REVIEW OF STRENGTHENING TECHNIQUES AND MECHANICAL TESTING FOR UNREINFORCED MASONRY

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Abstract

In this paper, it is presented a collection and a critical review on the most significant research done on unreinforced masonry, types of testing, behavior and strengthening techniques to improve structural its structural performance. Furthermore, these researches are categorized and critically analyzed to benefit verities of them and help further understand behavior of URM. This study provides summary and guidance for researchers who are working on strengthening, modeling and retrofitting methods.

Keywords

Unreinforced Masonry, Experimental Testing, Structural Rehabilitation, Mechanical Parameters

1. Introduction

Masonry, together with timber, is the oldest building material and one of the widely-used construction methods around the world. It is still used nowadays due to low material costs, good sound and heat insulation, locally availability, aesthetics and simplicity of construction. The construction technique which consists of assembling bricks, stone or block units on top of each other, laid dry or bonded with mortar, is essentially the same as thousands of years ago, making it an easy, simple, very effective and useful method of construction. (Mustafaraj, 2016).
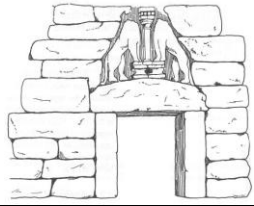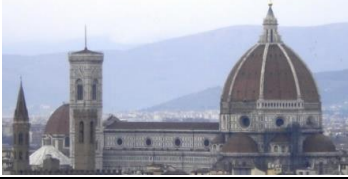
The first masonry material to be used was stone. Some of the earliest examples of permanent dry-stone masonry houses are found in Israel and date back to 9000-8000 B.C. Nowadays, we are witness of great masonry structures which are inherited from the past such as Egyptian architecture with pyramids, 2800-2000 B.C., temples, palaces, bridges and aqueducts of Roman and Romanesque architecture 0-1200 A.D.; the 8800 km long Great Wall of China (14th century) Gothic architecture with cathedrals 1200-1600, etc. (Table 1) (Lourenço, 1996).

Brick masonry constructions date back to 8350-7350 B.C. at Jericho in Palestine, where many round and oval houses made of sun-dried bricks of mud or clay have been found (Croci, 1998). Clay bricks were widely spread during Roman Empire when at the beginning mortar was placed only to fill the cracks and help masonry units to lay better, and afterwards addition of volcanic ash to lime mortars had a considerable improvement on mortar strength and bonding properties. It was only in 1858, with the invention of the Hoffman kiln, where all the stages of firing process could be carried out at the same time and continuously, made it possible the creation of more efficient bricks.

2. Mechanical Properties of Masonry

Nowadays, there are various types of masonry units produced by different raw materials such as clay, calcium silicate, stone and concrete in different production methods. The different arrangement of brick units forms the so-called "bond" which has aesthetics as well as structural functions. The most common types of bonds used worldwide are: (a) American or common bond; (b) English or cross bond; (c) Flemish bond; (d) Stack bond; and (e) Stretcher bond (Figure 1). English bond is one of the most popular types of arrangements of bricks as it is suitable for any wall thickness and is considered to be the strongest type of bond.

Table 1: *Examples of Historic Masonry Constructions*

Egyptian pyramids (2800-2000 B.C.)	Lion Gate at Mycenae (13th century B.C.)
Parthenon of Athens (5th century B.C.)	Colosseum, Rome (1st century A.D.)
Pont Du Gard (1st century A.D.)	Hagia Sophia, Istanbul (6th century A.D.)
Notre Dame de Paris, (14th century A.D.)	Florence Cathedral, (13th century A.D.)
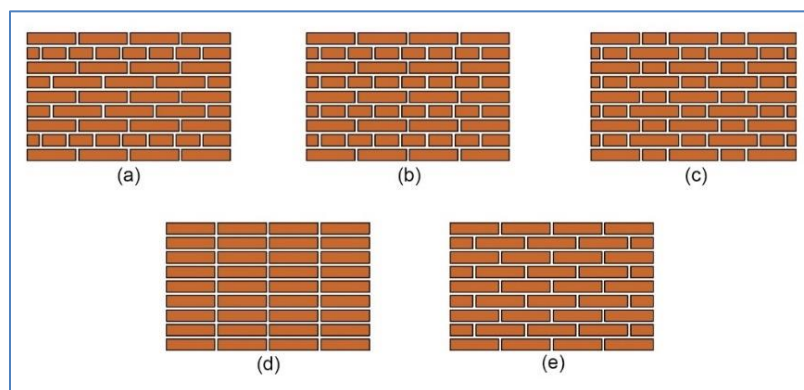
Figure 1: *(a) American or common bond; (b) English or cross bond; (c) Flemish bond; (d) stack bond; and (e) stretcher bond (reproduced after Lourenço, 1998)*
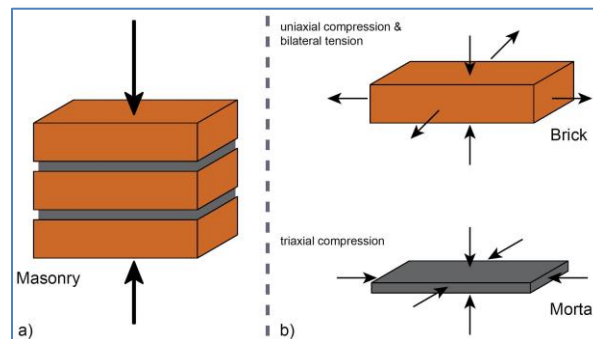
2.1 Masonry Compressive Strength

