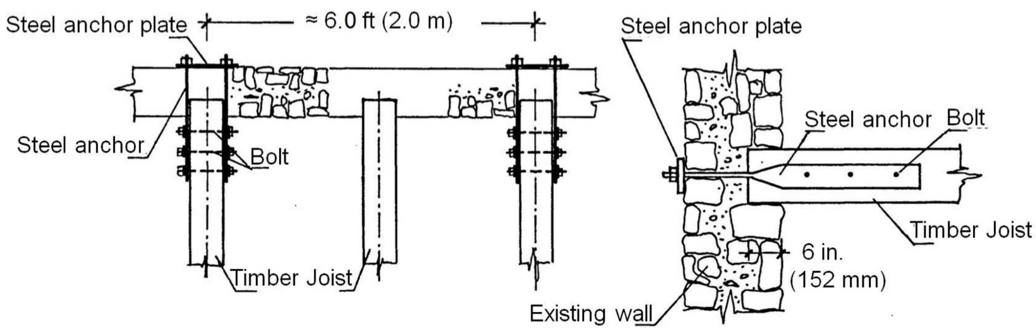
- Loosing the top support, change the support condition from simply supported top and bottom to a cantilever. This dramatically increase the out-of-plane moment (demand)





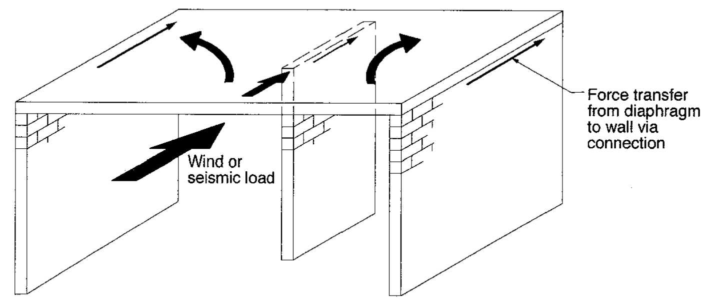
…Connecting Floor Diaphragms to Masonry Walls

- Masonry walls must be adequately tied to horizontal roof and floor diaphragms for global stability and robustness when subjected to out-of-plane loading. There are many approaches for anchoring walls to the diaphragms.
- The most widely used approach includes through-bolting with bearing plates at the exterior, combined with epoxy adhesive or grout in the walls, to provide a wa



…Connecting Floor Diaphragms to Masonry Walls

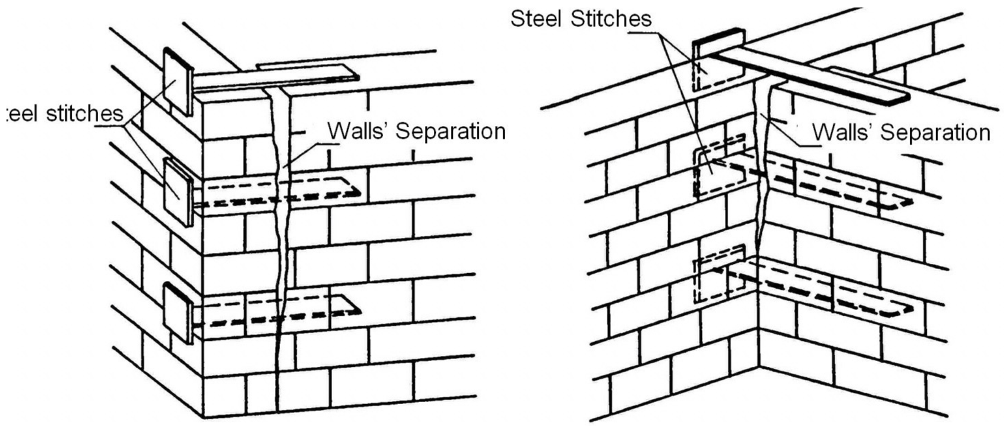
The ability of the floor or roof system to transmit lateral in-plane loads to the cross wall is also compromised. Retrofit of wall anchorage to connect URM walls to floor and roof diaphragms is a common retrofit component for reducing life safety threats for minor and moderate earthquakes.



