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# A REVIEW OF CONVENTIONAL SEISMIC RETROFITTING TECHNIQUES FOR URM

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## Abstract

In many seismically active regions of the world there are large numbers of masonry buildings. Most of these buildings have not been designed for seismic loads. Recent earthquakes have shown that many such buildings are seismically vulnerable and should be considered for retrofitting. Different conventional retrofitting techniques are available to increase the strength and/or ductility of unreinforced masonry walls. This paper reviews and discuses the state-of-the-art on seismic retrofitting of masonry walls with emphasis on the conventional techniques. The paper reviews retrofitting procedures, advantages, disadvantages, limitations, effect of each retrofitting technique.

## Key Words

Retrofitting, rehabilitation, repair, seismic

## 1 Introduction

Matthys and Noland (1989) estimated that more than 70% of the buildings inventory worldwide is masonry buildings. Moderate to strong earthquakes can devastate complete cities and villages resulting in massive death toll and cause extensive losses. Most of these losses are caused by failure of unreinforced masonry (URM) buildings. Since demolition and replacement of these masonry structures is generally not feasible due to several factors this rises the question whether such buildings should be retrofitted. Nuti and Vanzi (2003) proposed a simple procedure to make a decision whether it is economically pertinent to retrofit a structure or not.

Although a variety of technical solutions have been implemented for seismic retrofitting, there exists little information or technical guidelines with which an engineer can judge the relative merits of these methods. Furthermore, no reliable analytical techniques are available to evaluate the seismic resistance of retrofitted masonry structures. This paper reviews common conventional techniques used in retrofitting of

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existing URM buildings. Common causes of damage and failure of URM buildings as well as a state-of-the-art of modern retrofitting techniques (e.g. composites) is presented in ElGawady (2004a, b).