Masonry compressive strength defines the ability of the prism to resist compressive forces and varies to about 20-50% of the brick's compressive strength. Such a low value is due to the low mortar strength; the higher mortar strength, the higher the prism's strength (Paulay & Priestley, 1992; Drysdale et al., 1994). The compressive strength of masonry is affected by workmanship, properties of the masonry units, thickness of the mortar joints, age of mortar and the suction rate of bricks (Sahlin, 1971). It is also influenced by mortar and brick thickness; the thicker the bricks in comparison to mortar, the higher the strength of masonry. The optimum joint thickness is suggested to be between 5-10 mm. Any value above would reduce the overall masonry strength in compression (Deodhar, 2000).

The failure of masonry in compression is caused due to the interaction between brick units and the mortar joints which have different deformation characteristics (Berto et al., 2005). The compressive forces cause the prism (bricks and mortar joints together) to expand laterally. Generally, as the bricks are much stiffer than mortar, they do not expand laterally but constrain the mortar to be subjected under tri-axial compression. In order to maintain equilibrium, the confined mortar joints pull the brick units laterally, causing them to be under bi-lateral tension force in addition to the uniaxial compression.

According to Hilsdorf, one of the main causes of failure of masonry, is the difference in the elastic properties of brick and mortar. Uniaxial compression perpendicular to bed joints leads to a triaxial compression of the mortar and compression-biaxial tension in the brick (Figure 2 a, b) (Hilsdorf, 1969).

Figure 2: *a) Compression of masonry prism, b) state of stresses of brick and mortar (reproduced after Hilsdorf, 1969)*

The relationship between brick unit, mortar and masonry compressive strength is given by the following equation as of Eurocode 6 (CEN, 2005):

$$f'_m = k \cdot f_b'^{\alpha} \cdot f_j^{b} \quad \dots (1)$$

where **k**, **α** and **β** are constants and f'_b, f'_j and $f'm$ are brick, mortar and masonry compressive strength. The values of **α** = 0.7 and **β** = 0.3, whereas **α** and **β** has a range of values.

2.2 Masonry Flexural Tensile Strength

Masonry flexural tensile strength is mainly governed by the bond between the brick units and the mortar type. As in the compressive strength, the tensile strength of masonry is lower than the individual tensile strength of its constituents.

As it is difficult to achieve a relationship between masonry tensile strength to its compressive strength due to different shapes, material and manufacture processes, Hendry et al., from their research, observed that the tensile strength of masonry varies between 0.2-0.8 MPa (Hendry et al., 1997). Tomazeviç, on the other hand, proposed a correlation between tensile and compressive strength of masonry as follows (Tomazevic, 1999):

$$0.03f_m \leq f_t \leq 0.09f_m \quad \dots (2)$$

where f_m is masonry compressive strength and f_t is masonry tensile strength. Schubert 1988, suggested that the tensile strength of masonry is 0.03-0.1 times the compressive strength (Schubert, 1988).

2.3 Masonry Shear Strength

The shear strength under zero normal stress is one of the parameters required for prediction of numerical model for masonry as its exact definition plays a crucial role in the prediction of masonry behavior under seismic actions.