Connecting Cross and Flanged Walls

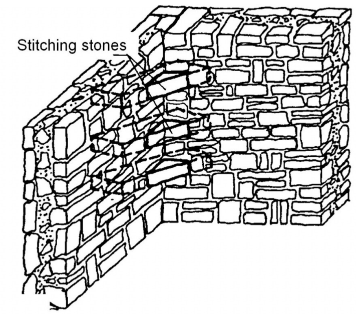
- System resistance to lateral loads, building stiffness, and overall system stability is enhanced if intersecting walls can be considered as flanged wall systems. Intersecting masonry walls may be analyzed as flanged wall systems if adequate connection is provided to resist shear that develops at the wall-to-wall intersection.
- Connections between intersecting walls are retrofitted by installing structural anchors, designed for shear stress developing at the interface, or by meeting the prescriptive requirements of TMS 402 Code for new masonry construction.
- TMS 402 Code requires 6 mm by 37 mm straps with a 50 mm upturn at each end, embedded 600 mm into the intersecting wall, at a maximum 1.2 m spacing

Connecting intersecting walls using steel stitches

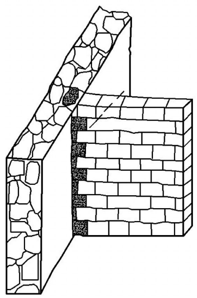


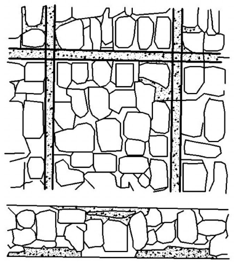
....Connecting Cross and Flanged Stone Walls-Stitching

- Intersecting stone masonry walls can also be connected by stone stitching.

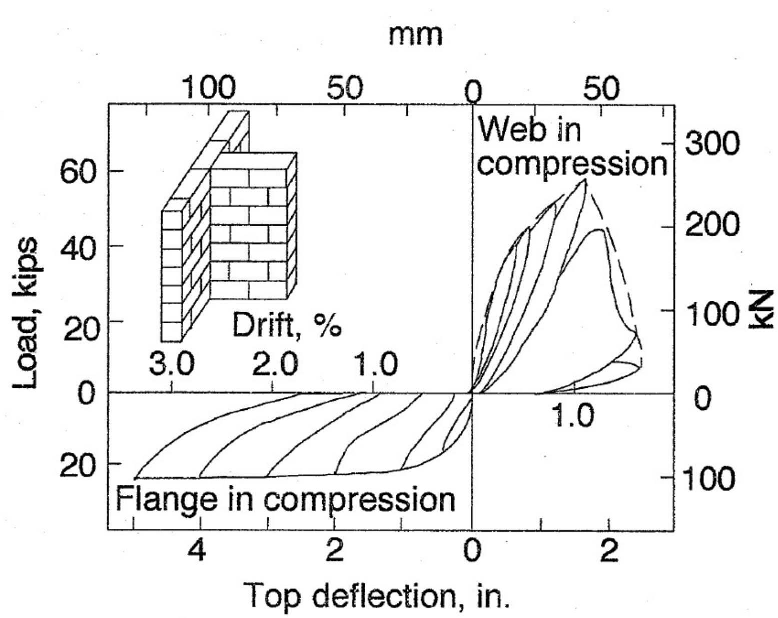


- Intersecting stone and brick walls can be connected using a horizontal bond beam connected to vertical reinforced columns embedded in the masonry wall.





Flanged Wall Behavior



- T-section has unsymmetrical lateral response.
- T-section Flange in compression results in lower strength and higher displacement ductility

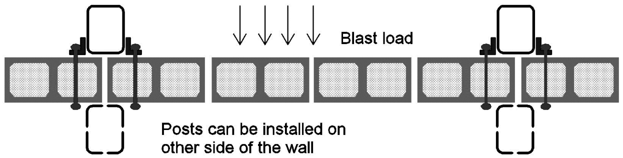
Installing Supplemental Structural Support

- Adding a supplemental backup wall to existing masonry construction effectively increases lateral resistance and stability against out-of-plane loads. a new steel stud wall is added to one side of a hollow clay tile wall.

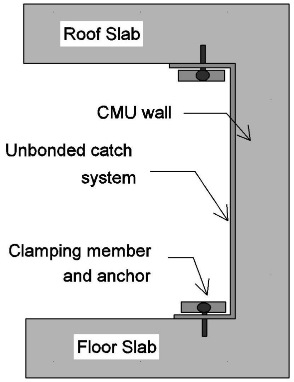
- External steel truss can be added and anchored to the masonry wall   for in-plane and out-of-plane load transfer

....Installing Supplemental Structural Support

- Steel posts and through bolts can be used to improve masonry resistance to blast loading.