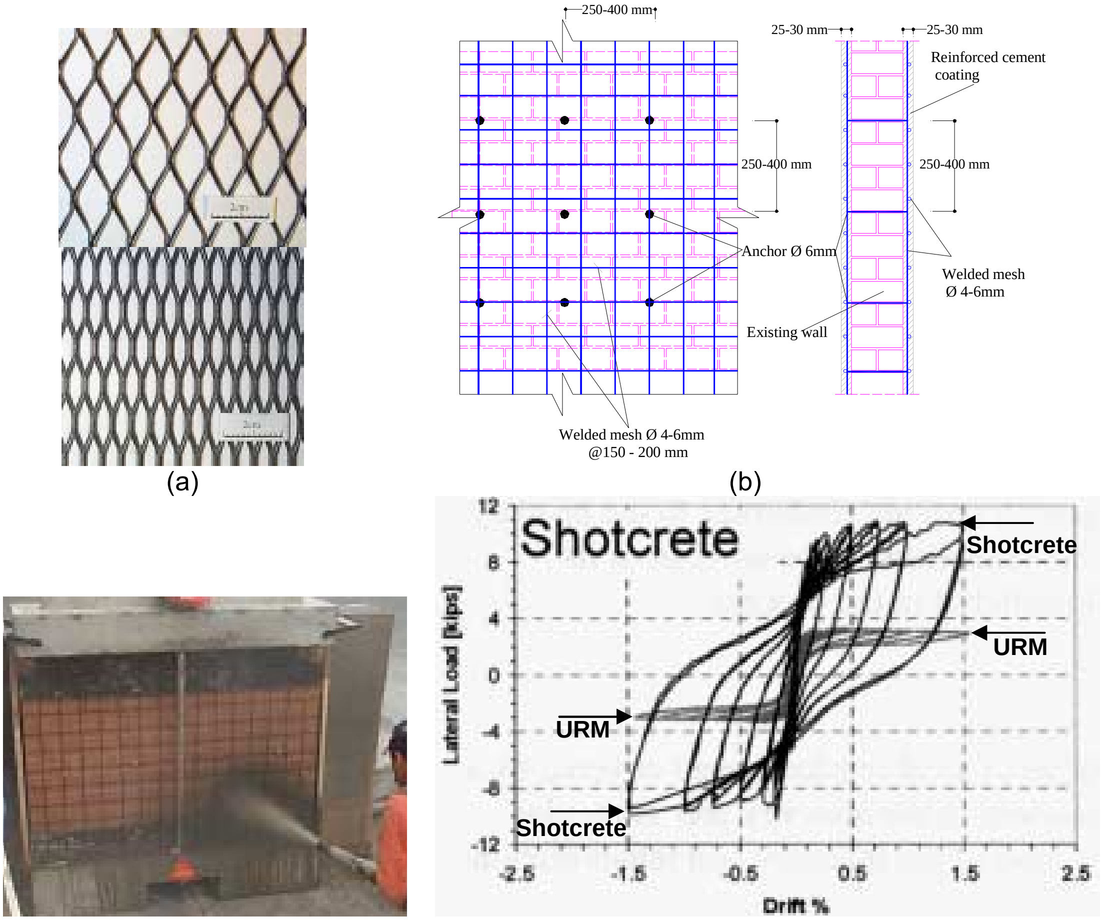
# 2 Retrofitting methods

## 2.1 Surface treatment

Surface treatment is a common method, which has largely developed through experience. Surface treatment incorporates different techniques such as ferrocement, reinforced plaster, and shotcrete. By nature this treatment covers the masonry exterior and affects the architectural or historical appearance of the structure.

### 2.1.1 Ferrocement

Ferrocement consists of closely spaced multiple layers of hardware mesh of fine rods (Figure 1 (a)) with reinforcement ratio of 3-8% completely embedded in a high strength (15-30 MPa) cement mortar layer (10- 50 mm thickness). The mortar is troweled on through the mesh with covering thickness of 1-5 mm. The mechanical properties of ferrocement depend on mesh properties. However, typical mortar mix consists of 1 part cement: 1.5-3 parts sand with approximately 0.4 w/c ratio (the ferrocement network, Montes and Fernandez 2001). The behavior of the mortar can be improved by adding 0.5-1% of a low-cost fiber such as polypropylene.



(a) (b)

(c) (d)

*Figure 1 Surface treatment:(a) hardware samples used in ferrocement (TWP Inc.), (b) reinforced plaster typical dimensions, (c) application of shotcrete for test specimen (ElGawady et al. 2004), and (d) hysteretic curves for a specimen before and after retrofit using shotcrete (Abrams and Lynch 2001)*

In order to reduce the mortar cost, it is possible to replace 20% of cement by fly ash or rice-husk; this replacement increases durability and decreases overall porosity as well as makes the mortar more plastic with a limited effect on overall strength (the ferrocement network).

Ferrocement is ideal for low cost housing since it is cheap and can be done with unskilled workers. It improves both in-plane and out-of-plane behavior. The mesh helps to confine the masonry units after cracking and thus improves in-plane inelastic deformation capacity. In a static cyclic test (Abrams and Lynch 2001), this retrofitting technique increased the in-plane lateral resistance by a factor of 1.5. Regarding out-of-plane behavior, ferrocement improves wall out-of-plane stability and arching action since it increases the wall height-to-thickness ratio.

### 2.1.2 Reinforced plaster

A thin layer of cement plaster applied over high strength steel reinforcement can be used for retrofitting (Sheppard and Tercelj 1980). The steel can be arranged as diagonal bars or as a vertical and horizontal mesh. A reinforced plaster can be applied as shown in Figure 1 (b).

In diagonal tension test and static cyclic tests, the technique was able to improve the in-plane resistance by a factor of 1.25-3 (Jabarov et al. 1980, Sheppard and Tercelj 1980). The improvement in strength depends on the strengthening layer thickness, the cement mortar strength, the reinforcement quantity and the means of its bonding with the retrofitted wall, and the degree of masonry damage.

### 2.1.3 Shotcrete

Shotcrete overlays are sprayed onto the surface of a masonry wall over a mesh of reinforcing bars (Figure 1 (c)). Shotcrete is more convenient and less costly than cast-in-situ jackets. The thickness of the shotcrete can be adapted to the seismic demand. In general, the overlay thickness is at least 60 mm (Abrams and Lynch 2001, Tomazevic 1999, Karantoni and Faradis 1992, Kahn 1984, Hutchison et al. 1984). The shotcrete overlay is typically reinforced with a welded wire fabric at about the minimum steel ratio for crack control (Karantoni and Fardis 1992).