Crisafulli et al., (Crisafulli et al., 1995) and Hendry et al. (Hendry et al., 1997) suggested that the basic form of the shear strength of unreinforced masonry is based on the Mohr Coulomb shear friction expression:

$$\tau_m = \tau_0 + \mu\sigma_n \quad \dots (3)$$

where τ_m: shear strength at the shear bond failure; τ_0: shear bond strength at zero normal stress due to adheration strength of mortar; μ: internal friction coefficient between brick and mortar; σ_n: normal stress at bed joint.

The most common tests that are used to determine masonry shear strength are as follow:

i) Couplet or Triplet Test: used to quantify the shear strength parameters of horizontal bend joints. The triplet test, defined by EN 1052-3 (EN, 2003), covers the determination of shear

strength by testing at least six specimens constituted by brick unit and mortar joints. The test can be performed with or without lateral pre-compression.

ii) Shear-compression test: firstly, performed by Turnsek and Sheppard in Slovenia (Turnsek & Sheppard, 1980). The shear strength is evaluated as the average shear stress of the wall panel subjected to in-plane loading by a horizontal force placed at mid-span of a masonry wall panel, with bed joints in horizontal direction, supported at the lower and upper sides. It is mainly performed on new masonry.

iii) Diagonal compression test: designed to evaluate the shear strength and the shear elastic modulus of masonry. Eurocode 8 (EN, 2004) also suggests that she shear parameters of existing masonry walls to be calculated using diagonal compression test. This test is applicable to new masonry, too.

The test as of **ASTM E-519-02** (ASTM International, 2002) simulates a pure shear state of stress, positioning the Mohr circle of stress state at the origin of the σ-τ axes. The shear stress of masonry, S_s, is equal to the principal tensile stress, σ_1:

$$S_s = \sigma_1 = \frac{0.707 \cdot P}{A_n} \qquad \text{.... (4)}$$

Additionally, the shear modulus, G, can be determined from:

$$\gamma = \frac{\Delta V + \Delta H}{g} \qquad \text{..... (5)}$$

The failure of the specimen usually occurs with the panel splitting apart parallel to the direction of the load. Development of cracks initially starts at the center and continues mainly along the mortar joints and, in some cases, through the bricks.

RILEM LUM B6 (RILEM TC, 1994) considers modeling of the masonry panel as it is an isotropic homogeneous material and running a linear analysis; but the stress state at the center of the specimen is not in a pure shear state:

$$\sigma_x = \sigma_y = -0.56 \cdot \frac{P}{A_n} \quad \text{..... (6)}$$

$$\sigma_{xy} = 1.05 \cdot \frac{P}{A_n} \quad \text{..... (7)}$$

The tensile strength is evaluated by:

$$f_t = 0.5 \cdot \frac{P}{A_n} \quad \text{..... (8)}$$

As it can be seen from the different methods above, determination of masonry shear strength is not a straightforward operation. The seismic behavior of URM walls can be

experimentally simulated by two kinds of tests: shear-compression test and diagonal compression test (Martinelli et al., 2010).

The diagonal compression test is largely used by many researchers who have studied the improvement of structural behavior of unreinforced masonry (Corradi et al., 2002; Faella et al., 2010; Borri et al., 2011; Ismail et al., 2011; Mahmood & Ingham, 2011; Kalali & Kabir, 2012; Dizhur & Ingham, 2013; Milosevic et al., 2013; Mustafaraj, 2014; Yardim & Mustafaraj, 2015; Yardim & Lalaj, 2016; Mustafaraj, 2016a, 2016b).

2.4 Elastic Modulus of Masonry

One of the difficulties when calculating stiffness of masonry is the nonlinear behavior of it. Obtaining the Modulus of Elasticity from just the linear part of the stress-strain diagram is virtually impossible due to micro-cracks development at relatively low loads.

The Modulus of Elasticity of masonry (E_m) is calculated as the modulus of the chord of the linear part of the masonry compression stress-strain curve, typically defined to be between 5% and 33% of the ultimate masonry compressive strength (f'_m) (ASTM, 2003).

$$E_m = k \cdot f'_m \quad \text{..... (9)}$$

$$E_m = k \cdot f_b^a \cdot f_m^c \quad \text{..... (10)}$$

$$E_m = \frac{0.70 f_m - 0.05 f_m}{\varepsilon_{0.70 f_m} - \varepsilon_{0.05 f_m}} \quad \text{.... (11)}$$

However, various design standards are using different formulas to calculate the modulus of elasticity (Table 2).