- Unbonded catch systems are also used with non-loadbearing masonry walls not as a strengthening measure, but to collect masonry debris during a blast event. Debris catchment systems use an unbonded sheet of` thin ductile retrofit material at the interior surface of the wall, anchored at the top and bottom supports.

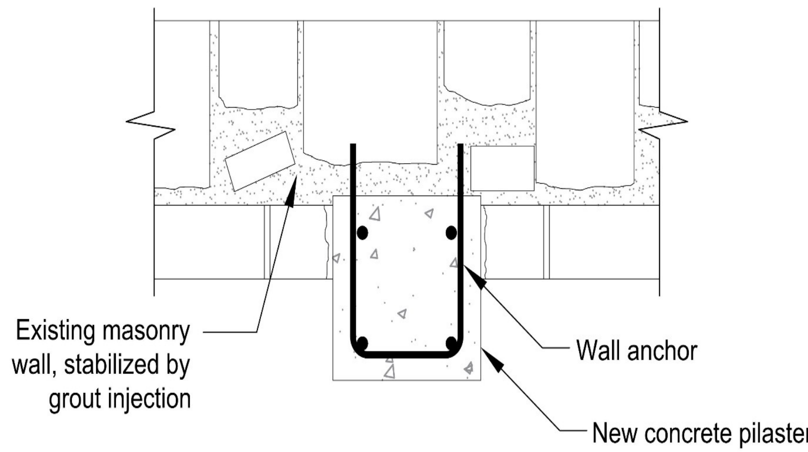


....Installing Supplemental Structural Support

- Supplemental structural supports are also used to distribute vertical loads at beam bearing points,
- The new structural steel element serves the dual purpose of transferring diaphragm loads to the walls and distributing the beam end reaction to the wall over the height of the connection.

....Installing Supplemental Structural Support

- Supporting systems may also incorporate discrete elements such as buttresses, pilasters, and counterforts, built integral with or anchored to existing walls.

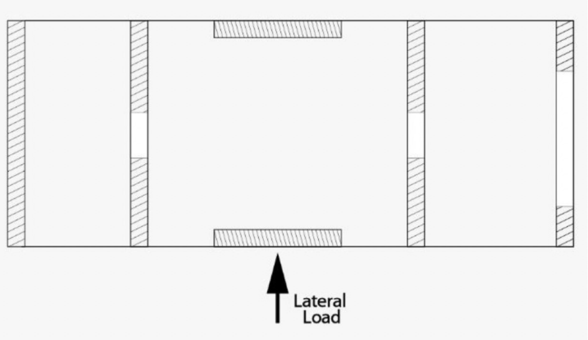


Adding An Opening to an Existing Wall

Purpose

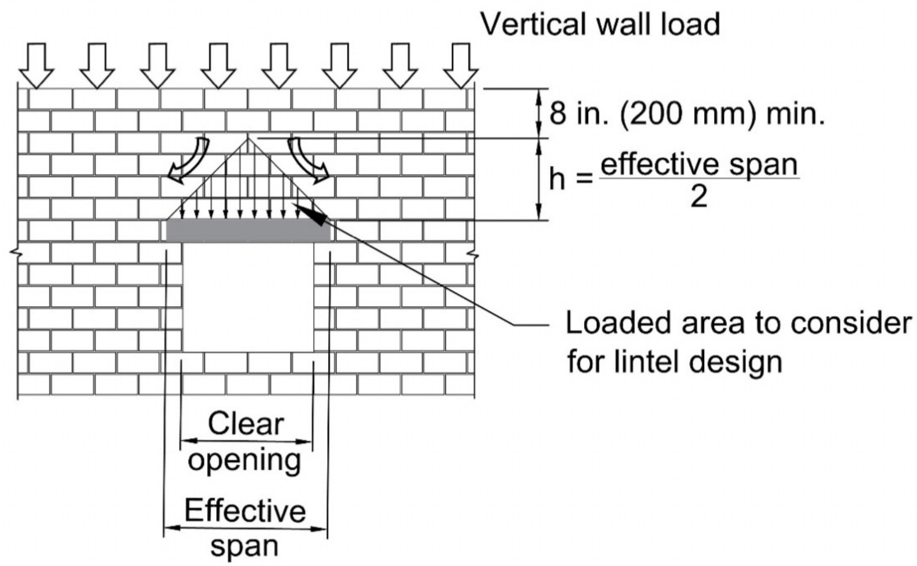
- Many building renovations require addition of windows, doors, and other openings cut into existing masonry walls. Such an opening allows access and/or natural light and vision.