In order to transfer the shear stress across shotcrete-masonry interface, shear dowels (6-13 mm diameter @ 25-120 mm) are fixed using epoxy or cement grout into holes drilled into the masonry wall (Abrams and Lynch 2001, Tomazevic 1999, Karantoni and Faradis 1992, Kahn 1984). Other engineers believe that a bonding agent like epoxy is required to be painted or sprayed on the brick so that adequate brick-shotcrete bond is developed (Kahn 1984). However, there is no consensus on brick-to-shotcrete bonding and the need for dowels. Diagonal tension tests of single and double wythe URM panels (Kahn 1984) retrofitted with shotcrete showed that, dowels did not improve the composite panels response or the brick-shotcrete bonding; header bricks satisfactory joined the wythe of existing masonry panels. In addition, Tomazevic (1999) and Kahn (1984) recommended wetting the masonry surface prior to applying shotcrete. Kahn (1984) shows that such brick surface treatment does not affect significantly the cracking or ultimate load, it affects to limited extend the inelastic deformations.

Retrofitting using shotcrete significantly increases the ultimate load of the retrofitted walls. Using a one-sided 90 mm thick shotcrete overlay and in diagonal tension test, Kahn (1984) increased the ultimate load of URM panels by a factor of 6-25. Abrams and Lynch (2001), in a static cyclic test, increased the ultimate load of the retrofitted specimen by a factor of 3. This retrofitting technique dissipates high-energy due to successive elongation and yield of reinforcement in tension (Figure 1(d)). Although in diagonal tension test (Kahn 1984) the improvement in the cracking load was very high, in static cyclic test (Abrams and Lynch 2001) the increment in the cracking load was insignificant.

Typically, the shotcrete overlay is assumed to resist all the lateral force applied to a retrofitted wall with the brick masonry being neglected all together (Abrams and Lynch 2001, Hutchison et al. 1984). This is reasonable assumption for strength design since the flexural and shear strength of the reinforced shotcrete overlay can be many times more than that of the URM wall. This assumption may result in some cracking of the masonry as the reinforcement in the shotcrete strains past yield. This may violate a performance objective for immediate occupancy or continued operation.

## 2.2 Grout and epoxy injection

Grout injection is a popular strengthening technique, as it does not alter the aesthetic and architectural features of the existing buildings. The main purpose of injections is to restore the original integrity of the retrofitted wall and to fill the voids and cracks, which are present in the masonry due to physical and chemical deterioration and/or mechanical actions. For multi wythes masonry walls, injecting grout into empty collar joint enhances composite action between adjacent wythe. The success of a retrofit by injection depends on the injectability of the mix used, and on the injection technique adopted. The injectability of the mix influences by mix's mechanical properties and its physical chemical compatibility with the masonry to be retrofitted.

For injection, epoxy resin is used for relatively small cracks (less than 2 mm wide); while, cement-based grout is considered more appropriate for filling of larger cracks, voids, and empty collar joints in multi-wythe masonry walls (Calvi and Magenes 1994, Schuller et al. 1994). However, Schuller et al. (1994) used a cement-based grout (100% type III Portland cement ASTM C150 with expansive admixture and w/c ratio of 0.75) to inject 0.08 mm wide cracks.

The retrofit of walls by cement grouting can be carried out as follows (Hamid et al. 1999, Calvi and Magenes 1994, Schuller et al. 1994):

- Placement of injection ports and sealing of the cracked areas in the basic wall as well as around injection ports.
- Washing of cracks and holes with water. Inject of water (soak of the bricks), from the bottom to the top of the wall, to check which tubes are active.
- Injection of grout (Figure 2(a)), with injection pressure of less than 0.1 MPa, through each port in succession. Begin injection at the lower-most port. After filling all large voids, a second grout mix (cement-based or epoxy) is used for fine cracks.