Table 2: *Various Formulas for Determining the Modulus of Elasticity*

Author/Standard	Proposed equation
Eurocode 6 (CEN, 2005)	$E_m = 1000 \cdot f'_m$
FEMA 273, 1997	$E_m = 550 \cdot f'_m$
NHERP, 2000; Paulay and Prestley, 1992	$E_m = 750 \cdot f'_m$
Tomazeviç, 1999	$200 f_{cb} \leq E_m \leq 2000 f_{cb}$
MSJC (MSJC, 2002)	$E_m = 700 \cdot f'_m$
Sahlin, 1971; Crisafulli et al., 1995	$E_m = 300 \cdot f'_m$
Drysdale et al., 1994	$E_m = 500 - 600 \cdot f'_m$
Lumantarna, 2012	$E_m = 294 \cdot f'_m$
ASCE, 2007	$E_m = 350 \cdot f'_m$
where E_m is the elastic modulus of masonry, f'_m is the compressive strength of masonry and f_{cb} is the compressive	

strength of bricks.

2.5 Shear Modulus of Masonry

The shear modulus (also known as modulus of rigidity), G, is a parameter calculated by the ratio of the shear stress to shear strain, measured as the secant modulus between 5% and 70% of the maximum shear stress, τ_{max}, in the shear stress-horizontal drift, $\tau - \delta$, curve along the initial loading arm prior to τ_{max} (Dizhur & Ingham, 2013; Lin et al., 2014).

It may also be calculated by:

$$G = \frac{\tau_{1/3}}{\gamma_{1/3}} \dots (12)$$

where $\tau_{1/3}$ is the shear stress for a load of 1/3 of the maximum load P_{max} and $\gamma_{1/3}$ is the corresponding shear strain (Milosevic et al., 2013).

The shear stiffness decreases substantially after cracking due to bed joint sliding or diagonal tension crack opening. The relationship between the Modulus of Elasticity and shear strength is given as follows:

$$E = 2G(1 + \nu) \dots (13)$$

where: ν is the Poisson's ratio (adopted $\nu = 0.25$, as suggested by Harris, [Harris, 1988] and Pande et al., (Pande et al., 1998), for unreinforced masonry).

In literature, there are found various estimations of shear stiffness that relate Modulus of Elasticity, E_m, or the compressive strength of brick masonry, f'_m. (Table 3).

Table 3: *Different shear modulus equations from various researchers*

Author	Proposed formula
Alcocer and Klinger, 1994	$G_m = 0.1E_m$ (for masonry with high-strength brick units); $G_m = 0.2E_m$ (for masonry with low-strength brick units) where G_m and E_m are shear and elastic modulus, respectively.
Paulay and Priestley, 1992; Fattal and Cattaneo, 1977	$G_m = 400f'_m$ where f'_m is the compressive strength of brick masonry
FEMA 273, 1997	$G_m = 0.4E_m$

4. Strengthening Techniques used in Existing URM Structures

In order to improve deficiencies related to poor structural performance of URM structures under seismic actions, various strengthening techniques have been developed and applied

throughout history of construction. The main aim of the strengthening techniques is to increase low parameters of masonry such as tensile and shear strength. As discussed in Section 2.5, URM structures are highly vulnerable against lateral loads. For this reason, this deficiency is to be overcome by strengthening techniques. Depending upon the method and materials used, these techniques are categorized as: traditional and modern techniques.

4.1 Traditional Retrofitting Techniques

Traditional techniques such as: i) filling cracks and voids by grouting; ii) stitching of large cracks and weak areas with metallic or brick elements; iii) external or internal post-tensioning with steel ties; iv) shotcrete jacketing; v) ferrocement and vi) center core vii) confining using RC tie columns (Kalali & Kabir, 2012; Triantafillou, 1998).

Surface Treatment: It is a technique that covers the exterior face of masonry by affecting the architectural appearance of the structure. It consists on constructing a steel or polymer mesh, coated by high strength mortar, around the exterior of the structure. This system confines the masonry after cracking and increases the ultimate load resistance. The surface treatment improves the out-of-plane resistance and reduces any "arching action". However, application of this technique seriously affects the architectural properties and the lack of "breathing" of the wall may accelerate degradation.