- An opening can also be added to reduce the wall stiffness to minimize torsional effect.

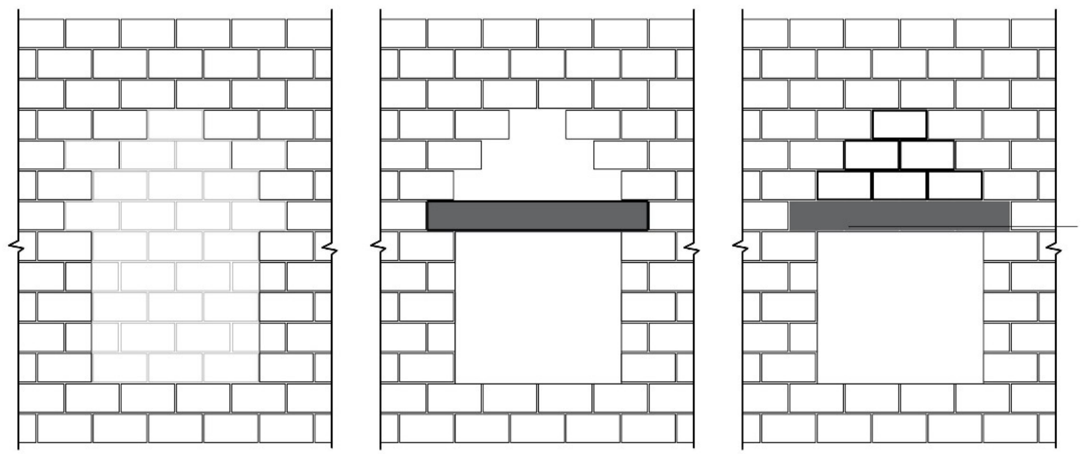


Design

Masonry has the unique characteristic of spanning openings through arching action, and this attribute is advantageous when forming new openings and designing lintels.



Arching

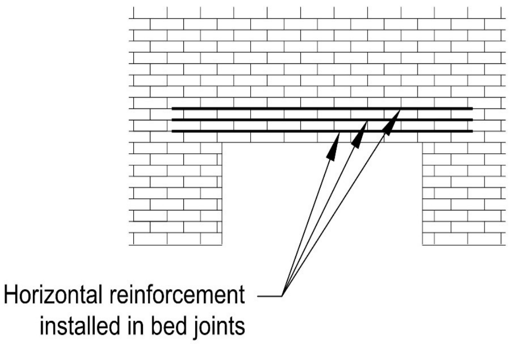


(a) Remove masonry, following lines of arching action

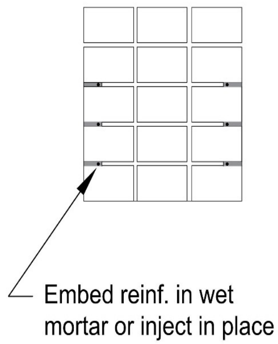
(b) Install new lintel

(c) Infill above lintel

Forming a New Lintel Above Opening

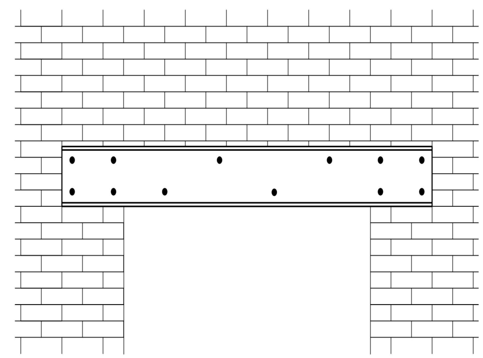


(a) Elevation



(b) Wall section

(a) Angle in horizontal slot



(b) Face mounted channel

Techniques Related to improving Serviceability

Repointing

- The term repointing, sometimes incorrectly called tuck-pointing, refers to the process of cutting out mortar joints and filling slots with new mortar.

- Repointing mortar joints is conducted as a regular maintenance item to repair mortar spalls, eroded joints, or other forms of deterioration.

- Mortar joints are also repointed to address cracks, delamination at the mortar-unit bond line, and to fill deficient joints.