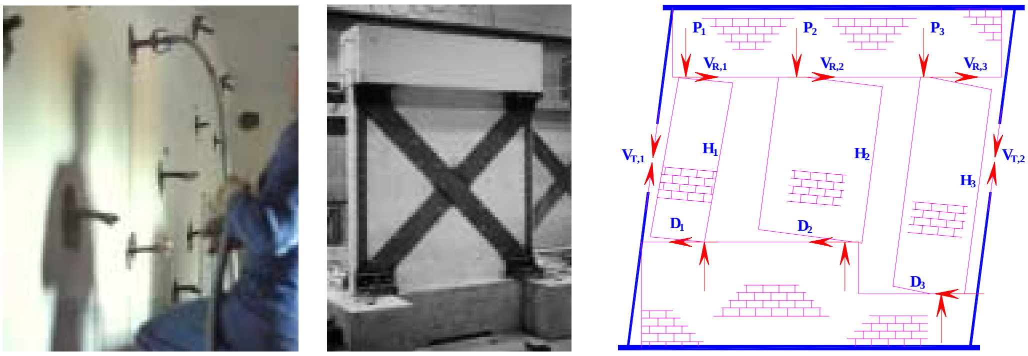
This retrofitting technique improves the overall behavior of the retrofitted URM; non-destructive testing (sonic tomography) of a bridge pier shows how the injection transformed relatively poor quality limestone masonry into relatively good in situ quality (Perret et al. 2002). The technique is effective at restoring the initial stiffness and strength of masonry. Cement-based grout injection is capable of restore up to about 0.8 of the unretrofitted masonry compressive strength (Schuller et al. 1984), 0.8-1.1 of the unretrofitted wall in-plane stiffness and 0.8-1.4 of the wall unretrofitted in-plane lateral resistance (Sheppard and Tercelj 1980, Manzouri et al. 1996, Calvi and Magenes 1994). In addition, cement-based grout injection can increase the interface shear bond of multi-wythe stonewalls by a factor of 25-40 (Hamid et al. 1999). Walls retrofitted with epoxy injection tend to be stiffer than the unretrofitted, but the increase in stiffness (10- 20%) is much less dramatic than the increase in strength. The increment in lateral resistance ranged from 2-4 times the unretrofitted resistance. The use of epoxy resins can be advisable when a through study of the structural consequences of such an increment in strength in selected portions of the building shows that there is no danger of potential damage to other portions.

## 2.3 External reinforcement

A steel plates or tubes can be used as external reinforcement for existing URM buildings. Steel system is attached directly to the existing diaphragm and wall (Figure 2(b)); however, Rai and Goel (1996) show that horizontal element can be connected to two vertical members (via pin connections), which are placed next to the existing wall (i.e. creating in-fill panel) can be used (Figure 2 (c)).

The relative rigidities of the unretrofitted structure and the new steel bracing are an important factor that should be taken into consideration. In an earthquake, cracking in the original masonry structure is expected and after sufficient cracking has occurred, the new steel system will have comparable stiffness and be effective (Hamid et al. 1996, Rai and Goel 1996).

The vertical and diagonal bracing improves the lateral in-plane resistance of the retrofitted wall by a factor of 4.5 (Taghdi 2000). The increment in the lateral resistance was limited by crushing of the masonry at ends (toes) followed by vertical strips global buckling. In the case of creating infill panel, the rocking motion of the pier is associated with a vertical movement of its corner butting against the support masonries and the steel verticals resist the motion by restringing this vertical movement. This mechanism put both vertical members under tension forces (Figure 2 (c)). The system increased the in-plane lateral resistance of the retrofitted wall by a factor of 10. In addition, the external steel system provides an effective energy dissipation mechanism (Taghdi 2000, Rai and Goel 1996).



(a) (b) (c)

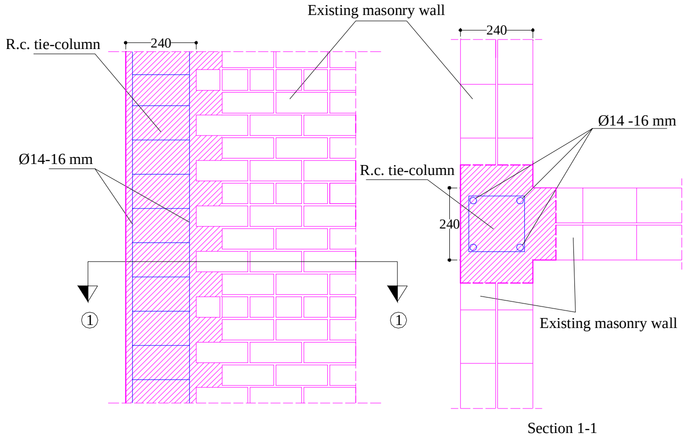
*Figure 2 (a) Grout injection (Tomazevic, personal communication), and external reinforcement (b) Using vertical and diagonal bracing (Taghdi 2000), (c) Creating in-fill panel (reproduced after Rai and Goel 1996)*