Ferrocement Jacketing: This technique is applied by embedding closely spaced meshes of fine rods with reinforcement ratio of 3-8% in high strength (15-30 MPa) cement-mortar layer of 10-50 mm thickness. The typical mortar mix consists of cement: sand ratios of 1: (1.5-3) with a w/c ratio of 0.4 (Montes, 2001). It causes considerable increase in stiffness. Strengthening of pre-damaged URM walls can restore the original capacity and stiffness. Ferrocement can control crack formation as it has high flexural and shear strength. It has been subject of many studies for both unreinforced masonry (Mustafaraj & Yardim, 2016a, 2016b) as well as concrete structures (Rosenthal, 1986; Winokur & Rosenthal, 1982; Razvi & Saatcioglu, 1989). Some of the advantages of ferrocement such as considerably low price and ability to be completed with unskilled workers, make it an ideal solution for low cost housing.

Reinforced Plaster: This technique is achieved by applying a thin layer of cement plaster over high strength steel reinforcement (diagonal bars or horizontal mesh). It was observed that in diagonal tension tests and static cyclic test, the in-plane resistance was increase by 1.25-3 times (Jabarov et al., 1980).

Grout and Epoxy Injection: It is applied by injecting grout into pre-drilled holes on the wall. The main purpose is to restore original integrity and to fill the voids and cracks which are present in the wall. Injection is sustainable and may also be able to restore the initial strength of masonry. However, the success of this technique lies on the fact that the mechanical properties of the grout mix are compatible with the physical and chemical properties of the masonry that is to be retrofitted.

Traditional strengthening techniques offer a suitable method for improving the structural behavior of URM buildings, but there are some limitations such as: time consuming to be applied, reduction of available space, affecting the aesthetics etc. Furthermore, the additional weight of the reinforcing techniques may also increase the earthquake induced inertial forces and may require strengthening of the foundations as well.

4.2 Modern Strengthening Techniques

Development of new materials and techniques came as a necessity to overcome the limitations of traditional strengthening techniques. The reinforced polymers are an efficient alternative, as they improve the behavior of masonry elements under monotonic, seismic and explosive loads. Additionally, since the added mass and stiffness are negligible, the dynamic properties of the reinforced structure will not be altered. Some of the most used techniques are as follow:

TRM (Textile Reinforced Mortar): It is a technique that combines the essential properties of both conventional and modern materials by using textile grids externally embedded in mortars. The grid is made of long fiber roving (made of carbon, glass or aramid) arranged in two orthogonal directions. Instead of polymer resins, cement or lime-based mortars are used. The composite action of TRM is achieved through the mechanical interlock of the grid structure and the mortar It increases shear strength, stiffness and ductility. Some of the advantages of usage of TRM and replacement of organic resins with an inorganic binder are the improvement of the following: poor behavior at high temperatures; high cost; vapor impermeability; incompatibility with masonry substrates; irreversibility and lack of recyclability (Papanicolaou et al., 2001).

Fiber Reinforced Mortar (FRM): It is a reinforcing technique that consists of microfibers made of steel, glass, synthetic fibers (acrylic, aramid, carbon, nylon, polyester, polyethylene and polypropylene) and natural fibers (straw, coconut, bamboo, etc.) embedded in

mortar. Polypropylene fibers are chemically inert fibers that bond mechanically with the mortar through contact area.

Fiber Reinforce Polymer (FRP) Reinforcement: A fiber reinforced polymer (FRP) system consists of two main materials: resin and fibers. These FRP composites are made of carbon (CFRP), glass (GFRP) or aramid (AFRP) fibers bonded together in an inorganic polymeric matrix (such as putty fillers, saturants and adhesives like epoxy, polyester or vinylester) that offer many advantages such as high strength and stiffness in the direction of the fibers, immunity to corrosion, low weight, availability in various forms as laminates, fabrics and tendons of unlimited lengths, exceptional durability in many environments, cost effectiveness.

The FRP systems' characteristics are defined by: type of fiber volume, orientation and thickness and type of resin. One of the most important characteristics of FRP composites is that when a structural member is reinforced with FRP, stresses are transferred from substrate to the FRP through shear and epoxy interface. Among other advantages, some of the most useful properties of FRP materials are: i) easy implementation; ii) requirement of minor preparation works, iii) well-preservation of the material integrity of the masonry wall.