.. Repointing-Compatibility and Formulation

- As discussed previously in this chapter, it is essential that new repointing mortar is compatible with existing mortar and masonry units. The new mortar should match the existing mortar as closely as possible in terms of colour, texture, and physical properties, as determined by laboratory or in situ tests.
- The choice of a repointing mortar formulation depends, not only on these compatibility requirements, but also the mortar's expected function, weather exposure and durability.
- Where original mortar or masonry units are relatively soft, a soft mortar with high lime content is preferred, being better able to respond to slight movement without cracking.

Compatibility

Where original mortar or masonry units are relatively soft, a soft mortar with high lime content is preferred, being better able to respond to slight movement without cracking. Use of high strength, high stiffness cement-based mortars can lead to cracking and spalls resulting from stress concentrations along joint edges. Further, using a dense mortar with soft historic brick or porous stone can shift the avenue of water vapor transmission from through mortar to through the masonry units, oftentimes leading to severe deterioration.

Steps for Repointing Mortar

1- Develop a repointing mortar formulation

2- prepare joints to be repointed by racking or cutting

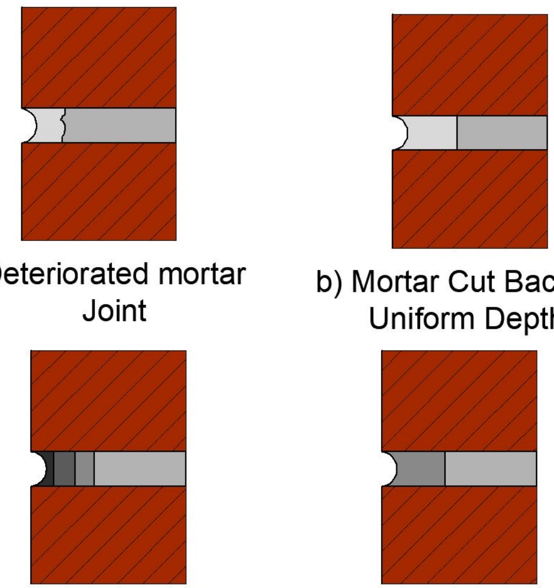
3- Clean out joints

4- Mix repointing mortar to a stiff consistency

5- Wet the prepared mortar joints

6- fill in joints by packing in 3 lifts

7- Allow the new mortar to stiffen and then tool the exposed surface to match adjacent joints profile



a) Deteriorated mortar Joint

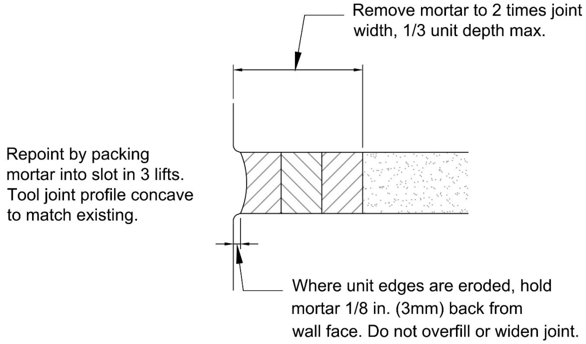
b) Mortar Cut Back to Uniform Depth

c) Pack Pointing Mortar in Thin Layers

d) Tool Joint Metal Original Profile

… Repointing Mortar Joints

For additional information on repointing mortar joints, refer to ASTM C270 Appendix X3



Crack Repair

- Before embarking on a crack repair program, the cause of the crack must be identified and remedied. Cracks should also be monitored before repair, to determine if the crack is actively moving or is dormant, as different repair approaches are required for active and dormant cracks.
- The appropriate crack repair method is chosen based on the intent of the repair: aesthetic, structural, or to address moisture infiltration. In cases where cracks propagate entirely through the wall section, repairs are often required at both sides of the wall.

Repair of Active Cracks-

- Actively moving cracks are best repaired by either installing an adjacent movement joint or by installing flexible sealant at the crack itself. Cracks to receive sealant are widened to a width of 6 to 13 mm and a depth of roughly twice the width.
- Flexible sealant is installed over backer rod, priming masonry bonding surfaces as necessary to ensure new sealant bonds well to existing masonry.
- Sealant joint appearance is improved by using sealants with integral silica aggregate, mimicking the appearance of a mortar joint.

Repair of Dormant Cracks

- Dormant, non-moving cracks are repaired by repointing, stitching, or injection.