## 2.4 Confining URM using r.c. tie columns

Confined masonry with r.c. “weak frame” represents one of the most widely used masonry construction system in Asia and Latin America. In Europe, Eurocode 8 (EC 8) recommends the usage of such confined system for masonry constructions. In China, they used such confinement in new masonry buildings as well as it is used as retrofitting for existing URM buildings. However, it is not easy to construct such confinement in existing masonry buildings. The basic feature of confined masonry structures is the vertical r.c. or reinforced masonry tie columns, which confine the walls at all corners and wall intersections as well as the vertical borders of doors and windows openings. In order to be effective, tie columns should connect with a tie beam along the walls at floors levels. An elastic finite element analysis (Karantoni and Faradis 1992) shows that tie columns alone i.e. without tie beams do not have a significant positive effect on walls behavior

The confinement prevents disintegration and improves ductility and energy dissipation of URM buildings, but has limited effect on the ultimate load resistance (Chuxian et al. 1997, Zhang et al. 1997, Zezhen et al. 1984). For new constructions, according to EC 8, no contribution of vertical confinement to lateral resistance should be taken into account in the design (Tomazevic and Klemenc 1997). However, the real confinement effect mainly depends on the relative rigidity between the masonry wall and the surrounding frame and to less extend on material characteristics. Before cracking, the confinement effect can be neglected (Tomazevic and Klemenc 1997, Chuxian et al. 1997, Karantoni and Faradis 1992). However, for very squat URM walls (geometrical aspect ratio of 0.33 and double fixed boundary conditions) the confinement increased the cracking load by a factor of 1.27. At ultimate load, the confinement increased the lateral resistance by a factor of 1.2 (Zezhen et al. 1984, Zhang et al. 1997, Chuxian et al. 1997). However, for walls with higher aspect ratio, the confinement increased the lateral resistance by a factor of 1.5 (Tomazevic and Klemenc 1997). In addition, the confinement improved the lateral deformations and energy dissipation by more than 50% (Tomazevic and Klemenc 1997, Zezhen et al. 1984).

The amount of reinforcement and concrete dimensions for this system is determined on the basis of experience, and depends on the height and size of the building. The Technology Code for Confined Brick Masonry (DB32/113-95) recommended spacing of 1.5-2.5 m between columns as well as minimum dimensions and reinforcement for a column as shown in Figure 3. In addition, it is recommended to use 120-180 mm depth ring beam with width equal to wall thickness and 4 bars 8-14 mm diameter.



(a)

*Figure 3 Placement of new tie-columns in a brick-masonry wall*

## 2.5 Post-tensioning

Post-tensioning involves a compressive force applied to masonry wall; this force counteracts the tensile stresses resulting from lateral loads. There has been little application of this technique; post-tensioning is mainly used to retrofit structures characterized as monuments. This is due in part to lack of knowledge about the behavior of post-tensioning masonry (Foti and Monac 2000, Lissel et al. 1999, Ingham et al. 1998, Karantoni and Faradis 1992). In addition, the codification of post-tensioning masonry has only begun recently (e.g. MSJC 1999). Much research has been conducted in the last decade on post-tensioning masonry worldwide (e.g. Lissel and Shrive 2003, Rosenboom and Kowalsky 2003, Schultz et al. 2003, Laursen et al. 2002). Post-tensioning tendons are usually in the form of alloy steel thread bars (Schultz et al. 2003, Foti and Monaco 2000, Karantoni and Faradis 1992), although mono-strand tendons are not uncommon (Mojsilovic and Marti 1996, Al-Manaseer and Neis 1987). Bars typically show higher relaxation losses (2-3 times strand losses) and much lower strength/weight ratio (VSL 1990); in addition, a major drawback for using of steel bars is corrosion. However, fiber reinforced plastic presents a promising solution for this problem (Lissel and Shrive 2003, Figure 4).

Tendons are placed inside steel tube (duct) either within holes drilled along the mid-plane of the wall or along groves symmetrically cut on both surfaces of the wall. Holes are cement grouted and external grooves are filled with shotcrete (Rosenboom and

Kowalsky 2003, Al-Manaseer and Neis 1987). In this case, the tendons are fully restrained (i.e. it is not free to move in the holes). This is true even if the tendon is un-bonded i.e. no grout is injected between the duct and the tendons (Mojsilovic and Marti 1996). However, the holes can be left un-grouted (unguided unrestrained). This simplifies the strengthening procedure and allows future surveillance, re-tensioning, or even removal of the post-tensioning bars (Schultz et al. 2003, Karantoni and Faradis 1992). It is important for un-bonded bars to continue the protection of the bar inside the foundation to avoid differential oxidation (Foti and Monac 2000). MSJC (1999) provisions for masonry new constructions accept both restrained and unrestrained post-tensioning systems (Schultz et al. 2003).