On the other hand, some of the disadvantages of FRP are: the difficulty on removal of FRP, the used resins are highly flammable and give off toxic vapors when burned; additional fire protection measures must be taken when implementing such a system; when exposed to ultraviolet light the resin slowly becomes brittle; the long-term reliability of FRPs is largely unproven; and FRPs are impermeable to moisture transport. For a successful application of FRPs, surface preparation is required as unfilled cracks or unsmoothed irregularities can cause premature debonding.

In many cases, FRP retrofitting techniques may be inadequate for heritage or historic constructions because of lack of compliance with conservation principles resulting from excessive invasivity and non-removability. It may be advisable to use a technique composed of traditional materials such as wood or ceramics glued on the wall surface and anchored with mechanical devices (Roca & Araiza, 2010).

Retrofitting of URM wall with FRP is a promising technique as it was observed that FRP improves the in-plane lateral resistance by 1.1-3 times and the out-of-plane resistance by more than 7 times. An important factor that has a big influence in the behavior of FRP reinforced URM is the reinforcement ratio. It was observed that the increase in the thickness of reinforcing

fibers slightly increases the load carrying capacity of the masonry wall. However, this fact is valid up to a certain level of thickness (Hamoush et al., 2003).

Valluzzi et al., investigated the efficiency of an alternative shear reinforcement technique, such as strengthening of brick masonry panels with by Fiber Reinforced Polymer (FRP) laminates using different reinforcement configurations. They conducted experiments to study the shear behavior of masonry panels reinforced with FRP laminates by testing in diagonal compression a series of nine unreinforced masonry (URM) panels and 24 strengthened panels were subjected to diagonal compression tests. As it was seen from the results, double-side configurations provided a less brittle failure and a noticeable ultimate capacity increase (Valluzzi et al., 2002).

According to the modern codes, safety evaluations of URM structures is clearly based on quantitative assessment of performances. Borri et al, in their study were focused on the shear behavior of masonry panels subjected to in situ diagonal compression tests on both unreinforced (mainly focused on diagonal cracking failure mode) and reinforced panels. The reinforced panels were tested to investigate the effectiveness of the methods of repair by comparing the traditional methods (deep repointing and FRP jacketing) with the innovative seismic-upgrading techniques "Reticolatus" method, embedding a continuous steel mesh cord in mortar joints whose nodes are anchored to the wall by means of transversal metal bars (Borri et al., 2011).

5. Conclusion

As it was seen from the literature survey, one of the main obstacles in analyzing the structural behavior of URM structures lies in the heterogeneity of the composite material (masonry assemblage) and the variability of mechanical parameters of masonry constituents (brick and mortar). Masonry properties are strongly related to brick's and mortar's properties, but it is the mortar layer the weakest link of masonry assemblage.

The most important property to be observed is the structural behavior of the URM building during earthquakes. The overall seismic performance depends on the capacity of in-plane walls to safely transfer the lateral loads to foundations. In this way, the masonry walls provide the post-earthquake stability necessary to avoid collapse of the entire structure. Simulation of this type of structural behavior can be achieved by inducing a diagonal compression force on a representative masonry wall panel of a standard dimension of 1.2m x

1.2m x 0.25m. As it is inferred in Section 2.5, the diagonal compression test has been a widely-used procedure to determine masonry shear strength and other shear related parameters for masonry.

It was seen that most of the researches were mainly focused on the undamaged state of the wall panels, considering only two types of specimen: either plain (unstrengthened) or strengthened. The implementation of the abovementioned techniques was done accordingly either on laboratory constructed panels or on existing vintage masonry. The studies were mainly focused on panels made of the same mortar mix and the comparisons were done only based on the applied techniques.

Traditional strengthening techniques offer a suitable method for improving the structural behavior of URM buildings, but there are some limitations such as: time consuming to be applied, reduction of available space, occupancy disturbance, building operation disruption and affecting the aesthetics of the existing wall. Furthermore, the added mass can also increase the earthquake induced inertial forces and may require strengthening of the foundations as well.

Modern strengthening techniques, on the other hand, provide an efficient alternative, as they improve the behavior of masonry elements without altering the dynamic properties of the reinforced structure. As stated earlier, masonry is good to bear compressive stresses but very weak in tension and shear, therefore polymeric materials which are very good in tension should be used for strengthening. Nevertheless, it should be subject of a very careful design, because if the areas subjected to compressive forces are reinforced, it would make this method ineffective.

In conclusion, it should be emphasized that, due to the masonry characteristics, analyzing the structural behavior of URM structures is a challenging task for engineers, it requires a careful experimental testing and a good engineering judgement.

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