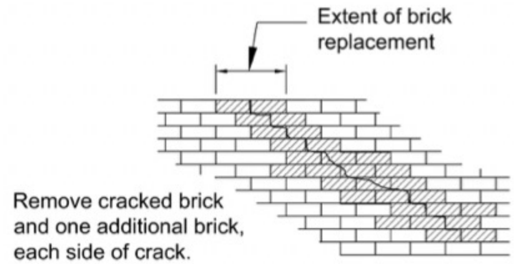
- A simple repair is to widen the crack along its length using a grinder or small rotary saw, and pointing new mortar into the slot or by installing new reinforcement in mortar bed joints in drilled core holes or as external steel straps bolted to the wall face.

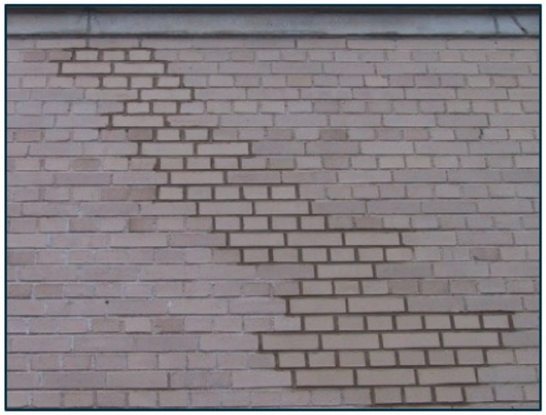
Repair of Dormant Cracks- Stitching

- Crack stitching is used to restore structural continuity and reinforce across cracked sections, minimizing potential for future crack development.
- Stitching is accomplished by either replacing cracked units and cracked mortar joints or by installing new reinforcement in mortar bed joints in drilled core holes or as external steel straps bolted to the wall face.

Crack Stitching using new

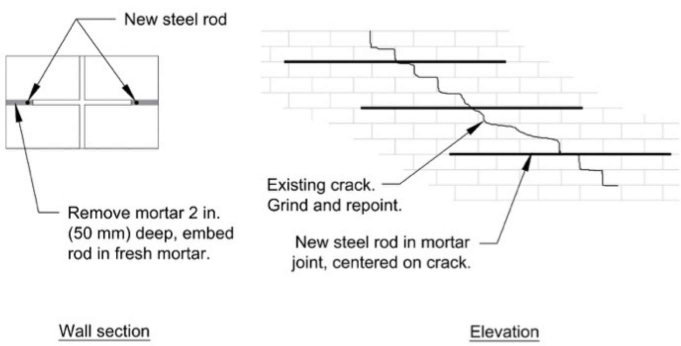
brick and mortar





....Repair of Dormant Cracks- Stitching

- The most common approach is to remove mortar at bed joints to receive new horizontal reinforcement. Rod strength is developed by extending reinforcement beyond the crack using a straight embedment or with 90-degree hooks, using a u-shaped rod with the ends inserted into holes drilled into the wall.



Creating New Movement Joints

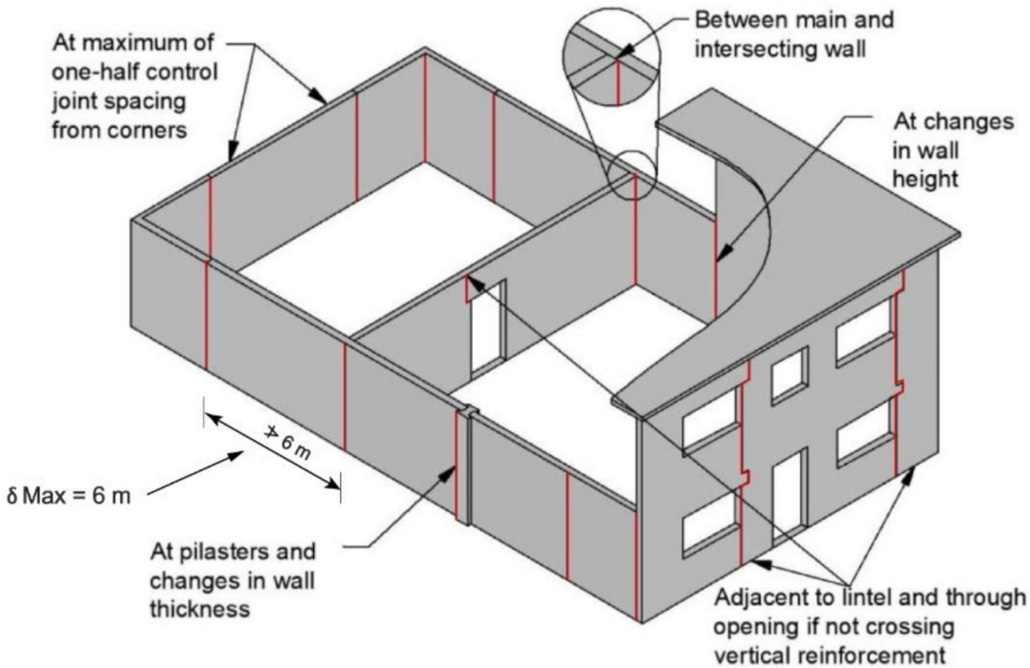
- Movement joints are required with most masonry systems to minimize build-up of internal forces and prevent cracking and/or instability. Many older buildings were constructed without provisions for accommodating movement, leading to cracks and displaced masonry.
- New movement joints, installed at strategic locations, will relieve internal strains and force movements to occur at locations where they can be managed.
- The effect of movement joints on loadbearing masonry requires careful consideration to ensure vertical and lateral load paths are not compromised and to determine the effects of movement joints on wall strength and rigidity.