Anchorage of post-tensioning in masonry is more complicated than in r.c. as masonry has a relatively low compressive strength. The self-activating dead end can be encasing to continuous and heavy r.c. foundation beams, constructed on either side of the wall bottom and connected well with it. At the top, post-tensioning is anchored in the existing r.c. elements (Figure 4 (c)) or in a new precast r.c. special beam or specially stiffened steel plates. Anchorage devices and plates are usually placed in a recess of the surface, and covered later on with shotcrete or cement mortar. The requirement for bottom anchorage penalizes considerably this retrofitting technique.

Vertical post-tensioning resulting in substantial improvement in wall ultimate behavior for both in-plane and out-of-plane; in addition, it improves both cracking load and distribution. Rosenboom and Kowalsky (2003) show that for cavity walls, the post-tension grouted specimen has lateral resistance much higher (40%) than the un-grouted one. For grouted specimens, although to bond or not the bars have insignificant effect on lateral resistance; the specimen who has un-bonded bars has higher lateral drift (70%) over the bonded specimen. The un-bonded grouted specimen has a drift up to 6.5%. However, un-bonded post-tension tendons may show low energy dissipation due to the lack of yielding of reinforcement (VSL 1990).

The effect of horizontal post-tensioning needs extensive experimental examination. Although some basic calculations of principle stresses show that the horizontal post-tensioning improves the resistance, Page and Huizer (1994) experimental test did not proof these calculations. In a linear finite element model, Karantoni and Faradis (1992) show that horizontal post-tensioning of spandrels did not significantly improve the building behavior. In addition, they show that if horizontal and vertical post-tensioning is combined together the resulting positive effect is higher than the sum of the individual effects of the two directions post-tensioning.

For bonded grouted post-tensioning the ultimate tendon force may be determined assuming rigid bond and plane sections similar to design of r.c. post-tensioning. Thus, the tendon will reach their yield force. For un-bonded post-tensioning the tendon force will increase from service up to ultimate load depending on the deformations. This increment in the tendon force may be estimated by applying rigid mechanisms. For short time behavior and under the same post-tensioning force, strand configuration and amount has insignificant effect on wall behavior (Al-Manaseer and Neis 1987).

## 2.6 Center core technique

The center core system consists of a reinforced, grouted core placed in the center of an existing URM wall. A continuous vertical hole is drilled from the top of the wall into its basement wall. The core achieved by this oil-well drilling technique may be 50-125 mm in diameter, depending on the thickness of the URM wall and the retrofitting required. With existing technology, this core can be drilled precisely through the entire height of two or three-story masonry wall. The drilling is a dry process with the debris removal handled by a vacuum and filter system that keeps the dust to a minimum.

After placing the reinforcement in the center of the hole, a filler material is pumped from the top of the wall to the bottom such that the core is filled from the bottom under pressure controlled by the height of the grout.


(a) (b) (b)

*Figure 4 (a) post-tensioning using FRP, (b) flexural crack in post-tension wall, (c) post-tensioning jacking frame (ISIS)*

The placement of the grout under pressure provided by the height of the core provides a beneficial migration of the grout into all voids adjacent to the core shaft. The strong bonding of the grout to the inner and outer wythes of brick provides a "homogeneous" structural element much larger than the core itself (Plecnik et al. 1986). This reinforced "homogeneous" vertical beam provides strength to the wall with a capacity to resist both in-plane and out-of-plane loading. Wall anchors for lateral ties to the roof and floors are placed at the core location to make a positive connection to the wall.

The filler material itself consists of a binder material (e.g. epoxy, cement, and polyester) and a filler material (e.g. sand). Shear tests (Plecnik et al. 1986) show that specimens made with cement grout were generally 30% weaker than specimens made with sand/epoxy or sand/polyester grouts. However, based on material price, it is recommended to use polyester and to keep the sand/polyester volume ratio between 1:1 and 2:1. For cement-based grout, the volume proportions of the components play an essential role in the shear resistance. However, of different grout types, the best type had components of 1:0.125:1 cement: lime: sand proportions by volume.

This technique is successfully used to double the resistance of URM wall in a static cyclic test (Abrams and Lynch 2001). Although the high lateral displacement achieved (Figure 5) during the test, the energy dissipated was limited. The tensile yield of the bar did not occur due to the bar anchorage problem. However, the system has several advantages: it will not alter the appearance of wall surface as well as the function of the building will not be impaired since the drilling and reinforcing operation can be done externally from the roof. The main disadvantage is this technique tends to create zones with widely varying stiffness and strength properties.