…Creating New Movement Joints

- For masonry veneer, the spacing and condition of veneer anchors is evaluated before installing movement joints.
- New veneer anchors are often required at each side of new movement joints. TMS 402 Code specifies a maximum anchor edge distance of 300 mm.

Movement Joints- at Corners

Locations of Movement Joints in Masonry Veneer

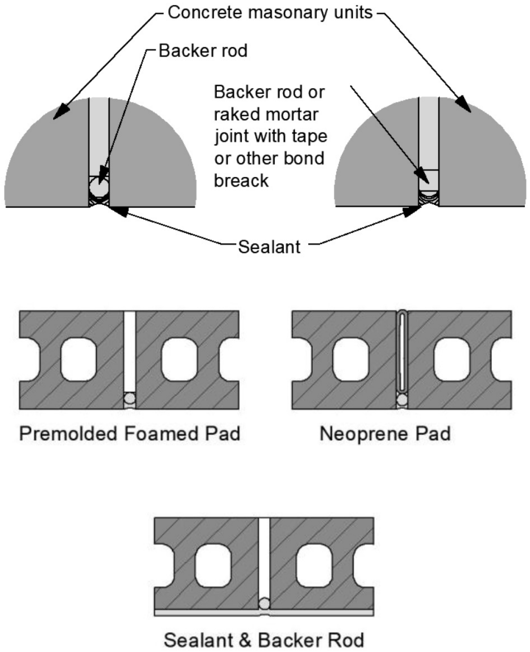


...Creating New Movement Joints
Joint sealants

- For successful performance of masonry joints, sealants have to be watertight, durable and capable of accommodating cyclic movements due to temperature and moisture changes.
- Adequate joint locations, sizing, appropriate product selection , and careful sealant installment are key issues to be considered.
- The choice of sealant material should be based on expected performance, durability and aesthetics.
- High performance sealants with low elastic modulus such as polysulfides, urethanes and silicones are recommended. Sealants that qualify as Grade NS, Class 50 (50% movement capacity) are recommended.
- For more information, refer to ASTM C920.

Installing Movement Joints in Brick Veneer

Polystyrene rod with caulking or flexible gasket type of joints is generally effective seals without creating restraint to movements.



Addressing Corrosion

Metal corrosion is an electrochemical process resulting from electrons flowing from embedded metals at anodic sites causing oxidation and formation of expansive oxidation products. Expansion not only results in metal section loss, but also causes damage to surrounding materials in the form of cracks, spalls, stains, and rust-jacking.

Addressing Corrosion

- Repairs are necessary to halt the corrosion process, restore section capacity, and prevent associated cracking damage, stains, and other forms of distress. For situations where corrosion activity is limited to minor or moderate section loss, an active impressed current cathodic protection (ICCP) system may be installed.
- Other techniques used to address corrosion in reinforced concrete include re-alkalization, chloride extraction, and installation of corrosion inhibitors can also be used with masonry construction but there is limited experience to date.

....Addressing Corrosion
Repair of a corroded steel Lintel

- The most common approach to address metal corrosion and associated damage is to selectively open wall sections for access to corroding metal followed by rebuilding. This invasive approach often requires temporary shoring or props to support structural loads during replacement.

- Steel exposed during reconstruction is cleaned, painted and inspected for ongoing use. Areas with significant steel section loss may require replacement or strengthening by adding new members. Replacement members should be hot-dipped galvanized, stainless steel, or FRP to minimize or prevent future corrosion activity.

....Addressing Corrosion
Repair of a corroded steel Lintel

- If adequate metal section remains, oxidation is cleaned and metal coated using a zinc-rich primer, cementitious coatings, two to three coats of aluminum epoxy, bituminous applications, or micaceous iron oxide.
- If corrosion is severe in steel lintels, replacement with a new hot-dipped galvanized lintel is preferred.

… Addressing Corrosion
Cathodic Protection

- For situations where corrosion activity is limited to minor or moderate section loss, an active impressed current cathodic protection (ICCP) system may be installed.

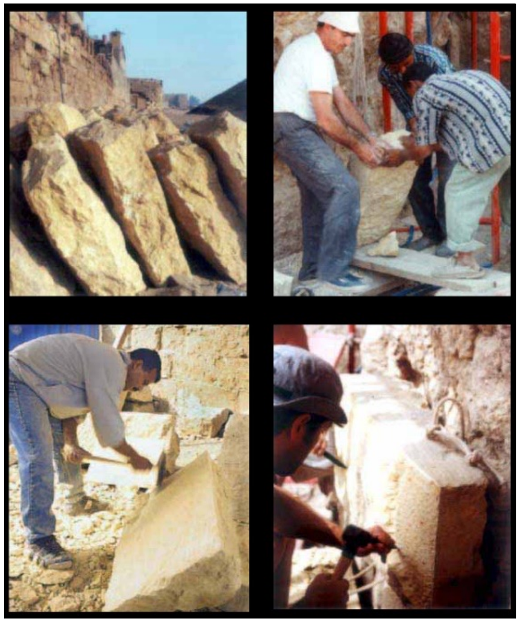
- Other techniques used to address corrosion in reinforced concrete include re-alkalization, chloride extraction, and installation of corrosion inhibitors can also be used with masonry construction but there is limited experience to date.

Replacement

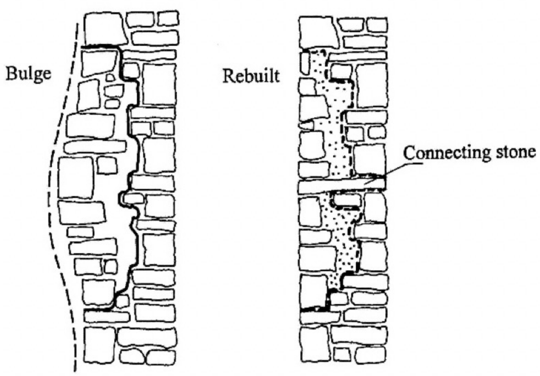
Replacement

- The extreme retrofit technique is to replace the damaged or nonperforming part of the building, also known as anastylosis.

- For buildings that are expected to perform satisfactorily for decades, removing and replacing parts of units, individual units or all of the affected area often produces not only the best technical result, but can also be most economical.



… Replacement



The End

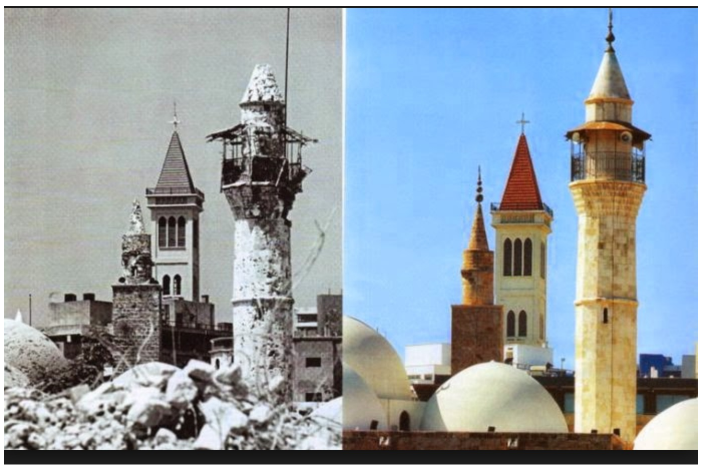


Figure 20: Example of damage to an intricate building, the fallen stones are visibly salvageable