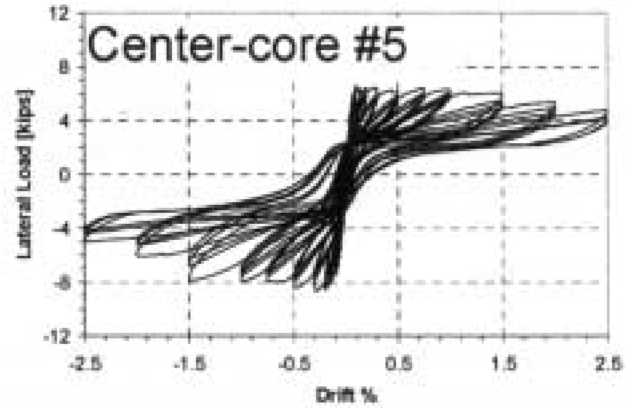


*Figure 5 hysteretic curve for a URM specimen after retrofitting using center core (Abrams and Lynch 2001)*

## 3 Summary

Based on the literature survey, Table 1 summarizes the efficiency, advantage, and disadvantage of each technique. Where available, figures from static cyclic or dynamic tests are given to indicate the improvement in the retrofitted walls.

*Table 1 Survey summary*

| Tech. | Efficiency | | Advantage | Disadvantage |
|---|---|---|---|---|
| | In-plane | Out-of-plane | | |
| Ferrocement | $F_r \rightarrow 1.5\ F_{ur}$<br>$D_r \rightarrow 1.7\ D_{ur}$ | Improves stability | Low cost<br>Low technology<br>Limited added mass | Space reduction<br>Arch. Impact<br>Requires arch. finishing<br>Limited efficiency<br>Limited E.D. |
| Reinforced Plaster | $F_r \rightarrow 2\text{-}3\ F_{ur}$<br>Improves $D_r$ | Improves stability | Low technology<br>Limited added mass | Space reduction<br>Arch. Impact<br>Required arch. finishing |
| Shotcrete | $F_r \rightarrow 3\ F_{ur}$<br>$D_r \rightarrow D_{ur}$ | Improves stability | High increment in $F_{ur}$<br>Very significant improvement in E.D. | Space reduction<br>Heavy mass<br>Violation of perform. level<br>Disturbance occupancy<br>Arch. Impact<br>Required arch. finishing |
| Injection | Restores initial stiffness<br>$F_r \rightarrow 0.8\text{-}1.4\ F_{ur}$ | Can restores initial stiffness | No added mass<br>No effect on building function<br>No space reduction<br>No arch. Impact | Epoxy create zones with varying stiffness and strength<br>High cost of epoxy<br>No significant increment in $F_r$ using cement-based grout |
| External Reinforcement | $F_r \rightarrow 4.5\text{-}10\ F_{ur}$<br>$E.D_r. > 1.5\ E.D_{ur}.$ | N.A. | High increment in $F_{ur}$<br>Prevent disintegration<br>Improves ductility and E.D. | Corrosion<br>Heavy mass<br>Violation of performance level<br>Requires arch. Finishing<br>Disturbance occupancy |
| Confinement | $F_r \rightarrow 1.2\text{-}1.5\ F_{ur}$<br>$D_r \rightarrow D_{ur}$ | Prevent disintegration | Prevent disintegration<br>Improve ductility and E.D. | Not easy to introduce<br>Limited effect on $F_{ur}$<br>Required arch. finishing<br>Disturbance occupancy |
| Post-tension | Improves $F_{ur}$ | Improves $F_{ur}$ | No added mass<br>No effect on building function | High losses<br>Anchorage system<br>Corrosion potential |
| Center Core | $F_r \rightarrow 2\ F_{ur}$<br>$D_r \rightarrow 1.3\text{-}1.7\ D_{ur}$ | Improves $F_{ur}$ | No space reduction<br>No arch. Impact<br>No effect on building function | Creation of zones with varying stiffness and strength. |

$F_r$, $F_{ur}$: lateral resistance for retrofitted and unretrofitted specimens respectively, $D_r$, $D_{ur}$: lateral displacement for retrofitted and unretrofitted specimens respectively, E.D.: energy dissipation

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